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Ring-based PON supporting multiple optical private networks using OCDMA technique

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Abstract This work is a novel attempt to provide local communications for multiple optical private networks (PNs) within ring-based passive optical network (PON). In order to improve network throughput performance, PNs traffic is decentralized from PON traffic let no extra traffic management into optical line terminal (OLT). To achieve multiple secure optical private networking over ring-based PON layout, optical code division multiple access (OCDMA) technique is applied. This technique leads to interconnect optical network units (ONUs) in the same PN sharing the same codeword while other PNs benefiting from different codewords. This scheme can be used in access networks to establish discrete communications between different sites in an enterprise or a university campus or even a residential accommodation. The proposed network architecture is then set up and its bit error rate performance is experimentally demonstrated. Finally, the network scalability and throughput performance of the proposed scheme are analyzed.

Keywords Optical access networks · PON · Optical CDMA · Ring topology

1 Introduction

Virtual private networks (VPNs) share the public network infrastructure, for example Internet, to establish a discrete and secure communication using logical virtual links at second,

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third or even higher layer of open systems interconnection (OSI) model. However, the security and the quality of service (QoS) are the main critical issues in the deployment of current VPNs (VPN Consortium and VPN technologies 2008). Optical private networking at physical layer over PON has been proposed to provide a local inter-connection between ONUs in optical access networks (Chae et al. 1999; Tran et al. 2006). The introduction of optical PNs overlaid on PON infrastructure reflected on a policy of reducing costs associated with a new network infrastructure. This solution results in higher bandwidth and enhanced security via physical dedicated links. Furthermore, by separating the optical PN traffic from PON traffic, as a decentralized solution, the total network throughput performance is increased (Su et al. 2005). In other words, PN data circulation between local sites such as peer-to-peer applications both video and data sharing, teleconferencing and information broadcasting will not add extra traffic management into OLT.

PON has been commercially deployed as a star topology; however a ring-based PON is well suited for distributing networks. Ring topology is interesting as a robust infrastructure behind many local area networks (LANs) and metropolitan area networks (MANs) architecture for reliable communications (Medard and Lumetta 2001). Moreover, ring topology can take advantage of protection against failures in optical distribution networks. Ring-based PON architecture using Ethernet technology has been employed to support local private networking among ONUs (Hossain et al. 2006; Pathak et al. 2009). Although, this concept cannot support multiple optical PNs within a PON layout. Multiple PNs can create different groups of inter-communication within a PON infrastructures (Nadarajah et al. 2006; Zhao and Chan 2007; Tian et al. 2007; Gharaei et al. 2010). We propose a ring-based PON architecture supporting multiple optical private networking using OCDMA technique. OCDMA can provide an all-optical processing, potential information security, protocol transparency, asynchronous access ability and simplified network control for access networks (Stok and Sargent 2002; Shake 2005). Our proposed system let multiple PNs access to the medium asynchronously by assigning different codewords to PNs with an enhanced security level. In other words, different inter-connected nodes are established in the ring without the traffic routing at OLT. In this paper we demonstrate experimentally two-PNs over ring-based PON operating at the data bit rate of 625 Mbps. Subsequently, the network scalability and throughput performance of this architecture supporting multiple optical private networking are analyzed.

The rest of the paper is organized as follows: Sect. 2 describes principles of proposed architecture and the functionality of multiple optical PNs over ring-based PON. In Sect. 3, an experimental set up is prepared to demonstrate two-PNs over ring-based PON. In Sect. 4, the network analysis on optical power budget determines the maximum number of ONUs in this scheme. Then the total network throughput performance is analyzed by changing the code length used in this system. Finally we offer some concluding remarks.

2 Architecture and principles

Figure 1 shows a ring-based PON architecture providing multiple inter-networking among ONUs by means of private networking. In this architecture OLT is connected to ONUs via a feeder fiber, a remote node (RN) and short distance distribution fibers. There are two separate functionalities in this scheme: The first one is PON up/downstream transmission between OLT and multiple ONUs which is performed at 1,490 nm wavelength in downstream direction and at 1,310 nm in upstream direction, respectively. The second functionality is optical

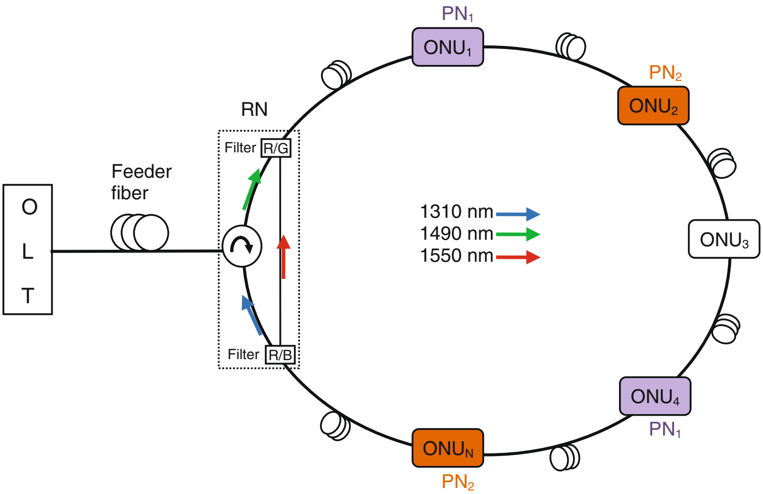

Fig. 1 Architecture of ring-based PON supporting multiple optical private networks

private networking well separated from PON by locating its 1,550 nm optical transmitter in ONUs. The idea is to provide multiple groups of communication in physical layer between ONUs independent of OLT.

PON up/downstream signals are multiplexed based on time division multiplexing (TDM) technique. PON downstream signals are generated from a transmitter at OLT towards ONUs which pass through each ONU to arrive to the destined ONU. For PON upstream, OLT allocates an appropriate time slot to each ONU, and during each time slot an ONU can forward its data toward OLT. It means that, it is passed by other ONUs to reach to the OLT. Generally, OLT and ONUs exchange control messages (REPORT and GATE messages) in order to grant a time slot to the ONU, which clarifying the start and duration of upstream transmission by an ONU. The control messages follow multi-point control protocol (MPCP) which is defined by the IEEE 802.3ah task force (IEEE 802.3ah 2004). At the end of the ring (after the last ONU), the downstream signal is removed and the upstream signal is routed toward OLT.

By using asynchronous OCDMA technique, multiple groups of PN are established without needing a new protocol to prevent from collision. Furthermore, enhanced security has often been cited as an important benefit of OCDMA signaling. Because each user's bit is encrypted by a given sequence of pulses into an optical fiber and it cannot be detected without the matched decoder (Cincotti et al. 2009). The data bit rate of ring-based PON like the star-based PON depends on the number of ONUs in the PON, since the total bandwidth is shared between ONUs. Furthermore, the number of associated ONUs in the ring depends on the optical power budget constraint. The data bit rate of private networking in our system depends on the OCDMA system. Here we use direct sequence optical code division multiple access (DS-OCDMA) system, which is a low cost time-based coding system providing a high bit rate for PN communication (Fsaifes et al. 2007). In this system, each PN is encoded with a given sequence of temporal pulses.

In accordance with codeword allocation in PN communication, different ONUs belonging to the same codeword can establish a private networking. In other words, PNs with unmatched en/decoders are unable to detect the given data. For example, the ONU_1 and ONU_4 belong

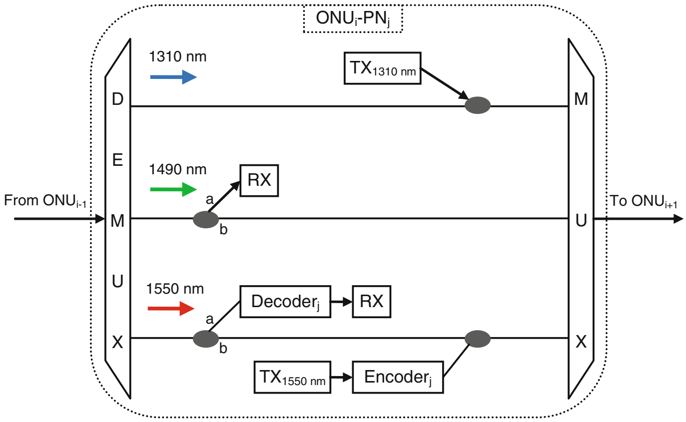

Fig. 2 Inside architecture of $\mathrm{ONU_i - PN_j}$

to the same private network (PN_1), possess the same codeword, and the other ONUs are potentially unable to decode their private data. Furthermore, in this architecture, it is possible to find an ONU (for instance ONU_3), which does not belong to any PN, with no assigned codeword. It is pointed out that, when the number of simultaneous PN increases, the multiple access interference (MAI) effect becomes a significant limiting factor (Ghafouri-Shiraz et al. 2007). This is due to the superimposition of different encoded users data within a chip time duration at detection process.

RN is applied for wavelength routing in the ring. PON downstream signals, after traversing the last ONU in the ring, are eliminated. While, PON upstream signals are recirculated toward OLT and private networking signals are permitted to circulate in the ring. Therefore, after the last ONU, a R/B filter is used to redirect the 1,310 nm wavelength to OLT and recirculate 1,550 nm wavelength in the ring.

Figure 2 depicts the inside architecture of ONU_i supporting PN_j and conventional PON up/downstream functionalities. Each ONU is provided with standard equipments for PON up/downstream communication and upgraded with en/decoding devices for PN communication. PN and PON datastream data from ONU_{i-1} is demultiplexed to three proper wavelengths, respectively. The PON downstream signal ($\lambda = 1,490\,\text{nm}$) passes through a splitter. Only a% of the optical signal power is received by the photodetector and the rest (b%) is multiplexed with other signals and is then launched to the subsequent ONU. Normally, it is anticipated to have $a < b$, to let data circulate with sufficient optical power. Furthermore, PON upstream signal ($\lambda = 1,310$ nm) can be added if the time slot has been before allocated. On the other hand, a% of PN data ($\lambda = 1,550$ nm) is decoded and received by a photodiode, while b% is multiplexed by other signals to ONU_{i+1}. It is pointed out that, ONUs within the same PN, can exchange their private messages using the encoder applied in the given ONU. To prevent collision between ONUs in the same PN, TDMA protocol can be used. However, it will not cause a collision with other PNs data since different codewords have been used. Therefore, this architecture provides multiple inter-ONU communications in which ONUs belonging to the same private network, receive the same codeword and they can communicate with each other in the ring with an enhanced security level.

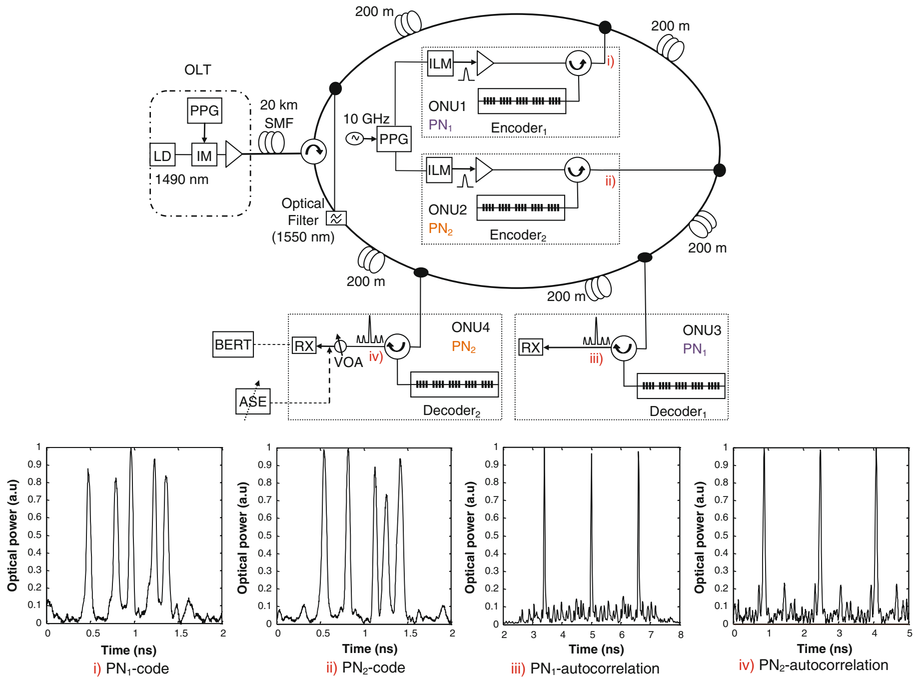

Fig. 3 Experimental setup supporting 2 PNs in the ring (PPG: pulse pattern generator, IM: intensity modulator, VOA: variable optical attenuator, ASE: amplied spontaneous emission). **i** $PN_1(Encoder_1)$: 10000001000100000100010000. **ii** $PN_2(Encoder_2)$: 100000100000001001000010000. **iii** Autocorrelation function of PN_1. **iv** Autocorrelation function of PN_2

3 Experiment and results

3.1 Experimental setup

Figure 3 shows the experimental setup for the ring-based PNs over PON. At OLT, a DFB laser at 1,490 nm wavelength is used for generating PON downstream data. Two PNs, totally consist of four ONUs, have been employed in the ring using 200 m single mode fiber (SMF) between ONUs. An ILM, DFB laser monolithically integrated with electro-absorption modulator, is used at 1550.55 nm wavelength in the ONU as a light source for private networking.

We employ direct sequence OCDMA technique for PN coding in which PN data bit is encoded with a given sequence of temporal pulses. The number of PNs on the ring not only depends on the code multiplexing capacity, but also depends on the correlation properties of the code family. Thus, sparser quadratic congruence (QC) codes with non-periodic structure have been used with agreeable correlation properties which result in less sensitivity to interferometric perturbations (Fsaifes et al. 2008). We use QC codes with the prime number of five ($p = 5$), which leads to have maximum 4 PNs at the data bit rate of 625 Mbps. However, in this experiment we have just taken 2 PNs into the consideration.

Here PN data generation and circulation are illustrated. The return to zero (RZ) pulse train of full width at half maximum (FWHM) of 50 ps is modulated with a pseudo random binary sequence (PRBS) signal at 625 Mbps data bit rate per user with a pulse ratio of 1:16. The pulse train is then encoded with QC codes in each PN employing superstructured fiber Bragg

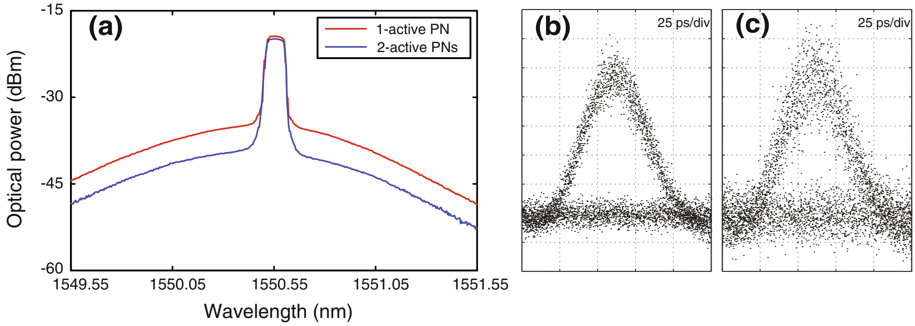

Fig. 4 **a** Experimental OSNR measurement. **b** Eye diagram of 1-active PN in the ring. **c** Eye diagram of 2-active PNs in the ring

gratings (S-FBGs) encoders generating an on-off keying (OOK) codeword. To have a perfect coding process, the output impulse of ILM should be at the same wavelength as the Bragg wavelength of S-FBG en/decoders. The encoding pulse is recirculated to the third port of the circulator and finally routed to the ring via a 3 dB coupler. In this experiment, for example, $ONU_1 - PN_1$ is in transmission mode while $ONU_3 - PN_1$ is at the reception mode. At the reception stage, only 10 % of PN signal is dropped and the rest circulate as a main branch in the ring. The encoded data is passed through the S-FBG based decoder to construct the autocorrelation function which is the sum of the different optical powers of all pulses to be combined within one chip time duration. In Fig. 3i, ii, temporal responses of the en/decoders are presented which show the asynchronous nature of coding in our system. At last, the decoded signal of a PN consists of the autocorrelation peak and MAI noise is received by a PIN-FET photodetector. It is noted that, MAI and beat noise are the main limiting factors in this coherent OCDMA system which degrade the bit error rate (BER) performance. At the end of the ring, a bandpass filter is used at the wavelength of 1,550 nm to stop PON downstream signals.

3.2 Experimental results

Figure 4a shows optical signal power and associated noise power received on an optical spectrum analyzer (OSA), in order to calculate required optical signal to noise ratio (OSNR) for a specified BER performance. It is pointed out that OSA is adjusted with a resolution bandwidth of 0.1 nm. For instance, 1-active PN in the ring needs an OSNR of 19 dB while 2-active PNs need 26 dB for achieving a BER of 10^{-8}. Figure 4b represents the corresponding received signals from 1-active PN in the ring without MAI and beating noise. Figure 4c shows the received signals from 2-active PNs with eye degradation. The noise distribution in this case is increased for both the "0" and "1" bits, which is the consequence of interferometric perturbation. We point out that, the large spectral spacing between PON and PN signals permits to neglect crosstalk effects by using a narrow band filter.

Figure 5 shows the measured BER performance for two configurations. BER is measured as a function of OSNR with the resolution bandwidth of 0.1 nm. The noise in this setup is generated from an amplified spontaneous emission (ASE) broadband source. We have successfully achieved a BER of 10^{-9} with the OSNR of 27 dB when two PNs are active in the ring. The degradation of BER performance after adding the second PN is due to MAI and beating noise between PNs. In order to bring into play a higher number of PNs, we can

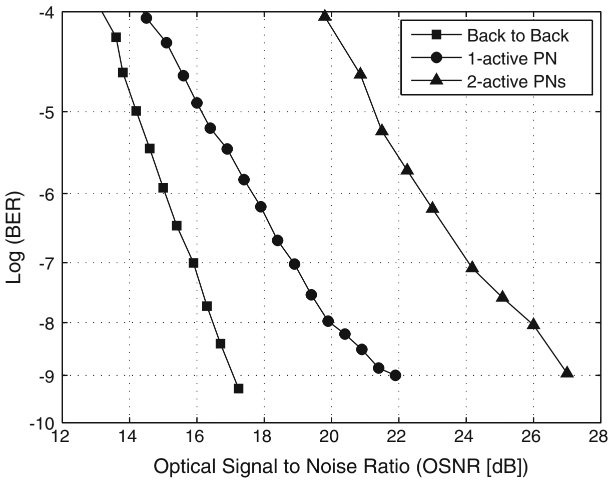

Fig. 5 Measured BER performance for ring-based PON supporting 2 PNs

use longer codes with good correlation proprieties. Although, in this case, optical threshold-er should be used to eliminate interferometric perturbation and enhance BER performance (Wang et al. 2005).

4 Network analysis

4.1 Network scalability

Using ring topology limits the optical power budget (PB), since downstream, upstream and PNs signals are recirculated at each node (ONU). Thus, optical power budget should be high enough to cover the optical distribution network (ODN) losses. Here we analyze the network architecture by means of power budget and network scalability. We consider N ONUs connected to the OLT via 20 km feeder fiber, supporting maximum $(N/2)$ PNs in the ring. A typical 200 m distribution fiber length is taken into consideration between ONUs in the ring which makes the last ONU (ONU_N), $20+(0.2)N$ km away from OLT in the downstream direction. In this architecture, ODN losses are due to the fiber, circulators, multiplexers and splitters losses. To evaluate the optical PB, we consider commercial device losses. Table 1, summarizes the optical losses and power management in the proposed network architecture.

The insertion losses of PON and PN signals as a function of ONU numbers are calculated. Receiver sensitivity, $\mathrm{RX}_{\mathrm{sen}}$, is defined as the minimum optical power required to yield a bit error rate of 10^{-9}. In this Table, power margin is defined as the difference between the received optical power and the minimum optical power required by the receiver to achieve the standard BER performance. Note that, the network scalability is considered for the maximum insertion loss case which is private networking in this case.

Figure 6 shows the network scalability of ring-based PNs over PON for different splitting ratio (a/b). As the number of ONUs is increased in the ring, ODN losses are also increased which limits the PON and PN communication performance. The comparison between three splitting ratios illustrates that in a low network dimensioning, the usage of 0.5/0.5 or 0.2/0.8 splitting ratio is more convenient while in a higher network dimensioning, the 0.1/0.9 is

Table 1 Power budget in the ring-based PON supporting multiple PNs

Parameter	Value
a/b coupler	$10\log(a) - 10\log(b)$ dB
Laser optical power	5 dBm
Fiber loss	0.2 dB/km
Mux/Demux loss	1.2 dB
Circulator loss	1.4 dB
R/B filter loss	0.7 dB
Amplifier nominal output power	13 dBm
Max. ODN loss: Class A–B–C	(20–25–30) dB
PON insertion loss (IL_{PON})	$6.1 + 10\log(a) + (1.2 + 10\log(b))N$ dB
PN insertion loss (IL_{PN})	$1.4 + 10\log(a) + (4.2 + 10\log(b))N$ dB
Power margin	$18 - RX_{sen} - IL_{PN}$

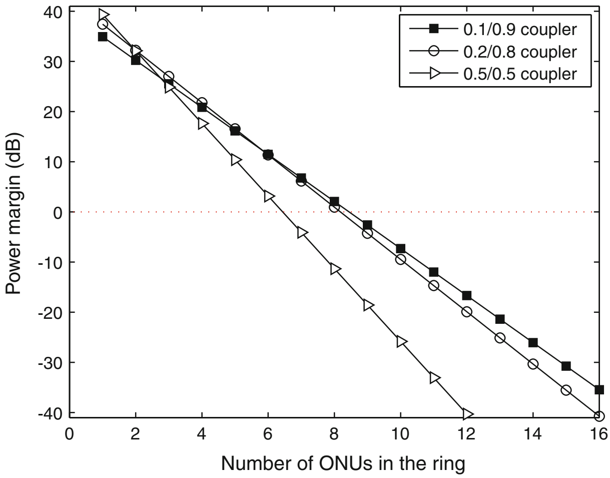

Fig. 6 Network scalability for multiple PNs over ring-based PON using different splitting ratio

more appropriate. Because, a higher portion of signal is recirculated to the next ONU. The ring-based PNs over PON can achieve a 8 ONUs using a 0.1/0.9 splitting ratio with a power margin of 2 dB, while it is the same value using 0.2/0.8 splitting ratio with 0.5 dB power margin. However, a system consisting of more than 8 ONUs in the ring does not have adequate power margin for data transmission and requires more power budget.

4.2 Network throughput

Optical PN over PON as a decentralized solution, can improve throughput performance of conventional centralized PON. We consider maximum 8 ONUs with multiple PNs over ring-based-PON, with PON data rate of 1.25 Gbps. In TDM PON, this data bit rate is shared

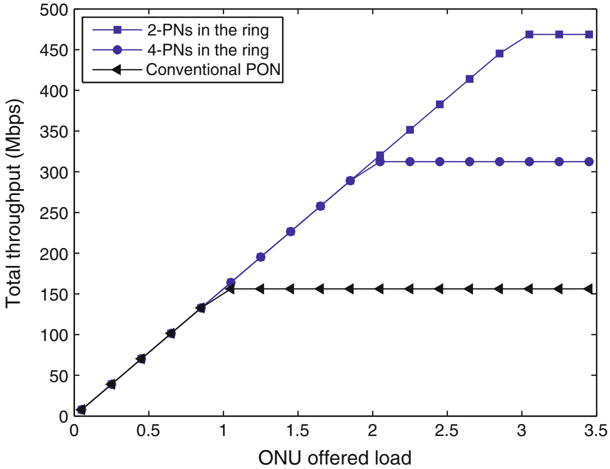

Fig. 7 Throughput performance of decentralized PNs over PON

between 8 ONUs which results in 156 Mbps data bit rate per ONU. PN default data bit rate is 625 Mbps supporting maximum 4 PNs using QC codes. There are two common scenarios: 2-PNs or 4-PNs over 8 ONUs, respectively. Figure 7 compares total throughput performance of the proposed scheme supporting 2-PNs and subsequently 4-PNS with conventional PON throughput. The PN throughput is given by $1/(T_c.L.K)$, where T_c is the chip time duration in a code sequence, L is OCDMA code length, and K is the number of ONUs within a PN. The QC code length is $L = p^2$, where p is the prime number. If we consider four ONUs within a PN, a QC code with $p = 5$ must be chosen since the multiplexing capacity is equal to $p - 1$. The total network throughput consists of PON and PN throughput can be about three times of the conventional PON system. Since the code capacity in DS-OCDMA system depends on the code length, a higher number of PNs results in a lower throughput. However, we have used a system with the same code length which results in the same data bit rate. PN groups can be increased by bringing into play higher multiplexing capacity codes with higher lengths; however, PN throughput is decreased. Furthermore, higher PNs also mean higher MAI level which degrade BER performance. In other words, the proposed network throughput is a compromise between the number of PNs and the OCDMA code length. Finally, the result shows the improved throughput performance of proposed decentralized scheme compared to conventional PON system.

5 Conclusion

The recent growths of the peer to peer applications both video and data sharing for inter-building applications, different enterprise sites or between university campuses, do not need necessarily to add extra traffic management into OLT. we propose a novel decentralized scheme supporting multiple optical private networking over ring-based PON. Optical PNs are established over local networks within a same ring-based PON infrastructure to offer new services supporting a secure inter-connection transmission. The simultaneous transmission of PNs data are available using asynchronous OCDMA technique. As a result, different ONUs belonging to the same PN, communicate with each other sharing the same codeword. We have demonstrated the feasibility of 2-active PNs over ring at 625 Mbps, respectively. Finally, separating PN data from PON data as a decentralized solution leads to decrease the extra traffic loads on OLT and consequently increases the total network throughput performance.

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