A Multicast Overlay Scheme for Wavelength Division Multiplexed Passive Optical Networks

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Abstract

With ever-increasing demand of bandwidth of broadband application, the wavelength division multiplexed passive optical network (WDM-PON) is very promising for the future access networks to deliver high bandwidth data traffic. However, conventional WDM-PON only supports point-to-point transmission between transceiver and receiver, while service provider needs to multicast information to certain set of ender users. Some efforts have been made to realize multicast function in WDM-PON. However, they either use specialized electronic devices which increase the system complexity, or adopt IRZ modulation format other than the commonly used NRZ-ASK format. To solve these drawbacks, a novel WDM-PON architecture with multicast overlay based on ASK-DPSK orthogonal modulation is proposed and experimentally demonstrated in this thesis.

In this thesis, we propose to employ quaternary ASK-DPSK modulation formats to realized multicast function in WDM-PON. By changing the extinction ratio of the NRZ-ASK signal, multicast sub-channel can be chosen to be enabled or disabled. Our scheme can support 10-Gbit/s for both point-to-point sub-channel and multicast sub-channel. In our scheme, no specialized electronic device is used, and multicast control is centralized at optical line terminal (OLT).

In second part of thesis, we study the principle of AWG filtering effect in our proposed scheme. Narrowband filtering would induce severe inter-symbol-interference (ISI) and phase-to-intensity conversion to the ASK-DPSK signals, and thus introduce performance degradation. The narrowband filtering induced penalty can be alleviated by either using flat-top AWG filter or increasing the

bandwidth of the filter passband. Based on our simulation results, we conclude that it is more effective to use flat-top AWG filter if certain bandwidth of the filter passband can be guaranteed.

In general, we propose a novel WDM-PON architecture with multicast overlay and investigate the narrowband filtering effect in our proposed scheme.

摘要

隨著寬帶應用需求的帶寬不斷增長，多波長無源光網絡（WDM-PON）爲光接入網傳輸寬帶數據提供了一個有效的解決方案。 然而由於傳統的多波長無源光網路只支援點對點（point-to-point）的傳輸方式，因而服務提供商不能把服務傳輸給特定的用戶群。爲了解決這一問題，研究者開發出一些具有組播（multicast）功能的無源光網路結構。但是現有的結構並不完美，這些結構要麼使用大量專有電子器件從而增加了系統的復雜度， 要麼采用了其他的調制格式而不是通用的非歸零振幅鍵控（NRZ-ASK)。爲了彌補這些缺點，我們在這篇論文中提出並實驗驗證了一種新的基於振幅鍵控差分相移鍵控碼（ASK-DPSK）的支援組播的無源光網路系統。

在這篇論文中，我們首先提出了基於振幅鍵控-差分相移鍵控碼（ASK-DPSK）的支援組播的無源光網路系統結構。通過改變點對點信號的信號消光比（extinction ratio）來實現組播信號抑制和通過之間的切換。我們提出的系統傳輸速率可以同時使組播信號和點對點信號達到 10-Gb/s 的速度。我們的系統沒有使用任何專有高速電子器件，並且組播控制模組被集中到光路終端（OLT）以利於服務提供商的控制。

論文的第二部分研究了在我們提出的系統中由於光波導耦合器（AWG）的濾過效應導致的系統性能衰退問題。基於仿真結果我們發現光波導耦合器的窄帶濾過效應可以導致嚴重的碼間干擾（ISI）和相位-幅度信號轉換，從而降低了系統性能。減輕窄帶濾過效應可以通過兩種方法：使用平頂濾波器或者增加耦合器帶寬。通過仿真我們發現，在一定的帶寬已經被保證的情況下，使用平頂濾波器比增加帶寬有效。

綜上所述，在這篇論文中我們提出了一種新的可實現光組播功能的多波長無源光

網路結構並且研究了在我們提出的系統中出現的窄帶濾過效應。

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Chapter 1

Introduction

1.1 Telecommunications network hierarchy

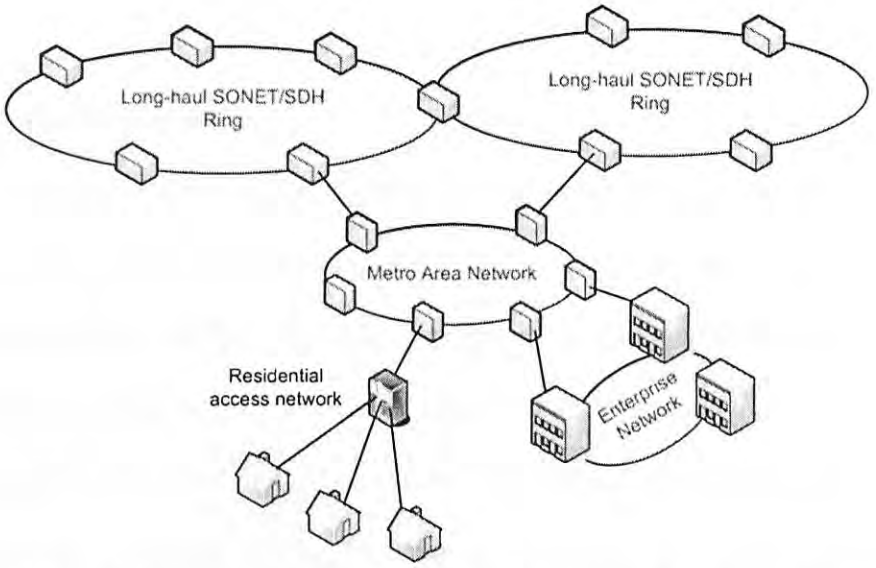

Figure 1-1 Schematic diagram of the fiber network infrastructure

With the ability to support ultrahigh capacity for data transmission, optical communications play a major role in telecommunications network infrastructure nowadays. The telecommunications network can be divided into 3-tier hierarchy [1]: long-haul transport networks, metropolitan networks and access networks. The role of fiber optics system will be examined in these three layers.

Long-haul networks

The long-haul transport networks, also known as backbone networks, are located at the top of the hierarchy illustrated in the Figure 1-1. The long-haul networks usually span thousands of kilometers connecting major network hubs in different countries across different continents. Such networks are optimized in terms of transmission distance and capacity. In this area, the optical fiber has been the dominant media to support such long distance and high speed transmission systems. The technology breakthrough of Erbium-doped fiber amplifier (EDFA) [2] and wavelength division multiplexing (WDM) dramatically brought down the cost of long-haul networks and also increased the system capacity.

Metropolitan networks

Between the access networks and the long-haul networks, metropolitan networks, with area coverage between 10-km and 100-km, serve as feeder networks which gather and distribute traffics from access networks and aggregate them for long-haul transmission when necessary. To successfully deliver the voice traffic in the past, a circuit-based synchronous optical network (SONET)/synchronous digital hierarchy (SDH) has been adopted as the dominant metropolitan network architectures. To enhance the protection and restoration, the metropolitan networks can be formed together to a ring. Nowadays, to satisfy the Internet bandwidth demand, the WDM technique is pushing to metropolitan networks to increase the system capacity.

Access networks

At the bottom layer of the hierarchy, access networks, which span only tens of kilometers (0 – 20-km), provide the broadband connection for end users. Although the backbone networks have experienced great success of fiber-optics communication technology over the last decades, the access networks still remain in low capacity and cannot satisfy the increasing bandwidth demand from end users. There are several solutions to relieve the "last mile" bottleneck: digital subscriber line (DSL), hybrid fiber coax (HFC), Wi-Fi, powerline communication, Fiber to the home (FTTH) and so on. Because it is very cost-sensitive for subscribers in access networks, the copper wire based access networks technologies play a dominant role in nowadays access networks. However, with the ever-increasing bandwidth demand of subscribers, the traditional copper wire based broadband access networks could not support such a high bandwidth to deliver the emerging broadband applications such as high-definition television (HDTV) in the future. Therefore, fiber optics based FTTH access networks will be very promising for access networks. Among all optical access networks solutions, passive optical network (PON) is the most promising broadband optical fiber access networks solution. This type of optical access networks employs only passive optical components in the outside plant. Therefore, the network deployment and maintenance cost can be effectively reduced.

1.2 PON architectures for access networks

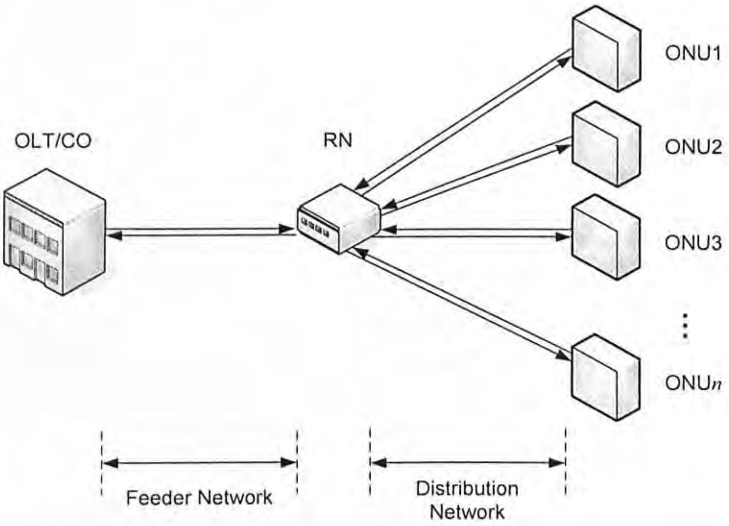

Figure 1-2 Network architecture of passive optical network

The common optical access network is based on a tree topology as shown in Figure 1-2. The optical network units (ONUs) located at end user premises are connected to a remote node (RN) through distribution fibers, which usually span about several kilometers. At the RN, specific components are employed to multiplex and de-multiplex the downstream and the upstream signals, respectively. Then the RN is connected to the central office (CO) of network operators through a long fiber link, which is named as feeder fiber. Because the RN is shared by all ONUs in the network and the required fiber length is much less than the case of direct connections between ONUs and CO, the network deployment cost can be significantly reduced [1]. PON is the most popular broadband optical fiber access networks solution. It employs only passive optical components, without the presence of any electronic amplifier or regenerator, between CO and ONUs. Therefore, the network maintenance cost can be effectively reduced. Moreover, without electronic component, it can benefit the network operators to construct a robust network infrastructure for broadband application.

1.2.1 TDM-PON

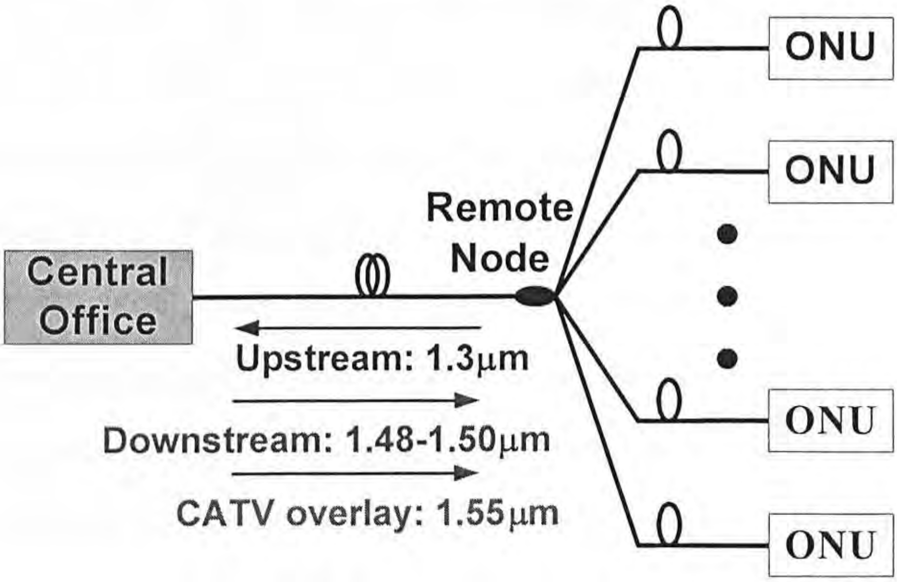

Figure 1-3 Architecture of TDM-PON

The time-division multiplexing technology is adopted in conventional PON, which is known as time-division multiplexed PON (TDM-PON) or power splitting PON (PS-PON) [3]. Figure 1-3 Architecture of TDM-PONshows a typical architecture of a TDM-PON [4]. A passive tree coupler is employed at the RN in a TDM-PON to achieve the downstream and the upstream services. Both of the downstream and the upstream bandwidths are time-shared among all ONUs by time division multiplexing technique. Downstream optical signal is power-split into multiple replicas at the RN to be broadcasted to all subscribers in the network. At each ONU, the desired downstream signal will be filtered out by its designated time slots. On the other hand, the upstream signals from all ONUs will be coupled together at the RN, then be transmitted back to the OLT. A point-to-multipoint media access control (MAC) protocol is required to schedule the data transmission to avoid data collision.

TDM-PONs are mature PON architectures. There are several commercial PON standards: ATM PON[5], Ethernet PON[6], and Gigabit-capable PON[7]. Because the implementation for TDMA is achieved in the electronic domain and identical transceivers can be employed for all ONUs, TDM-PONs become practical and cost-effective solutions for access networks around all the world. However, by the time-sharing nature of TDM-PONs, each subscriber can only get a small portion of the downstream and the upstream bandwidths. It can be anticipated that the available bandwidth for each subscriber in a TDM-PON cannot satisfy the bandwidth requirement for broadband applications in the future. Moreover, as the downstream signal is broadcasted to all subscribers in the network, the privacy issue cannot be satisfied unless encryption is employed. Lastly, the ranging problem and burst-mode receivers are required in the TDM-PONs. They will increase the system cost for the comparably high electronic complexity.

In general, this power-splitting and time-sharing nature of TDM-PON impose some limitations on the scalability and security of the system. They can be alleviated by introducing wavelength division multiplexing (WDM) into PON.

1.2.2 WDM-PON

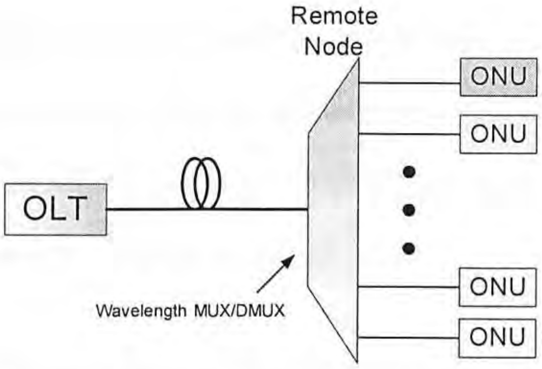

Figure 1-4 Architecture of WDM-PON

To overcome the limitations for TDM-PON, wavelength division multiplexed PON (WDM-PON) [8][9][10] has attracted more and more attention in the academia and industry to provide an ultimate solution for broadband access networks. In the typical WDM-PON architecture shown in Figure 1-4, multiple wavelengths are employed as the downstream and the upstream carriers for the communication between ONU and OLT. At the RN, a WDM multiplexer and demultiplexer are required to route the specific wavelength to a particular ONU. This multiplexer is usually made of an array waveguide grating (AWG)[11] or thin-film filter. Therefore, each subscriber is designated with dedicated wavelength for upstream and the downstream transmissions. Each ONU can be guaranteed a certain quality of service (QoS) for broadband applications. Moreover, there is no ranging problem and power deviation problem of the upstream signal in the WDM-PON. This can simplify the electronics in the network.

Although the cost for dedicated transceiver for each ONU is still high compared with that in a TDM-PON, both of the network operators and subscribers can benefit from the "unlimited" bandwidth provided by a WDM-PON. Therefore, many aggressive network operators pay a lot of attention to the deployment of WDM-PONs. *NTT* in Japan [12], *Verizon* [13] and *SBC* [14] in USA are the leading companies to deploy the practical FTTx access networks. With the maturity of WDM technologies and novel WDM-PON architecture with "colorless" ONUs in future, it can be expected that the cost for WDM-PONs can be potentially reduced further.

1.3 Data delivery mode in WDM-PON

With the increasing popularity of high quality video service, data delivery becomes a big issue as optical network may bear heavy burden to meet the flexible requirement of the service providers. Basically WDM-PON is a kind of point-to-point architecture. Thus, when implementing a WDM-PON, the service providers face a huge challenge: how to deliver information to a certain set of end users. In order to meet this requirement, it is critical to develop various data delivery methods supported in a WDM-PON. Generally speaking, there are three modes of data delivery: point-to-point (unicast), multicast and broadcast.

1.3.1 Point-to-point

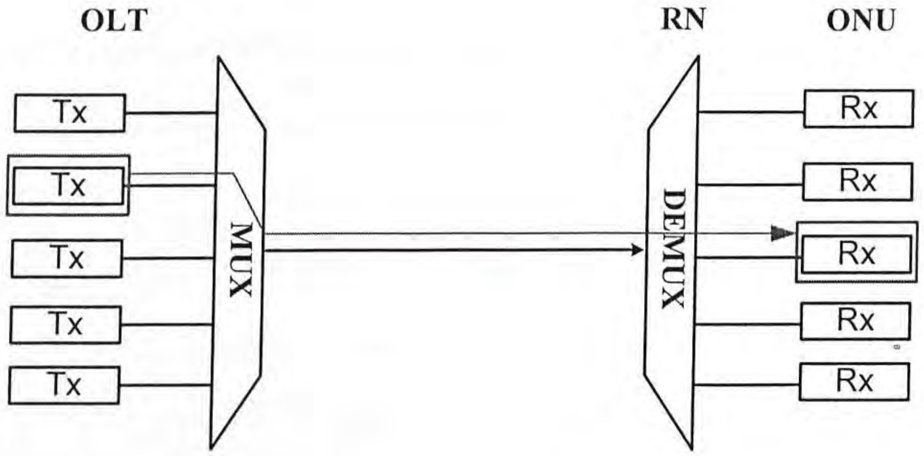

Figure 1-5 Point-to-point data delivery

In telecommunication, point-to-point (unicast) is the term used to describe communication where a piece of information is sent from one point to another point. In this case there exists only one single pair of sender and receiver. As shown in Figure 1-5, WDM-PON is a point-to-point transmission system where only a pair of transceiver and a receiver involves in a connection. At the RN, arrayed waveguide grating (AWG) works as multiplexer and de-multiplexer to assign different wavelength channels to their dedicated ONUs. Point-to-point transmission is usually used to deliver highly dedicated information, such as internet data flow.

1.3.2 Broadcast

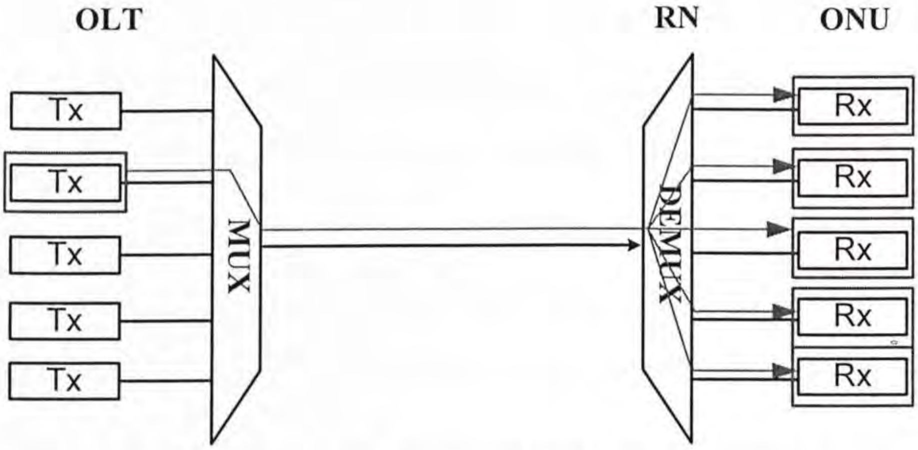

Figure 1-6 Broadcast data delivery

As shown in Figure 1-6, broadcast technique is needed when the OLT is transmitting information to all ONUs. To realize broadcast function in WDM-PON, usually, the information should be modulated onto every wavelength channel in order to be received by all ONUs. Lots of efforts have been made to realize broadcast function in WDM-PON, including injecting broadband laser source in transceiver, re-use AWG and broadcast overlay [15],[16],[17],[18]. Broadcast is usually used to deliver public-shared programmes like public radio, television and other broadband services.

1.3.3 Multicast

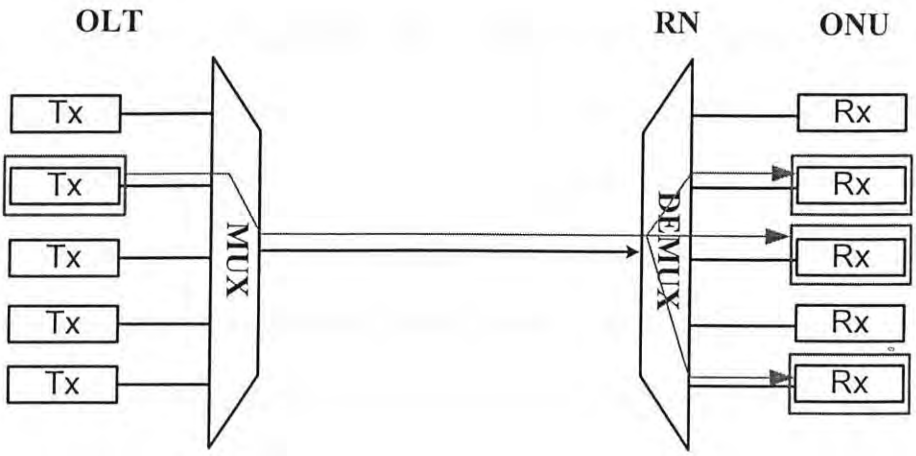

Figure 1-7 Multicast data delivery

As shown in Figure 1-7, multicast is a method enabling the OLT to deliver a piece of message to a certain set of ONUs. Broadcast can be treated as a special case of multicast in which information is sent to all ONUs. Today, with the emergence of high quality TV delivery, high speed multicast enabled WDM-PON catches people's attention as it supports more flexible transmission functions. To realize multicast architecture, multicast enabled WDM-PON should be capable of switching between the ON/OFF states of every multicast channel. At the same time, the cost of the whole system should be minimized. This thesis will focus on developing a WDM-PON architecture to achieve high speed, and cost-effective multicast function.

1.4 Motivation of this thesis

As mentioned earlier, WDM-PON is considered as an ultimate solution to meet the ever-increasing bandwidth requirement of next generation broadband service. Nevertheless, WDM-PON architecture only establishes a dedicated wavelength channel between a pair of transceiver and the receiver thus supports only point-to-point transmission. Recently, various kinds of broadcast enabled WDM-PON architectures have emerged to empower optical networks with more flexible functions. However, broadcast is not enough for today's broadband communication as the subscribed contents of ender user differ widely. One possible choice is to deliver subscribed services via existing point-to-point channel, which makes all information "private". However, this method consumes a large portion of point-to-point bandwidth and would jam the point-to-point channel. Besides, wavelength scheduling as well as fast electronic processing is required to combine all signals together, which would add latency to the real-time signal. Therefore, it is desirable to realize multicast function in WDM-PONs to facilitate future broadband service delivery.

When implementing multicast enabled system, several factors should be considered. Firstly, multicast channel should seize enough bandwidth to accommodate future broadband video service. Secondly, multicast control should be centralized at the optical line terminal for easy control and management. Finally, multicast sub-channels should not generate any disturbance to the existing point-to-point channel. In other words, multicast signal should be "independent" to the point-to-point system leaving the original service intact and secure.

To meet such requirements, we proposed a novel multicast enabled WDM-PON architecture by using ASK-DPSK orthogonal modulation format. In our scheme non-return-to-zero (NRZ-ASK) format is used to carry point-to-point data, while differential-phase-shift-keying (DPSK) format is used to carry multicast data. To realize multicast operation, we change the extinction ratio of the multicast DPSK signals so that it can be enabled or suppressed without interruption of the point-to-point signals. By implementing this scheme, both the point-to-point signal and the multicast signal can reach a data rate of 10-Gb/s, thus our scheme can support broadband multicast video service and high speed point-to-point data transmission, simultaneously. In terms of multicast control, our scheme centralizes the switching units at the OLT, which greatly facilitates multicast control for the service providers.

In general, our proposed scheme can provide high speed and flexible function, as well as guaranteed information safety to information transmission in WDM-PONs.

1.5 Outline of this thesis

The organization of the remaining chapters of this thesis will be as followings:

Chapter 2: Previously proposed multicast enabled WDM-PON architectures are reviewed.

Chapter 3: A novel WDM-PON architecture with multicast overlay based on ASK-DPSK orthogonal modulation format is proposed and experimentally demonstrated.

Chapter 4: Effect of AWG filtering on proposed ASK-DPSK multicast enabled system is studied.

Chapter 5: Summary and future works.

Chapter 2

Previously proposed Multicast Architectures in WDM-PON

2.1 Introduction

As mentioned in Chapter 1, WDM-PON is considered as an ultimate solution for next generation broadband networks. To realize flexible network functions, broadcast function is a possible choice. However, in broadcast, the information received by all subscribers is identical, thus service providers may have to use much bandwidth resource to deliver unnecessary information to certain customers. To make the network function more flexible, a multicast enabled WDM-PON architecture is highly desirable.

The major research interest of this topic focuses on three aspects: 1) minimize the modification added to the existing network architecture; 2) centralize the multicast switch control at the OLT; 3) minimize the number of additional dedicated electronic devices used. In this chapter we will review several available schemes providing such multicast function. In terms of modulation techniques, they can be divided into two categories: subcarrier multiplexing (SCM) based methods and all optical modulation based methods.

2.2 Previous WDM-PON architectures with multicast capability

The basic idea to achieve multicast function is overlaying the multicast signal to the conventional point-to-point architecture. Moreover, every channel in the network should be capable of being switched between multicast enabled and disabled modes. Recently, several schemes have been reported to achieve such function. In terms of the modulation method, they can be divided into two categories: subcarrier multiplexing [19], [20] and all optical modulation based multiplexing[19].

2.2.1 Subcarrier multiplexing

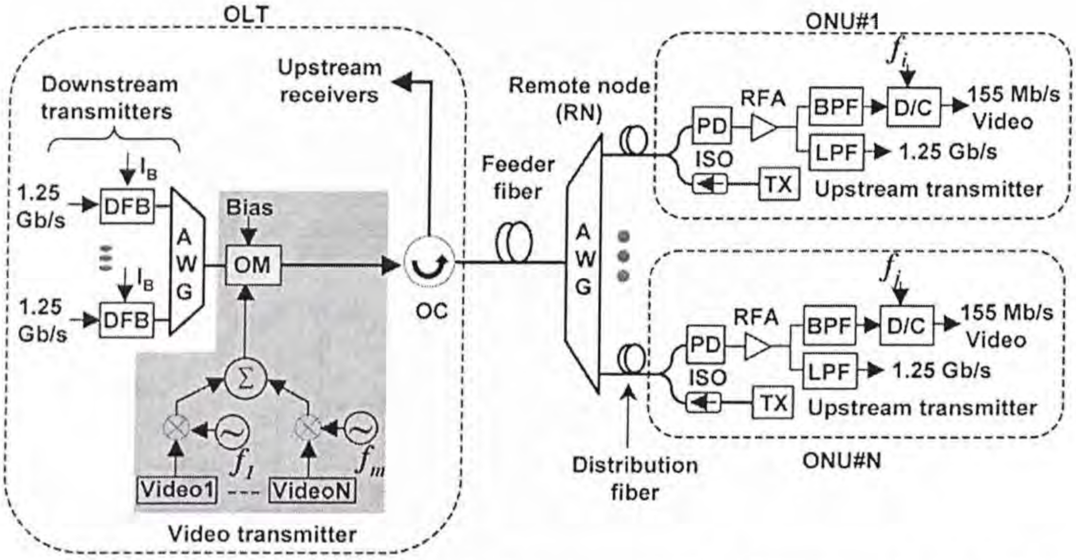

Figure 2-1 Subcarrier multiplexing system with multicast capability[19]

Figure 2-1 Subcarrier multiplexing system with multicast shows a WDM-PON architecture with multicast capability[19]. In this scheme, direct-modulated distributed feedback (DFB) lasers at the OLT generate the point-to-point NRZ-ASK signals, while the subcarrier multiplexed multicast BPSK video signals generated by a common radio frequency (RF) video transmitter are superimposed onto the composite multiplexed point-to-point channels. All wavelength channels from the OLT are fed into a feeder fiber and transmitted to their assigned ONUs respectively. At the ONU, the combined multicast SCM video signal and the point-to-point NRZ-ASK signal are detected by a wide-band photo detector first and then separated in electrical domain by different electrical filters before sampling. The operational principle of the multicast control in this system is to switch the extinction ratio of the point-to-point NRZ-ASK signal by changing the bias current of the DFB laser such that the multicast subcarrier signals can be enabled or disabled. In this scheme, the multicast control is centralized at the OLT, which greatly reduces the system complexity. However, at the transceivers, several dedicated electronic devices, including subcarrier modulation module, local frequency synthesizer, and RF combiner are required to modulate and demodulate the subcarrier signals, which dramatically increases the system complexity.

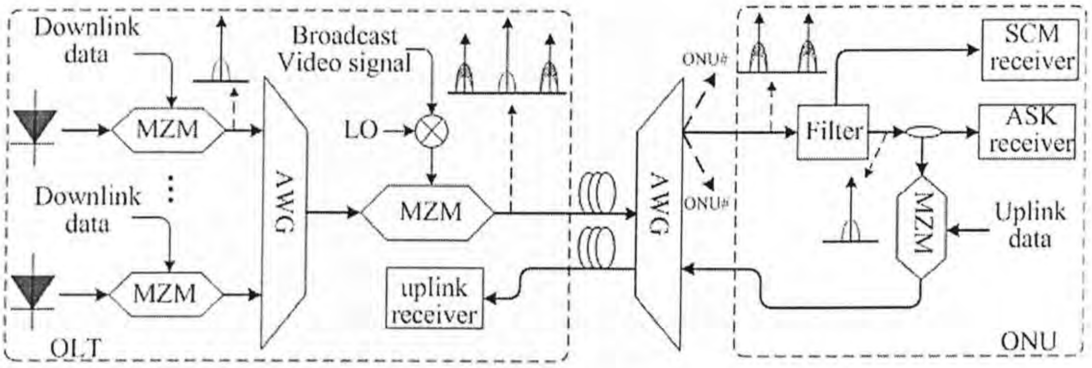

Figure 2-2 Another ASK/SCM multicast WDM-PON architecture[20]

Figure 2-2 shows another multicast enabled WDM-PON architecture employing ASK/SCM which does not require any costly high frequency electronic devices at the receiver side[20]. At the OLT, continuous wavelength (CW) light source with external intensity modulator is implemented instead of direct-modulated DFB laser to generate high extinction ratio NRZ-ASK signal. For overlaid multicast video signal, NRZ-ASK format is employed instead of BPSK format to facilitate detection at the ONUs. By carefully tuning the frequency of the local oscillator, dedicated high speed electronic devices can be avoided at receiver. Similar to the previous scheme, multicast control is realized by changing the extinction ratio of the downstream NRZ-ASK signals except that this scheme changes the bias voltage of the intensity modulator to realize different extinction ratios.

The advantages of utilizing ASK/SCM schemes to realize multicast enabled WDM-PON is threefold. Firstly, few changes are required to upgrade the conventional point-to-point system to provide more flexible function. Secondly, the multicast control unit of this system consists of only simple electrical switching circuit. This feature allows the system to perform high speed, effective and centralized switching. Finally, the subcarrier multiplexing system is a well-developed system with a long period of practical deployment in commercial broadcast radio/video services. Thus, the SCM based multicast enabled WDM-PON would be highly compatible to the existing broadcast systems, reducing the cost and the instability of the whole architecture.

The main disadvantage of SCM based multicast system is that the transmission speed of the subcarrier modulated signal is limited by the processing speed of electrical devices in the SCM module. Usually, SCM can be used effectively for lower-speed, lower-cost multiuser systems. To reach a high data rate for the multicast signal (≥1-Gb/s), the system would become extremely costly as it requires expensive electrical devices with high bandwidth. On the contrary, this problem can be well alleviated if all signals are processed in optical domain.

2.2.2 All optical based multicast enabled architecture

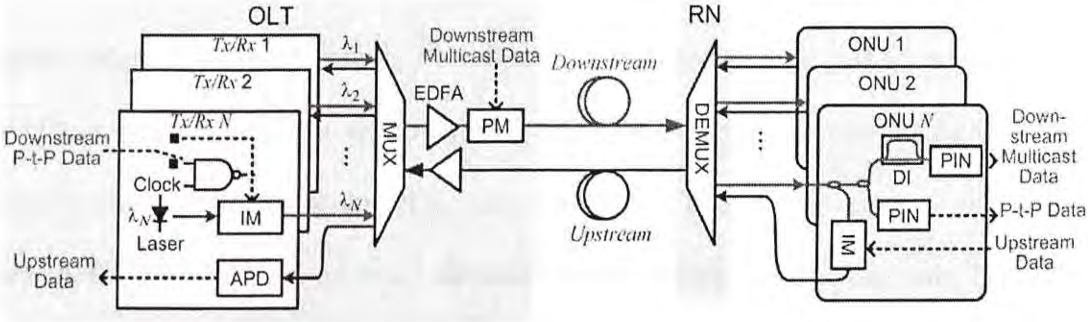

Figure 2-3 An all-optical multicast enabled WDM-PON architecture [21]

Figure 2-3 depicts an all-optical WDM-PON architecture with multicast overlay[21]. The principle of multicast control is based on changing the modulation format of the downstream point-to-point data. The point-to-point inverse-return-to-zero (IRZ) format is used to carry differential phase-shift-keying (DPSK) video signal, while high extinction ratio non-return-to-zero (NRZ-ASK) format is adopted to suppress the multicast DPSK signal. As shown in Figure 2-3, at the OLT side, a logic NAND gate is used to generate RZ-shaped data sequence to drive the optical intensity modulator (IM) to generate point-to-point IRZ signal. After wavelength multiplexing, combined wavelength channels are fed into a common phase modulator to carry multicast DPSK signals. Since IRZ format always consists of a period of high power at every bit, multicast DPSK signal can be successfully superimposed onto it. For multicast disabled mode, none-return-to-zero (NRZ-ASK) format, instead of IRZ format, is adopted at the transceiver. In this case, with high extinction ratio of the NRZ-ASK signal, the multicast DPSK signal cannot be correctly recovered at the ONUs due to excessive intensity fluctuations[24]. To realize multicast control, an electronic switching circuit can be implemented at each transceiver to switch between the multicast enabled and disabled modes.

The main advantage of this scheme is that it avoids any dedicated high frequency electronic device at the ONU side as both the point-to-point signal and the multicast signal can be directly detected. Therefore, this system can take full advantage of the available fiber bandwidth without using costly high speed electronic devices. The disadvantages of this architecture are twofold. Firstly, this system still needs cost-ineffective high speed logic devices at the multicast switching unit. Secondly, this system employs IRZ signal which is not often used in common WDM-PONs. To upgrade existing WDM-PON to support multicast function, service providers may need extra components in order to generate the IRZ format.

2.2.3 Carrier suppress based multicast scheme

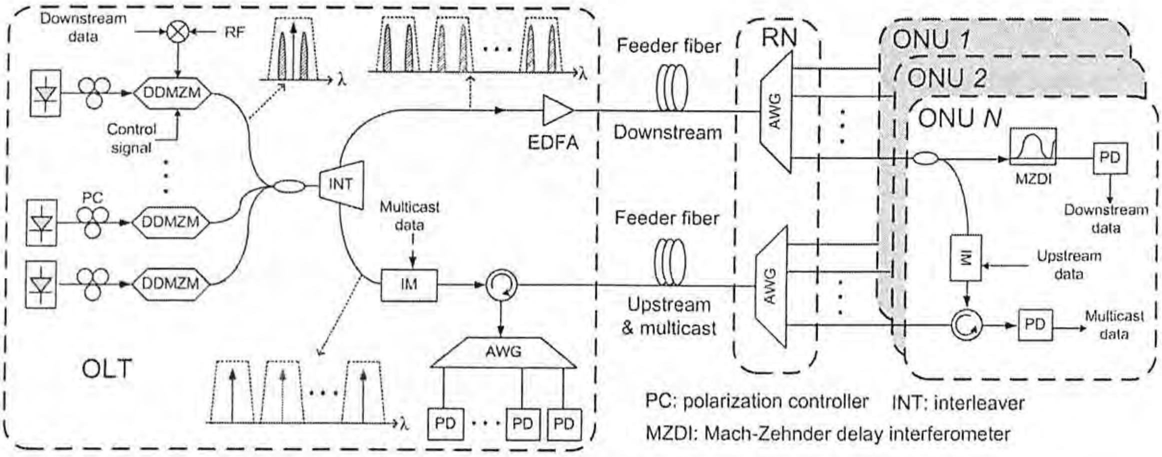

Figure 2-4 A carrier suppression based multicast architecture[22]

Figure 2-4 depicts a multicast scheme based on carrier suppression. The basic idea of this scheme is, in certain degree, similar to SCM-based schemes except that this scheme employs a separate optical carrier to carry multicast signal while point-to-point signals are shifted to the higher spectrum region to save the multicast signal spectrum. At each transceiver, a dual-drive Mach-Zehnder modulator (DDMZM) is employed to generate a SCM-like downstream signal, where the point-to-point signal is shifted to higher frequency region of the signal by a RF mixer. The carrier and point-to-point signal are then separated by an interleaver, and the separated carrier is then fed into a common intensity modulator for multicast signal modulation. During transmission, the point-to-point signal and multicast signal pass through two independent transmission links to reduce the potential crosstalk between two channels. To switch between the multicast enabled mode and multicast disabled mode, a control signal can be employed at every transceiver to change the bias current of the DDMZM, thus the carrier signal can be switched between the on and off states. The main advantage of this architecture is that this architecture has little performance tradeoff between point-to-point signal and multicast signal. However, this architecture would not be cost-effective to support a high data rate, say 10-Gb/s, since the RF signal must be high enough to shift point-to-point signal to higher spectrum region. In addition, this scheme still needs a dedicated electrical device, increasing the cost of the whole system.

2.3 Summary

In this chapter, previously proposed multicast enabled WDM-PON architectures have been reviewed. In terms of modulation techniques, these architectures can be divided into two categories: subcarrier multiplexing based system and all optical modulation based system.

For subcarrier multiplexing based system, the cost is relatively low and the multicast control is centralized at OLT. Moreover, this system is compatible to conventional broadcast system, which simplifies the upgrading of existing point-to-point WDM-PON system. However, such system is not suitable to support high multicast data rate (≥1-Gb/s) since it requires expensive dedicated high speed electronic devices at the transceivers. For all optical modulation based multicast enabled system, the data rate of the multicast and the point-to-point channels can be as high as 10-Gb/s, respectively. The multicast control is also centralized at OLT. However, this system still needs dedicated high speed logic gate at the transceiver to realize the multicast control. For carrier suppression scheme, the data rate can reach 2.5-Gb/s for both point-to-point signal and multicast signal. The multicast control is also centralized at the OLT. However, this system would not be cost-effective to support high data rate since it employs a high frequency mixer to shift point-to-point signal to higher spectrum region.

In the next chapter, a novel multicast enabled WDM-PON system with ASK-DPSK orthogonal modulation format is proposed. In our proposed system, we employ conventional NRZ-ASK and DPSK modulation formats without using any dedicated electronic device.

Chapter 3

A Multicast enabled WDM-PON Architecture Using ASK-DPSK Orthogonal Modulation

3.1 Introduction

For future optical passive network, the major challenge for broadband network is to deliver large bandwidth and flexible application to the end users. Multicast overlay is a promising technique to achieve both large bandwidth and flexible network function for future WDM-PONs. To date, several schemes have been proposed to realize delivering both point-to-point signal and overlaid multicast signal to end users[19],[20],[21]. Among these alternatives, one kind of approaches implements subcarrier multiplexing to superimpose the multicast signal to the downstream point-to-point signal[19],[20]. This kind of scheme provides a simple solution to be compatible with common WDM-PON architecture and TV/radio broadcast system. However, this solution has several drawbacks. Firstly, this solution is not cost-effective for higher data rate (≥10-Gb/s), as it requires dedicated high-speed radio-frequency electronic devices at the transmitter and the receiver sides. Another kind of solution implements IRZ/DPSK orthogonal modulation formats to allow multicast service[21]. As all of the signals used are modulated in optical domain, it can support higher data rate (10-Gb/s) with cost-effective components. However, this scheme employs IRZ modulation format for the point-to-point signal which requires high-speed logic circuits for the signal generation. Secondly, this scheme increases the complexity of system as it requires switching between two different modulation formats at the OLT. Another scheme uses separate carrier to carry downstream multicast signals to reduce the crosstalk between point-to-point signal and multicast signal[22]. However, this scheme still employs a RF mixer to shift point-to-point signal to higher frequency region, making it cost-ineffective to upgrade transmission speed.

In this chapter, we propose a novel WDM-PON architecture with multicast overlay based on ASK/DPSK orthogonal modulation. The multicast signal is encoded in DPSK format and is superimposed onto the point-to-point channel which is in the form of conventional NRZ-ASK format. The multicast operation is based on the principle that proper demodulation of the DPSK signal at an optical network unit (ONU) required sufficiently small extinction ratio of the point-to-point NRZ-ASK signal. Hence, by carefully adjusting the extinction ratio of the individual NRZ-ASK point-to-point channel at the OLT, the downstream multicast DPSK signal could flexibly be either transmitted or interrupted on every wavelength channel. Compared to the previous schemes, our scheme has several excellent features. Firstly, our scheme reaches high data rate (≥ 10-Gb/s) without using any dedicated high speed electronic devices. Secondly, multicast switch control is centralized at OLT to ease the multicast control for service provider. Finally, our scheme uses uniform and conventional modulation formats which are highly compatible with common WDM-PONs.

3.2 System architecture

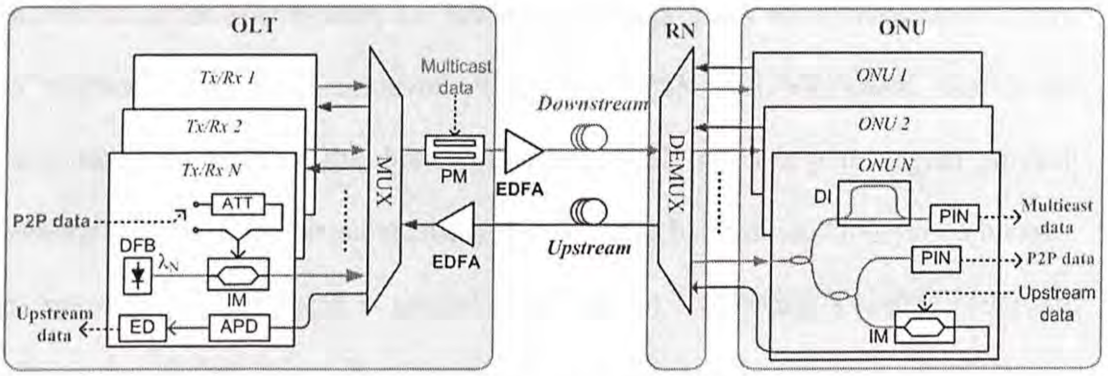

Figure 3-1Proposed system architecture

Figure 3-1 depicts our proposed WDM-PON architecture with multicast overlay. At the OLT, the transceiver of each individual point-to-point channel generates the downstream NRZ-ASK signal and receives the upstream re-modulated signal from its respective designated ONU. The downstream signal is intensity modulated by a Mach–Zehnder intensity modulator. In order to obtain optical NRZ-ASK signals with different extinction ratios, the input amplitude of the electrical data signal is properly adjusted via an electrical attenuator. All of the downstream point-to-point signals on different wavelength channels are multiplexed before being fed into a common optical phase modulator (PM), where the DPSK multicast data is further superimposed onto them. If the extinction ratio of a downstream NRZ-ASK point-to-point signal is set at a relatively low value, say 2~4-dB, both the superimposed DPSK multicast data and the point-to-point NRZ-ASK data can be demodulated and received properly at its destined ONU[24]. On the contrary, if the extinction ratio of the downstream NRZ-ASK signal is relatively high, say 5-dB, only the NRZ-ASK data can be received properly, as the superimposed DPSK multicast signal would suffer from excessive intensity fluctuation induced by the NRZ-ASK signal and thus could no longer be correctly demodulated at its destined ONU. Hence, by properly selecting the extinction ratio of the downstream NRZ-ASK point-to-point signal on individual wavelength channels at the OLT side, only those downstream channels with low extinction ratio are able to carry the multicast signal properly to the designated ONUs, thus multicast overlay is achieved. Since the DPSK and NRZ-ASK signals are orthogonal to each other, the downstream NRZ-ASK point-to-point signal on each wavelength channel can be successfully demodulated by destined ONU in both cases. The control of the multicast is centralized at the OLT by using a simple electronic switch. At each ONU, a portion of the received signal power is tapped off for the downstream data reception. The NRZ-ASK point-to-point data is detected via direct detection, while the DPSK multicast data is demodulated via a delay interferometer (DI) before detection. The rest of the received power is re-modulated with the upstream data, via an intensity modulator, given the limited extinction ratio of the downstream NRZ-ASK signal (~8-dB). No light source is needed at the ONU. To avoid the possible Rayleigh backscattering induced performance degradation, a pair of feeder and distribution fibers is used to separate the downstream and the upstream data in the transmission link.

3.3 Experimental Demonstration

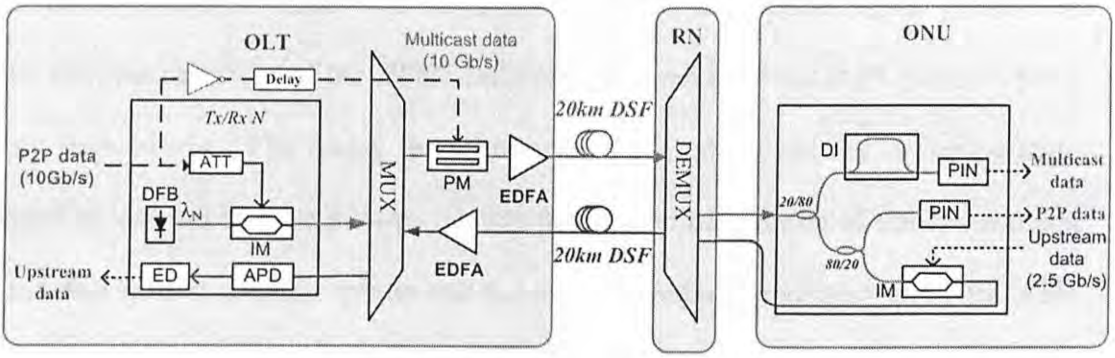

Figure 3-2 Experimental setup

To verify the feasibility of our proposed scheme, we have experimentally demonstrated the multicast WDM-PON architecture based on the setup shown in Figure 3-2. At the OLT, a distributed feedback (DFB) lasers was used as light source to generate continuous-wave (CW) light. The generated CW light with wavelength at 1546.8-nm was first fed into an intensity modulator (IM) and NRZ-ASK modulated by a 10-Gb/s pseudorandom binary sequence (PRBS) as the downstream point-to-point signal. In this experimental demonstration of the multicast operation, we have adopted an extinction ratio (ER) of 3.5-dB for the multicast-enabled mode and an ER of 6.5- dB for the multicast-disabled mode at each transceiver. After being multiplexed by a standard ITU 100-GHz grid array waveguide grating (AWG) with a 3-dB bandwidth of 0.35-nm, all of the downstream point-to-point wavelength channels were further modulated by another decorrelated 10-Gb/s PRBS data via an optical PM, such that the DPSK multicast signal could be superimposed on them. The point-to-point data and the multicast data were bit synchronized by using a common clock signal. This synchronization could be saved if the point-to-point data and superimposed multicast data have a relatively large difference in their data rates. After being amplified to around 6.5-dBm, the downstream signal was then coupled into a piece of 20-km dispersion-shifted fiber to emulate the dispersion-compensated transmission between the OLT and the remote node (RN). No waveform distortion induced by nonlinear effect was observed. At ONU, the optical signal power was 3-dB split for detection of the DPSK multicast data and the NRZ-ASK point-to-point data, respectively. The delay interferometer (DI), stabilized by a temperature controller, was set to have a 94-ps relative delay. Another portion of the downstream signal was split by a 20/80 splitter and fed into an intensity modulator and NRZ-ASK modulated by upstream data at 2.5-Gb/s. To get better performance, a reflective semiconductor optical amplifier (RSOA) can be adopted to re-modulate the downstream signal instead of the intensity modulator. The upstream NRZ-ASK signal was then transmitted back, via another 20 km DSF and detected by an avalanche photodetector (APD) at OLT side.

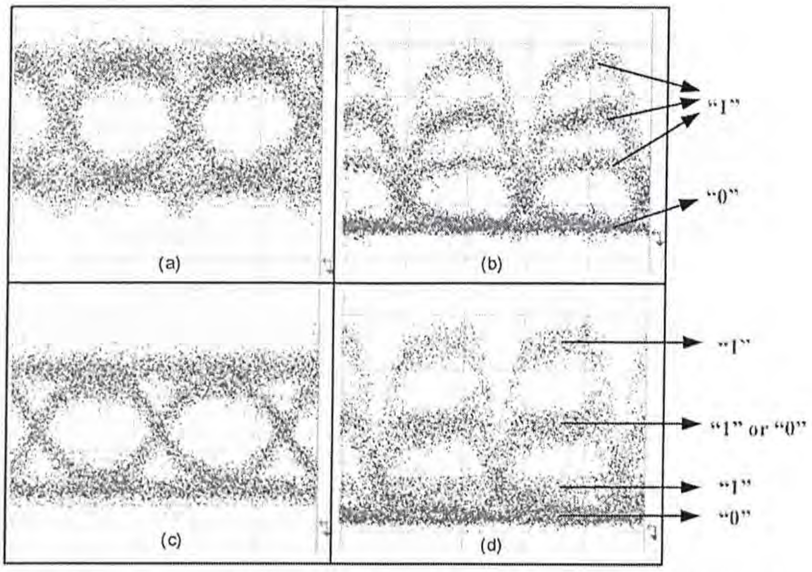

Figure 3-3 Eye diagrams of (a) 10-Gb/s downstream NRZ-ASK data with low extinction ratio (multicast enabled), (b) 10-Gb/s multicast DPSK signal after DI when multicast was enabled, (c) downstream NRZ-ASK signal with high extinction ratio (multicast disabled), and (d) downstream DPSK signal after DI when multicast was disabled (detection failed). Time scale: 50-ps/div.

Figure 3-3 depicts the eye diagrams of the downstream signals measured at different modes. When a downstream channel was set at the multicast-enabled mode, that is, when its NRZ-ASK point-to-point signal was at low extinction ratio, the superimposed DPSK signal could be correctly demodulated at the receiver. As both the high level and the low level of the NRZ-ASK signal provided enough power for the DPSK multicast signal, the demodulated DPSK signal showed a clear eye diagram with three intensity levels, as depicted in Figure 3-3(b). On the other hand, when the multicast was disabled by setting a high extinction ratio value to the NRZ-ASK point-to-point signal, the NRZ-ASK point-to-point signal was still properly detected, while the superimposed DPSK multicast data could no longer be demodulated properly, as shown in Figure 3-3(c) and (d), due to excessive fluctuation induced by the NRZ-ASK data.

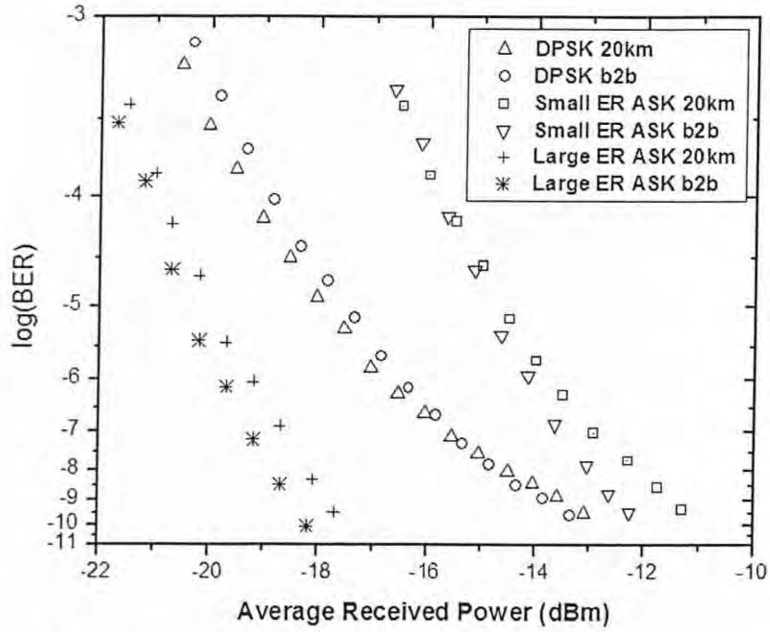

Figure 3-4 BER measurements of NRZ-ASK point-to-point tributary and the multicast DPSK tributary of the ASK/DPSK downstream signal, under multicast enabled (small ER) and disabled (large ER) modes.

Figure 3-4 depicts the bit-error rate (BER) of the measured downstream signals. The signal power was measured in front of the pin receiver. When the multicast was enabled, both the DPSK and the NRZ-ASK signals could achieve error-free detection. We observed some phase-to-amplitude conversion after the AWG at the RN, as shown in Figure 3-3(a), due to mainly non-flat frequency response of the AWG. With proper bit synchronization, this influence on NRZ-ASK performance was minimized and a power penalty of around 1-dB was measured. The relatively low receiver sensitivity was mainly due to the combined effect of low extinction ratio and phase-to-amplitude-converted noise. The DPSK multicasts signal after 20-km transmission showed identical performance with back-to-back signal. When the multicast was disabled by applying high extinction ratio to the NRZ-ASK signal, the NRZ-ASK signal was still properly detected, while the superimposed DPSK signal [as shown in Figure 3-3(d)] could not be demodulated at the ONU and thus its BER is too high to be measured.

3.4 Discussion

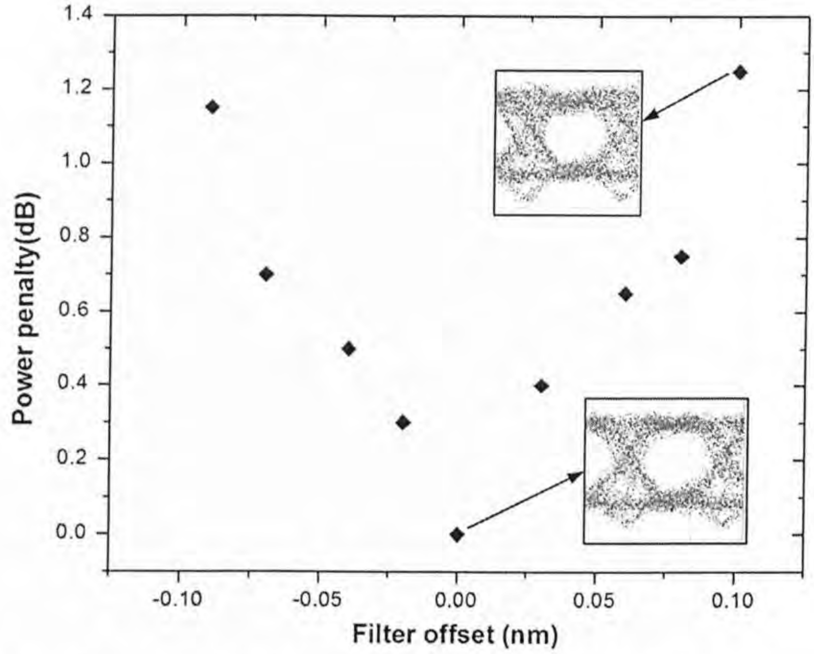

Figure 3-5 Power penalty of downstream NRZ-ASK signal (ER = 3.5dB) with respect to filter offset at the multicast enabled mode.

For the downstream ASK/DPSK signal in which the DPSK multicast data has been imposed onto the NRZ-ASK point-to-point signal, the DSPK component is more vulnerable to the optical filtering effect as it is carried at a relatively higher frequency region, as compared to the NRZ-ASK component at the same data rate. Thus, the phase-to-amplitude conversion present at the DPSK component would ruin the NRZ-ASK component with low extinction ratio. In our experiment, such phase-to-amplitude conversion originated from the possible wavelength misalignment induced filtering effect at the AWG at the RN. As Gaussian type AWG was used in our experiments, any wavelength misalignment would lead to excessive phase-to-amplitude conversion at the phase transition region of the filter passband. Our measurement results showed that it could tolerate up to 0.15-nm filter offset for 1-dB power penalty, as depicted in Figure 3-5. Nevertheless, this kind of degradation could be alleviated by employing AWGs with flat-top passband. On the contrary, the NRZ-ASK component in multicast-disabled mode would not suffer from this kind of degradation, as the extinction ratio of the signal was high enough to combat the influence of such intensity fluctuations.

	Data rate	Centralized switch	Electrical device	Performance tradeoff
SCM based scheme (1)	1.25-Gb/s & 155-Mb/s	Yes	Yes	Yes
SCM based scheme (2)	1.25-Gb/s	Yes	Yes	Yes
Carrier suppression	2.5-Gb/s	Yes	Yes	No
IRZ/DPSK orthogonal	10-Gb/s	Yes	Few	No
ASK/DPSK orthogonal	10-Gb/s	Yes	No	Yes

Table 3-1 Comparison of different multicast schemes

We compare available multicast schemes in terms of data rate, electrical device usage and performance tradeoff, etc, as shown in Table 3-1. Notably, all the available schemes have realized centralized multicast switch such that multicast control can be effectively implemented in the central office (CO).For the costly electrical device usage, we find that all the schemes except our proposed ASK/DPSK scheme employ dedicated electrical devices. For SCM-based schemes and carrier suppression based scheme, a pair of RF source and mixer has to be employed at each set of transceiver to realize frequency shifting, which makes the system cost-ineffective with the growing data rate of transmitted signals. For IRZ/DPSK based system, an "AND" logic gate is still required to generate IRZ signal to carry multicast DPSK signal in later stage. In our scheme, switching between multicast enabled and disabled modes does not need to work at a high frequency. Thus the electrical switch could be a normal electronic device working at a low switch rate. As for the performance tradeoff between point-to-point signal and multicast signal, we note that both the SCM-based scheme and ASK/DPSK based scheme involve performance tradeoff between two sub-channels, meaning that one has to sacrifice the performance of one sub-channel in order to guarantee the safe transmission of the other. It should be noted that, for the carrier suppression scheme, the independent performance of the two sub-channels is realized by separate transmission of two sub-channels via separate fiber links, slightly increasing the system cost by an additional AWG in the remote node.

For the transmission data rate of the system, the experiment verified transmission data rate is led by IRZ/DPSK scheme and ASK/DPSK scheme both at the data rate of 10-Gb/s for both multicast signal and point-to-point signal, respectively. All the date rates of other schemes were significantly below 10-Gb/s. How about the potential data rate of these systems? For SCM based systems, to elevate the transmission date rate of downstream point-to-point signal and multicast signal, the RF source has to work at much higher frequency in order to guarantee enough spectrum room for high speed multicast signal. And by doing so, the mixer and RF source would be highly costly depending if the data rate is high, say 10-Gb/s. Moreover, the spectrum space seized by the individual combined signal may become too wide to be de-multiplexed by traditional AWG at the remote node. For carrier suppression based scheme, similar problem would happen if one tries to increase the data rate of downstream signal. For all-optical based scheme, like IRZ/DPSK and ASK/DPSK schemes, the spectrum efficiency is much higher than those without using orthogonal modulation format. As a consequence, the de-multiplexing will not be an annoying problem as whole spectrum of signal is restricted within specified spectrum area of standard AWG.

	Multicast enabled		Multicast disabled
	DPSK	ASK	NRZ-ASK
20-km DSF	5-dB		
16×16 AWG	5.5-dB		
DI loss	3.5-dB	0-dB	
Connector loss	4-dB	6-dB	
Total loss	18 dB	16.5-dB	
Transmitted power	6.5-dBm		
Received power	-11.5-dBm	-10-dBm	
Receiver sensitivity	-13.5-dBm	-11.5-dBm	-17.5-dBm
System margin	2-dB	1.5-dB	7.5-dB

Table 3-2 Power budget of proposed system

In our demonstration, the signal power fed into the transmission link was around 6.5-dBm. The downstream loss caused by the 20-km DSF transmission link was around 5-dB, and the optical demultiplexing induced another 5.5-dB loss. For downstream DPSK signal, a delay interferometer introduced another 3.5-dB loss. The connector loss for DPSK and downstream NRZ-ASK signal were 4-dB and 6-dB respectively. Thus the total losses for downstream DPSK signal and NRZ-ASK signal were 18-dB and 16.5-dB. The receiver sensitivity of downstream DPSK signal and NRZ-ASK signal with low extinction ratio were -13.5-dBm and -11.5-dBm respectively, implying that at least 1.5-dB margin for downstream NRZ-ASK point-to-point signal and 2-dB for DPSK multicast signal when the multicast was enabled. For multicast-disabled mode, the system margin was around 7.5 dB. In our scheme, the system margin of both multicast signal and point-to-point signal could be improved by increasing the EDFA output power. However, it should be noticed that too large output power may incur severe nonlinear effect in the transmission.

Summary

In this chapter, we have proposed a novel scheme to overlay multicast data on a wavelength-division-multiplexed passive optical network (WDM-PON) with point-to-point data delivery. The multicast differential phase-shift keying (DPSK) signal is superimposed onto all point-to-point nonreturn-to-zero (NRZ-ASK) signals. By adjusting the extinction ratios of the individual NRZ-ASK point-to-point signals, multicast can be realized and only the designated optical network units can properly receive the multicast data. We successfully demonstrated the proposed WDM-PON with 10-Gb/s downstream point-to-point signals and 10-Gb/s multicast signals.

Chapter 4

AWG filtering and its suppression in quaternary ASK-DPSK based WDM-PON

4.1 Introduction

Upgrading of existing DWDM systems to higher bit rates requires wider channel spacing or advanced modulation formats with higher spectral efficiency[25]. Recently, quaternary modulation formats attract wide attention in various applications due to their high spectral efficiencies[24],[26]-[32]. Nevertheless, quaternary modulation formats may suffer from some detrimental effects. One of such effects is narrowband filtering, which can also be widely found in other scenarios[33]-[36]. Usually, narrowband filtering occurs when the signal passes through a bandwidth-limited filtering device. As a result, the signal will experience a band-limited transmission and thus may suffer from performance degradation due to possible signal filtering. For quaternary ASK-DPSK based multicast enabled system demonstrated in the last chapter, narrowband filtering may add extra crosstalk between two sub-channels after passing through the AWG at the RN. In this chapter, we investigate the principle of such narrowband filtering effect and the possible remedies. In particular, we discuss two important factors which may affect the system performance of our proposed system: extinction ratio and transmission profile of AWG filter.

4.2 Principle of narrowband filtering

With wide application of erbium-doped fiber amplifiers (EDFAs), optical filter becomes one of the important devices to suppress or limit the amplified spontaneous emission (ASE) noise induced by EDFA. However, due to technological constraints, the bandwidth of optical filter following the EDFA is usually broader than the signal's bandwidth to accommodate the whole spectrum of the transmitted signal[37], [38]. Today, with the increasing data rate of the signal and the employment of RZ and

DPSK formats, many the optical filters start to deteriorate the optical signal transmitted. The most usual distortion brought by narrowband filtering is inter-symbol-interference (ISI). Take an NRZ-ASK signal, for example, this ISI introduced by narrowband filtering will cause neighboring pulses to overlap with each other, which results in eye closure and power reduction of the "1" bits. For an RZ signal, this kind of ISI is less detrimental since the signal waveform is guarded by large space between the neighboring pulses. On the other hand, for DPSK signal, the ISI-corrupted signal would experience phase-to-intensity conversion, and consequently the signal waveform would not be "flat" in time domain.

For our proposed quaternary ASK-DPSK, the problem is a little bit complicated. In general, the whole effect can be treated as combined effects brought by the NRZ-ASK sub-channel and the DPSK sub-channel. In our system, the main source of narrowband filtering is at the arrayed waveguide grating (AWG) working as the channel mux/demux. The AWG is intrinsically a periodical Gaussian filter with its channel spacing and bandwidth governed by ITU standard[39]. For the DPSK sub-channel, the main effect induced by AWG filtering is phase-to-intensity conversion causing signal to lose part of its power. For the NRZ-ASK sub-channel, the effect is twofold. Firstly, the NRZ-ASK sub-channel suffers from its own ISI induced by AWG, causing pulse overlapping and eye closure. On the other hand, the NRZ-ASK sub-channel also suffers from the intensity fluctuations induced by the DPSK sub-channel. In our proposed system, two factors are considered to be responsible for narrowband filtering: extinction ratio and transmission profile of AWG. Extinction ratio is mainly responsible for distributing energy between two sub-channels; while transmission profile of the filter governs the degree of ISI induced to signal waveforms. In the rest of this chapter, we analyze the influence of these two factors on the system performance, in terms of OSNR penalty.

4.3 Simulation model

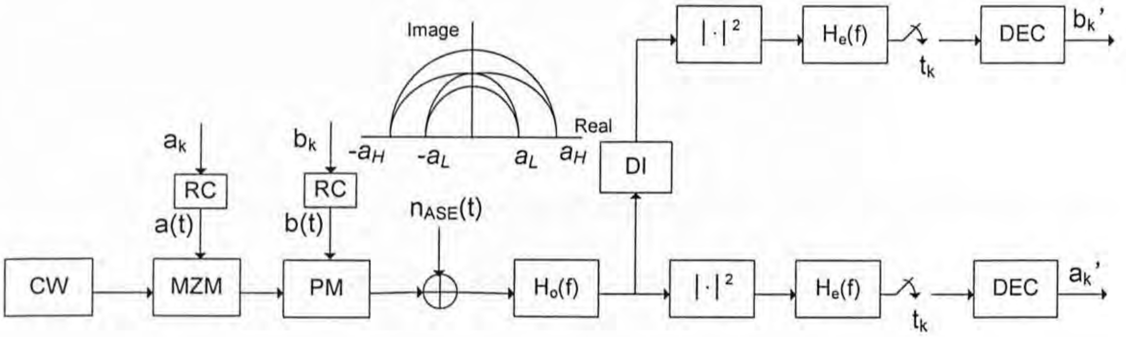

Figure 4-1 Proposed quaternary ASK-DPSK system model

Figure 4-1 shows the simulation model of a quaternary ASK-DPSK architecture used in this chapter. At the transmitter side, a Mach-Zehnder modulator (MZM) and a phase modulator (PM) are used to generate the point-to-point NRZ-ASK signal and the multicast DPSK signal, respectively. The electrical driving signal (*a(t)*), generated from a sequence of logic bits a_k, amplitude-modulates the input continuous-wave laser, generating the point-to-point NRZ-ASK signal with its high and low power levels: a_H and a_L. Another electrical driving signal (*b(t)*), generated from a differentially encoded bit sequence (b_k), phase-modulates the injected NRZ-ASK signal, generating the multicast DPSK signal with its two phase states: *0* and π. The extinction ratio of the composite signal can be obtained by $20*\log(a_H/a_L)$. To avoid direct intensity fluctuation from the DPSK sub-channel, a phase modulator instead of dual-drive-MZM is used to generate the phase-modulated signal. The constellation map and the signal transition paths between different signal states are also shown in the figure. In our model, the transmitted optical signal, *Es(t)*, is equally split into two orthogonal polarization states. At the output of the transmitter, EDFA noise, modeled as additive white Gaussian noise (AWGN), is added to the signal channel to simulate ASE noise dominated transmission. Moreover, the ASE noise is also separated equally and independently into two orthogonal polarization states, $n_y(t)$ and $n_x(t)$, respectively. Identical to the previous experimental demonstration, the transmission link is assumed to be dispersion compensated.

After transmission, the composite signals pass through an optical bandpass filter with a frequency response of *Ho(f)* to simulate de-multiplexing of different wavelength channels by the AWG. After that, the composite signal is split and fed into two tributaries to performance DPSK and NRZ-ASK demodulation, respectively. The DPSK signal will pass through a delay interferometer (DI) before detection. After square-law detection, two sub-channels are filtered by a low-pass filter with a frequency response of *He(f)* to further suppress the induced noise. The filtered signal, $t_{k,}$ is then fed into a typical sampling and decision module. The two generated received bit sequences, a_k' and b_k', are compared with their original bit sequences, a_k and b_k, to calculate the bit error rate.

Here, we describe several key components used in our model. The input electrical pulse of logic "1" bit is shaped to raised cosine profile with the impulse responses of

$$h(t) = \begin{cases} 1 & , \quad |t| \le \frac{T}{2}(1-\alpha) \\ cos^2\left[\frac{\pi}{4}\frac{2|t| - T(1-\alpha)}{\alpha T}\right] & , \frac{T}{2}(1-\alpha) \le |t| \le \frac{T}{2}(1+\alpha) \\ 0 & , \quad |t| \le \frac{T}{2}(1+\alpha) \end{cases}$$

where $T = 1/Rs$ denotes the symbol duration time, Rs is the symbol rate equaling half bit rate, R_b, for the quaternary ASK-DPSK signal. α is the roll-off factor to specify the pulse shape, varying from 0 to 1.

Similar to our previous experimental demonstration, the AWG profile is set to a Gaussian-type profile with transfer function of

$$\mathrm{Ho}(f) = \exp(-\log(2) * (\frac{2f}{\mathrm{Bo}})^{2n})$$

where *Bo* denotes the 3-dB bandwidth of the AWG, *n* is the order of Gaussian filter, varying from 1 to +∞.

At the receiver, the detected photocurrent can be written into

$$I_o(t) = R\left(|E_x(t)|^2 + |E_y(t)|^2\right) = I_{SIG} + I_{ASE} + I_{ASE-SIG}$$

where *R* is the responsivity of the photodetector, *Ex(t)* and *Ey(t)* are the received optical signal in two orthogonal polarization states, respectively. The generated current is contributed by signal part (I_{sig}), ASE-ASE beating noise part (I_{ASE}) and ASE-signal beating part ($I_{ASE\text{-}sig}$). The generated current is then filtered by an electrical low pass filter (LPF) with the frequency response of *He(f)* before it is sampled. The *He(f)* is set to a 5-th order Bessel type filter which can be given by

$$\mathrm{He}(f) = 945/(jf^5 + 15f^5 - 105jf^5 - 420f^5 + 945jf^5 + 945).$$

The filter's 3-dB bandwidth is evaluated to 0.96 time of the signal symbol rate. Based on the system model described above, we conduct Monte Carlo simulation to study the system performance degradation induced by the AWG, in terms of BER performance.

4.4 Simulation results and discussion

In this section, we discuss our simulation results based on the system model described above. Our Monte Carlos simulation is based on the following assumptions:

chromatic dispersion (CD) and polarization mode dispersion (PMD) are fully compensated at the receiver, ASE-ASE beating noise (I_{ASE}) and signal-ASE ($I_{ASE\text{-}sig}$) beating noise are the dominant noise at the receiver, and the AWG works only as a channel demultiplexer without limiting the noise bandwidth, as the discussion here only focuses on the filtering effect influencing the signal waveform. In the following discussion, we will first study the BER performance, in terms of different extinction ratios, and then another simulation will explain how to consider the tradeoff between filter shapes and filter bandwidth so as to minimize OSNR penalty induced.

4.4.1 Different extinction ratios

Extinction ratio, defined as the ratio of the average optical power of "1"-bit to that of "0"-bit, is an important factor affecting the performance of the quaternary ASK-DPSK signals as it governs the energy distribution between two signal tributaries. For example, with lower extinction ratio, the relative energy contributed to the DPSK signal tributary is larger. As a result, the BER performance of DPSK sub-channel is better than that with higher extinction ratio. When passing through a narrowband filter, DPSK sub-channel with lower extinction ratio suffers from more OSNR penalty due to phase-to-intensity conversion, since it contains more energy. On the contrary, if the extinction ratio becomes higher, the adverse effect of this crosstalk will become less severe and eventually negligible as the energy conserved by the DPSK sub-channel becomes less.

We conducted a Monte Carlo simulation to analyze the BER performance of our system, in terms of different extinction ratios. In our experimental configuration, the data rates of NRZ-ASK and DPSK signals were set to 10-Gb/s, the electrical pulse shape was set to raised cosine with roll factor $\alpha = 0.4$, the AWG filter was set to 4th order or 1st order Gaussian type filters with bandwidth of 0.35-nm (43.70-GHz) to simulate a typical ITU standardized 100G grid AWG, and the electrical filter was set to 5th order Bessel filter with a bandwidth of 0.96-GHz to optimize the received pulse shape and suppress the electrical noise as well. The simulation was based on the test of 100,000 bits for a single extinction ratio case, and then the BER was calculated by counting the erroneous bits detected.

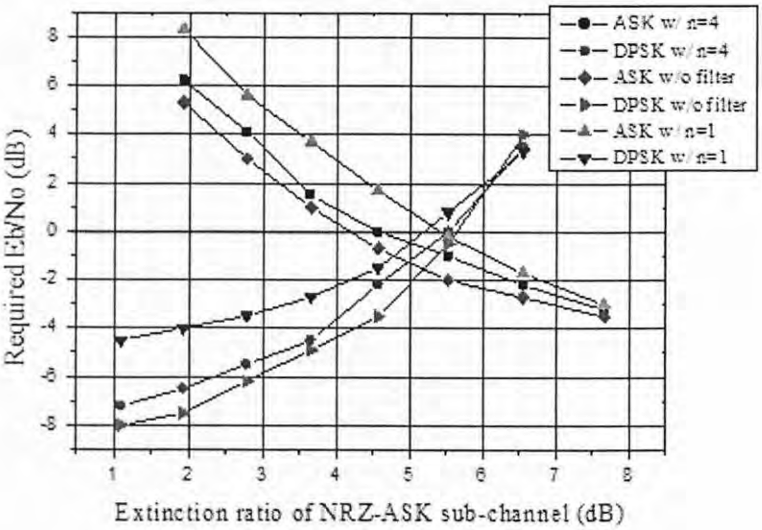

Figure 4-2 Relative required OSNR on different extinction ratios and filter shapes

Figure 4-2 shows the relative required OSNR as a function of the extinction ratio and the AWG filter shape with 43.70-GHz bandwidth (0.35 nm). All the signal-to-noise ratios (E_b/N_o) in the figure were measured at the bit error rate of 1×10^{-4} to ease the computation. As shown in figure, under the same optical filter shape, the performance of the NRZ-ASK sub-channel showed an increasing tolerance to the AWG filtering with the growth of the extinction ratios. Similarly, the DPSK sub-channel also showed an increasing trend of the tolerance against AWG filtering with increasing of extinction ratios. For the NRZ-ASK sub-channel, the reason of such tendency is twofold: 1) the eye opening of the NRZ-ASK signal is smaller at lower extinction ratio; 2) DPSK sub-channel seizes a large portion of energy at lower extinction ratio of the NRZ-ASK sub-channel thus generates more severe intensity fluctuations. For the DPSK sub-channel, at low extinction ratio of the NRZ-ASK sub-channel, the OSNR penalty was significantly larger than that of high extinction case. It is mainly due to the fact that a large portion of energy conserved by DPSK sub-channel is converted to intensity fluctuations at low extinction ratio case.

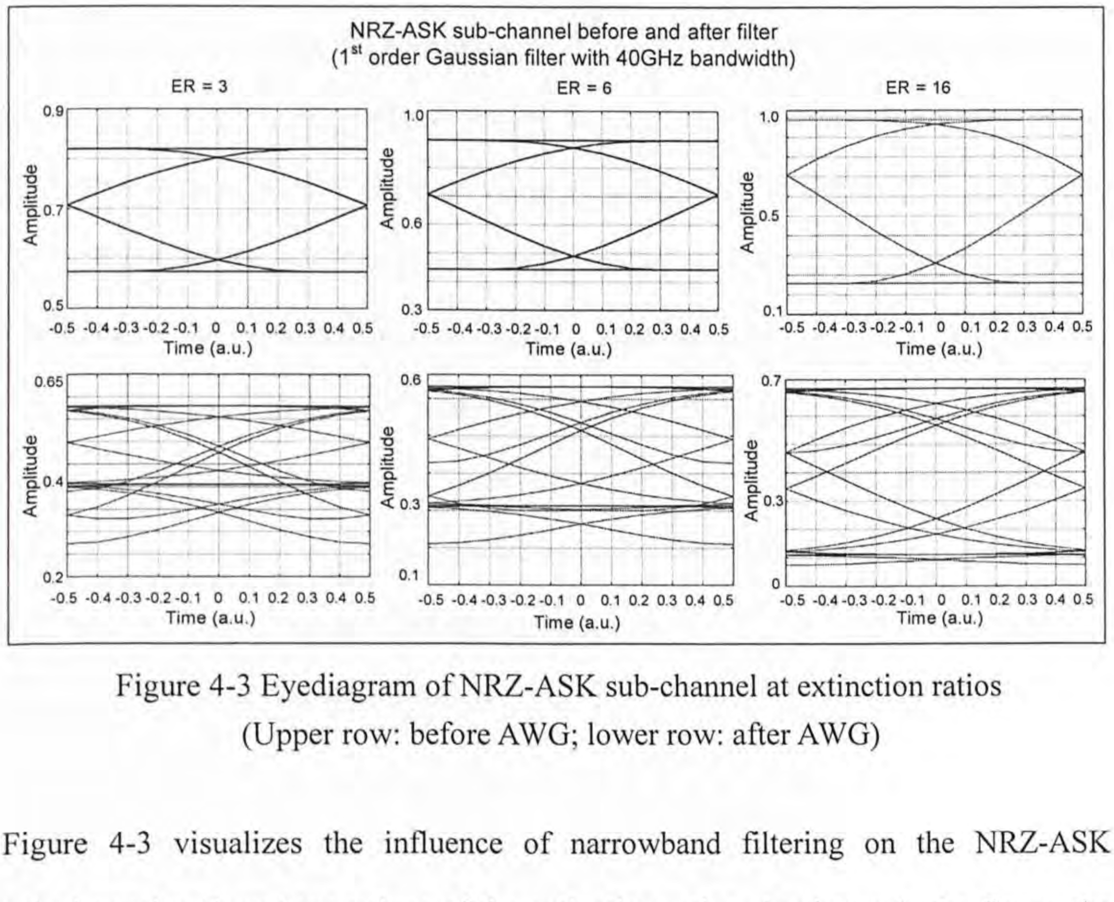

Figure 4-3 Eyediagram of NRZ-ASK sub-channel at extinction ratios
(Upper row: before AWG; lower row: after AWG)

Figure 4-3 visualizes the influence of narrowband filtering on the NRZ-ASK sub-channel with various values of the extinction ratios. As shown in the figure, the adverse effect of narrow bandwidth filtering can be twofold: inter-symbol-interference (ISI) and phase-to-intensity conversion. When the extinction ratio of NRZ-ASK sub-channel is at a low value, say 3-dB, both ISI and phase-to-intensity conversion induce severe detrimental noise to the NRZ-ASK signal, leading to closed eye at sampling region, lower power of "1" and lower extinction ratio after passing through filter. With the increment of the extinction ratio, the intensity fluctuations become less severe as the energy distributed to the DPSK sub-channel is smaller. Meanwhile, ISI is also less detrimental but is still the dominant adverse effect corrupting the NRZ-ASK signal.

Comparing between ISI and phase-to-intensity conversion, we learn that the phase-to-intensity conversion would not affect the sampling region if the two sub-channels are well synchronized as this effect only exits in phase transition region. However, phase-to-intensity conversion will lower OSNR of NRZ-ASK sub-channel which in turn acts as received power penalty. On the other hand, ISI would significantly close the eye and draw down extinction ratio of NRZ-ASK sub-channel. To combat these adverse effects, two ways could be considered. Firstly, a flat-top type AWG could be implemented to make signal spectrum intact after filter. As demonstrated in Figure 4-3, when higher order optical filter is implemented, half received power penalty could be reduced. Another way to ease the adverse effect to ASK-DPSK signals is to increase the bandwidth of the AWG filter. In next section, we will study these two ways on the BER performance of ASK-DPSK signals and show how effective these two ways could be.

4.4.2 Different AWG filter shape and bandwidth

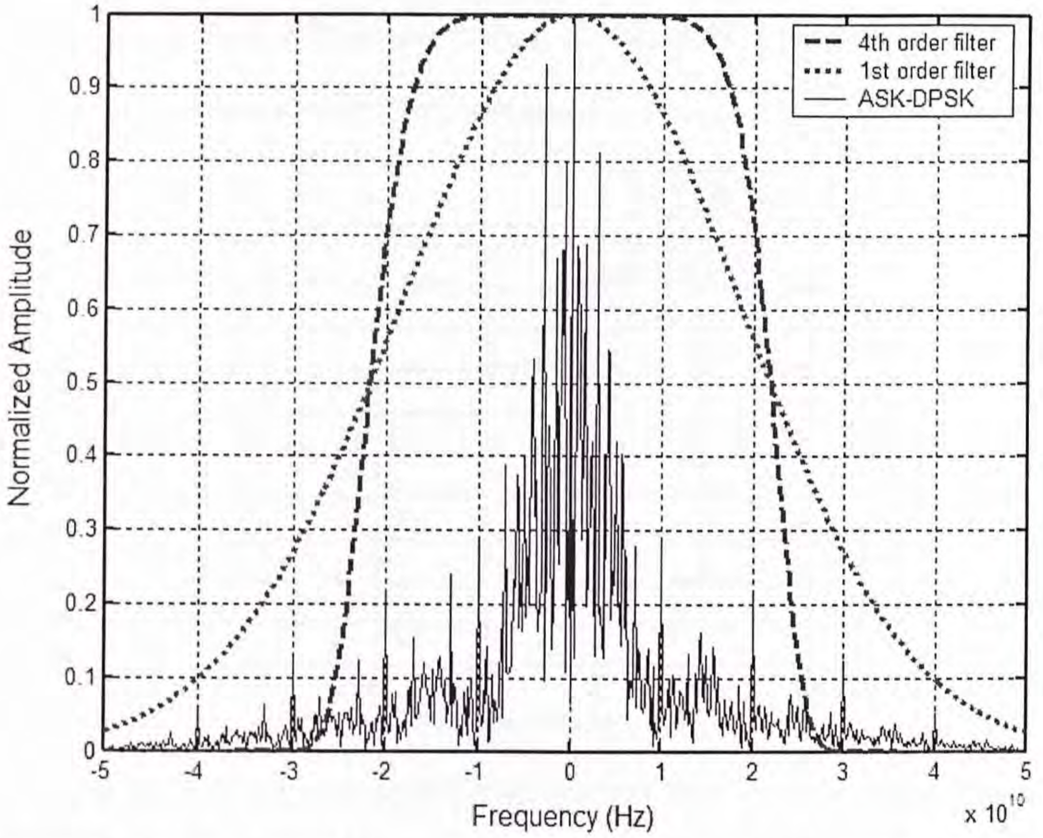

Figure 4-4 The spectra of ASK-DPSK signal and AWGs with different filter shapes

Figure 4-4 shows, as an example, the transmission spectra of the AWG with different filter shapes and also the proposed 10-Gb/s ASK-DPSK signal with an extinction ratio of 6-dB. The AWG filter shapes are 1^{st} order or 4^{th} order Gaussian type with 3-dB bandwidth of 43.70-GHz (0.35nm) respectively. Since amplitude modulated information is mainly confined within ±10-GHz spectral region, the 1^{st} order Gaussian filter with non-flat-top profile could corrupt the spectral region carrying the amplitude information and would introduce severe ISI consequently. On the contrary, the 4^{th} order Gaussian filter presents a flat-top profile within the bandwidth of the signals and preserves the signal spectrum carrying amplitude information. However, for phase information, it is mainly carried at the higher spectral region, since the phase signal is modulated by a phase modulator which creates a "chirp" like signal. As a conclusion, for phase information, both 1st order and 4th order AWG corrupt the information carrying region. For amplitude information, 4th order AWG preserves the information carrying region, while 1st order AWG corrupts it.

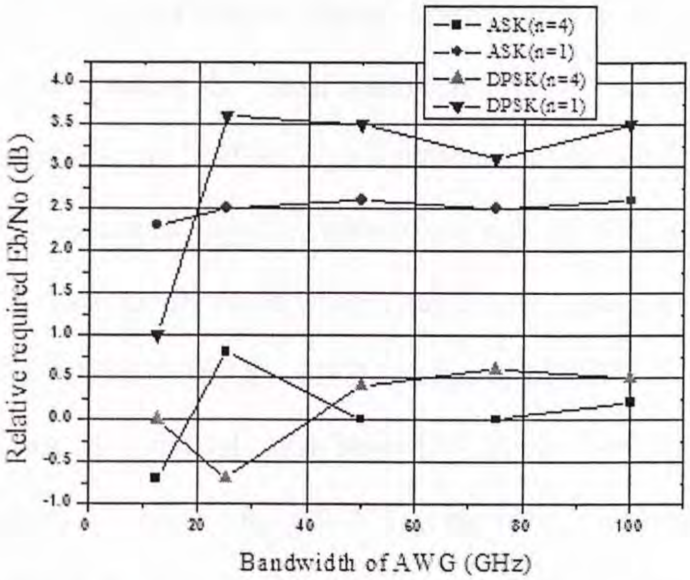

Figure 4-5 Relative received OSNR on different AWG shapes and bandwidth

In Figure 4-5, we show the simulation results of relative required OSNR on different AWG shapes and bandwidth. In this simulation, we set the extinction ratio of NRZ-ASK sub-channel to 4-dB. Five different bandwidths have been taken into consideration, varying from 12.5-GHz (1.25×symboal rate) to 100-GHz (10×symboal rate), respectively. As shown in figure, for the NRZ-ASK sub-channel, little sensitivity improvement could be achieved by increasing the bandwidth of the filter when the 1st order Gaussian filter was used, though the transfer profile of the Gaussian type filter becomes flatter with the increasing of filter order. Similarly, little OSNR advantage could be enjoyed for the 4th order AWG filter by increasing bandwidth from 12.5-GHz to 100GHz, implying that flat-top filter already preserves signal-carrying region intact. When the filter shape was changed to the 4th order, the NRZ-ASK sub-channel could enjoy 2.5-dB OSNR advantage with flatter filter shape.

Please note that severe penalty was observed for NRZ-ASK sub-channel when the bandwidth of filter was below 40-GHz, showing that signal suffers critical damage by the narrowband filter. On the other hand, for the DPSK sub-channel, little OSNR advantage could be found by increasing the bandwidth of the filter even the phase information resides at higher spectral region. This is partially because that the filter shape becomes flatter within the signal bandwidth with the growing bandwidth of filter. As consequence, the DPSK signal information is better protected when bandwidth of filter becomes larger. Similar to the case of NRZ-ASK sub-channel, with higher order filter, DPSK could enjoy around 3-dB power advantage compared to that with the 1st order filter. Since ITU standardized 0.35nm bandwidth AWG becomes ubiquitous, it is unlikely that bandwidth of the AWG in 10-Gb/s system would be a problem. To reduce the AWG filtering effect, for both NRZ-ASK and DPSK sub-channels, it is more effective to implement flat-top AWG instead of merely increasing the bandwidth of filter. In our simulation results, fluctuations of curves confined in ±0.5-dB have been observed when filter bandwidth is larger than 40-GHz. This is due to the insufficient test bits of Monte Carlo simulations we conducted.

4.5 Summary

In this chapter, we have studied the narrowband filtering effect based on our proposed quaternary ASK-DPSK multicast overlay scheme for WDM-PONs. This effect mainly comes from limited-bandwidth and "non-flat-top" AWG implemented in system. With the influence of the narrowband filter, quaternary ASK-DPSK signal would suffer from inter-symbol interference (ISI) and phase-to-intensity conversion which result in closed eye, lower power of "1" bits and time domain intensity fluctuations. We evaluated the BER performance of system as a function of different filter bandwidths and filter shapes by conducting Monte Carlo simulations. Based on our simulation results, in order to reduce such effects, we have concluded that it is more effective to use filter with "flatter" profile than merely increasing the bandwidth of the filter.

Chapter 5
Summary and Future Works

5.1 Summary of the thesis

This thesis comprises two topics. In the first part of the thesis, we proposed a novel multicast enabled WDM-PON architecture by using ASK-DPSK modulation formats. Our scheme can reach a data rate of 10-Gb/s for both multicast and point-to-point sub-channels without using any additional dedicated high speed electronic devices. Moreover, the multicast control is centralized at the OLT. In the second part of the thesis, we studied the narrowband filtering effect induced by the AWG in our proposed network. Based on our simulation results, we concluded that using flat-top filter shape is more effective than merely increasing bandwidth of filter.

In chapter 1, the modern telecommunication network hierarchy has been reviewed. In particular, three data delivery modes in WDM-PON, namely point-to-point, broadcast and multicast, were discussed.

In chapter 2, previously proposed multicast enabled architectures in WDM-PON have been reviewed. In general, the previous proposed schemes had several drawbacks, including limited data rate, cost ineffectiveness and relatively high system complexity.

In chapter 3, a novel multicast enabled WDM-PON architecture by using ASK-DPSK modulation format has been proposed and experimentally demonstrated. In our proposed scheme, both sub-channels were modulated in the optical domain, and thus our scheme avoids any dedicated high speed electronic devices at both the transceiver at the OLT and the receiver at the ONU. To switch between the multicast enabled mode and the multicast disabled mode, a simple electrical switching unit centralized at the OLT is used to change the extinction ratio of the downstream point-to-point signal. Therefore, by using our scheme, a high speed and cost-effective multicast enabled WDM-PON architecture can be achieved.

In chapter 4, the narrowband filtering effect induced by AWG in quaternary ASK-DPSK system has been studied. Verified by Monte Carlo simulations, we found that filtering effect introduces inter-symbol-interference (ISI) and intensity fluctuations to ASK-DPSK signals. To ease such detrimental effects, we found that implementing "flat-top" filter is more effective than merely increasing the bandwidth of the filter.

5.2 Future works

Our future work on multicast enabled optical network will focus on two aspects: better system performance and broader area of application. To get better performance, there are three major drawbacks of our system need to be improved. First of all, synchronization between the multicast sub-channel and the point-to-point sub-channel can be relaxed. In our proposed system, every point-to-point channel has to be synchronized with the multicast signal, which in turn increases the complexity and instability of the system. The synchronization might be avoided either by using different data rates for multicast and point-to-point signals or by changing modulation schemes of system. Secondly, the possible crosstalk between the multicast sub-channel and the point-to-point sub-channel should be suppressed. To alleviate this crosstalk, one might choose to transmit multicast and point-to-point signals via separate transmission routes. Finally, performance tradeoff between the two sub-channels should be reduced. This problem may be solved by implementing different modulation schemes. For broader application, we consider to expand our multicast enabled architecture to metro area network (MAN). With the improvement in these two aspects, we expect the multicast enabled architecture for optical networks could be promising.

List of Publications

[1] Y. Zhang, N. Deng, C.K. Chan, L.K. Chen, "A Selective-broadcast Overlay Scheme for WDM-PON Using ASK/DPSK Orthogonal Modulation Technique," *International Conference on Photonics in Switching,* Paper S-06-1, Hokkaido, Japan, Aug. 2008.

[2] Y. Zhang, N. Deng, C.K. Chan, L.K. Chen, "A Multicast WDM-PON Architecture Using DPSK/ASK Orthogonal Modulation," *IEEE Photonics Technology Letters,* vol. 20, no. 17, pp. 1479 - 1481, Sep. 2008.

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