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Fiber-to-the-Home System with Remote Repeater

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1. Introduction

In the last few years, there has been rapid deployment of fixed wireline access networks around the world based on fiber-to-the-home (FTTH) architecture. Passive optical network (PON) is emerging as the most promising FTTH technology due to the minimal use of optical transceivers and fiber deployment, and the use of passive outside plant (OSP) (Dixit, 2003; Kettler et al., 2000; Kramer et al., 2002). However, large scale PON deployment is to some degree still limited by the high cost of the customer's optical network unit (ONU), which contains a costly laser transmitter. The active optical network (AON) architecture is one potential solution that can reduce the ONU cost by utilizing low-cost vertical cavity surface emitting laser (VCSEL) based transmitters. However, this system requires an Ethernet switch at the remote node, which is expensive in terms of cost and maintenance, and needs additional transceiver per customer. Another drawback of traditional PON systems is that it has a split ratio limitation of 1:32, which makes it harder and much more expensive to upgrade the network once more customers are connected.

In this book chapter, a FTTH system to reduce the ONU transmitter cost based on the use of an upstream repeater at the remote node is reported. The repeater consists of standard PON transmitter and receiver and therefore, does not significantly increase the overall system cost. Moreover, by utilizing bidirectional Ethernet PON (EPON) transceiver modules to regenerate the downstream signals as well as the upstream signals, we are able to extend the feeder fiber reach to 60 km and split ratio of the FTTH system to 1:256. The repeater-based system is demonstrated for both standard EPON-based FTTH and extended FTTH systems and shows insignificant performance penalty.

In order to achieve higher user count and longer range coverage in the access network, the repeater-based FTTH system can be cascaded in series. This will result in a lower network installation cost per customer, especially when FTTH take-up rate is low. In this chapter, we also investigate the jitter performance of cascaded repeater-based FTTH architectures via a recirculating loop. Our demonstration shows that we can achieve up to 4 regeneration loops with insignificant penalty and the total timing jitter is within the IEEE EPON standard requirement.

With the presence of the active repeater at the remote node of a FTTH system, we can provide additional functionalities for the network including video service delivery and local

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internetworking. These systems will be investigated and presented in this chapter together with an economic study of the repeater-based FTTH system compared with other technologies.

2. FTTH system with remote repeater

A schematic of the proposed FTTH architecture with an upstream repeater is shown in Fig. 1 (Tran et al., 2006b). In this architecture, a conventional 1×N star coupler (SC) is replaced by a 2×N SC. One arm of the SC on the optical line terminal (OLT) side is connected to the remote repeater, which could be at the same location as the SC or at a different location for access to commercial power lines with a battery back-up. The other arm of the SC is to transmit downstream signals through the SC and bypass the remote repeater. An isolator is installed on this downstream path to prevent upstream signals from entering. The downstream and upstream signals are separated/combined using a coarse wavelength division multiplexer (CWDM). The upstream signals can be 2R or 3R regenerated at the remote repeater using a burst-mode receiver (BMR), a burst-mode transmitter (BMT) and/or a clock-data recovery (CDR) module. The BMR and BMT can have the same specification as the OLT-receiver and ONU-transmitter, respectively. The CDR should be able to recover the clock and data at a rate of the PON system.

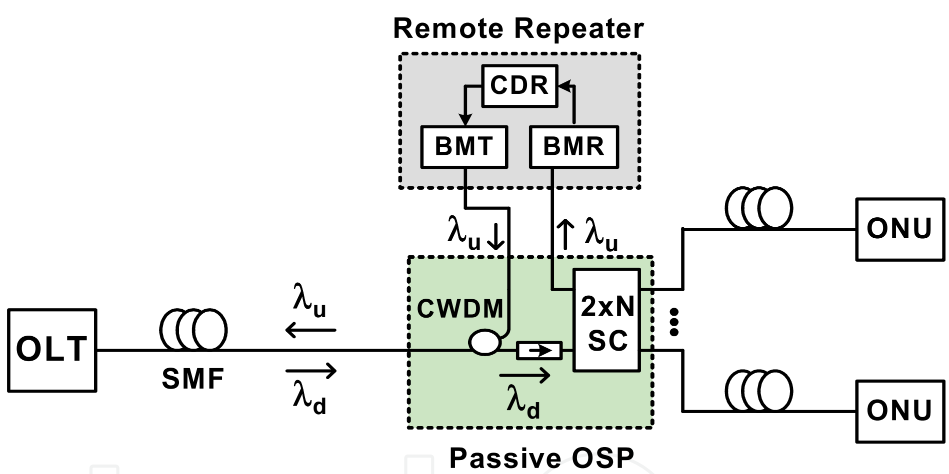


Fig. 1. FTTH system with upstream repeater.

The use of an upstream repeater provides the opportunity for much lower cost implementation of ONU using low power and low cost optical transmitters, such as 0.8/1.3/1.55 μm VCSEL-based transmitters. The ONU transmitters will now need much less output power (up to 10 dB lower) than standard PON system due to feeder fiber and OLT coupling losses. The use of simple and standard PON transceivers at the repeater significantly saves cost, maintenance expenses and power compared to an Ethernet switch as in the case of the AON architecture. Our proposed technique uses the conventional PON fiber plant for both downstream and upstream transmissions. Moreover, it is compatible with any existing media access control (MAC) protocols in the conventional PON systems as the repeater simply regenerates the upstream signals without any modification to the internal frame structure. Another advantage of our proposed FTTH system is that the downstream signals need not to be regenerated at the remote repeater and as a result, downstream channel can be upgraded without any change in the repeater allowing broadcast services to be transmitted transparently through the 1.55 μm wavelength window. PON transmitter and receiver are usually commercially available as a single bidirectional transceiver (TRX) unit. By utilizing the bidirectional property of the transceiver, we can achieve regeneration on the downstream path as well as the upstream path. This downstream regeneration enables the feeder fiber length and the split ratio at the SC to be increased, which in turn extends the coverage area of the PON system. This can offer cost effective broadband service delivery by removing the need for a separate metro network and connecting users directly to core nodes, similar to the long-reach PON structure reported in (Nesset et al., 2005). Our proposed concept is illustrated in Fig. 2. By using standard EPON OLT and ONU transceivers, we can increase the feeder fiber reach from 20 km to approximately 60 km (due to 15 dB loss saving on the SC) and the split ratio from 1:32 to 1:256 (due to 10 dB loss saving on the feeder fiber). This increase in reach and split ratio provides an attractive upgradeability solution for the existing PON deployment using very low cost components. The remote node, which houses the repeater in this FTTH system, can be placed at a location close to the community in the proposed broadband-to-the-community architecture (Jayasinghe et al., 2005a; Jayasinghe et al., 2005b). At this repeater station, digital satellite TV signals and local area network (LAN) interconnection are re-distributed to the PON system. This architecture is useful in situations, where the conventional service provider has restricted right for TV signal broadcasting and the community will have control over the TV signals that they receive. We will be discussing these features with experimental demonstrations in Section 4.

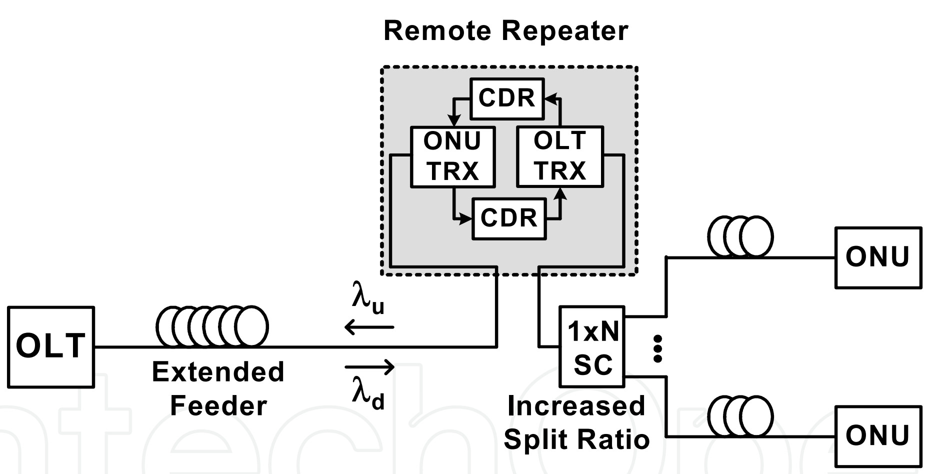
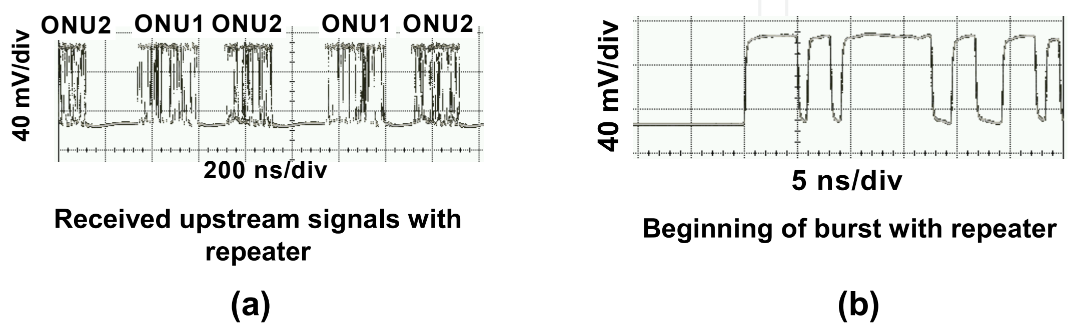


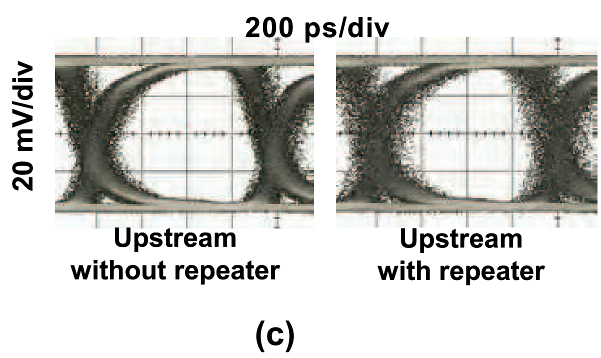
Fig. 2. FTTH system with bidirectional repeater.

2.1 Experiments and results for the upstream repeater

The first experimental setup to demonstrate the proposed FTTH system with upstream repeater is similar to that shown in Fig. 1. In this setup, we used commercially available 1.25 Gb/s EPON OLT and ONU TRXs. The feeder fiber is 20 km long using standard single-mode fiber (SMF) and we only used upstream regeneration. A 1.25 Gb/s BMR at 1310 nm was used at the repeater to receive the bursty signals from two ONUs. The electrical outputs from this BMR were used to drive a BMT at 1490 nm directly without retiming (i.e. no CDR was used in this experiment). The ONU signals were generated using user-defined patterns at 1.25 Gb/s to simulate bursty signals and the OLT signals were generated using continuous pseudo-random binary sequence (PRBS) $2^{23} - 1$.

Fig. 3(a) shows the upstream signals from ONU_1 and ONU_2 received at the OLT when the upstream repeater was used. Fig. 3(b) shows the measured eye diagrams for the upstream signals received at the OLT with and without the upstream repeater. Fig. 3(c) shows the zoomed-in beginning of the upstream burst signals from ONU_1. The waveform clearly shows that the OLT can quickly recover the first few bits from the bursty regenerated upstream signals. As shown in the table, the average total timing jitter from the upstream repeater was measured to be 90 ps and is smaller than 599 ps, which is specified by the IEEE 802.3ah EPON standard (IEEE, 2004). The rise time and fall time of the pulses were measured to be 118 ps and 115 ps, respectively, which are well within the 512 ns rise time and fall time specification of the IEEE 802.3ah standard.





	Measured	IEEE 802.3 EPON
Average total timing jitter	90 ps	599 ps
Rise-time	118 ps	512 ps
Fall-time	115 ps	512 ps

(d)

Fig. 3. Measured eye diagrams and waveforms with and without upstream repeater.

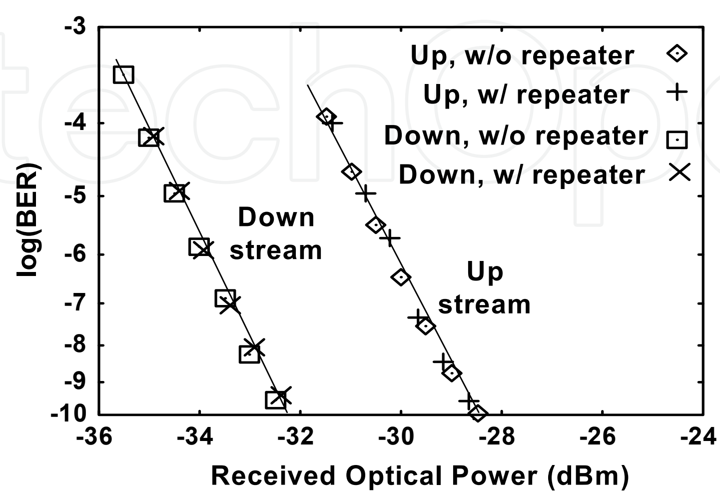


Fig. 4. Measured BERs for upstream and downstream signals with and without upstream repeater.

Fig. 4 shows the measured bit-error-rates (BERs) for downstream and upstream signals with and without the upstream repeater. No power penalty due to the upstream repeater was observed. The measured waveforms and BER results confirm that the upstream repeater can be used to reduce the requirement on the ONU transmit power without introducing penalty to the existing PON system and still conforming to the IEEE EPON standard requirements.

2.2 Experiments for video transmission

We also used this upstream repeater in a commercial EPON evaluation system from Teknovus to test its performance. The Teknovus system implements the IEEE 802.3ah EPON standard for delivery of triple-play services. Fig. 5 shows the experimental setup along with the measured upstream spectrum and captured video when video signals were streamed from the ONU to the OLT through the upstream repeater. No degradation in received upstream video quality was observed in the experiment.

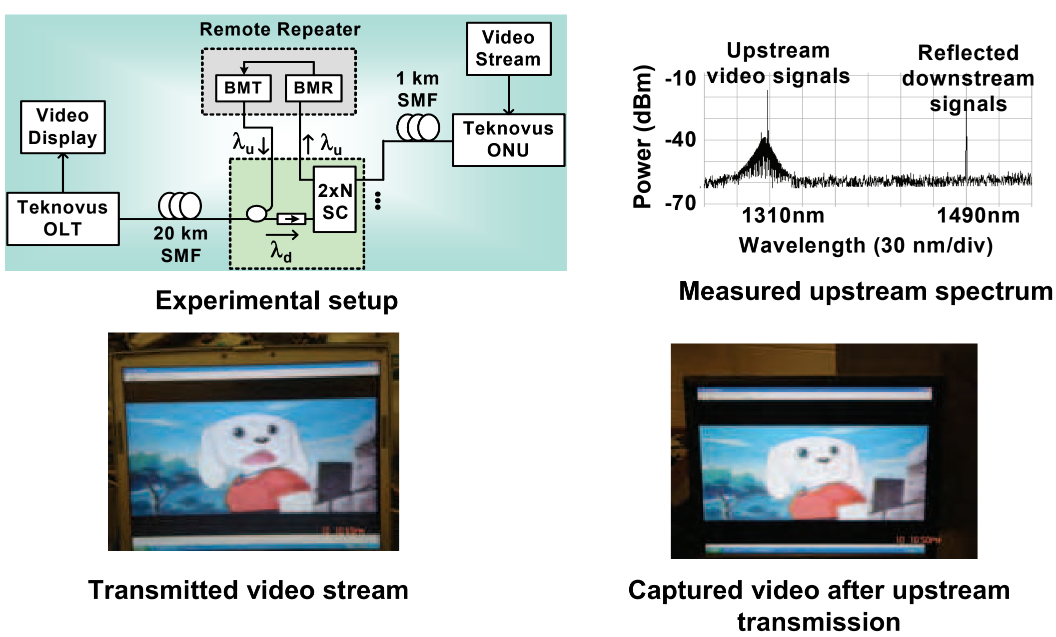
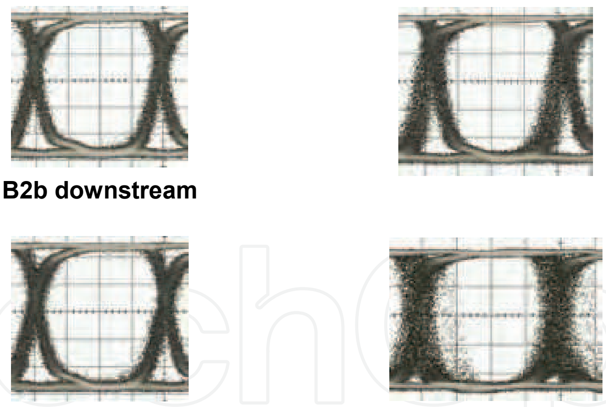


Fig. 5. Experimental setup and observed upstream spectrum and captured video after transmission through Teknovus system with upstream repeater.

2.3 Experiments and results for the bidirectional repeater

An experimental setup to demonstrate the reach extension and split ratio increase of the PON system was constructed and is similar to that shown in Fig. 2. In this case, a pair of bidirectional OLT and ONU TRXs were used at the remote node to provide both upstream and downstream regeneration. The feeder fiber is 50 km long. No CDR modules were used at the repeater. Fig. 6 shows the measured eye diagrams. The total timing jitter due to the repeater for downstream and upstream signals was measured to be 30 ps and 210 ps, respectively, which are still within the jitter specification of 599 ps of the IEEE 802.3ah standard. The rise time and fall time for downstream and upstream signals are 93 ps, 85 ps, 120 ps, and 140 ps, respectively, which are also well within the limit of the IEEE 802.3ah standard. It is expected that by using CDR modules at the remote repeater these jitter values would be further improved.



	Downstream	Upstream	IEEE 802.3 EPON
Jitter	30 ps	210 ps	599 ps
Rise-time	93 ps	85 ps	512 ps
Fall-time	120 ps	140 ps	512 ps

Fig. 6. Measured eye diagrams and waveform with and without bidirectional repeater.

Fig. 7 shows the measured BERs for the upstream and downstream signals. No power penalty was observed for downstream signals when the signals were transmitted through the repeater compared to the results when the signals were transmitted without the repeater. A small penalty < 0.2 dB was found for upstream signals, which could be attributed to non-perfect clock synchronization between the BER test-set and the pattern generator as no CDRs were used in the experiments. These results confirm that commercially available EPON transceivers can be used as bidirectional repeater to increase EPON reach and split ratio without introducing significant penalty to the existing system and without violating the IEEE 802.3ah standard. This is a very important feature of the proposed remote repeater-based optical access network scheme as it can certainly support existing interfaces at the OLT and ONU terminals.

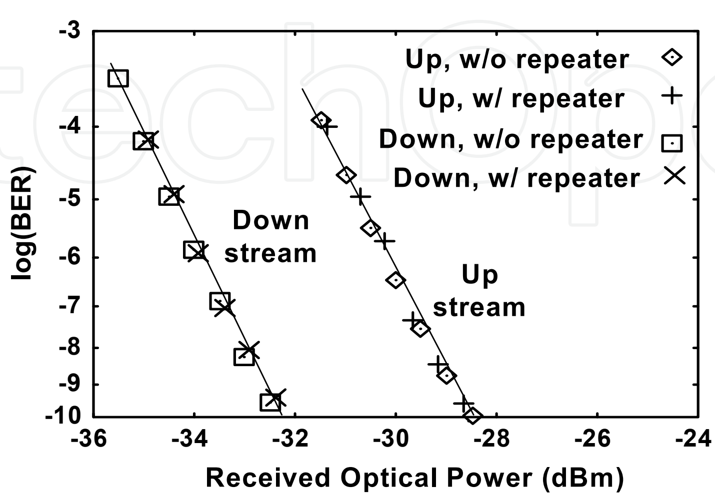


Fig. 7. Measured BERs for upstream and downstream signals with and without bidirectional repeater.

3. Jitter analysis of cascaded repeater-based FTTH system

The use of the remote repeater allows much lower cost implementation of ONU using low power and low cost optical transmitters, such as 0.8/1.3/1.55 µm VCSEL-based transmitters. If standard EPON components are used, the repeater can help increase the feeder fiber reach from 20 km to 50 km (due to 15 dB loss saving on the star coupler (SC)) and the split ratio from 1:32 to 1:256 (due to 10 dB loss saving on the feeder fiber). We can achieve higher user count and longer range coverage in the access network by cascading repeater-based FTTH systems as shown in Fig. 8 (Tran et al., 2006c). This will result in a lower network installation cost per customer and provide more effective broadband service delivery.

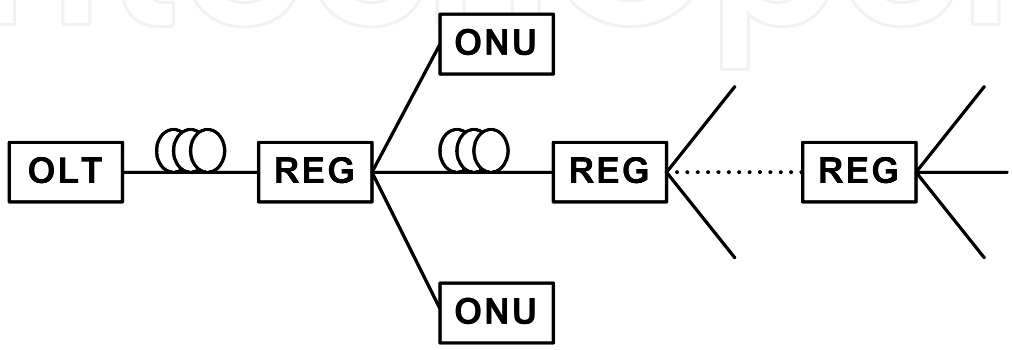


Fig. 8. Cascaded repeater-based FTTH system.

When the FTTH systems are cascaded, there are issues affecting the performance such as media access control (MAC) protocol designs, bandwidth allocation algorithms, jitter and delay parameters, etc. In this section, we investigate the jitter performance of cascaded repeater-based FTTH architectures via a recirculating loop. Other issues are beyond the scope of this work. Fig. 9 shows the experimental setup to investigate the jitter performance of cascaded FTTH systems with remote repeater. We used a 1.25 Gb/s EPON transmitter at 1490 nm with a PRBS of $2^{23} - 1$ to feed signals into the recirculating loop. The two acousto-optic switches and a 2x2 coupler control the signals coming in and out of the loop. Inside the loop, there is 20 km of standard single-mode fiber (SMF) to simulate the feeder fiber in a standard PON. Followed the SMF are the EPON receiver (RX) and transmitter (TX) connected directly to each other without any CDR modules. An attenuator is used inside the loop to simulate the star coupler loss. At the output of the loop, an EPON RX is used to detect the signals after recirculation.

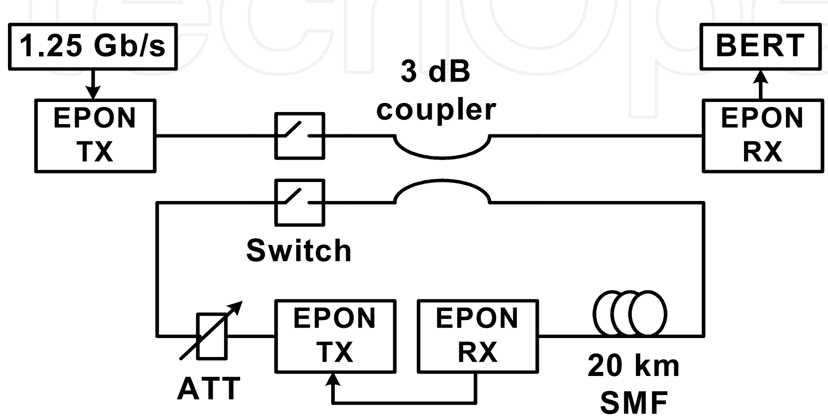


Fig. 9. Experimental setup to demonstrate cascaded remote-repeater-based FTTP systems.

Table 1 shows the measured timing jitter performance of the received signals after each loop. As seen, after 6 regenerations, the total jitter is only 380 ps, still smaller than 599 ps, which is specified by the IEEE 802.3ah EPON standard (IEEE, 2004). Note that, the measured total jitter has contribution from regeneration as well as clock misalignment due to the absence of clock recovery at the receiver.

Loop No.	Mean jitter RMS (ps)	Mean peak-to-peak jitter (ps)
0	18	62
1	18	70
2	24	81
3	49	215
4	70	228
5	76	298
6	90	380

Table 1. Measured timing jitter for different loop numbers.

Fig. 10 shows the measured eye diagrams of the 1.25 Gb/s signals. As seen in Fig. 10(c), the eye is still clear and open after 4 loops, enabling error-free operation. After 6 loops (Fig. 10(d)), the eye becomes distorted and partly closed. This eye closure is due to both regeneration and the absence of clock recovery at the receiver.

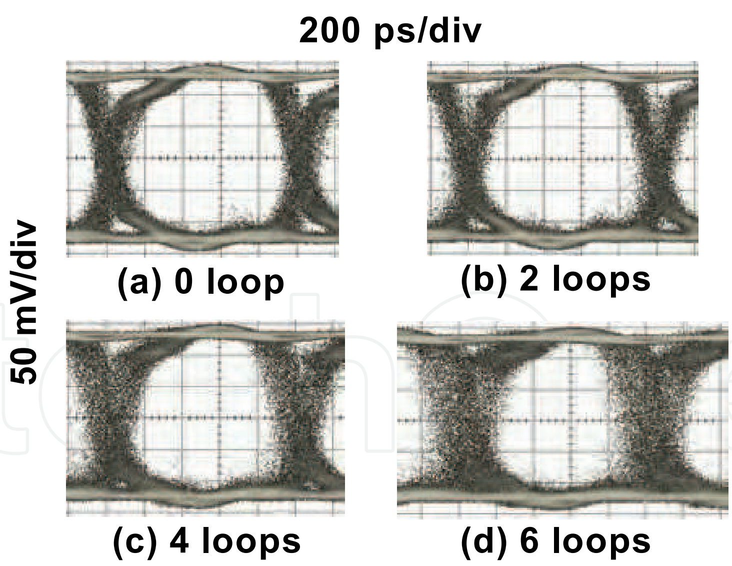


Fig. 10. Measured eyes at 1.25 Gb/s without clock recovery.

We measured the BERs for the 1.25 Gb/s signals after 0 loop as the baseline, and then repeated the measurement after each loop. The results are shown in Fig. 11. Compared with the BER results for the 0 loop, the power penalty is less than 0.5 dB for the cases up to 4 loops. After 5 loops, the power penalty is more than 4 dB at BER = 10^{-8}. After 6 loops, we reached an error floor at 10^{-5}. We can conclude that without clock recovery, our proposed FTTH architecture with remote repeater can be cascaded 4 times without introducing significant penalty to the system performance. This result illustrates that if we take into account a single repeater-based FTTH system with a feeder fiber of 50 km and a customer base of 256, a cascaded system can then theoretically extend the reach to 200 km and 256^4 customers with no jitter performance degradation. However, the actual number of customers will eventually be limited by the MAC protocol and dynamic bandwidth allocation scheme.

In order to investigate the effect of clock recovery on the receiver jitter performance, we used 155 Mb/s PON transceivers at the transmitter, receiver and regenerator. A CDR module was also used at the receiver. Fig. 12 shows the measured eye diagrams after 0 regeneration and 10 regenerations through the recirculating loop with and without clock recovery. Without clock recovery, the timing jitter was measured to be 489 ps and 1.9 ns for

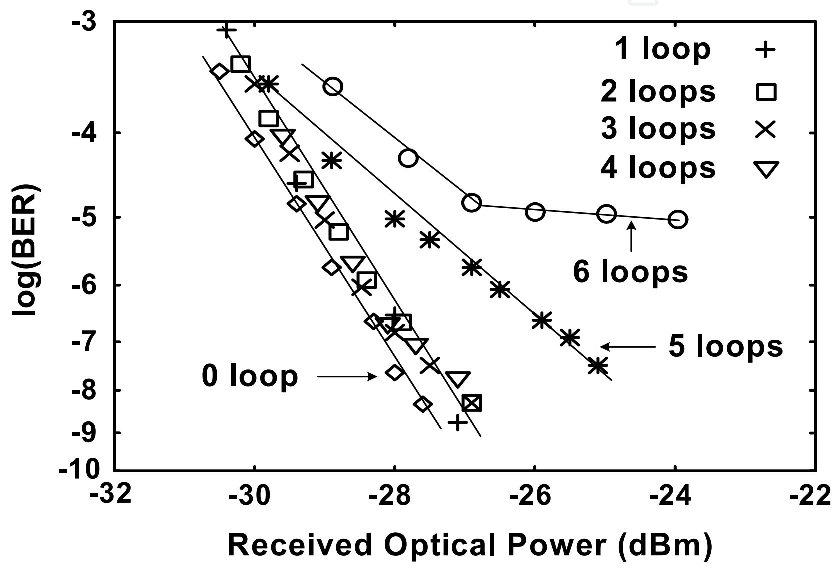


Fig. 11. Measured BER curves at 1.25 Gb/s.

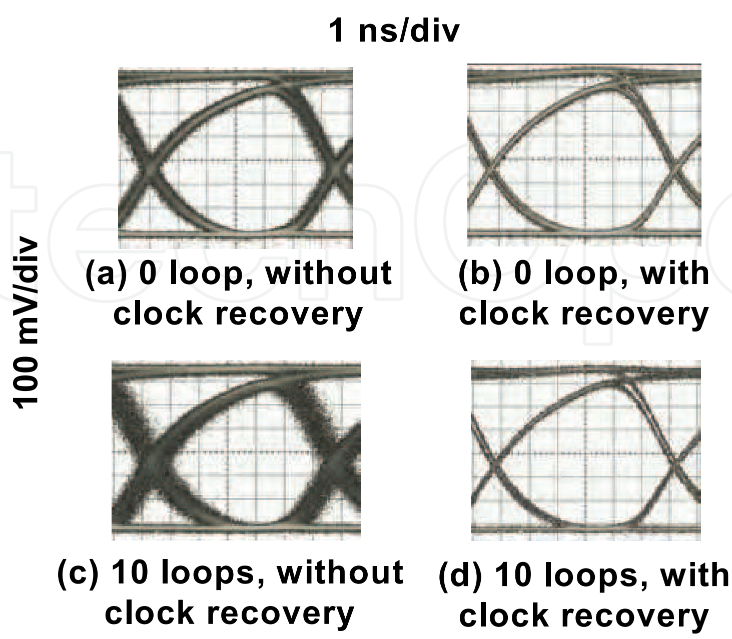


Fig. 12. Eyes at 155 Mb/s with and without clock recovery.

0 and 10 loops, respectively. With clock recovery, the timing jitter was approximately 390 ps for both 0 and 10 loops. This illustrates that with clock recovery at the receiver, we can cascade our FTTH systems for up to 10 times and the total jitter is still within the EPON standard requirement.

4. Video service integration over a repeater-based FTTH system

Integrating video services over a PON has become important since it could reduce the cost of operation. Generally, cable TV and satellite TV services are delivered over coaxial cables within the premises. As the transmission distance and the number of video channels increase, the coaxial cable based infrastructure may not support larger number of video channels. Considering a scenario whereby multiple video channels have to be delivered to densely populated areas such as multi-dwelling units, apartment houses, or hotels, a cost-effective solution is essential. Due to regulatory issues in several countries, video services may not be delivered over a PON from the CO. Moreover, the unbundling of fiber bandwidth in the access networks enables the provisioning of video service delivery by many cable TV providers. However, due to the competition between the cable TV providers and the telecom companies, certain video services may not be delivered through a PON from the CO. Therefore, a cost effective architecture that enables the video service delivery by multiple service providers in an access network is required. As an added feature for the remote repeater, we demonstrate a video service delivery scheme for a large-split repeater-based FTTH network whereby the video channels are carried on a radio frequency (RF) subcarrier multiplexed (SCM) format.

A generic integrated optical access network to support data, voice and video services is shown in Fig. 13(a). The proposed architecture is based on the repeater-based optical access network that could potentially support a larger number of customers (Nadarajah et al., 2007). In this setup, cable TV and satellite TV signal distribution links can be overlaid on the downstream link at the repeater to be delivered to the customers. We proposed the video service delivery using RF SCM transmission, whereby the chosen RF carrier frequency for the delivery of the video channels is placed outside the bandwidth of the downstream data signals as shown in Fig. 13(b). At the repeater, the received video channels are upconverted to the designated RF frequency and then electrically combined with the regenerated downstream data signals before the transmission to the customers. Integration of RF video channels with the downstream signals at the repeater has several advantages. Time multiplexing video channels with the downstream data at the CO increases the total downstream bandwidth. The scalability of this scheme is potentially limited by the power budget and therefore limits the number of video channels. As the number of splits in the star coupler (SC) increases, this issue becomes even more pronounced. In a large-split PON, the delivery of RF video channels from the CO suffers from inadequate signal-to-noise ratio (SNR) to receive the video channels error-free. As the bandwidth requirements and the number of customers increase, it becomes more difficult. However, the SNR requirements can be satisfied in a repeater-based optical access network as the signals are regenerated at the RN enabling the video delivery for a larger number of customers. On the other hand, the video channels that are regenerated at the remote repeater can be optically combined with the downstream wavelength channel. Compared to SCM based scheme, this scheme does not use electrical combination of the RF video channels with the downstream data at the repeater. At the ONUs, the received wavelength channels can be detected using a single

receiver. As the RF video channels are placed outside the bandwidth of the baseband downstream data, one receiver setup at each ONU becomes feasible.
Fig. 14 shows the experimental setup to demonstrate the capabilities of the proposed scheme. A 1.25 Gb/s downstream signal of 2^{31} - 1 pseudo random binary sequence non-

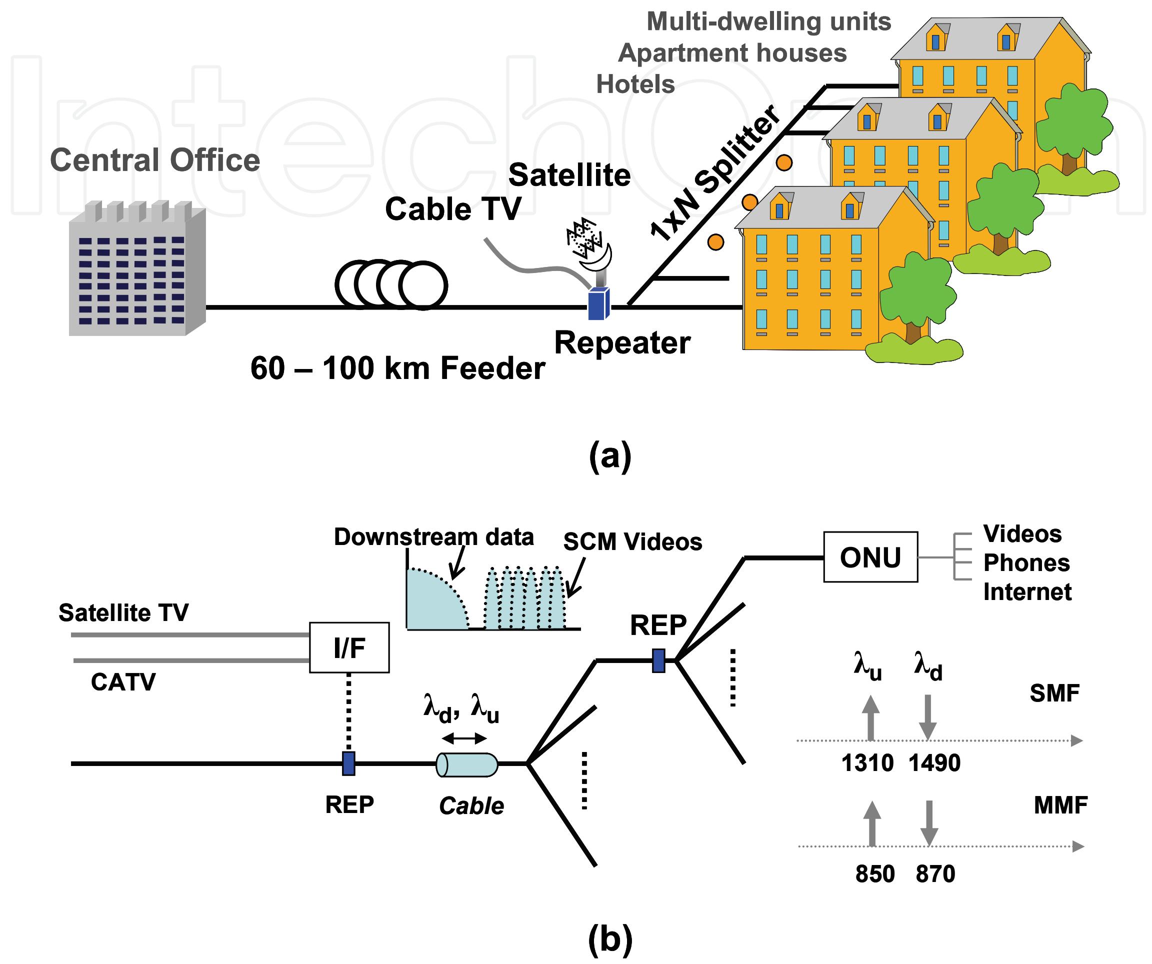


Fig. 13. (a) Generic integrated repeater-based optical access network architecture for video service delivery; (b) Repeater-based distribution network providing simultaneous RF SCM videos and data services.

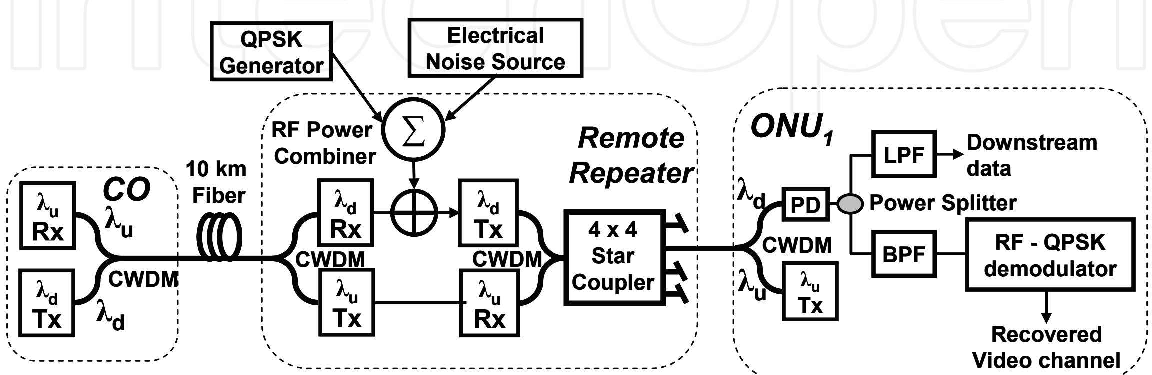
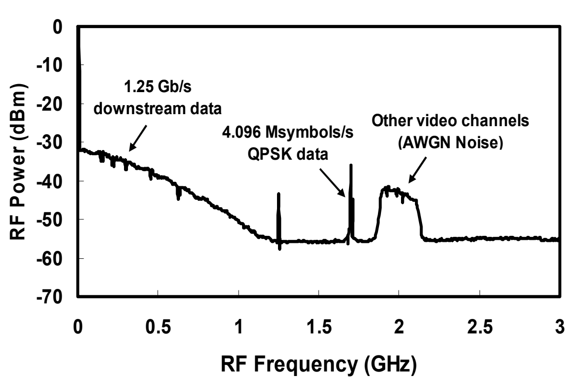


Fig. 14. Experimental setup to demonstrate the video service delivery over a repeater based optical access network.

return-to-zero (PRBS NRZ) data was directly modulated onto downlink carrier, λ_d (1490 nm), and transmitted to the repeater through a 10 km standard single mode fiber. At the repeater, the downstream signal was detected using a commercially available 1.25 Gb/s receiver. A 4.096 Msymbols/s quadrature phase shift keyed (QPSK) data was generated using a vector signal generator and upconverted onto a RF carrier frequency at 1.7 GHz.

As shown in Fig. 15, the generated signal was electrically combined with additive white gaussian noise (AWGN) generated from an electrical noise source that simulated multiple video channels. Before the combination, AWGN was band limited using a band pass filter (BPF) with a center frequency of 2 GHz and bandwidth of 300 MHz to reduce the spectral overlap with the QPSK signal and the downstream data. The detected downstream signal was then sent through a low pass filter (LPF) with a cut-off frequency of 1.25 GHz to avoid crosstalk to the RF signals before electrically combining with the RF signals. The composite signals were directly applied to a distributed feedback laser operating at 1550.92 nm and transmitted to the ONUs. The downstream wavelength channel from the repeater was passed through a 4x4 SC and detected using a 2.5 Gb/s receiver. The received signals were split using a RF splitter and 1.25 Gb/s dowstream data was recovered using a LPF with a cut-off frequency of 1.25 GHz while the RF signals were separated from the downstream data using a BPF and QPSK signal was recovered using a demodulator. In the upstream direction, a 1.25 Gb/s 2^{31} - 1 PRBS NRZ continuous data was directly applied to a Fabry-Perot laser diode operating at 1310 nm wavelength window (λ_u) and transmitted to the repeater, where it was regenerated and transmitted to the CO through the 10 km fiber. It should be noted that longer fiber transmission would not have made significant difference in the results because the combination of video channels with downstream data is performed at the repeater that is closer to the ONUs and the downstream data can be regenerated using cascaded repeaters. Coarse wavelength division multiplexing couplers were used at the repeater to separate λ_u and λ_d before and after the regeneration of the signals.



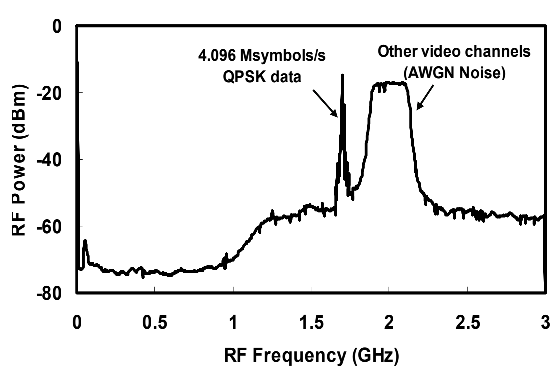


Fig. 15. Observed RF spectra of the downstream signals and RF video channels at the repeater and ONU.

Fig. 16 shows the BER measurements for the upstream and downstream data signals. For the upstream signal, less than 0.4 dB penalty was observed when the signals were passed through the repeater compared to back-to-back (B-B) measurements and this penalty was introduced at the repeater electronics. For the downstream data, no penalty was observed when the RF SCM signals were added with the downstream data signals. The sensitivity of the upstream data signal was approximately 2 dB better than that of downstream data signal. The modulation depth of the downstream data was reduced to avoid intermodulation products as it was modulated with the RF video signals at the repeater.

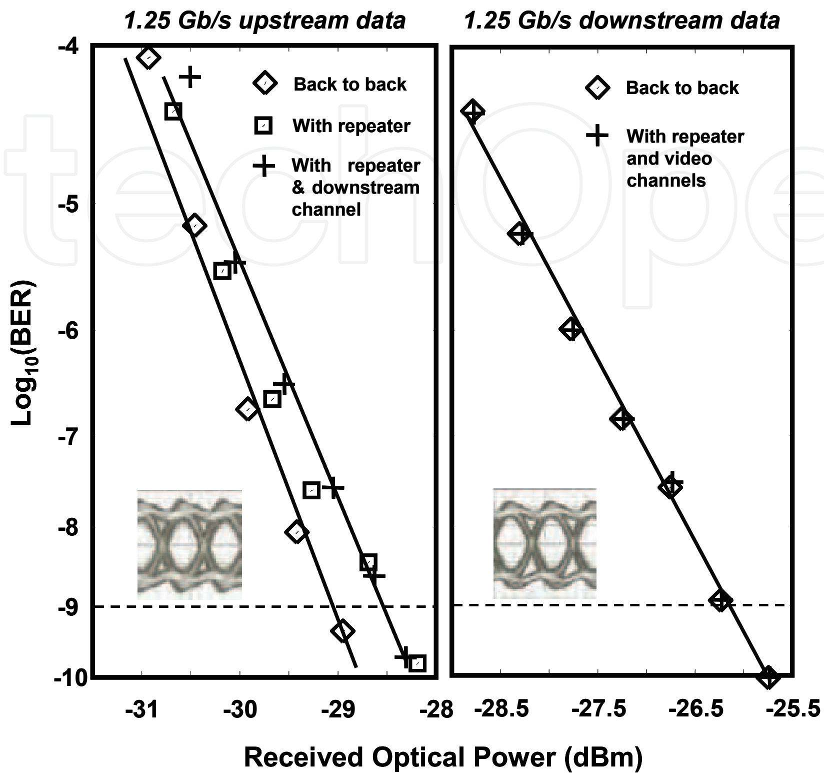


Fig. 16. Measured BER curves for 1.25 Gb/s upstream data and 1.25 Gb/s downstream data signals.

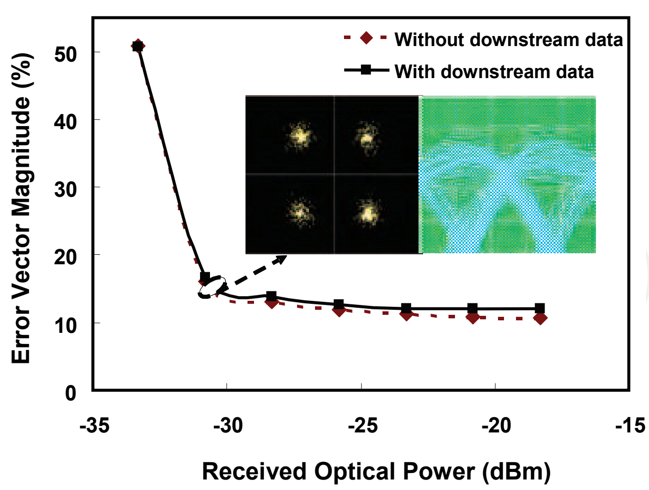


Fig. 17. Measured EVM values for QPSK signals. Insets show the observed constellation & eye diagrams.

Fig. 17 shows the measured error vector magnitude (EVM) for the recovered QPSK signal. An EVM of 16.6% (corresponds to a BER of 10^{-9}) was measured for the recovered QPSK data signal when the received optical power was -31.81 dBm. The graph also shows that QPSK signal did not suffer from crosstalk penalty from to the downstream data signal. The insets of Fig. 17 show the constellation diagram and the eye diagram for the recovered QPSK signal when the received optical power was -31.81 dBm. As the bandwidth requirements for the digital video channels increase, higher order modulation formats can be adopted without changing the allocated frequency spectrum. The experiment was repeated for 4.096 Msymbols/s 16-quadrature amplitude modulation (QAM) video channel transmissions and the resulting constellation diagram is shown in Fig. 18.

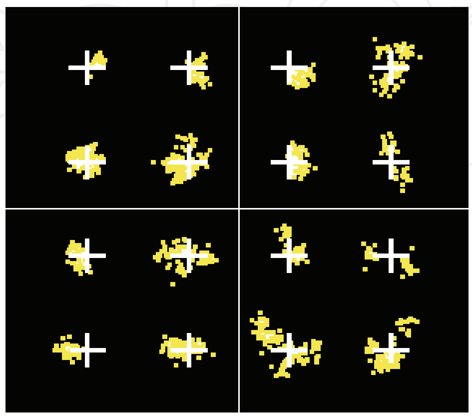


Fig. 18. Observed constellation diagram for the recovered 4.096 Msymbols/s 16-QAM.

A power budget calculation for the video channels was performed based on parameters given below. The transmitted optical power from the repeater, distribution fiber length, attenuation of fiber, WDM coupler loss, sensitivity for 2.5 GHz optical receiver and loss of the 64-split SC are chosen to be 0 dBm, 5 km, 0.2 dB/km, 0.75 dB, -26 dBm and 21 dB respectively. Under these circumstances, a power margin of 2.5 dB can be obtained for the video channels. Assuming the bandwidth of each RF video channel is 6 MHz, more than 100 video channels can be simultaneously delivered. As the bandwidth of the downstream data increases, higher bandwidth receiver is required to receive both signals. Higher bandwidth RF video channel transmissions can be performed using higher order modulation formats that require higher SNR for error-free recovery. As the optical modulation index of the video channels increases, the modulation index of the downstream data decreases. This leads to the reduction in sensitivity of the downstream data and limits the power budget of downstream data signal. Therefore, the modulation index for both signals has to be taken into account considering the power budget requirements.

5. Local area networking over a repeater-based FTTH system

As the access network grows with increasing number of customers and demand for more bandwidth, several value added services also need to be delivered in an efficient way. For example, customers within a PON environment may require private communication links between themselves for various computer applications and telecommunication services, such as distributed data processing, broadcast information systems, teleconferencing, and interactive video games. Moreover, some customers leasing several floors within a building may require their own private network such as LAN apart from the standard communication links with the CO. To serve this purpose, two solutions can be found. The first one is to deploy another optical network interconnecting all customers within the PON to facilitate the local customer networking. Intercommunication between the customers may be realized by overlaying a separate network in which each ONU is connected to all other ONUs via a point-to-point optical link. Deploying a separate network for inter-networking amongst the customers is extremely complex and costly especially in a densely populated area. Moreover it also becomes impractical and inefficient to connect to each customer in the network via this setup (Cohen, 2003; Venkateswaran, 2001). The second solution is to intelligently use the existing PON infrastructure to provide the additional services. Reuse of the PON infrastructure to facilitate intercommunication links between customers of the same PON can greatly reduce the cost and simplify management issues of the network. Overlaying a LAN on the existing PON incurs a minimum additional cost since it utilizes the existing facility. The overlaid network can be used to interconnect several customers in scattered buildings to form a group of community (IEEE, 2004; Park et al., 2004). The resulting PON system enables fiber-to-the-premises so that the tenants in a building can subscribe to telecommunications, internet, and video services individually while keeping their own network. Moreover, the change in bursty data traffic patterns opens up an opportunity for an efficient use of inherent PONs with distributed statistical multiplexing to increase the efficiency of the access networks. Using distributed multiplexing, LAN capabilities amongst the customers can be developed. The overlaid virtual PON technologies bring multiple campuses and multi-tenant business buildings onto a same optical fiber facility and therefore making savings on fiber facilities' capital and ongoing operational costs (Arnaud et al., 2003; Iannone et al., 2000).

A number of higher layer LAN emulation schemes have been proposed to the Ethernet in the First Mile alliance (EFM) IEEE 802.3ah (Dixit, 2003; Hernandez-Valencia, 1997). One of these solutions considered the use of PON tags and a trivial reflector function at the CO to emulate a shared medium and therefore reflecting all upstream traffic back to the ONUs. Even though this scheme is compatible with higher layer, to enable multicasting to several ONUs, the frame transmission should be carried multiple times, which wastes bandwidth. In the advanced upper-layer shared LAN emulation (ULSLE) scheme, the LAN traffic is separated using the bridges and/or routers located at the CO. Using the media access control (MAC) address of the packet, intelligent decisions are made and the LAN traffic is rerouted back to the appropriate ONUs using the downstream wavelength channel. The bridges or routers that are equipped at the CO need to be very complex to obtain relatively higher efficiency of transmission bandwidth of the wavelength channels. These bridges or routers must be capable of supporting higher layer protocols, thereby potentially increasing the cost and complexity of the network. Furthermore, the effective downstream channel bandwidth is reduced as the LAN traffic is routed back to the ONUs on the downstream wavelength channel. Moreover, the redirected LAN traffic needs to be separated from the downstream traffic using complex filtering mechanisms that are employed at the ONUs. Even though using a fiber access facility to communicate with another user in the network is more efficient and practical, using ULSLE schemes for the transmission of LAN traffic amongst the customers increases the complexity at the ONUs. Therefore, a simplified LAN that is overlaid on the existing PON with high flexibility is required for the intercommunications amongst the customers in the PON. By comparison, emulating point-to-point links amongst customers directly on the optical layer in the PON can effectively overcome several drawbacks (Chae et al., 1999; Chae et al., 2001; Nadarajah et al., 2005; Tran et al., 2006a; Wong et al., 2004). Compared to the higher layer LAN emulation schemes, an optical layer LAN emulation can also be provided whereby the LAN traffic is physically redirected back to the ONUs without the use of higher layer bridges or routers located at the

CO. This effectively reduces the required higher layer interfaces at the CO while obtaining higher bandwidth utilization for the downstream wavelength channel. It has been shown that in the optical layer LAN emulation schemes, as the percentage of LAN traffic increases the available upstream and downstream bandwidth per ONU also increases whereas it decreases in the higher layer LAN emulation schemes. Moreover, no further complex filtering mechanisms are required at the ONUs to separate the LAN traffic from the downstream traffic. The use of more complex filtering and packet forwarding schemes that are used in the bridges or routers at the CO are also eliminated and therefore reduces the cost and complexities associated with the operation at the ONUs and CO. We have proposed and experimentally demonstrated a multi-functional high split repeater-based optical access network architecture that enables simpler and bandwidth efficient LAN capabilities amongst the customers.

5.1 System architecture

A generic integrated optical access network to support LAN services is shown in Fig. 19 (Nadarajah et al., 2009). In this network, a 1×N (N < 256) splitter is used at the remote node, whereby the larger split is enabled by a remote repeater that regenerates the upstream and downstream signals. The repeater not only performs regeneration of the signals to support larger number of customers but also provides intelligent LAN capabilities. The LAN traffic that is carried from one ONU to another along with the upstream traffic to the CO is physically separated at the remote repeater. Thereafter, LAN traffic is combined with the downstream traffic and carried to the ONUs. We propose the LAN traffic delivery for the repeater based optical access network using RF subcarrier multiplexed transmission, whereby the chosen RF carrier is placed outside the bandwidth of the baseband upstream traffic and downstream traffic as shown in Fig. 19. The repeater consists of transceiver modules and an electrical LPF, and BPF for the separation and combination of the LAN traffic.

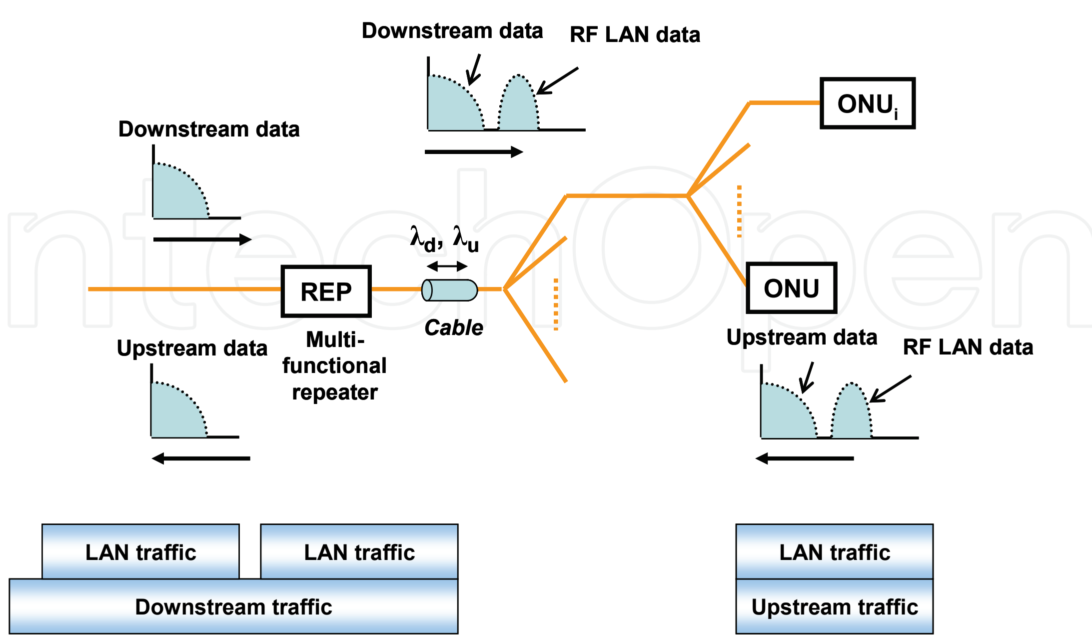


Fig. 19. Integrated repeater based optical access network architecture for local area networking.

5.2 Experiments and results

Fig. 20 shows the experimental setup to demonstrate the capabilities of the proposed scheme. A 1.25 Gb/s downstream signal of 2^{31} - 1 PRBS NRZ data was directly modulated onto downlink carrier, 1490 nm and transmitted to the repeater through a 10 km fiber. At the repeater, the downstream signal was detected using a 1.25 Gb/s receiver. For the upstream transmisisons a 155 Mb/s 2^{23} - 1 PRBS NRZ was upconverted onto the RF frequency at 2.5 GHz using a mixer. The upconverted RF LAN data was then electrically combined with 1.25 Gb/s 2^{23} - 1 PRBS NRZ and directly modulated onto a DFB laser operating on a wavelength at 1550.92 nm and transmitted to the repeater through a 3 km fiber and 4×4 SC.

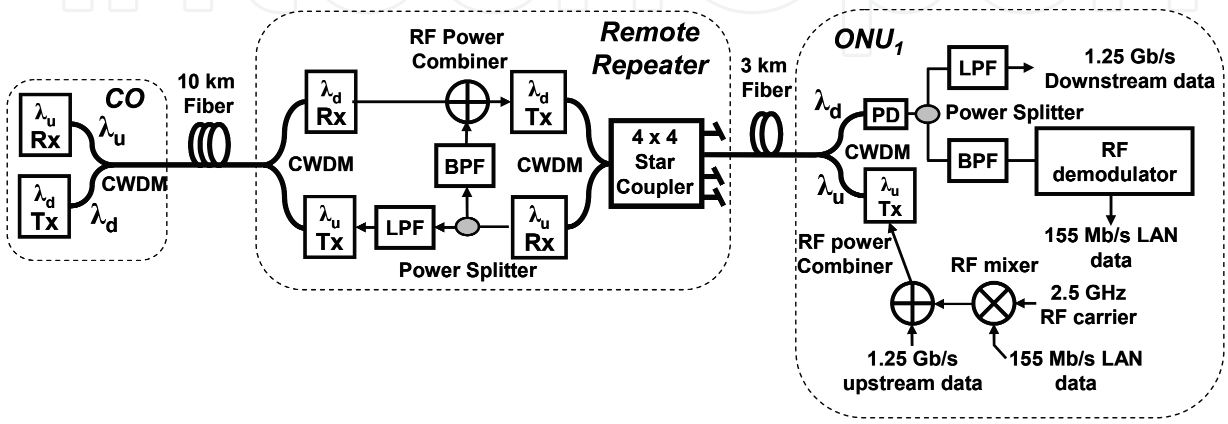


Fig. 20. Experimental setup for the demonstration of the proposed LAN scheme.

Fig. 21 shows the RF spectra of the transmitted composite signals. The received upstream signals at the repeater were detected and RF power split. One portion of the signals was passed through a LPF with a cutoff frequency of 1.25 GHz to separate the 1.25 Gb/s upstream data. This upstream data was then directly modulated onto a FP-LD operating at 1310 nm and transmitted to the CO through a 10 km fiber. The other portion of the signals was then sent through a BPF with a center frequency of 2.5 GHz and bandwidth of 300 MHz to separate the LAN data. The separated LAN data was then combined with the 1.25 Gb/s downstream data and directly modulated onto DFB laser operating at 1554.13 nm and transmitted to the ONUs through a 4×4 SC and 3 km fiber. The received signals at the ONU were split using a RF splitter and 1.25 Gb/s dowstream data was recovered using a 1.25 GHz LPF while the RF signals were separated from downstream data using a BPF and 155 Mb/s LAN data was recovered using a demodulator.

Fig. 22 shows the BER measurements for the upstream data, downstream data, and LAN data signals. For the downstream signal, no significant penalty was observed for the 10 km fiber transmission compared to back-to-back (B-B) measurements. After the RF LAN data was added at the repeater, more than 5 dB penalty was observed for the downstream data. This larger penalty was a result of the reduction of the extinction ratio. This larger penalty can be minimized by optimizing the combination of both downstream data and LAN data signals. For the 1.25 Gb/s upstream data, less than 0.5 dB penalty was observed when the RF LAN data signals were added and transmitted with the upstream signals. For the LAN data signal, less than 0.5 dB penalty was observed in the presence of 1.25 Gb/s upstream data signals. An additional 0.5 dB penalty was observed when the LAN data signals were carried to the ONUs with the downstream data signals. These penalties can be attributed to the crosstalk from the baseband signals.

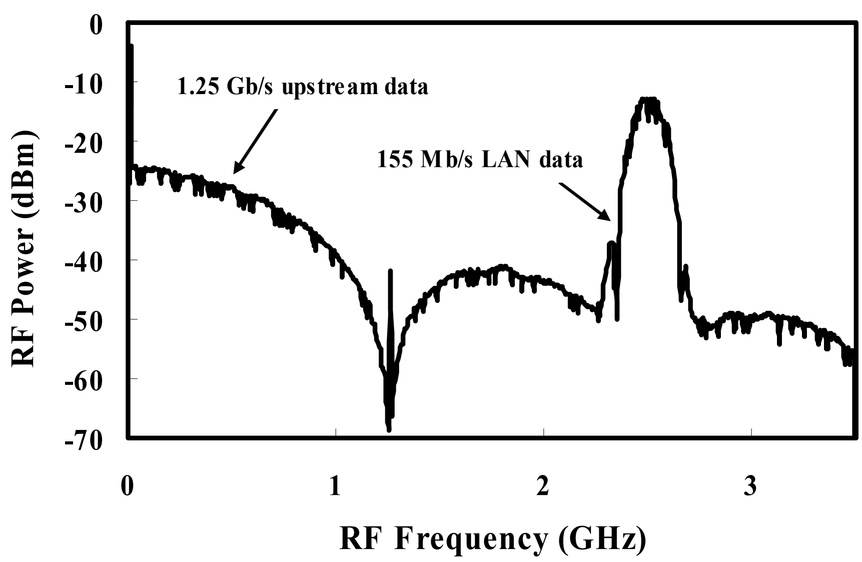


Fig. 21. Observed downstream signals at the repeater.

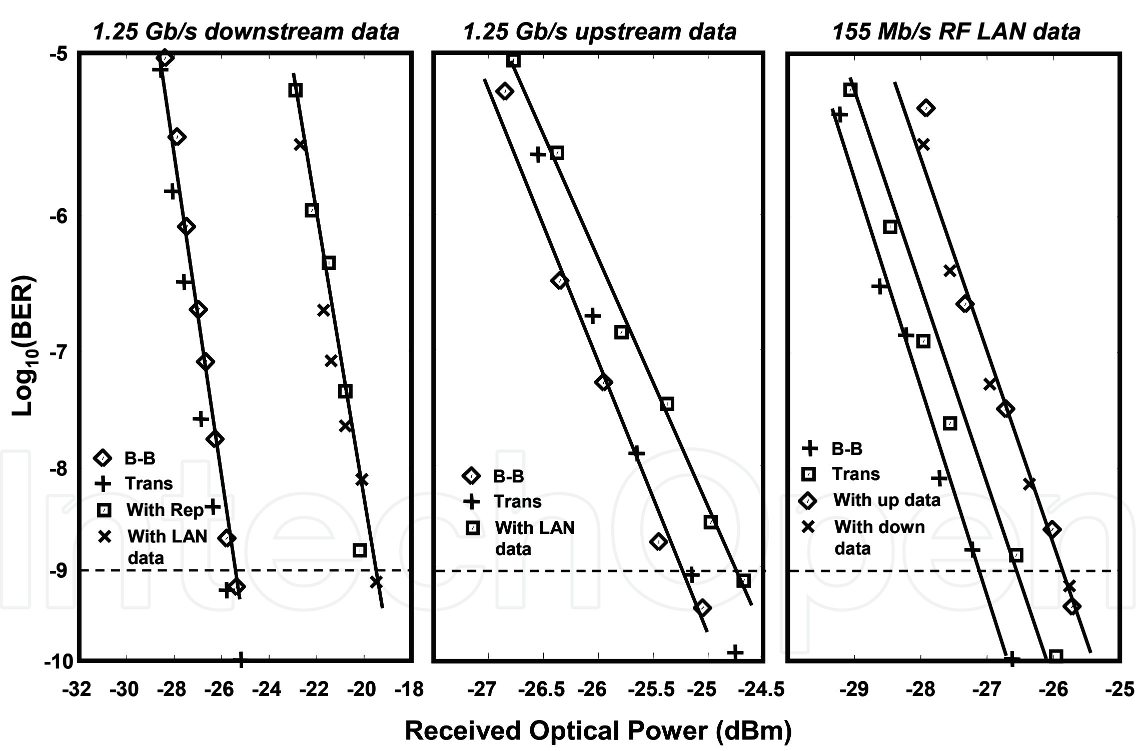


Fig. 22. Measured BER signals for all the signals.

6. Econometric modelling

We have shown the proposed architecture for a repeater-based FTTH system that could potentially increase the number of subscribers served by a single optical access network infrastructure to 256 and extend the feeder fiber transmission distance up to 100 km.

Supporting a larger number of subscribers using a single PON infrastructure is more cost effective and an economic model has been developed to study the cost effectiveness of this particular architecture in comparison with the conventional PON architecture and fiber-to-the-node (FTTN) architecture that incorporates digital subscriber lines (DSL) from the remote node (RN) to the customer units (CUs). At the RN, a digital subscriber line access multiplexer (DSLAM) is placed for the collection and distribution of signal from/to each of the CUs through the already built-in DSL lines. The objective of this section is to identify the essential costs of building passive optical access networks and to perform a comparison of different technologies using varying performance criteria. Simple generic models are used to calculate trenching and cable costs taking into account different deployment cases.

6.1 Network model

A model framework of generic connections, housings, and equipment are considered for this study. In this model, all links between OLT, RN and ONU are via single-mode fiber. The distance between the OLT and the RN is taken as 10 km. Moreover, it is considered that the RN is placed between the subscriber's ONU and the OLT. The RN is the equivalent of the active switch in the AON structure, the SC in the PON structure and the repeater and the SC in the repeater-based optical access network. As these types of FTTH architectures are more suitable for the multi-tenant buildings, it is considered that the RN is placed at the basement of the building while the houses are located on each floor.

Fig. 23 shows the layout of the houses in a floor of the building. There are n (typically n = 8) houses in one row, while the N rows (typically N = 4) in the single floor. The size of each house is 15 x 15 m.

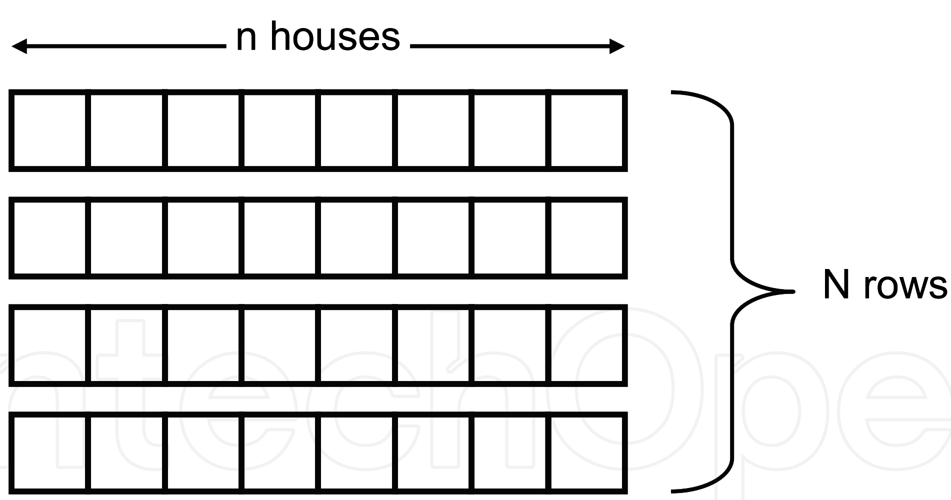


Fig. 23. Layout of the houses in a floor of the building.

If there are m floors in a building, then the average fiber cable length between the RT and the customer unit can be given as

$$\text{Average cable length} = \frac{(n+1)(m+1)}{4} \times 15 \text{ m.} \quad (1)$$

$$\text{Average trench length} = \frac{n(m+1)}{4} \times 15 \text{ m.} \quad (2)$$

6.2 Network economics

Fig. 24 shows the architectures that are considered for the economic model analysis. The conventional PON architecture uses multiple SCs in the RN and they are connected to the OLT using multiple feeder fibers and ONUs using distribution fibers. No active electronics is used in the RN. The repeater-based FTTH network architecture is similar to that of conventional PON architecture, however a simple repeater is used at the RN. Moreover, a higher split (1x256) SC is used instead of multiple (1x32) SCs. The fiber-to-the-node and DSL (FTTH-DSL) architecture uses a point-point link optical fiber link between the OLT and the RN. At the RN, the CUs are connected using DSL lines and a DSLAM is used at the RN for the aggregation of the upstream signal from each subscriber.

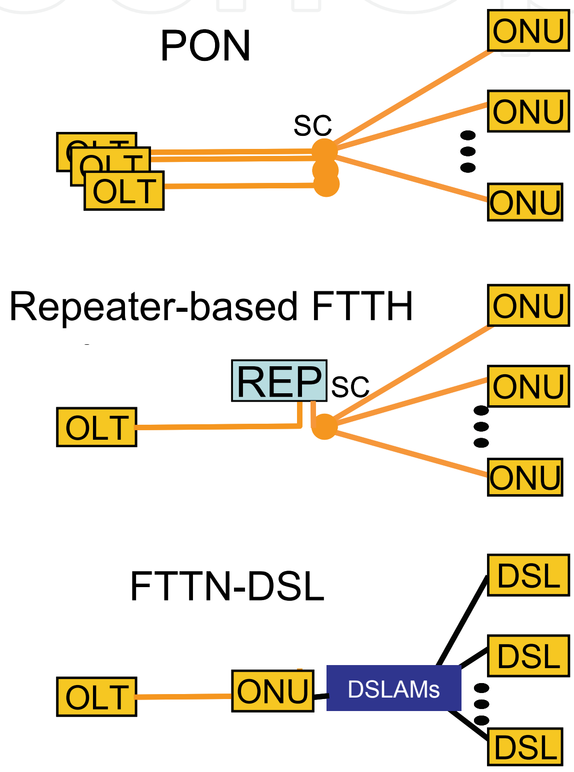


Fig. 24. Conventional PON, repeater-based FTTH, and FTTN-DSL architectures for the economic analysis.

Table 2 shows the parameters that are used for the equipment cost for each network model. The optical transceiver cost for each scheme remains the same even though repeater-based hybrid network supports a larger number of CUs. This is because the downstream and upstream signals are regenerated at the RN and therefore high power lasers and high sensitivity receivers are not required at the OLT. In the conventional PON, 32 CUs are supported through a single OLT interface while repeater-based hybrid optical access network supports 256 CUs through a single interface. Therefore, 8 optical transceivers with interfaces are required for the conventional PON to support 256 CUs using a single infrastructure. The housing cost of the RN is higher for the FTTN-DSL as it contains an active DSLAM requiring larger space with higher installation costs. In repeater-based FTTH, the power requirement and the chassis costs are higher than that of conventional PON; but lower than that of FTTN-DSL. The cost of the optical transceiver used at the RN for repeater-based FTTH architecture is lower than that of FTTN-DSL.

	Repeater-Based FTTH	PON	FTTN-DSL
OLT Parameters			
Housing cost ($)	50000	50000	50000
Transceiver cost ($)	10000	10000	10000
RT Parameters			
Housing cost ($)	1000	500	8000
Chassis cost ($)	500	100	2000
Remote powering cost ($)	250	0	2500
Transceiver cost ($)	1000	0	2000
Output port cost ($)	N/A	160	N/A
Max house per RT	256	32	256
Max RT boxes	1	8	---
SC cost ($)	9000	3000	---
Switch cost per port ($)	---	---	80
Cable Costs ($/km)			
OLT to RT	128	128	128
RT to CU	128	128	---
Cost per splice ($)	24	24	24
Trenching Costs ($/km)			
OLT to RT	5000	5000	5000
RT to CU	1000	1000	0
ONU Costs			
Install cost ($)	100	100	100
CU cost ($)	150	200	100
Interface cost ($)	500	500	500

Table 2. Component and installation costs.

In the repeater-based FTTH system, as the number of splits is higher compared to that of in the conventional PON, the cost of the SC used in the repeater-based FTTH is also higher. In the FTTN-DSL, it is considered that the DSL lines are already in place however requires further rearrangement.

Fig. 25 shows the cost of each CU for the FTTH systems for 256 CUs and 128 CUs for the take rate of 100%. In both scenarios, conventional PON architecture requires higher cost for each CU while the FTTN-DSL requires the lowest cost for each CU of all architectures. All the FTTH architectures with 128 CUs require higher cost for each CU compared to that with 256 CUs as the infrastructure is shared by many CUs. For the repeater-based FTTH architecture with 256 CUs the cost per customer is approximately $2459 while it is $3412 for the FTTN-DSL. Similarly, the cost per customer in the repeater-based FTTH network is approximately $137 higher than that in FTTN-DSL with 128 CUs. We define take rate is the percentage of homes covered by the access network infrastructure that subscribe to the service. As a consequence, all infrastructure costs (e.g. housing, electronics, and trench deployment) are incurred for all homes, even though they can only be recovered from the revenue by those that subscribe.

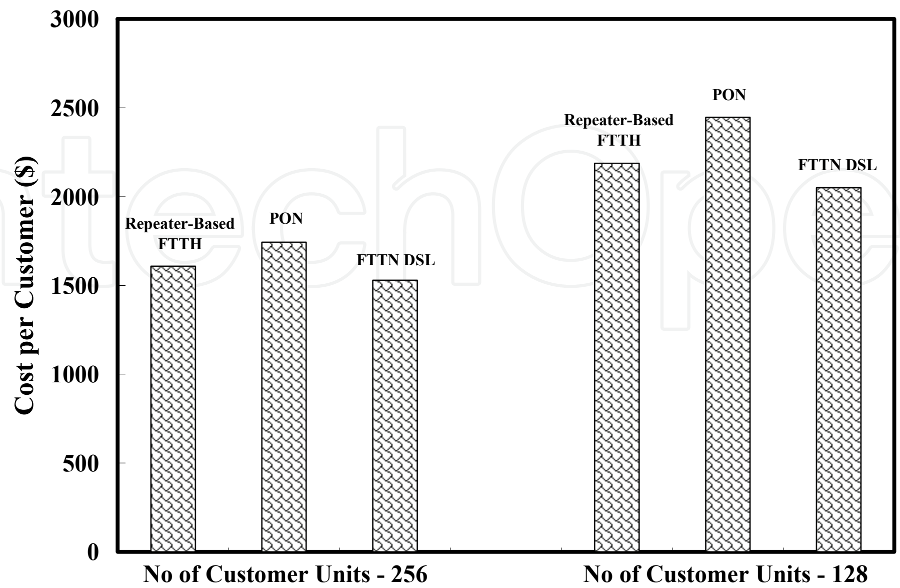
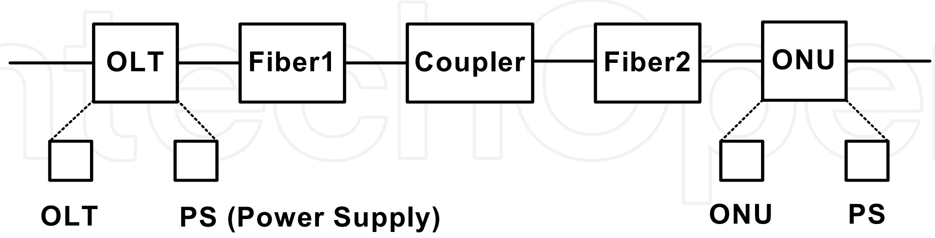


Fig. 25. Cost per customer for the FTTH architectures with 128 and 256 CUs for 100% take rate.

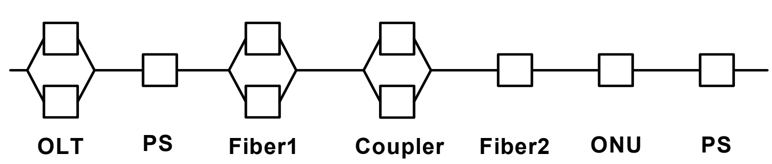
The network cost per subscriber is calculated as:

$$\text{Cost per Subscriber} = \frac{\text{Infrastructure Cost per Home}}{\text{\% Take Rate / 100}} + \text{per-subscriber costs} \tag{3}$$

We now use the model framework with the above parameters, cost elements, and calculation of shared trench and cables to evaluate the deployment costs of various access technologies with/without protection. The protection model for each of the considered FTTH architectures is shown in Fig. 26.



(a) Unprotected architecture



(b) Protected architecture

Fig. 26. Optical access protection models.

In this model, OLT, feeder fiber, and RN costs are duplicated whereas the ONU and the distribution costs are not. Fig. 27 shows the cost per customer for varying take rate for the considered architectures in both protected and unprotected cases. As expected the protected networks cost higher than that of unprotected networks. The protected networks require more than 34% cost increase compared to the unprotected architectures for the take rate of 100%. The conventional PON architectures require more than 40% increase in costs for the protected architecture.

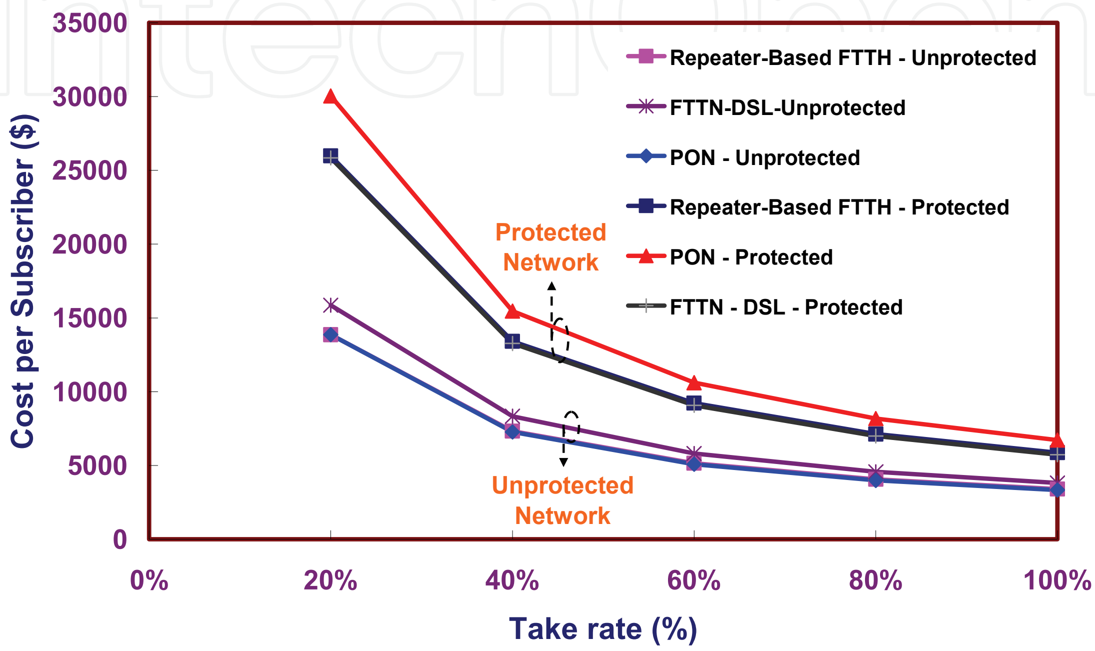


Fig. 27. Cost per subscriber for different access architectures vs. take rates.

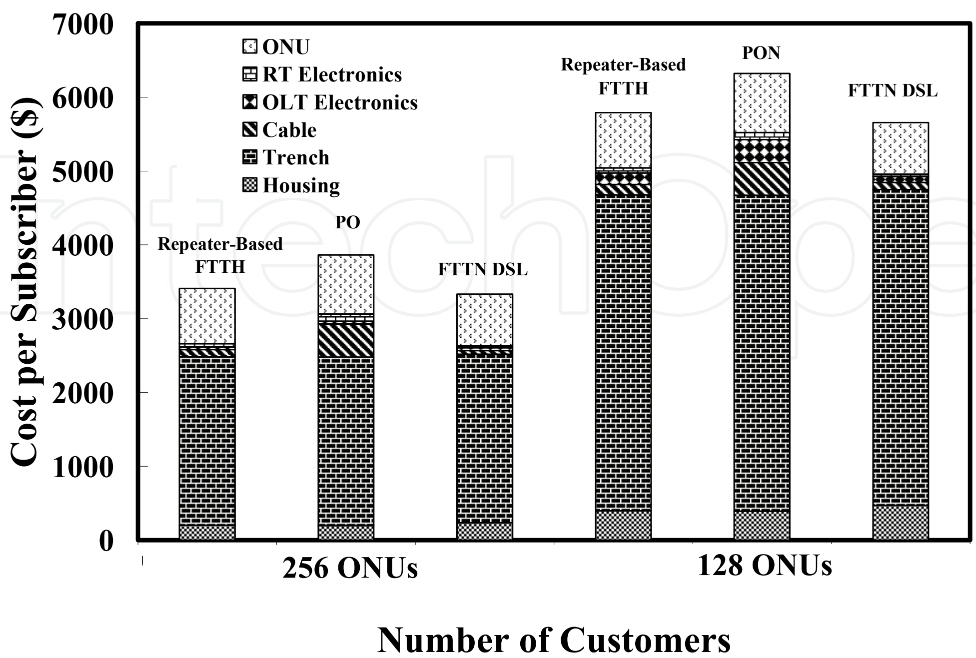


Fig. 28. Cost per subscriber for different access architectures for take rate of 100%.

Fig. 28 shows the cost per subscriber for different architectures for the take rate of 100% showing the cost splits. As can be seen, the ONU costs and the trenching costs dominate the total cost per subscriber for each scheme. As the feeder fiber length is 100 km, the trenching costs dominate the total CU costs and approximately are more than 67% of the total costs, while the ONU cost is more than 21% of the total cost.
For this economic modelling, the cost of the OLT transceiver is considered to be $10,000 while the cost of the ONU transceiver is $500 for all architectures. If the optical transceiver cost used at the CU for the repeater-based FTTH architecture is $453 or less while the optical transceiver cost used at the CU in the FTTN-DSL architecture is $500, then the total cost per subscriber for both repeater-based FTTH and FTTN-DSL architectures is $3459. Therefore, the optical transceiver cost used the CU in the repeater-based FTTH network has to be less than $453 to make this architecture cheaper than other considered solutions.

7. Conclusions

We have reported a new FTTH system to reduce ONU transmitter cost using an upstream repeater at the remote node. The system can be further modified to provide both downstream and upstream regeneration by utilizing bidirectional property of standard transceivers. This is to extend conventional PON system's feeder fiber reach to 60 km and split ratio to 1:256. The use of the repeater introduces insignificant penalty to the existing PON performance and meets the IEEE 802.3ah standard requirements. We show that the system achieves good performance compared to a standard PON using SMFs. The system has a large network coverage and potentially provides a low-cost solution to accelerate broadband access deployment. Furthermore, we investigated the jitter performance of cascaded repeater-based FTTH systems through a recirculating loop. The results show that the system without clock recovery can be cascaded up to 4 times with insignificant performance degradation and the total jitter is within EPON standard specification. When clock recovery at the receiver is used, we can extend the system's coverage area significantly. We have shown that value-added services such as video service integration and LAN emulation can intelligently be added in the repeater-based access networks. We have demonstrated a cost-efficient video service delivery scheme for this type of densely populated repeater-based optical access network, whereby the remote repeater enables the integration of the video services to the downstream traffic transport. The video signals are carried on a RF carrier that is placed outside the bandwidth of the downstream traffic. The BER results and the constellation diagrams measured from the experimental demonstrations show that both signals can be recovered with minimal penalty. For the local area networking amongst the customers in the repeater-based FTTH network, the remote repeater performs intelligent functionalities to provide optical layer LAN capabilities while regenerating the signals. The experimental results show that all signals can be recovered error-free after transmissions. We have also performed an economics study of different FTTH technologies taking into account 1+1 protection. It is shown that the repeater-based FTTH architecture is competitive with the FTTN-DSL architecture in terms of cost per subscriber whereas the conventional PON architecture requires higher costs. The trenching costs and the ONU costs are far more dominant of all costs in all kinds of architectures. It has also been shown that longer feeder fiber incurs more cost per subscriber and therefore to make a feasible and more economical solution to provide broadband services, a larger number of customers have to be supported over a single infrastructure.

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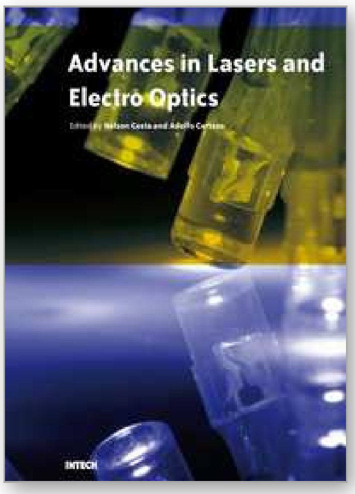

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Lasers and electro-optics is a field of research leading to constant breakthroughs. Indeed, tremendous advances have occurred in optical components and systems since the invention of laser in the late 50s, with applications in almost every imaginable field of science including control, astronomy, medicine, communications, measurements, etc. If we focus on lasers, for example, we find applications in quite different areas. We find lasers, for instance, in industry, emitting power level of several tens of kilowatts for welding and cutting; in medical applications, emitting power levels from few milliwatt to tens of Watt for various types of surgeries; and in optical fibre telecommunication systems, emitting power levels of the order of one milliwatt. This book is divided in four sections. The book presents several physical effects and properties of materials used in lasers and electro-optics in the first chapter and, in the three remaining chapters, applications of lasers and electro-optics in three different areas are presented.