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A Quantum Access Network Suitable for Internetworking Optical Network Units

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ABSTRACT Quantum access networks allow a large number of users to access quantum networks, which can be regarded as an important part of the practical application for quantum communication. However, current quantum access networks have not considered as the peer-to-peer multimedia service between optical network units (ONUs) that have become the dominant service in the access networks. Thus, we propose a quantum access network that can support direct quantum and classical ONU–ONU communication by using an N:N splitter. In addition, we improve the efficiency of quantum key distribution (QKD) from both the physical and the data link layer. For the former, we analyze spontaneous Raman scattering (SRS) that is the main impairment source to QKD due to the co-propagation of the classical and quantum signal. Then, we propose a collision-avoiding scheme to reduce the influence of the SRS. For the latter, a dynamic time slot assignment protocol is proposed to reduce discarding secure keys greatly. The two methods are verified by simulations, and the results show that each method can effectively optimize QKD performance.

INDEX TERMS Quantum key distribution, quantum access network, direct ONU–ONU communication, spontaneous Raman scattering.

I. INTRODUCTION

Quantum key distribution (QKD) allows two parties to exchange secret keys which can be used to encrypt data [1]. Its security results from the laws of physics as modeled by quantum mechanics. Compared with traditional encryption whose security relies on computational complexity, it can provide provable protection from all eavesdropping [2], [3]. Since its first introduction in 1984 [1]. many schemes have been performed to promote its practical use [4]–[7].

Optical network is an advanced solution to achieve high speed, long reach, and low latency communication, which plays an important role on the transformation of information networks [8]. QKD integrating in optical network is an promising method for its application. The main challenge of this integration is the noise from classical signals. Many schemes have been proposed to relieve the noise, such as spontaneous Raman scattering (SRS) [9], [10] and four-wave mixing [11].

In order to achieve multi-user access, multiple access technologies are widely studied, such as time division multiple access (TDMA), wavelength division multiple access (WDMA), and code division multiple access [12]–[14]. Also, many networks which support the access of multiple quantum users are proposed [15]–[17]. The concept of quantum access network was firstly introduced and experimentally demonstrated in [18]. The quantum access network allowed multitude of users to access the QKD network through point-to-multipoint connections. They adopted a tree topology to realize the point-to-multipoint connection by using an optical power splitter. Then a quantum secured gigabit optical access network was proposed in [19]. They integrated QKD in gigabit passive optical network (GPON) and considered the SRS which is the main impairment of the QKD.

Recently, multimedia applications such as High-Definition television (HDTV), Internet Protocol television (IPTV), Peer-to-Peer (P2P) video streaming, and Video on Demand (VoD) is becoming more and more popular [20], [21]. And most of access network traffic is related to these P2P applications [22], [23]. In fact, it has been predicted that these multimedia services will represent around 90 percent of global consumer traffic by 2014 [24], [25]. Thus such P2P traffic will be the main challenge for the quantum access networks in the near future. However, direct ONU-ONU communications are

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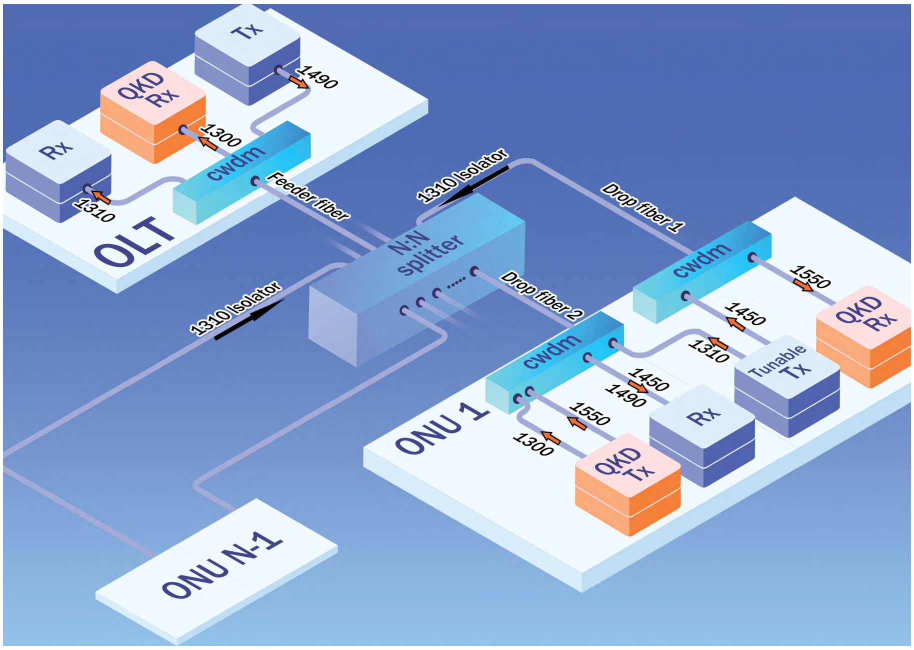

FIGURE 1. System architecture. Tx: Classical transmitter, Rx: Classical receiver, tunable Tx: Tunable transmitter, QKD Tx: QKD transmitter, and QKD Rx: QKD receiver.

not supported in the quantum access networks proposed in [18] and [19]. It means peer-to-peer traffics can only be transmitted from the source ONU to the optical line terminal (OLT) by using the upstream channel. And then the OLT broadcasts the data packets to all ONUs in the downstream channel. The destination ONU receives these data packets while other ONUs discard the packets according to the packet header. This manner of transmission has several shortcomings. Firstly, it occupies both the upstream and the downstream bandwidth which is an inefficient usage of this precious resource. Furthermore the packet delay time of the point-to-point communication will increase significantly due to the ''two-times'' long distance transmission. Besides, both the secure keys between the source ONU and the OLT and those between the OLT and destination ONU are consumed. This is an undesirable waste due to the low generation rate of the secure key. Lastly, if secure communication is required, the security of the OLT must be guaranteed.

Based on the above problems and the classical access network [26]–[29], we propose a quantum access network which can support direct quantum and classical ONU-ONU communication by replacing the traditional 1:N beam splitter with a N:N beam splitter. The architecture we propose can be integrated with existing TDM-based access networks. We analyze the influence of classical signals on quantum signals since the quantum signal and the classical signal are transmitted in a single fiber. QKD between ONU and OLT can be performed normally and can support up to 64 ONUs due to the reasonable wavelength assignment of different signals. QKD between ONUs can also support 64 ONUs with the collision-avoiding scheme we proposed and the secure key rate is on the order of 10^5 b/s. Moreover, we propose a dynamic time slot assignment protocol that can greatly improve the efficiency of QKD. The simulation results show that the consumption of keys that the system can support will increase greatly compared with the static scheme.

II. SYSTEM ARCHITECTURE

Fig. 1 illustrates the system architecture. N-1 ONUs connect to the OLT via an N:N splitter. Each ONU consists of two coarse wavelength division multiplexers (CWDM) connecting different classical and quantum devices. The classical devices are composed of classical transmitter and receiver. The tunable transmitter in ONUs can transmit classical signals at both 1310 nm (upstream channel) and 1450 nm (ONU-ONU channel). And the receiver in ONUs can receive both the ONU-ONU traffic and the downstream traffic because of its broad receiving bandwidth. In the OLT, the classical transmitter can transmit signals at 1490 nm (downstream channel) and the classical receiver can receive the signals at 1310 nm. The quantum devices in each ONU are made up of QKD transmitter and QKD receiver. The QKD transmitter can transmit quantum signals at 1300 nm (used for communicating with OLT) and 1550 nm (used for communicating with other ONU). The quantum receivers in ONUs can receive quantum signals at 1550 nm. In the OLT, only QKD receiver which can receive quantum signal at 1300 nm is installed. The frequency of the synchronization signals are 200 GHz lower than the two types of quantum signals, respectively, which are not shown in the figure. The isolator installed in drop-fiber-1 is used to prevent the upstream data from going back to the ONUs.

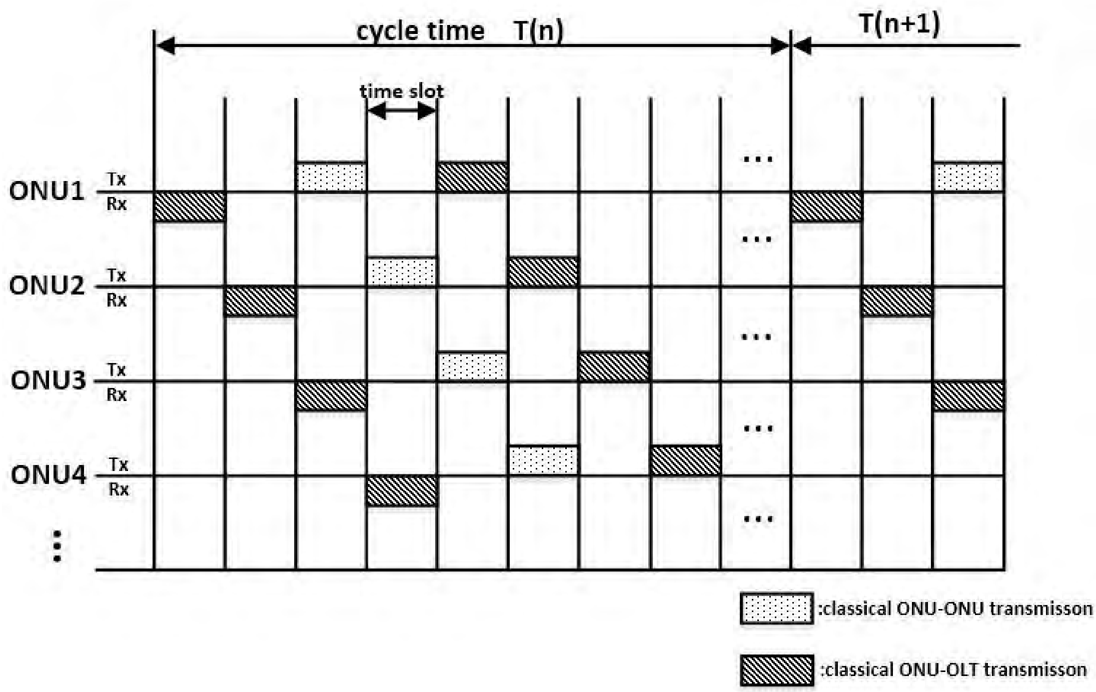

FIGURE 2. Time slot assignment of the classical communication.

In OLT-ONU transmission, upstream classical traffic (at 1310 nm) sent out from an ONU tunable transmitter goes through the splitter and will be received by the receiver in the OLT. Downstream traffic (at 1490 nm) will be broadcast from OLT to all ONUs through the splitter. The destination ONU will receive the packets while other ONUs will discard them. In ONU-ONU communication, classical ONU-ONU traffic (at 1450 nm) will be transmitted into the drop-fiber-1 and will be broadcast to all ONUs through the N:N splitter. Also, the destination ONU will receive the packets according to the packet header while other ONUs will discard them. It leads to a virtual optical star network which facilitates direct ONU-ONU capability.

Likewise, ONU-OLT quantum signals (at 1300 nm) that sent from ONUs go through the splitter and will be detected in the OLT. The wavelength of ONU-OLT quantum signal is set at 1300 nm, since it can avoid the SRS from the classical signal at 1450 nm and 1490 nm. Also, SRS has less impact on quantum signals when the wavelength of quantum signal is 10 nm lower than classical signals. ONU-ONU quantum signals (at 1550 nm) are sent into drop-fiber-1 from ONUs. And will be detected after going through the splitter and drop-fiber-2.

In the OLT-ONU classical transmission, the downstream traffic transmitted from OLT to ONUs is based on time division multiplexing (TDM) as shown in Fig. 2. Upstream transmission is based on the time division multiple access (TDMA) protocol. In ONU-ONU classical transmission, TDMA protocol is also employed. Each ONU is assigned a time slot to transmit ONU-ONU traffic and destination ONU will receive the packets according to the packet header.

Likewise, in ONU-OLT quantum transmission, the transmission protocol is also based on TDMA. In ONU-ONU quantum transmission, the cycle time is equal to the cycle time of classical. And the explicit time slot assignment of it will be discussed in the following sections.

The channel speed in our system is considered to be 1 Gb/s and the time slot for classical communication is 125 μs. In OLT-ONU communication, both quantum and classical transmitters send individual signals at a rate of 1GHz/N in the direction of upstream. The cycle time is $125 \times \mathrm{N}\mu$s. The OLT broadcasts the downstream traffic to all ONUs with the time slot of 125 μs. In ONU-ONU communication, each classical transmitter sends signals based on TDM with the time slot of 125 μs. The cycle time of the quantum transmitters is set to $125 \times \mathrm{N}\mu$s.

III. SPONTANEOUS RAMAN SCATTERING ANALYSIS

The major challenge with the proposed quantum access network is the co-propagation of the low power quantum signals and the high power classical signals in one fiber. Several kinds of impairment source generated by classical signals may damage QKD, such as four-wave mixing, Rayleigh scattering and SRS. There is no obvious four-wave mixing effect in the architecture due to the wavelength assignment [11]. The bandwidth of Rayleigh scattering is very narrow [30]. Thus the Rayleigh noise will not fall into quantum channels due to the wide wavelength spacing between the quantum signals

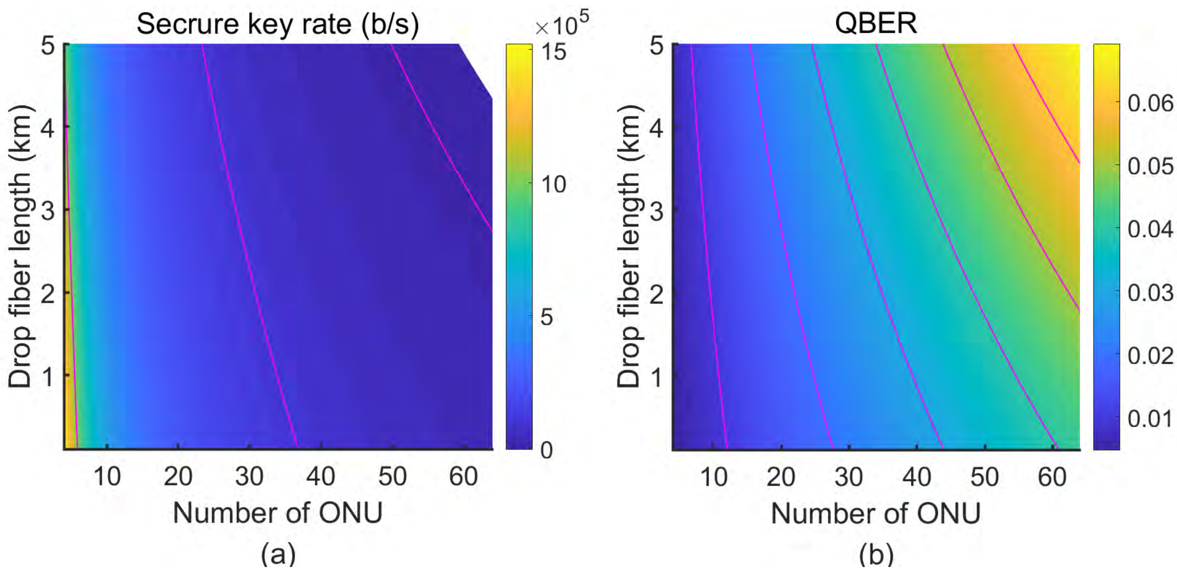

FIGURE 3. The feeder fiber length is set to 14 km. (a) Secure key rate. (b) QBER.

and classical signals, and can be eliminated by CWDM module or filters effectively. The main factor preventing the coexistence of quantum and classical channels is SRS. The spontaneous process converts photons from classical channel into a broad band of wavelengths [31]. It leads to a significant wavelength shift of about 200 nm. Also, the power of the SRS is large enough to affect QKD which makes it the main impairment source to the QKD.

A. ONU-OLT SUBNETWORK

In the ONU-OLT subnetwork, the wavelength of the quantum channel is set at 1300 nm. It is reasonable to neglect the SRS generated by the downstream channel and the ONU-ONU channel since they are far away from the quantum channel in the perspective of wavelength. We take into account the separate contributions of the feeder and drop fibers and the SRS is given by

$$\begin{aligned} P_{ONU-OLT} &= P^f_{drop} + P^f_{feeder} \\ &= \eta_{10} P_{US1} exp(-\alpha_O L_{drop}) L_{drop} \\ &\quad \times exp(-\alpha_O L_{feeder}) A_1 \\ &\quad + \eta_{10} P_{US2} exp(-\alpha_O L_{feeder}) L_{feeder}, \end{aligned} \tag{1}$$

where the P^f_{drop} is the Raman power generated in the drop-fiber-2, P^f_{feeder} is the Raman power generated in the feeder fiber and A_1 is the transmission loss caused by optical devices. The transmission loss is mainly caused by the N:N splitter (The splitter will introduce 3 dB of loss each time the number of ONU is doubled). P_{US1} is the launch power of upstream channel which is adjusted to maintain a received power of −20 dBm (5 dB above the receiver sensitivity specified for GPON class A optics [19], [32]). And P_{US2} is the input power of the feeder fiber corresponding to P_{US1}. The Raman scattering coefficient η_{10} is taken typical value of $4 \times 10^{-9}\ km^{-1}$. α_O is the attenuation coefficient of O-band which is taken the value 0.3 dB/km.

We calculate the quantum bit error rate (QBER) and secure key rate of the entire system, with considering the SRS noise and the dark count, as a function of the number of ONUs and the length of drop fiber.

As can be seen from the Fig. 3, in case that the number of ONUs is lower than 64 and the length of the drop fiber is less than 3 km, the value of QBER is between 2% and 6% and the secure key rate is on the order of 10^4 and 10^5 b/s.

B. ONU-ONU SUBNETWORK

In the ONU-ONU subnetwork, the wavelength of quantum channel is set at 1550 nm. SRS generated by the downstream channel and the ONU-ONU channel will have an impact on QKD. The expression for the Raman power at the input port of the quantum receiver is given by

$$\begin{aligned} P_{ONU-ONU} &= P^b_{drop2-DS} + P^b_{drop2-OO} + P^b_{drop1-OO} \\ &= \frac{\eta_{60} P_{DS1}}{2\alpha_C}[1 - exp(-2\alpha_C L_{drop})]N \\ &\quad \times A_2 exp(-\alpha_C L_{drop}) \\ &\quad + \frac{\eta_{100} P_{OO2}}{2\alpha_C}[1 - exp(-2\alpha_C L_{drop})]N \\ &\quad \times A_2 exp(-\alpha_C L_{drop}) \\ &\quad + \frac{\eta_{100} P_{OO1}}{2\alpha_C}[1 - exp(-2\alpha_C L_{drop})], \end{aligned} \tag{2}$$

where the $P^b_{drop2-DS}$ is the back-scattering Raman power which is generated in the drop-fiber-2 by the downstream traffic, $P^b_{drop2-OO}$ is the back-scattering Raman power generated in the drop-fiber-2 by the ONU-ONU traffic and $P^b_{drop1-OO}$ is the back-scattering Raman power generated in the drop-fiber-1 by the ONU-ONU traffic. A_2 is the

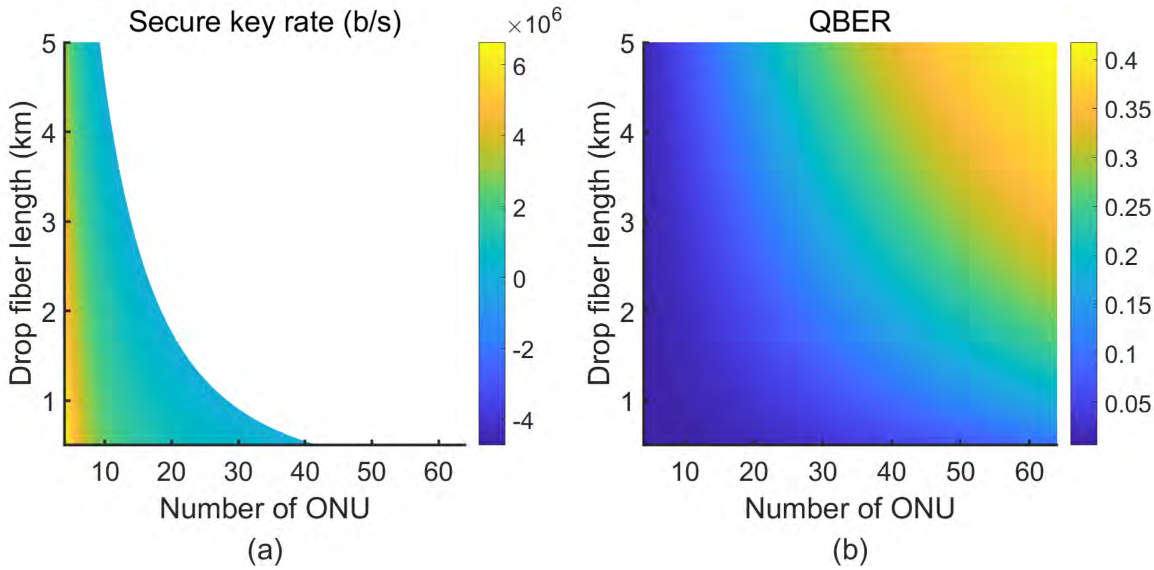

FIGURE 4. **(a) QBER of the ONU-ONU QKD. (b) Secure key rate.**

transmission loss which is caused by optical devices. P_{DS1} is the power of downstream channel at the input port of drop-fiber-2. P_{OO1} and P_{OO2} are the power of ONU-ONU channel at the input port of drop-fiber-2 and drop-fiber-1, respectively. All of them are adjusted to maintain a received power of -20 dBm. The Raman scattering coefficients, η_{60} and η_{100}, are taken typical value of $7 \times 10^{-9}\ km^{-1}$ and $6 \times 10^{-9}\ km^{-1}$.

As shown in Fig. 4, the simulation results are not so satisfactory under this case. Most of the values in Fig. 4(b) are larger than 6%. In Fig. 4(a), the blank part represents that no secure keys can be generated. With the ONU number of 16, the drop fiber length can't be longer than 2 km and the secure key rate is extremely low.

After analyzing the data, we find that the third item, $P^b_{drop1-OO}$, in Eq. (2) is the dominant one. Thus we propose the collision-avoiding scheme to avoid the back-scattering Raman generated in drop-fiber-1. Each ONU will be assigned an ONU number. In the process of QKD, quantum signal will be transmitted from the ONU with smaller ONU number to that with larger ONU number. However, while the ONU with smaller ONU number is transmitting ONU-ONU classical signal, the quantum signal will be transmitted from the ONU with larger ONU number to that with smaller ONU number. In this case, the item $P^b_{drop1-OO}$ is avoided and the performance of QKD is greatly improved. We simulate the QBER and the secure key rate of this scheme and the results are shown in Fig. 5. The secure key rate increases dramatically compared with that in Fig. 4. Most of the values in Fig. 5(a) are in the order of 10^5 b/s. In practical application scenarios, the length of drop fiber usually does not exceed 3 km. Thus the system can even support more than 64 ONUs.

IV. DYNAMIC TIME SLOT ASSIGNMENT PROTOCOL

In Sec. III, we analyze the secure key rate of the network. However, the secure key rate obtained in Sec. III is the maximal value in theory since key pool is not considered [33]. In practical application scenario, secure keys can be stored in the corresponding secret-key memory which is embedded in OLT and each ONU. The secure keys between each pair of secret-key memory can be virtualized into a key pool. However, the capacity of each key pool is limited and the secure keys generated cannot be stalled all. In order to store the generated secure keys as much as possible, we propose the dynamic time slot assignment protocol.

We consider an architecture with 16 ONUs. For classical communication, the link capacity is C = 1 Gb/s and the bit rate of OLT-ONU and ONU-ONU is 62.5 Mb/s for each ONU. The communication is based on TDMA with a time slot of 125 μs, thus the cycle time is 2 ms.

Firstly we propose the conventional static scheme for QKD which means each pair of ONUs transmits quantum signals with equal time in each cycle. The times of key transmissions for the $n-th$ pair of ONUs in one cycle can be represent as

$$K_s(n) = \lfloor \frac{t_c \times F_q}{n_{ONU}} \rfloor, \tag{3}$$

where $K_s(n)$ is the times of key transmissions for the $n-th$ pair of ONUs in one cycle in the static scheme. t_c, F_q and n_{ONU} is the cycle time (2 ms), QKD frequency of the network (10^9 Hz) and the number of ONU pairs, respectively. With the parameters described above, $K_s(n)$ can be expressed as

$$K_s(n) = \lfloor \frac{2 \times 10^6}{120} \rfloor. \tag{4}$$

However, if there are sufficient remaining keys for one pair of ONUs, too many times of key transmission will be a waste. Since secure keys which exceed key pool capacity will be discarded. Therefore we propose the dynamic scheme which takes the dynamic situation into account. In this scheme, the times of key transmissions for the $n-th$ pair of ONUs

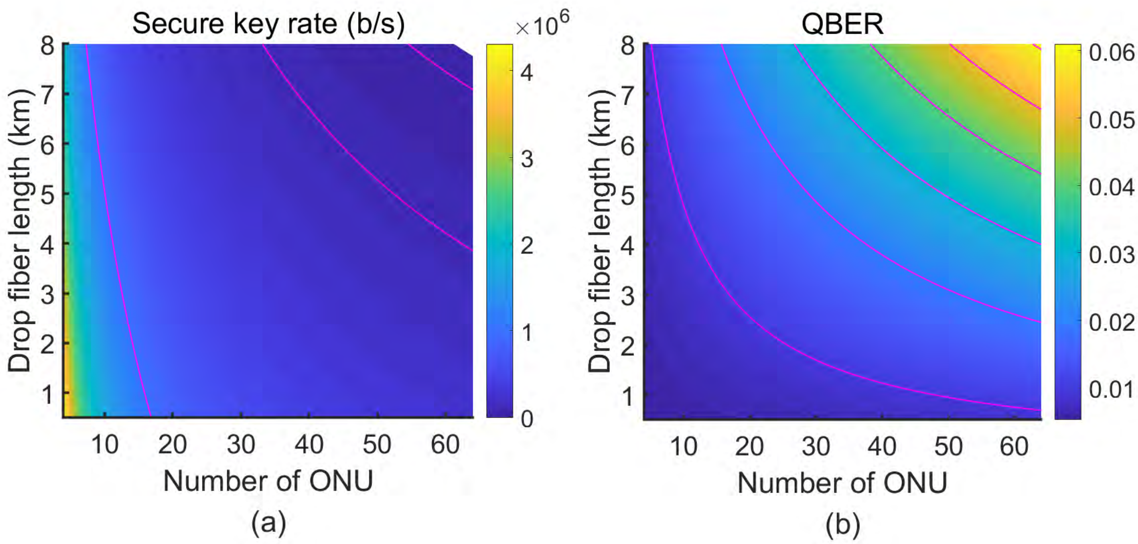

FIGURE 5. (a) Secure key rate without the SRS generated in drop-fiber-1. (b) QBER of the ONU-ONU QKD without the SRS generated in drop-fiber-1.

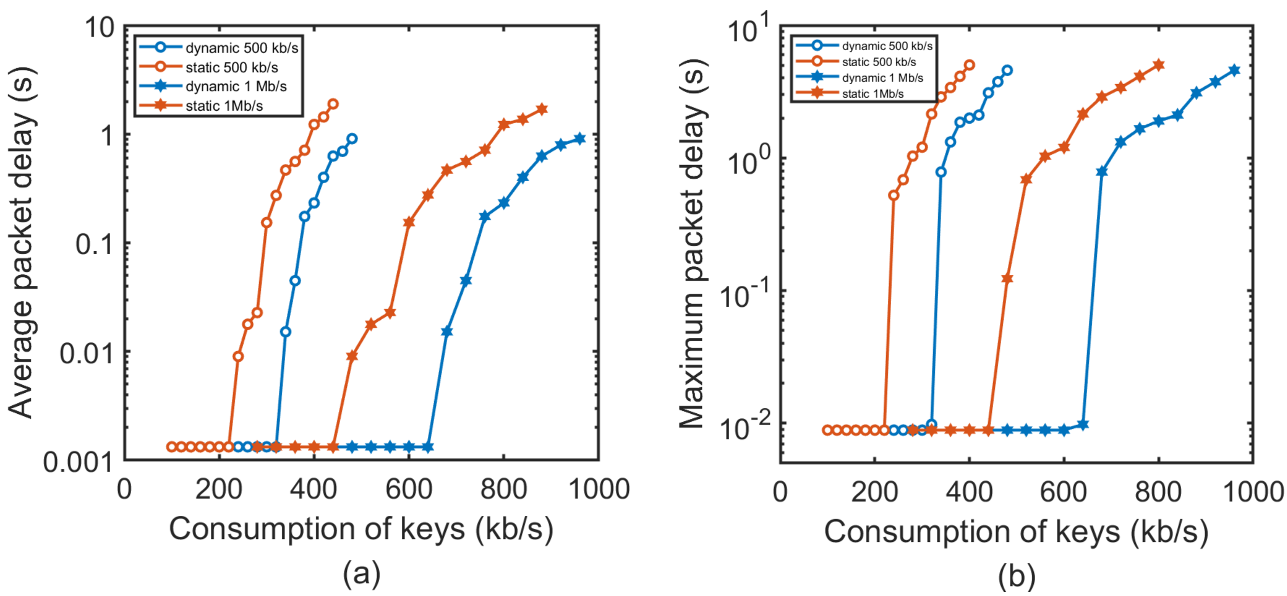

FIGURE 6. (a) Average packet delay as a function of the consumption of the secure key rate. (b) Maximum packet delay.

in one cycle is

$$K_d(n) = \lfloor t_c \times F_q \times \frac{C_p - k_n}{n_{ONU} \times C_p - \sum_n k_n} \rfloor, \quad (5)$$

where C_p is the capacity of key pool, k_n is the remaining keys in the key pool of the $n-th$ pair of ONUs. With the parameters described above, $K_d(n)$ can be expressed as

$$K_d(n) = \lfloor 2 \times 10^6 \times \frac{C_p - k_n}{\frac{(1+15)\times 15}{2} \times C_p - \sum_n k_n} \rfloor. \quad (6)$$

We demonstrate the performance of the dynamic scheme through the simulation. The key transmission times for each pair of ONUs in one cycle time follow the rules shown by Eq. (3) or Eq. (5). The sum of the secure key rate of all ONU pairs is the same as that of the network which is shown in Fig. 5(a). Two sets of simulations are done with the secure key rates of 500 and 1000 kb/s for the whole ONU pairs. The traffic which consumes secure keys is modeled as Poisson arrivals with average inter-arrival times for 0.5 ms and the length of service obeys a negative exponential distribution, which means the secure keys are consumed following Poisson distribution. The C_p for each pair of ONUs is set to be 20 kb. The information of remaining key is sent to the OLT in the upstream traffic and the information about the times of key

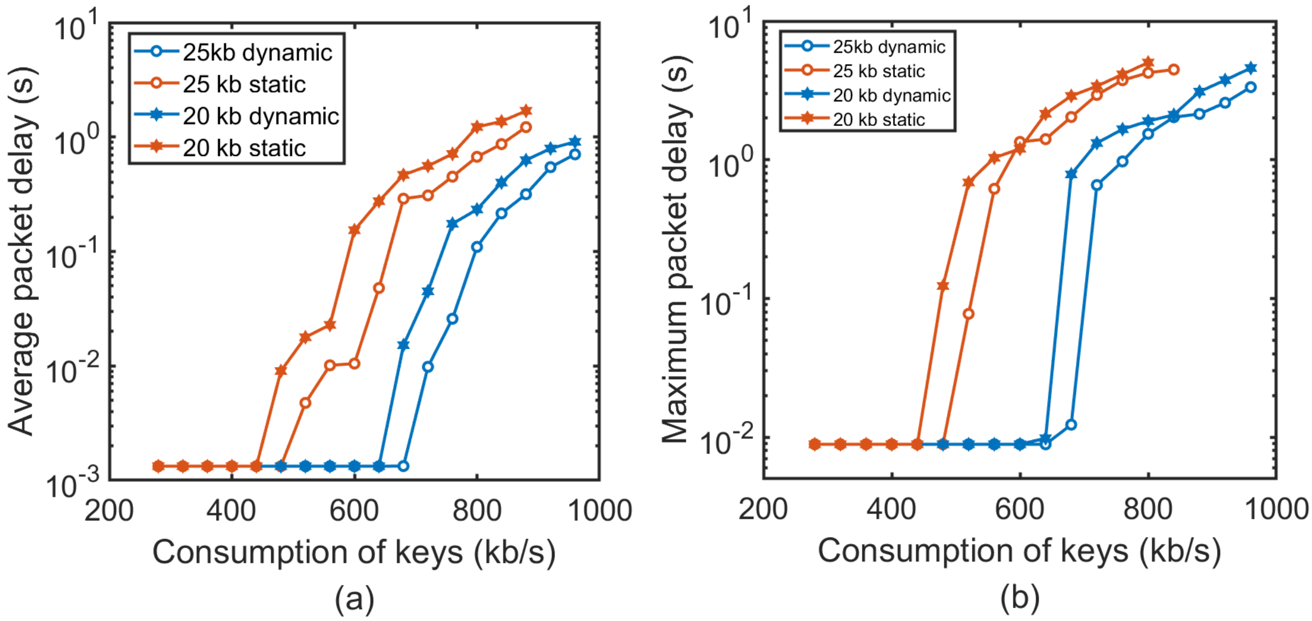

FIGURE 7. (a) Average packet delay as a function of the consumption of the secure key rate. (b) Maximum packet delay.

transmission is sent to the ONUs through the downstream traffic. The data of post-processing is also transmitting in this way. The ONU-OLT communication is not considered in this simulation. Then we simulate the average packet delay (the waiting time in the source ONU) for the dynamic scheme and the static scheme.

The simulation results are shown in Fig. 6. For the secure key rate of 500 kb/s, the average packet delay begins to increase when the consumption of the key reaches 260 kb/s in the static scheme. When the secure key is consumed about 300 kb/s, the average delay time is on the order of 0.1 s. However, the performance is improved considerably in the dynamic scheme. The average packet delay can be maintained at a very low level when the consumption of key is below 320 kb/s. And the average delay is on the order of 0.1 s when the consumption of key is about 360 kb/s. For the secure key rate of 1 Mb/s, the dynamic scheme also achieves smaller packet delay than static scheme with the same consumption of keys. The corresponding maximum packet delay is shown In Fig. 6(b) and similar trends can be obtained. With the same secure key rate, the dynamic scheme always shows better performance than the static scheme. The performance of dynamic scheme improves significantly because lots of keys are discarded in the static scheme when the key pool is full, while fewer keys will be discarded in the dynamic scheme.

The C_p is another key parameter affecting the performance of the network. Thus another set of simulation is done with the key pool capacity of 25 kb for each pair of ONUs. The results are shown in Fig. 7. Under the situation of other conditions being equal, the packet delay is smaller with the key pool of 25 kb. Also, the performance of dynamic scheme is always better than that of static scheme under the same condition.

V. CONCLUSION

We propose a quantum access network that can support direct quantum and classical ONU-ONU communication by using a N:N splitter. The system can support more than 64 ONUs with drop fiber of 7 km by using the proposed collision-avoiding scheme. The secure key rate is on the order of 10^5 b/s. Of course, more ONUs can be supported in the future with more advanced QKD equipment. The proposed dynamic time slot assignment protocol can reduce the time delay significantly and the consumption of keys that the system can support will increase greatly with the protocol because it can reduce discarding secure keys. The quantum access network is more suitable for network with more peer-to-peer service such as a university campus, business building and residential apartment block, and provides feasibility for potential applications of QKD.

APPENDIX A
SPONTANEOUS RAMAN SCATTERING

The SRS occurs in both the forward and backward directions. The forward-scattering Raman power generated by a single classical channel can be described by Ref. 34

$$P^f_{raman} = \frac{\eta P}{\alpha_r - \alpha_p}[exp(-\alpha_p L) - exp(-\alpha_r L)], \quad (7)$$

where L is the length of fiber, P is the launch power of the classical channel, α_p is the loss coefficient for the classical channel, α_r is the fiber loss coefficient for the SRS light and η is a proportional constant. If $\alpha_p \approx \alpha_r$, the forward-scattering Raman power is approximated as

$$P^f_{raman} \approx \eta P exp(-\alpha_p L)L. \quad (8)$$

Similarly, the back-scattering Raman power is given by Ref. 34

$$P_{raman}^{b} = \frac{\eta P}{\alpha_r + \alpha_p} exp(-\alpha_p L)[exp(\alpha_p L) - exp(-\alpha_r L)]. \quad (9)$$

If $\alpha_p \approx \alpha_r$, the back-scattering Raman power is approximated as

$$P_{raman}^{b} = \frac{\eta P}{2\alpha_p} [1 - exp(-2\alpha_p L)]. \quad (10)$$

Raman photon number per time window at a quantum channel receiver can be written as

$$d_{raman} = P_{raman} \times \delta f \times \delta t \times \frac{1}{h \times fre}, \quad (11)$$

where δf is the bandwidth of the quantum channel, δt is the time window of the detection, h $(6.63 \times 10^{-34} J \cdot s)$ is the Planck's constant, and fre is the center frequency of the quantum channel. In our numerical simulation, δf is set to 0.14 nm and δt is set to 127 ps.

APPENDIX B
SECURE KEY RATE AND QBER

We implement the standard BB84 protocol with decoy states in our system [1], [35], [36]. The secure key rate is lower bounded by [35], [36]

$$\begin{aligned} R &= \frac{1}{2}[Q_1[1 - H(e_1)] - f(E_\mu)Q_\mu H(E_\mu)], \\ Q_\mu &= p_\mu^a(1 - p_\mu^b) + (1 - p_\mu^a)p_\mu^b, \\ E_\mu Q_\mu &= e_d p_\mu^a(1 - p_\mu^b) + (1 - e_d)(1 - p_\mu^a)p_\mu^b, \\ p_\mu^a &= 1 - e^{-\mu\eta}(1 - Y_0) + e^{-\mu\eta}(1 - Y_0)P_{ap}, \\ p_\mu^b &= Y_0 + (1 - Y_0)P_{ap}, \end{aligned} \quad (12)$$

where $H(p) = -plog_2 p - (1-p)log_2(1-p)$, for $0 \le p \le 1$, $f(E_{\hat{\imath}\mathrm{ij}})$ is the error correction efficiency which is set to 1.2. Q_1 and e_1 are the gain and the error rate of a single-photon state. Q_μ and E_μ are the overall gain and the quantum bit error rate, respectively. μ is the average number of photons in a single pulse and η is the overall transmission of the channel. e_d (0.01) represents the misalignment error. P_{pa} is the probability of the afterpulse which is set to 5%. Y_0 is the yield of the vacuum state which includes the dark current $(2 \times 10^{-6}$ dark counts per gate) of the single photon detector and the Raman noise in our system.

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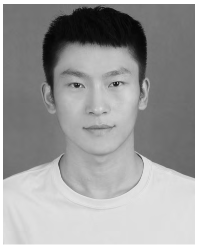

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