國 立 交 通 大 學
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碩士論文

嶄新正交分頻多址混合式接取網路架構
整合寬頻和無線傳輸服務

A Novel OFDMA Hybrid Access Network Architecture for Future Integrated Broadband and Wireless Services

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中 華 民 國 九 十 八 年 七 月

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嶄新正交分頻多址混合式接取網路架構

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摘要

現今，各式各樣新興的網路服務使得消費者對網路頻寬的需求遽增。如今以銅為傳輸媒介的 DSL 技術已無法提供足夠的頻寬，而光接取技術是一個明顯的解決方案，因為光纖能提供相當高的頻寬。無線服務所提供的機動性是另一項重要的需求，我們的目標就是結合有線和無線傳輸來建立一個高成本效益的系統。正交分頻多址被動式光纖網路是此一新興系統，它擁有高頻寬使用效率和易於整合有線及無線傳輸等優點，但迄今已被提出的系統都需要配合使用 WDM 雷射，這非但提高系統成本也使得系統有光拍差雜訊的問題。因此，我們提出一個嶄新的正交分頻多址被動式光纖網路架構，此架構無須使用到 WDM 雷射，它更兼具成本效益和頻寬使用效率。此外，我們提出了三種方式去改善寬頻訊號和無線訊號間的相互干擾，我將會詳細的分析這三種方法。其中我們以一系列的實驗來驗證此系統的可行性。

A Novel OFDMA Hybrid Access Network Architecture for Future Integrated Broadband and Wireless Services

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ABSTRACT

Today, a variety of new network services make users' demands for bandwidth grow dramatically. The DSL technology based on copper cannot provide enough bandwidth. Optical network is the solution, because fiber can provide very high bandwidth. The mobility of wireless service is another primary demand. Thus, our goal is to integrate wireline and wireless service to build a cost-effective system. The OFDMA PON is this new system which has high spectral efficiency and it can integrate wireline and wireless service. But the OFDMA system which has been proposed so far needs to be operated with the WDM laser. The process not only increases the cost of system and but also leads to the OBI problem. So, we propose a novel architecture of OFDMA PON which can go without WDM laser. It is cost-effective and bandwidth-effective. In addition, we propose three methods to improve the interference between broadband signal as well as wireless signal. And I will analyze these three methods in details below. And we carry out a series of experiments to demonstrate the feasibility of the system.

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CHAPTER 1 Introduction

1.1 Evolution of Access network

Access network means the network connects each user to the central office of service provider. Most broad access still relies on copper, like the digital subscriber line (DSL) or coaxial cable. But these technologies are limited by noise, the transmission distance becomes shorter when increasing the transmission distance. The trend of network service is triple play, the combination of Internet, TV and telephone services distributed over one network. It makes the demand of transmission bandwidth increase a lot. Today, the access networks which rely on copper are not able to maintain the demand of bandwidth. Fiber is a better solution that it can provide much higher bandwidth than copper. Optical access network such as fiber to the Home (FTTH), fiber to the building (FTTB) or fiber to the curb (FTTC) brings the fiber to the user's home, building or the service node near the user [1],[2]. Figure. 1 shows the architecture of a passive optical

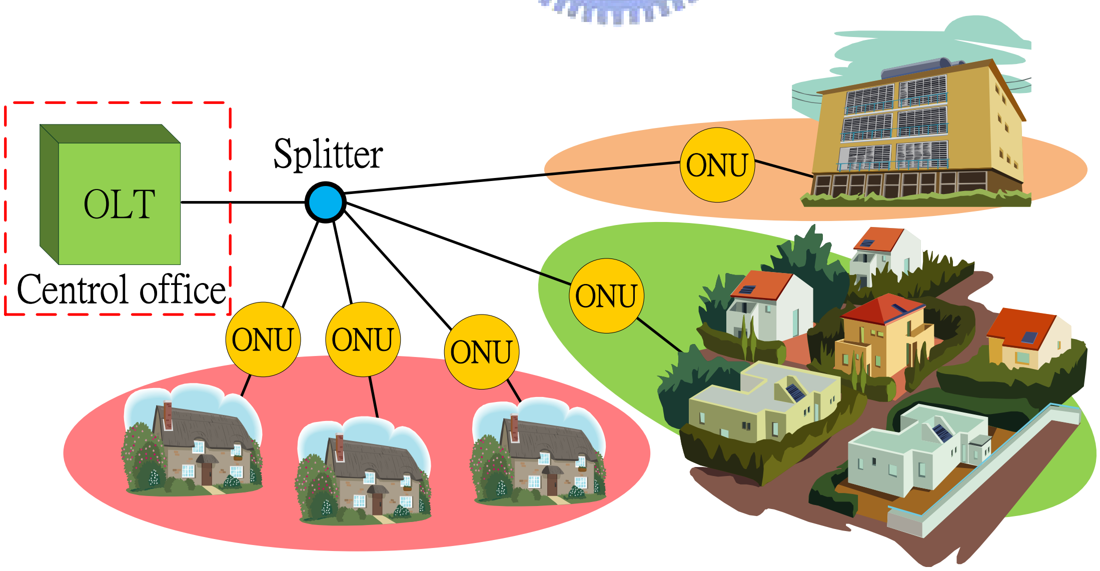


Figure. 1 Passive optical network architecture

network. It uses a splitter to connect OLT with several ONUs. And ONU provides the interface between network and users.

Besides the demand of high bandwidth, another trend in the current access networks is mobility [3]. Wireless access network can provide ultimate service for users with Internet access anywhere and anytime. One of the most popular technologies of wireless service is WiMAX which can provide high bandwidth and mobility. Cost is an important concern to build a network system, so it needs to minimize the equipment cost and maximize the bandwidth. Cost is the reason that the passive optical network (PON) dominates in the access network market. Next let us see some high speed PON architecture.

1.1.1 TDM PON

Time division multiplexing passive optical network (TDM-PON) has been developed for a long time such as Ethernet-PON (EPON) and Gigabit-PON (GPON) [4],[5]. The TDM-PON is a one point to multi point architecture. There is an optical line terminal (OLT) at the central office (CO) to communicate with many remote optical network units (ONU) and there is a splitter to connect OLT with different ONUs.

It uses single wavelength for downstream. The downstream data broadcasts to all ONUs (Figure. 2), and each ONU identifies its own part by the address information located in the header, the preamble of Ethernet packet. For the upstream (Figure. 3), it uses another wavelength, and each remote ONU uses the same wavelength so that this ONUs must use dedicated time slot to transmit data.

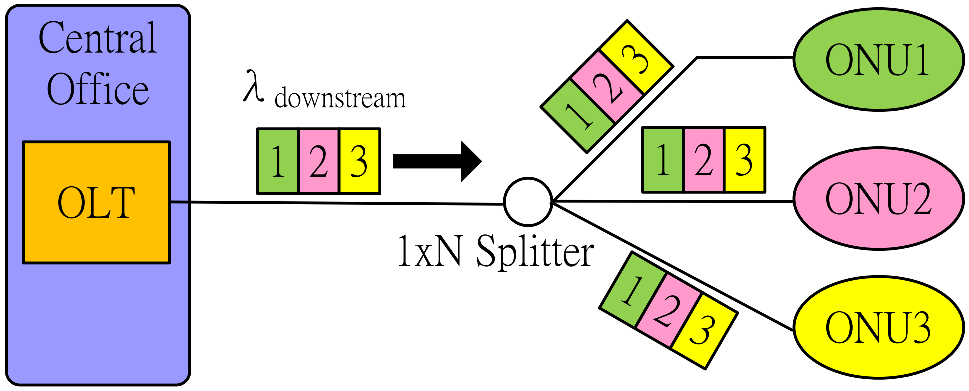


Figure. 2 Downstream concept of TDM-PON

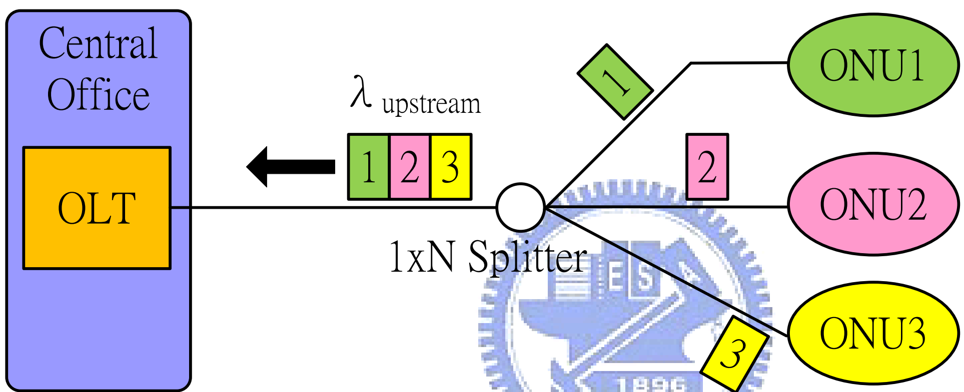


Figure. 3 Upstream concept of TDM-PON

Dynamic bandwidth allocation (DBA) is one of the advantages of TDM system. For upstream, OLT needs to control the transmission time of each ONU in order to avoid data collision, we can use the control information to allocate bandwidth dynamically. For instance, if all users need to transmit data, OLT can control each ONU transmit data tack turns. Also, if users do not transmit data at some time, OLT can allocate these vacant time slot to other ONU so that the bandwidth could be used efficiently.

There are three problems in TDM-PON. Firstly, since the TDM-PON system uses the optical splitter to connect OLT with ONU, the optical power loss of both direction signals increase as the number of ONUs increases, in other words, the optical power of the transmitter limits the number of ONUs. Secondly, although dynamic bandwidth allocation is one of the advantages, it complicates the system. While the system needs to support more and more users, precise timing control becomes more difficult and the algorithm becomes more complex. Thirdly, it is difficult to achieve higher data rate of TDM-PON, because the data rate is limited by the speed of component.

1.1.2 **WDM PON**

Wavelength division multiplexing passive optical network (WDM-PON) is a point-to-point transmission technology [6]. WDM-PON uses multiple wavelengths in a single fiber to increase capacity instead of direct data rate increasing. Because WDM-PON uses multiple wavelengths, it can promote capacity of transmission easily. For example, if one wavelength has 2.5Gbps data rate, then we use four wavelengths simultaneously so that the fiber would have 10Gbps data rate. Some researchers consider WDM-PON a potential technology for NG-PON.

The concept of WDM-PON is shown in Figure. 4 used passive optical wavelength router such as arrayed waveguide grating (AWG) to multiplex different wavelength and de-multiplex each wavelength. Each ONU uses its own wavelength, so it needs many OLT&ONU pairs and each pair has a dedicate wavelength. In this condition, the structure supports 32 users, AWG has an optical loss about 5dB which is less than a 1x32 optical power splitter.

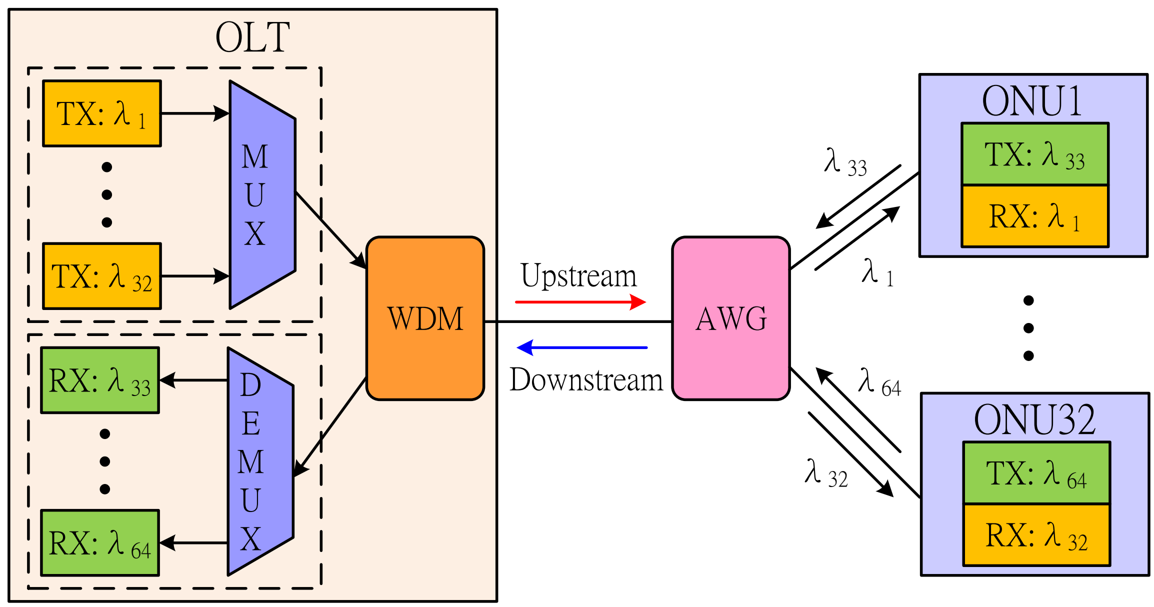


Figure. 4 Concept of WDM-PON

The critical problem of WDM-PON is the cost. The system needs a lot of different light sources. WDP-PON supports 32-ONU (Figure. 4), that is, it needs 32 different light sources for upstream as well as another 32 different light source for downstream. Using so many light sources is expensive. What's more, each ONU needs its own bandpass filter to filter out its own signal. The structure of the system is very cost-wasting.

1.1.3 OFDM PON

Orthogonal frequency division multiplexing passive optical network (OFDM-PON) transmit data uses OFDM signal. OFDM signal uses several frequencies to increase transmission capacity instead of increasing data rate of single carrier signal. I will talk about details of OFDM signal in next chapter. Traditionally, if we want to create several different frequencies, we need several local oscillators. Adding too many oscillators would make the system complex. And OFDM system uses fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) to simplify the structure. Thanks to the mature Very-large-scale integration (VLSI) technology, FFT and IFFT can implement with single integrated circuit (IC).

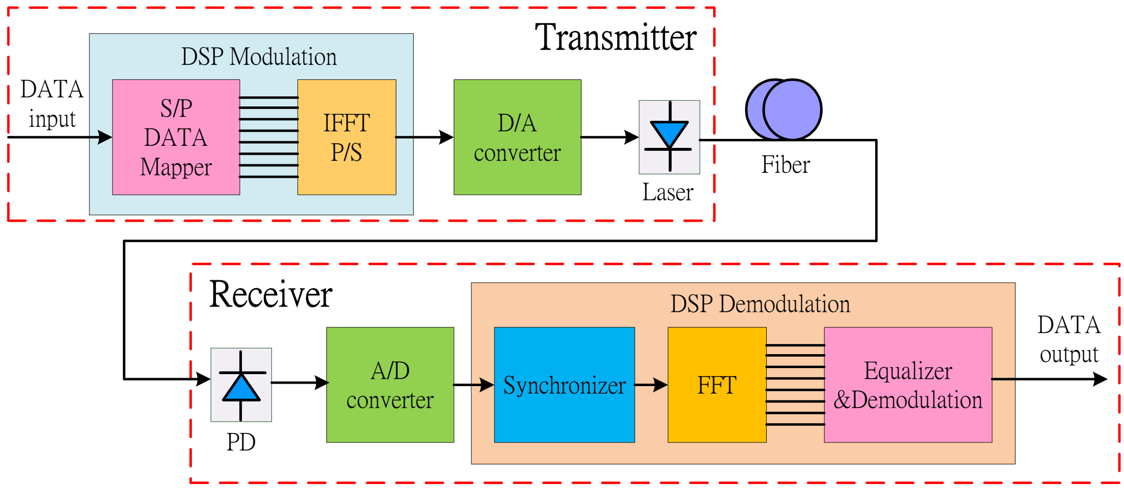


Figure. 5 Transmission concept of OFDM system

The transmission concept of OFDM system is shown in Figure. 5. At the transmitter, it maps serial data into parallel subcarriers, and then executes IFFT to get serial digital data. After DSP modulation, it uses a digital-to-analog converter to convert the digital signal to analog signal. At the receiver, it uses an analog-to-digital converter to convert analog signal to digital signal, then executes synchronization and FFT. After FFT, it equalizes data in frequency domain.

The OFDMA-PON has a lot of advantages such as simple equalizer, which can support high order QAM modulation for OFDM signal is strong against channel response. In addition, the orthogonal characteristic of OFDM signal can make transmission more efficient, because we can adjust the modulation type of each sub-channel according to channel response. For example, if sub-channel is located at the good channel response part, we can use high order QAM modulation format (ex: 128QAM, 64QAM) [7]. On the other hand, if sub-channel is located at the bad channel response part, we can use lower order modulation format (ex: QPSK, BPSK). So the transmission would not be limited by the channel response. I will talk about more details of OFDMA-PON in next chapter.

1.2 The Emerging of Hybrid access network and the synergy behind it

As mention in 1.1, wireless service is an indispensable access technology because it can satisfy users' demand for mobility. But it is a problem in wireless access network that the higher the bandwidth is, the lower the coverage would be. The loss becomes serious when the bandwidth grows, so it is difficult to maintain bandwidth and coverage at the same time. Radio over fiber (RoF) is created to solve this problem. We can build some remote antennas to provide wireless service for a small area, and connect it with the base station by the fiber. Therefore, it can provide high bandwidth along with mobility and maintain the coverage. Wireless signal is a narrow band signal to the fiber transmission, so a fiber transmitting the wireless signal is wasteful. We should combine the RoF signal with the Internet signal, transmitting them in the same fiber simultaneously. As this process, we call it hybrid access network. With the hybrid access network technology, it reduces a lot of cost because the RoF signal can use the original optical network system and do not built any other fibers.

1.3 A Novel OFDMA based hybrid access network architecture for future integrated broadband and wireless services

We propose a novel OFDMA based hybrid access network architecture without using WDM lasers. The architecture enables seamless integration of broadband transport and wireless Radio-Frequency (RF) signals. Figure. 6 is the concept of the novel OFDMA-PON. The

OFDMA-PON connects multiple ONU with OLT through an optical distribution node (ODD). The details of the architecture and operation of ODD and ONU will be described in 0. The OFDMA-PON uses two wavelength, λ_d for downstream and λ_u for upstream. The downstream signal broadcasts to each ONU through the ODD. For upstream data, ONU-1 first sends its upstream data and controls information to ONU2 through ODD. Upon receiving data and controlling signal, ONU-2 determines which subcarrier is carried. It regenerates the OFDM signal and sends it to next ONU. If there is a remote antenna at ONU, the ONU will put the radio signal at the

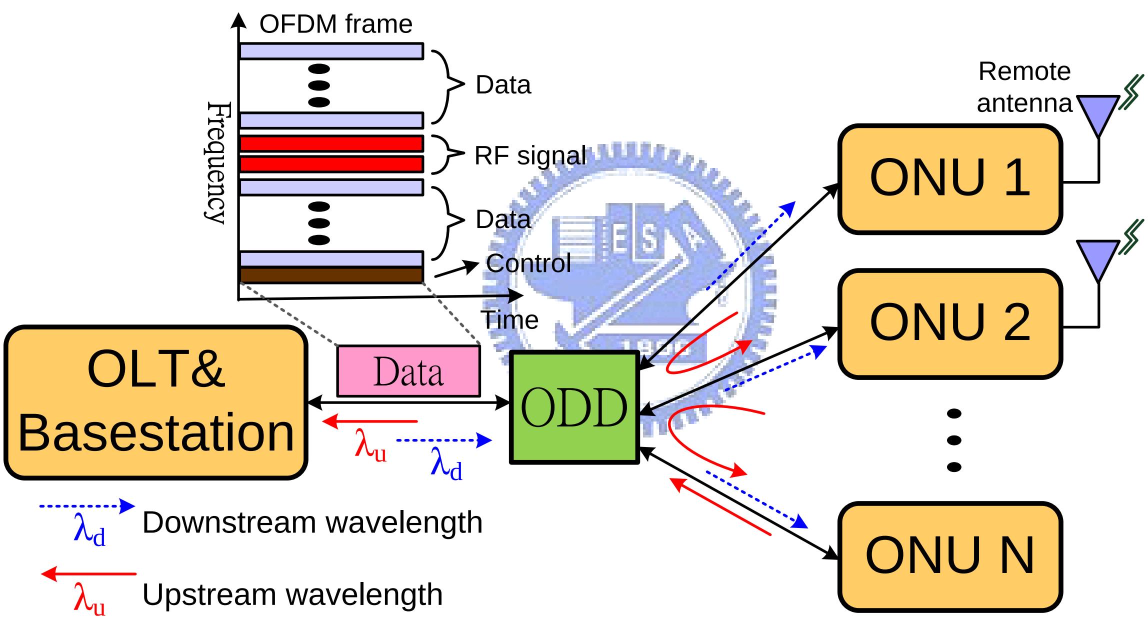


Figure. 6 Concept of the novel OFDMA-PON architecture

allocated band and transmit it with broad band data. Finally at ONU-N, the signal is transmit to OLT through ODD.

Because of OFDM signal, it can allocate each ONU's data to each subcarrier and it can turn on some subchannels to provide transmission of wireless signal easily. This novel architecture does not use WDM laser to achieve multiple access due to the design of cascade structure. So it does not encounter optical beat interference (OBI) issue and costs effectively. The novel OFDMA-PON has not only the advantage of OFDM-PON but also the advantage of integrating broadband signal and wireless services easily.

1.4 Structure of this thesis

I will introduce OFDM PON system in CHAPTER 2 that includes the introduction of OFDM signal in 2.1, why we use OFDM signal in optical access network in 2.2 and disadvantages of OFDM signal in 2.3. Next I will introduce the novel architecture of OFDMA PON that we proposed in CHAPTER 3, includes the network architecture in 3.1, operation of integrating broadband and wireless signal in 3.2, advantages of the architecture in 3.3, disadvantages of the architecture in 3.4, and three solutions to improve the system in 3.5. Three solutions to improve the system include windowing, subcarriers decreasing and add notch filter. Next, CHAPTER 4 is the result of simulation. Firstly, I build the model of interference caused by OFDM signal, and the model of windows in 4.1. And then I compare the efficiency of three different windows in 4.2. In 4.4 I talk about how we choose a suitable notch filter for our system. In 4.5 I introduce how windowing method improves the distortion caused by notch filter. CHAPTER 5 is the experimental results. I introduce the experimental setup in 5.1 and signals performance in 5.2. Finally, I make a conclusion in CHAPTER 6.

CHAPTER 2 OFDM PON System

2.1 What is OFDM

Before looking OFDM system, we need to know what are OFDM signal and its characteristics first. Orthogonal frequency division multiplexing signal is composed of many narrow band subcarriers, and each subcarrier is independent. It uses multiple subcarriers to transmit low speed data instead of using signal carrier to transmit high speed data (Figure. 7). Traditionally, producing multiple frequency signals needs several local oscillators as mention in 1.1.3, and OFDM signal uses IFFT to accomplish it (Figure. 8).

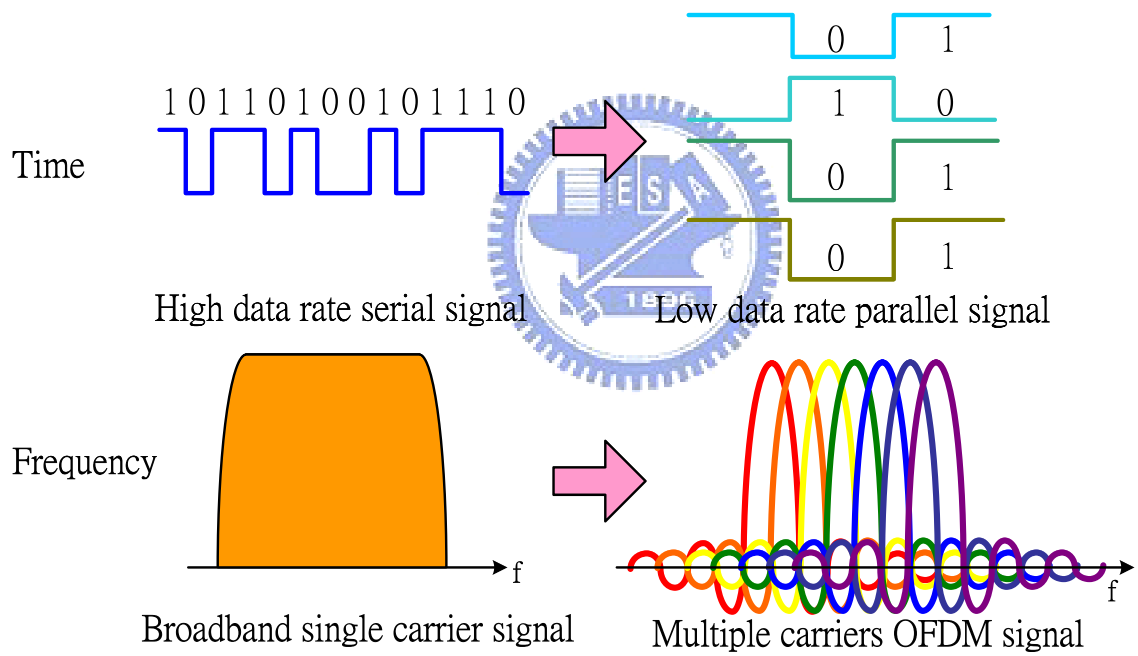


Figure. 7 Using OFDM signal instead of broadband single carrier signal

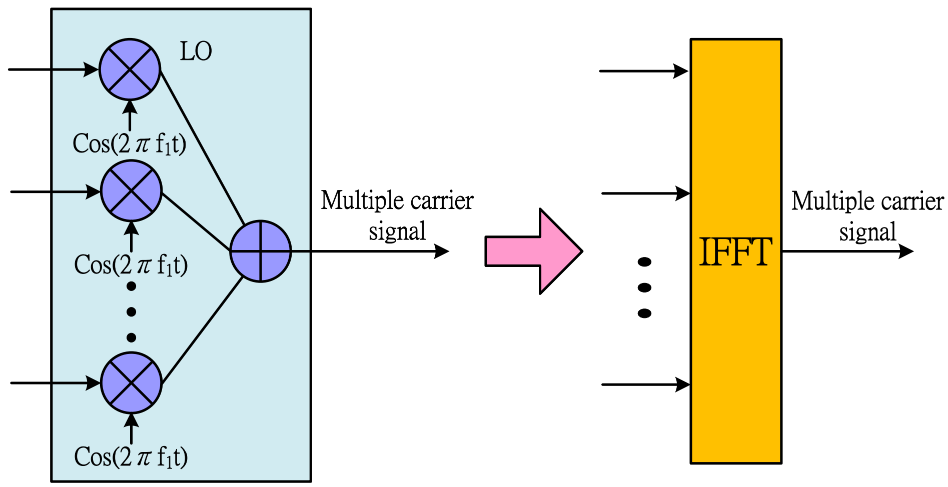


Figure. 8 Using IFFT block instead of a large number of LO

2.2 Advantages of using OFDM signal over fiber

2.2.1 Robust against channel imperfection

Because of the demand of high speed transmission, broadband transmission is needed. Using broadband single carrier signal to transmission data will encounter some problems. If channel response is not smooth or the components has frequency ripple in the signal's band, the signal would have serious distortion after transmission. OFDM can solve the problem. OFDM signal uses a lot of narrow band subcarriers to transmit data (Figure. 7), so it can view the channel response of each subcarrier as flat. In addition, it can use a simple frequency domain equalizer to compensate the response of each subcarrier, so OFDM signal is robust against channel imperfection.

2.2.2 Eliminates ISI through use of a cyclic prefix

When light transmission in the fiber, it will encounter optical dispersion issue. Optical dispersion is a phenomenon that different frequency of light transmitting in the same fiber will have different transmitted speed, so a broadband signal will encounter inter symbol interference

(ISI). In some conditions, i.e. single side band transmission, OFDM signal can eliminate it. In wireless communication, one of the most important characteristics of OFDM signal is that it can solve the multiple paths problem by adding cyclic prefix. We can view different frequency as different paths, so the dispersion issue is as same as multiple path issue, and OFDM signal can eliminate the ISI.

2.2.3 Supporting broadband data and wireless signal simultaneously

As I mentioned in chapter 1, wireless transmission plays an important role in access network today, but its coverage is limited when we need to transmit broadband data. So we need the radio over fiber (ROF) technology to extend the coverage. Wireless signal is a narrow band signal, so we want to transmit wireless and wireline signal simultaneously. OFDM is a good choice for combining these two signals. The subcarriers of OFDM are independent and able to operate separately, so we can turn off some subcarriers. Those vacant frequency space can provide wireless for transmission. The combination is easy. Thus, we do not change the PON's structure. The idea is implemented in our novel OFDMA-PON structure.

2.3 Disadvantages of OFDM signal

2.3.1 Synchronization issues

The OFDM signal requires precise symbol synchronization as well as frequency synchronization. OFDM signal needs precise symbol synchronization, if the symbol synchronization is not precise enough, it may induce serious inter symbol interference (ISI) especially when the sampling offset is over the cyclic prefix. And frequency synchronization includes sampling frequency synchronization and carrier frequency synchronization. OFDM signal is sensitive to frequency offset, so both sampling frequency offset and carrier frequency offset may induce ISI or destroy the orthogonality of OFDM signal.

2.3.2 High peak to average power ratio

OFDM signal is a multi-carriers signal, so its signal is the linear summation of each subcarrier, and it makes the peak to average power ratio (PAPR) of OFDM signal high. High PAPR makes the system need high linear power amplifier which increases the cost of the system. High PAPR also increases the quantization error of analog to digital (A/D) or digital to analog conversion (D/A).

2.4 Architecture of OFDMA PON

Figure. 9 is the Concept of OFDMA-PON. For downstream [8],[9], OLT sends data using wavelength λ_d and the splitter generates multiple signal copies to send to each ONU. Each ONU demodulates the data and gets its own data. For upstream, each ONU

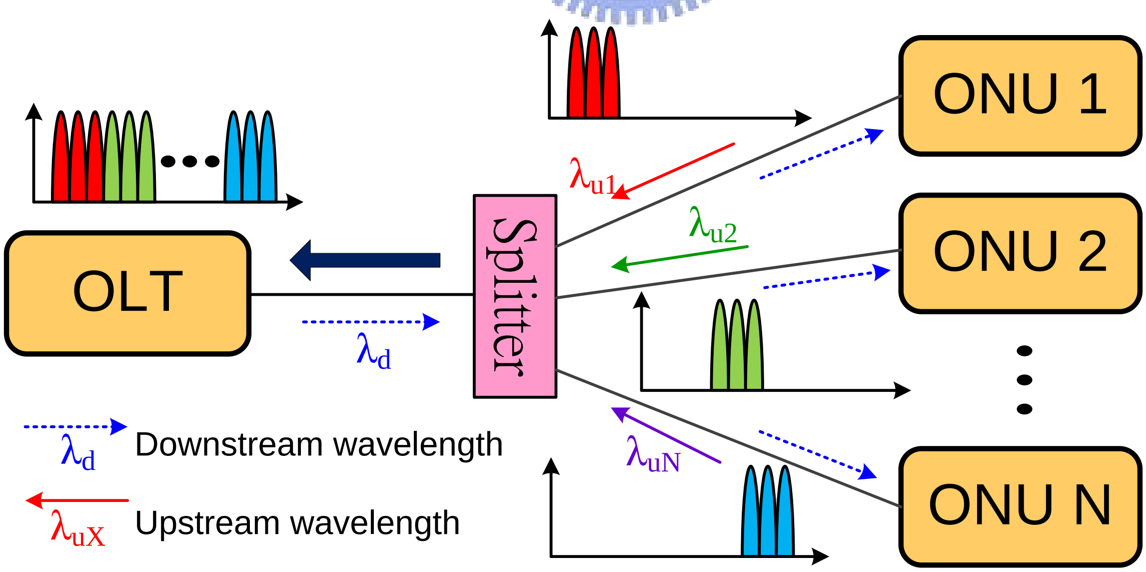


Figure. 9 Concept of OFDMA-PON

sends data via different wavelength. Different ONUs put data on different subcarriers. The architecture uses different light sources like WDM, and the bandwidth allocation is achieved by the subcarriers of OFDM signal, so it can change each user's bandwidth easily. Because of OFDM signal, the architecture has the advantages of OFDM. In addition, because subcarriers are all independent, several ONU or subcarriers can replace with other services like wireless service.

On the other hand, the architecture uses multiple wavelengths to achieve upstream transmission, so it will have the same problem with WDM system. Furthermore, the subcarrier of OFDM signal is overlapped in frequency domain, if the wavelengths of some light sources are not stable, the frequency shift might destroy the orthogonality of OFDM signal. To improve the OFDMA-PON architecture, we propose a novel architecture of OFDMA-PON, I will introduce the architecture and discuss its details.

CHAPTER 3 A novel architecture of OFDMA PON

3.1 Network architecture

We propose a novel architecture of OFDMA-PON (Figure. 10) without using WDM laser. As mention in CHAPTER 1, the OFDMA-PON uses two wavelength, λ_d and λ_u, to convey downstream and upstream signal and the downstream signal that is broadcast to each ONU. OLT combines the downstream broadband data and wireless radio frequency signal (RF), and transmit both signals to ONU through the ODD. There

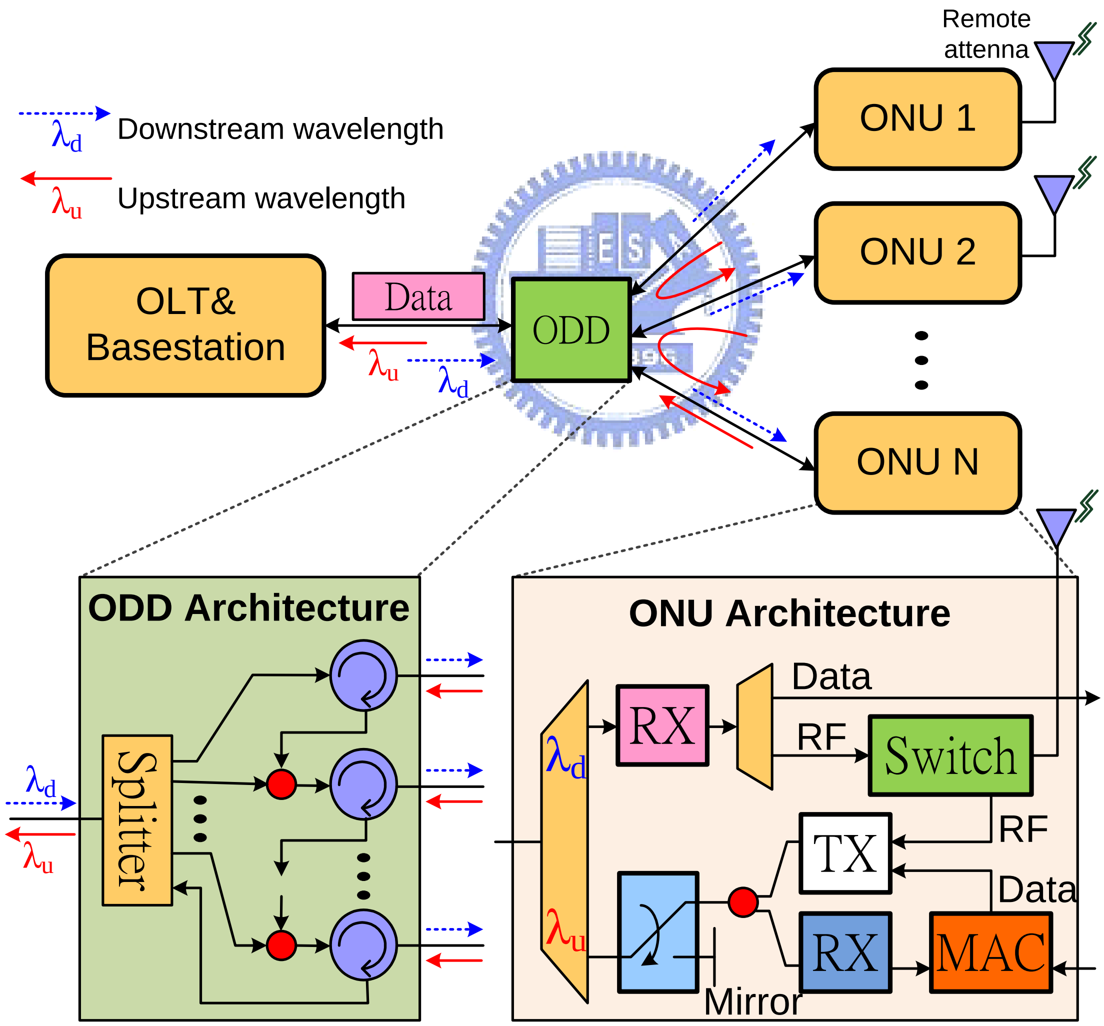


Figure. 10 The novel architecture of OFDMA-PON

is a splitter in ODD which makes several copies of downstream data and transmits the data to ONUs through the circulators which are located in ODD, too. ONU separates the broadband data and radio signal after receiving the downstream signal. The RF signal passes through a switch and is broadcasted by the remote antenna. For upstream, the wireless signal is received by remote antenna and passes through a switch. The upstream broadband data of ONU-1 adds control information by media access control (MAC) and transmits to next ONU with the RF signal simultaneously. ONU-1 sends its upstream data to ONU-2 through a circulator which is located in ODD. After receiving the upstream data from ONU-1, ONU-2 determines which the subcarriers on which its upstream data is carried out. ONU-2 regenerates the upstream data with its upstream data and the ONU-1 data. And combines the RF signal from remote antenna which is located at ONU-2. Moreover, the OFDMA-PON includes a 1x2 optical switch at ONU to avoid from accidental blackout or shutdown of ONUs. If ONU-2 is shutdown, the upstream data from ONU-1 will be reflected by the mirror of ONU-2.

3.2 Integration of OFDMA-PON signal and wireless RF signal

Next I am going to illustrate how the ONU integrates broadband OFDMA data and RF signal (Figure. 11). I assume that the wireless RF signals are received by two remote antennas which are located at ONU-1 and ONU-2. Firstly, the wireless RF signal received by a remote antenna is frequency-shifted to the allocate band by a mixer and a local oscillator (ONU-1 frequency-shifted to f1). There is bandpass filter (BPF) to filter out the RF signal. Note that we need some clear band for RF signal, so we keep the band clear by inserting zeros on corresponding IFFT points. The shifted RF signal is then combined with the broadband OFDMA signal by a coupler. The upstream signal is sent by the directed modulated laser to ONU-2.

When ONU-2 receives the upstream wavelength from the previous node, ONU-1, it firstly splits the received signal into two paths. The first path is the upstream OFDMA-PON signal from ONU-1. In the block of digital signal processing, it firstly uses an analog to digital converter (ADC) to convert analog signal to digital signal, and demodulates the OFDMA-PON signal. The MAC uses the control information from

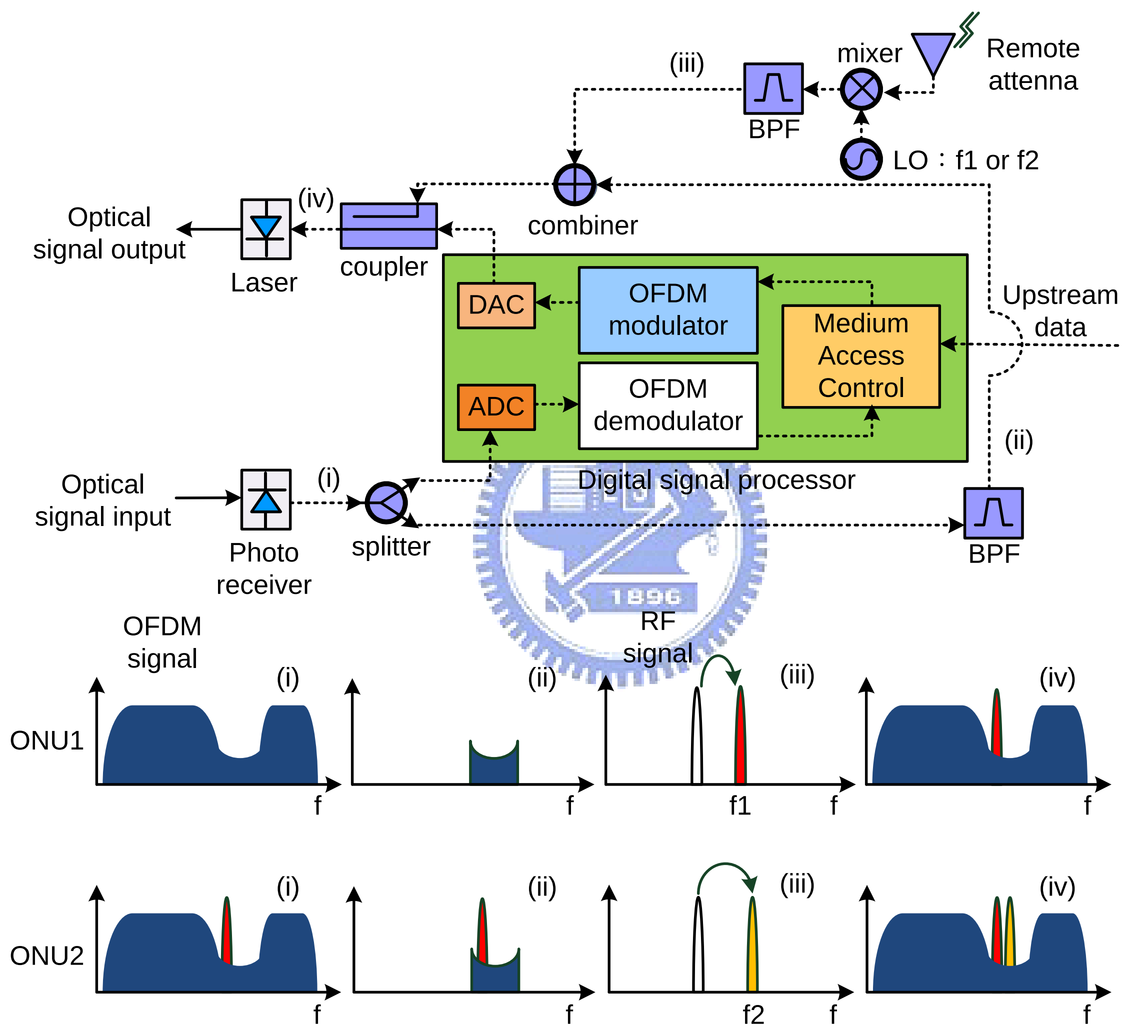


Figure. 11 Broadband OFDM data integrated with RF signal

control-channel to identify which subcarrier is occupied, and then adds the local data. It modulates the data to regenerate OFDMA-PON signal. Next, it uses a digital to analog converter to convert digital signal to analog signal. For the second path, the system uses a bandpass filter

BPF2 on the allocated radio band to remove the OFDMA-PON signal but preserve all previous wireless signals intact. The wireless RF signal from the remote antenna of ONU-2 is frequency-shifted to another allocated band (ONU-2 frequency-shifted to f2). The RF combiner then combines the local antenna's signal from BPF1 with the previous ONU's wireless signals from BPF2. Finally, the system integrates the radio signal with the upstream OFDMA-PON signal via an RF directional coupler before driving the upstream laser.

3.3 Advantages

3.3.1 **Optical Beat Interference free**

Optical beat interference (OBI) occurs when signals from more than one optical light sources are incident same photo detector simultaneously [10]. If the optical frequencies of the signals are close, the output of detector will include a beat note at the difference frequency that can increase noise within the electrical bandwidth occupied by a signal channel. So the wavelength division based subcarrier multiple access is limited by OBI. The subcarrier of OFDM signal is overlapped with adjacent spectrum band, so if we use the WDM based structure to achieve multiple accesses, the OBI will become a big obstacle of the performance. The novel architecture of OFDMA-PON we have been proposed has no OBI problem because it uses single wavelength for upstream. We use the ring structure for upstream in this architecture now. So we won't use WDM lasers and we will not encounter the OBI problem.

3.3.2 **Bandwidth enhancement by employ high spectra efficiency modulation formats**

To support emerging new network services, high speed transmission is needed. Executing high speed system directly may be a viable solution, but it needs relatively expensive high speed components and semiconductor optical amplifier. In our architecture, it uses the high spectral efficiency of M-QAM in each subcarrier of OFDM signal, so high data rate could be provided by using low bandwidth optical components. The reason why it can use high spectral sufficiency M-QAM modulation is because OFDM signal uses several narrow band subchannels instead of high data rate single carrier signal, and it enables easy equalization of frequency response by baseband digital signal processing. So it can maintain the performance of subcarriers, it is robust against the channel response.

3.4 Disadvantages

3.4.1 Interference by OFDM signal

One of the disadvantages in the design of ONU is the interference from OFDMA signal. The phase of every OFDMA symbol is not continuous, so the OFDMA signal has high side-lobe, which is a noise for wireless RF signal. We can see the signal transmission step concept in Figure. 11. At step (ii), it uses a BPF to filter out the wireless RF signal, and this signal will combine with the next wireless RF signal, transmitting to next node. So in the transmission process the wireless signal never demodulates. At step (ii) the in-band interference from OFDM will accumulate. Assuming the OFDMA-PON architecture supports 32 ONU, if there is a remote antenna at ONU-1, it can accumulate 32 times in-band noise caused by OFDMA signal at most. The noise accumulation is a big problem in the cascade ring architecture.

3.4.2 Interference by Wireless signal

Wireless signal also has side-lobe, and it is a noise for OFDMA signal. Wireless signal is a narrow band signal, The side-lobe would not be a problem to OFDMA signal if we give them a part of guard band. For example, Figure. 12 shows the spectrum of one broadband OFDMA signal and three narrowband RF signals. The interference caused by RF signal seems small. The nearest part between OFDMA signal and RF signal exceeds 40 dB. In the traditional single carrier system, we can roughly estimate that the OFDMA signal has about 40dB signal to noise ratio (SNR). OFDMA signal is not a traditional single carrier signal, it uses N point FFT and IFFT to achieve multiple carrier signal, so

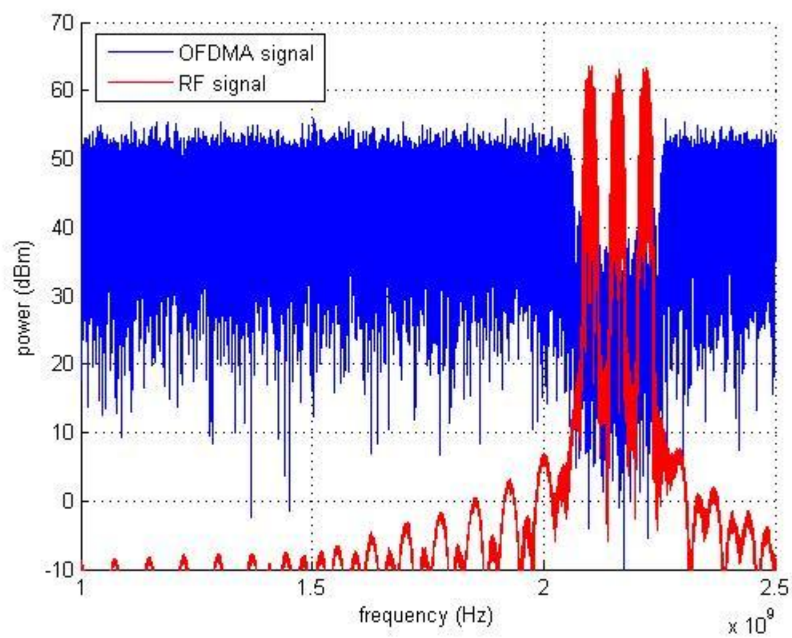


Figure. 12 Spectrum of one OFDMA signal and three RF signal

the modulation of OFDMA signal only concern the N point spectrum. What we need to see is N point spectrum, Figure. 13 shows N point spectrum of the OFDMA signal and RF signal. The nearest part between OFDMA signal and RF signal is about 10 dB. It is a very serious interference to OFDMA signal. Thus, when OFDMA signal and RF signal are close to each other in frequency domain, the interference caused by the RF signal must be reduced.

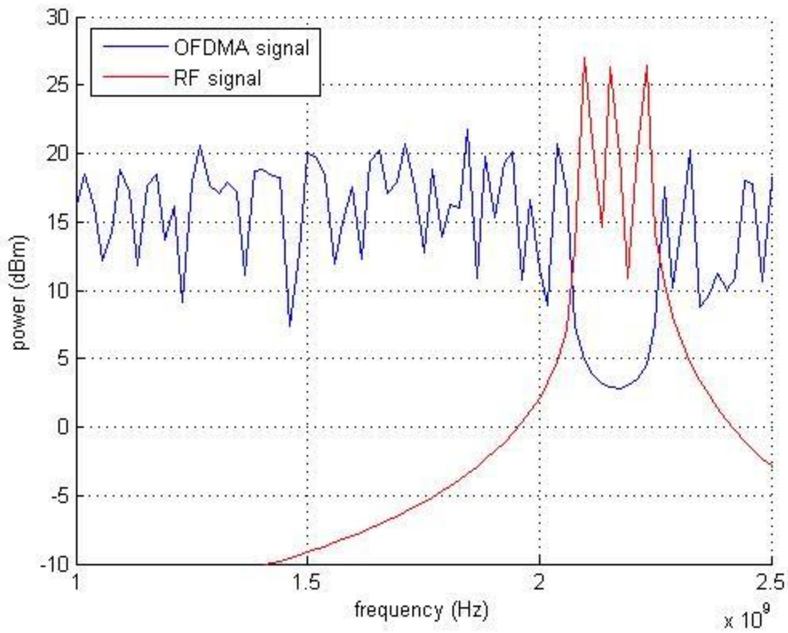


Figure. 13 Spectrum of N point OFDMA signal and RF signal

3.5 Optimize OFDMA-PON system

3.5.1 **Windowing**

Time domain windowing is one of methods which can reduce the side lobe of signal [11],[12]. In our architecture, the interference from OFDMA signal is caused by side lobe, so time domain windowing is a method that we put into consideration in order to reduce the interference. The side lobe is caused by the discontinuous phase of signal. If we can smooth the phenomenon, we can reduce the side lobe. Windowing is a method that we let the signal multiplied by a window in time domain to smaller the signal gradually to the discontinuous point, so the effect of the discontinuous phase will be reduced.

Figure. 14 is the concept of adding time domain window to one symbol of the OFDMA-PON signal. At first, beside the OFDMA data and the cyclic prefix we add guard interval at the two side of the signal. The method of adding guard is as same as the method of adding cyclic prefix. To maintain the continuity phase, guard interval should use the cyclic part of the signal. We multiply the OFDMA signal by the window and the window only shapes the guard interval part of the signal, so the data is not affected by the window. The side lobe of OFDMA signal is reduced by reducing the effect of phase discontinuity.

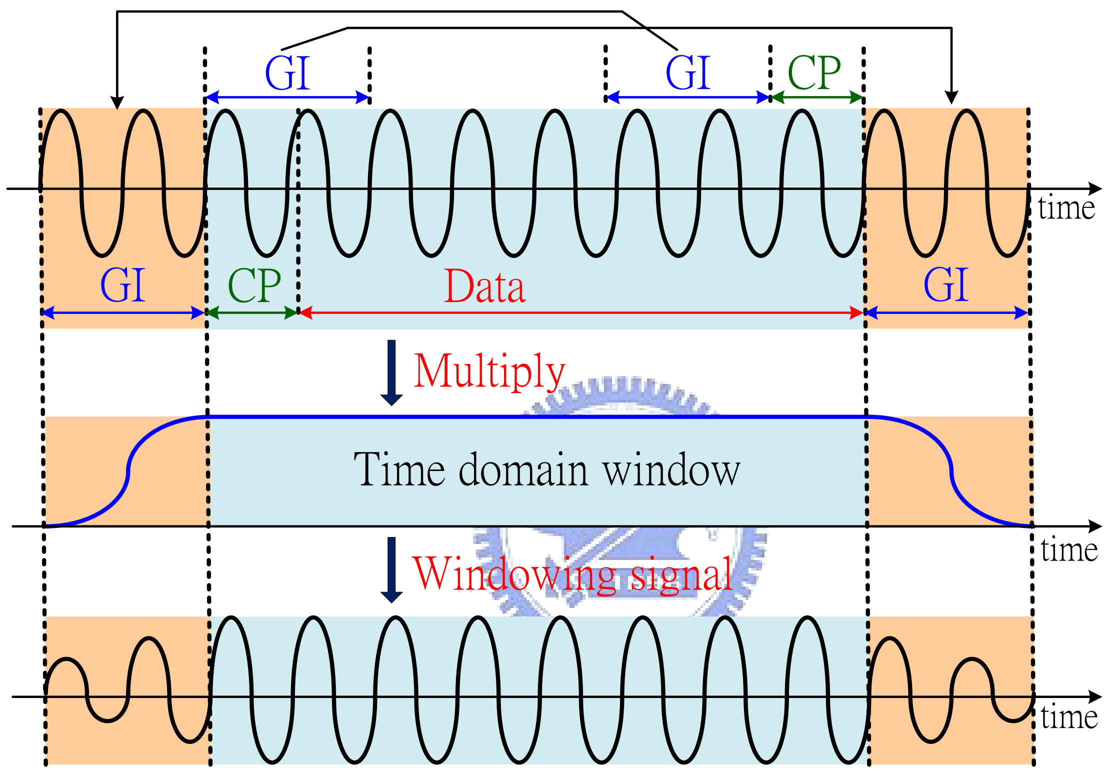


Figure. 14 Concept of time domain windowing

3.5.2 **Subcarrier decreasing method**

Because we want the system to have the best bandwidth efficiency, we hope the turnoff subcarriers of OFDM signal would be as less as possible. So the OFDM subcarrier is very close to wireless RF signal, and it makes the interference become very serious. The windowing method is trying to reduce the side lobe of OFDM signal, but it needs to add guard interval. To reduce the side lobe effect, we can also turn off more subcarriers to increase the spectrum space between the broadband signal and RF signal. Both methods of adding GI and turnoff subcarrier are wasting transmission bandwidth, so we could consider subcarrier decreasing as a method to reduce interference. Next I will compare the two methods later.

3.5.3 **Adding notch filter**

Since we know the interference from wireless RF signal has serious effect on OFDMA signal. Reducing the effect becomes an important issue. Removing the wireless RF signal is a direct way to eliminate the interference. We can add a notch filter to remove the wireless RF signal. Because we do not want to turn off too many subchannels to vacate spectrum band for wireless RF signal, we will let the guard band which is between OFDMA subchannel and wireless signal become as narrow as possible. Narrow guard band makes the design of notch filter difficult. The notch filter needs sharp transition band. So the demands of notch filter include sharp transition band, enough depth of stop band, flatness of pass band, and linear phase in order to protect data. To achieve the these demands, we should choose high order FIR filter. It will increase the complexity of system. In conclusion, there are many tradeoffs between each condition; we need to choose a suitable notch filter to filter out the wireless RF signal.

CHAPTER 4 Simulation result and the model of interference

4.1 The model of second order polynomial Nyquist window and the interference which caused by OFDMA signal

4.1.1 The model of the interference which caused by OFDMA signal

Before trying to reduce the out-of-band power of OFDMA signal, we firstly model this interference. The OFDMA signal with N=128 subcarriers and the power spectrum density (PDS) from 100th to 109th subcarriers has been turned off. The interference power of the notched band is from the out-of-band radiation of OFDM sub-carriers. Assuming the normalized frequency is f_n, and $f_n=0$ denotes the center frequency of the first sub-carrier. $f_n \in \{99, \cdots, 108\}$ are set to be zero. The PDS of rectangular window can be written as：

$$\boldsymbol{\psi_{rect}(f_n) = |sinc(f_n)|^2} \qquad (1)$$

The PDS function of windowed OFDM (WOFDM) is the summation of all the sub-carrier's PDS:

$$\boldsymbol{\psi_{wofdm}(f_n) = \sum_{\Delta f=0}^{98} \psi(f_n - \Delta f) + \sum_{\Delta f=109}^{127} \psi(f_n - \Delta f)} \qquad (2)$$

The Δf is the normalized distance between two adjacent sub-carrier frequency, and ψ can be ψ_{rect} or other PDS of window. The interference power of the turn off band is then：

$$\mathbf{I_{notch}} = \int_{99}^{108} \boldsymbol{\psi_{wofdm}(f_n)} \mathbf{dfn}$$

$$= \int_{99}^{108} \left[\sum_{\Delta f=0}^{98} \psi(f_n - \Delta f) + \sum_{\Delta f=109}^{127} \psi(f_n - \Delta f) \right] df_n$$

$$= \int_{99}^{108} \psi(f_n) df_n + \int_{98}^{107} \psi(f_n) df_n + \cdots + \int_{1}^{10} \psi(f_n) df_n$$

$$+ \int_{-10}^{-1} \psi(f_n) df_n + \int_{-11}^{-2} \psi(f_n) df_n + \cdots + \int_{-28}^{-19} \psi(f_n) df_n$$

$$= \int_{99}^{108} \boldsymbol{\psi}(\mathbf{f_n})\mathbf{df_n} + \int_{98}^{107} \boldsymbol{\psi}(\mathbf{f_n})\mathbf{df_n} + \cdots + \int_{1}^{10} \boldsymbol{\psi}(\mathbf{f_n})\mathbf{df_n}$$

$$+ \int_{1}^{10} \boldsymbol{\psi}(\mathbf{f_n})\mathbf{df_n} + \int_{2}^{11} \boldsymbol{\psi}(\mathbf{f_n})\mathbf{df_n} + \cdots + \int_{19}^{28} \boldsymbol{\psi}(\mathbf{f_n})\mathbf{df_n}$$

$$= \mathbf{2} \cdot \sum_{\mathbf{k=1}}^{\mathbf{19}} \int_{\mathbf{k}}^{\mathbf{k+9}} \boldsymbol{\psi}(\mathbf{f_n})\mathbf{df_n} + \sum_{\mathbf{k=20}}^{\mathbf{99}} \int_{\mathbf{k}}^{\mathbf{k+9}} \boldsymbol{\psi}(\mathbf{f_n})\mathbf{df_n} \quad (3)$$

4.1.2 The second order polynomial Nyquist window

The Nyquist window is one of windows which can reduce the spectrum side lobe, and second order polynomial window (SOCW) uses second order Taylor series expansion to expand the Nyquist window [13],[14]. The higher order Taylor series expansion of window can reduce assigned notch band more precisely in comparison with the lower order terms. The Nyquist window $w_N(t)$ can be generally expressed as below：

$$w_N(t) = \begin{cases} \dfrac{1}{T_u}, & 0 \le |t| < \dfrac{T_u(1-\alpha)}{2} \\ \dfrac{1}{T_u}\left[1 - x\left(-|t|\dfrac{2}{\alpha T_u} + \dfrac{1}{\alpha}\right)\right], & \dfrac{T_u(1-\alpha)}{2} \le |t| < \dfrac{T_u}{2} \\ \dfrac{1}{T_u}\left[x\left(|t|\dfrac{2}{\alpha T_u} - \dfrac{1}{\alpha}\right)\right], & \dfrac{T_u}{2} \le |t| < \dfrac{T_u(1+\alpha)}{2} \\ 0, & |t| \ge \dfrac{T_u(1+\alpha)}{2} \end{cases}$$

$$x(t) = 0.5 + a_1 t + (-0.5 - a_1)t^2 \qquad (4)$$

$x(t)$ is the normalized elementary function, α is the roll-off factor, and T_u is the duration of OFDM symbol. Taking the Fourier transform of $w_N(t)$ we can get as below：

$$\mathbf{w_{SOCW}(f) = sinc(fT_u)\left[2(1+a_1)sinc(\boldsymbol{\alpha} fT_u) - (1+2a_1)sinc^2(\frac{\boldsymbol{\alpha}}{2}fT_u)\right]} \qquad (5)$$

Replacing fTu with the normalized frequency f_n, the PDS of the SOCW is then：

$$\boldsymbol{\psi_{SOCW}(f_n) = \left|sinc(f_n)\left[2(1+a_1)sinc(\alpha f_n) - (1+2a_1)sinc^2\left(\frac{\alpha}{2}f_n\right)\right]\right|^2} \qquad (6)$$

Then we can chose appropriate a_1 to minimizing $I_{notchSOCW}$. $I_{notchSOCW}$ is obtained by substituting ψ_{socw} in (6) for ψ in (3)：

$$\boldsymbol{I_{notchSOCW} = \int_{99}^{108} \psi_{SOCW}(f_n)dfn} \qquad (7)$$

4.1.3 **Optimize a_1 of second order polynomial window**

To avoid changing OFDMA data, I let the data part and cyclic prefix part locate in first part of $w_{SOCW}(t)$, so I choose α be：

$$\alpha = \frac{GI}{Sym + CP + GI} \qquad (8)$$

Sym is the length of OFDMA symbol, in our case Sym=512 and CP=8 in sampling rate=10G. and the GI is guard interval. We can choose the length of GI and we can get a corresponding α, so we can assume α to be a constant. Then a_1 is the only variable. From (6), we get the formula as below：

$$\psi_{SOCW}(f_n) = Aa_1^{\,2} + Ba_1 + C \qquad (9)$$

$$\boldsymbol{A = sinc^2(f_n)\left[4sinc^2(\alpha f_n) - 8sinc(\alpha f_n)sinc^2\left(\frac{\alpha}{2}f_n\right) + 4sinc^4\left(\frac{\alpha}{2}f_n\right)\right]} \qquad (10)$$

$$B = sinc^2(f_n)\left[8sinc^2(\alpha f_n) - 12sinc(\alpha f_n)sinc^2\left(\frac{\alpha}{2}f_n\right) + 4sinc^4\left(\frac{\alpha}{2}f_n\right)\right] \qquad (11)$$

$$C = sinc^2(f_n)\left[4sinc^2(\alpha f_n) - 4sinc(\alpha f_n)sinc^2\left(\frac{\alpha}{2}f_n\right) + sinc^4\left(\frac{\alpha}{2}f_n\right)\right] \qquad (12)$$

Substitute (9) into (3), we can get：

$$I_{notchSOCW} = Da_1{}^2 + Ea_1 + F \quad (13)$$

$$D = 2 \cdot \sum_{k=1}^{19} \int_k^{k+9} Adf_n + \sum_{k=20}^{99} \int_k^{k+9} Adf_n \quad (14)$$

$$E = 2 \cdot \sum_{k=1}^{19} \int_k^{k+9} Bdf_n + \sum_{k=20}^{99} \int_k^{k+9} Bdf_n \quad (15)$$

$$F = 2 \cdot \sum_{k=1}^{19} \int_k^{k+9} Cdf_n + \sum_{k=20}^{99} \int_k^{k+9} Cdf_n \quad (16)$$

Based on (15), the a1 is the only variable, solving the following function：

$$\frac{\partial I_{notchSOCW}}{\partial a_1} = 0 \quad (17)$$

We can get the a_1：

$$a_1 = -\frac{E}{2D} \quad (18)$$

Table. 1 is the numerical result, I initially choose the length of GI and we can get α by using (8). And then substitute α in to (18) and then we can get the numerical result by using mathematical software. Finally substitute a_1 into (13) and we can get the power of the notched band. According to the result, we can see that longer the GI is, deeper the notched band would be. It means more GI points, the window can make the transition more smooth.

GI	15	20	25	30	35	40	45	50	55
α	0.028	0.037	0.046	0.055	0.063	0.071	0.080	0.088	0.096
a1	0.878	0.590	0.362	0.203	0.098	0.026	-0.027	-0.069	-0.104
$I_{notchSOCW}$	0.182	0.163	0.148	0.135	0.124	0.114	0.105	0.097	0.090

Table. 1 optimal a_1 and the power of notched band for different GI

4.2 Compare of windows

I choose another two types of windows, raised-cosine window and Kaiser window [15],[16], to compare with the second order polynomial Nyquist window. Raised-cosine window is a usual type of windows which is implemented to reduce the side lobe of OFDM signal. Raised-cosine window $w_{rs}(t)$ can express as：

$$w_{rs}(t) = \begin{cases} \frac{1}{T_u}, \quad 0 \le |t| < \frac{T_u(1-\alpha)}{2} \\ \frac{1}{2T_u}\left\{1 + \cos\left[\frac{\pi}{\alpha T_u}\left(|t| - \frac{T_u(1-\alpha)}{2}\right)\right]\right\}, \quad \frac{T_u(1-\alpha)}{2} \le |t| < \frac{T_u(1+\alpha)}{2} \\ 0, \quad |t| \ge \frac{T_u(1+\alpha)}{2} \end{cases} \qquad (19)$$

α is also the roll-off factor as mention before, we can select GI to get α, too. The Kaiser window is a common type of windows in the textbook. And it has roll-off factor which can achieve different effects of side lobe. Thus, I directly use the model of Kaiser window in Matlab.

All these windows have the common characteristic which is adding more guard interval to shape more effects for cutting down the side lobe of the signal, but using guard interval is wasting bandwidth. To reduce the length of guard interval, we can overlap the guard interval part (Figure. 15), and it can save half GI.

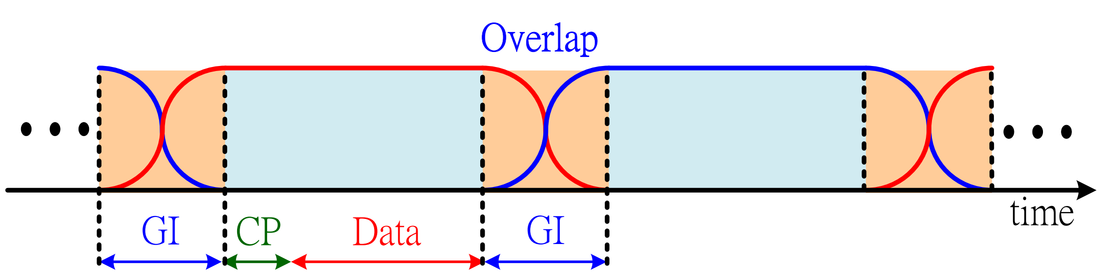


Figure. 15 The concept of overlap of guard interval

At the turnoff band we put three single carrier QPSK signal with bandwidth of 20MHz to simulate wireless RF signals. The center frequency of three RF signal are 2100MHz, 2160MHz and 2220MHz respectively. Figure. 16 is the comparison of the effect of the 2100MHz RF signal by adding three different type of windows, the horizontal axis is the guard interval bandwidth percentage of the whole symbol. And the vertical axis is represents for the SNR comparison between 2100MHz RF signal with window and the same signal without adding window. The SNR of the original 2100MHz RF signal is 26.6dB.Among these three methods as I mention above, using the second order polynomial Nyquist window is the best way to reduce side lobe of OFDMA signal Besides, it would be much more effective to reduce side lobe for all of windows if we add more length of GI into this signal.

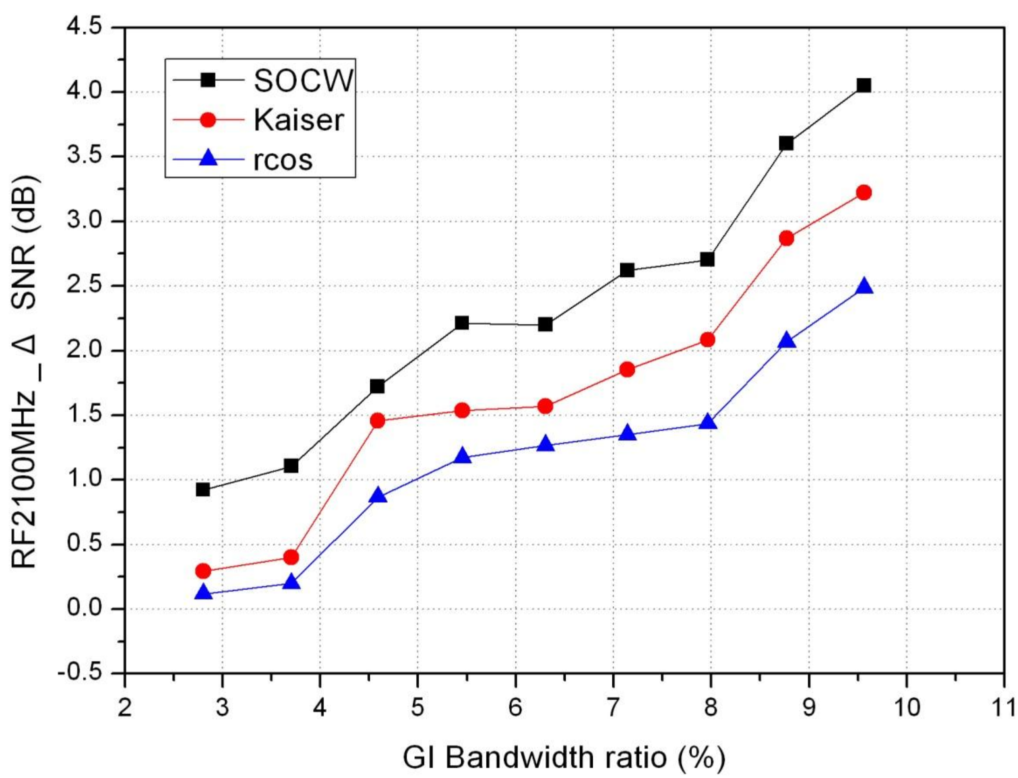


Figure. 16 The comparison of three different type windows

4.3 Modeling the accumulated noise of RF signal

If we assume the noise is added in each node of ONU to be a constant N_{system}, we can show SNR of the N_{th} ONU as follow：

$$\frac{S}{N_0+(N-1)N_{system}} \qquad (20)$$

S is the signal power and N_0 is the noise after first node. We can put RF signal at different positions which have different side-lobe level of OFDM signal. Figure. 17 shows three different results under different interference. It uses VPI to simulate the RF signal's SNR at first and second node, and then we can use (20) to compute the SNR at every node. And it also includes the result of direct using VPI to simulate first node to fifth node. The result is similar between these two methods.

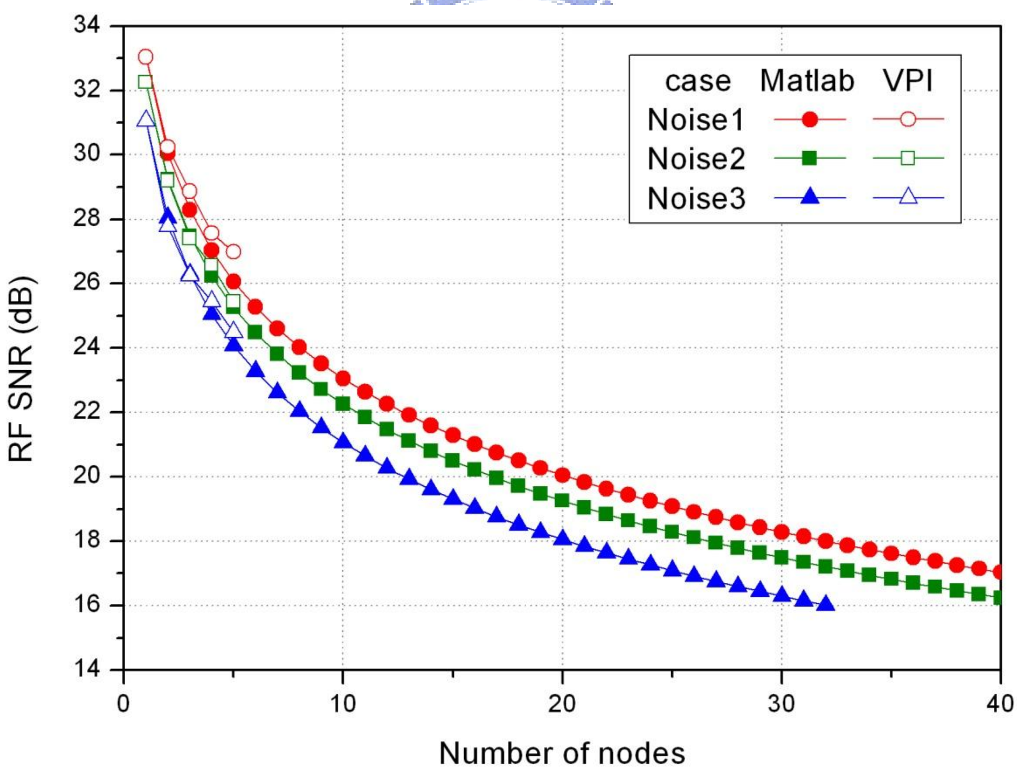


Figure. 17 RF SNR estimation after cascade several ONU

4.4 Chosen of notch filters

We choose to use the digital notch filter in the digital signal block because the digital FIR filter can achieve constant group delay. It will not harm the phase of signal. FIR filter design has two methods, the first one is window method and the second one is optimal method [16],[17],[18]. In window method, Kaiser window is the most common type of windows to design filter because it can adjust roll-off factor to change the shape of window to fit the demands. In optimal method, there are two methods to optimize the filter, one is least-squares method and the other is equiripple method. Least-squares method is used to minimize the energy of the error, the equiripple method has the smallest "maximum deviation" from the ideal filter. There are some trade-offs between filter's order, stop band depth, pass band ripple, transition band width, so we only can choose one suitable filter in our system.

We use Matlab's filter design tool to design FIR notch filter. We fix the filter order at 200 and to choose other conditions. At first, let us find what notch depth that the system needs. We combine the OFDM signal and RF signal in the same power. It is the largest interference to OFDM signal from RF signal. And we choose three different notch depths, 15dB, 20dB and 30dB, to see its effects with each different notch depths. Figure. 18 shows each OFDM subcarrier's SNR under different notch filters. I choose the Kaiser window to design notch filter with 30dB and 20dB notch depth. The 15dB notch depth uses the least-squares method to design because the Matlab cannot design it by window method in this condition. Next, I compare several SNRs of OFDM signal that adding with different notch depths separately. Obliviously, 20dB depth is better than 15dB depth, but the effect of 30dB depth notch filter is almost as same as the effect of 20dB depth notch filter. So we can observe that the notch depth of 20dB is able to remove the RF signal and more depth is unnecessary. However, the OFDM signal does not return to the original SNR after adding notch filter, because the filter is not ideal one and it harms the signal.

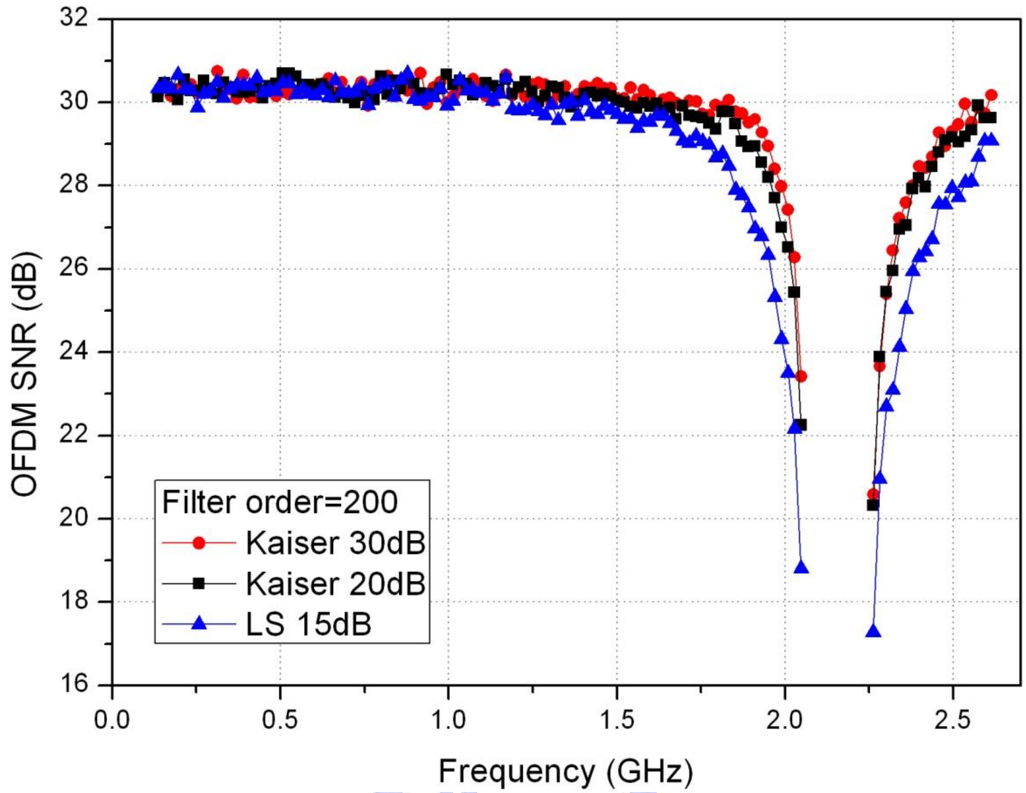


Figure. 18 OFDM subcarrier's SNR under different notch filter condition

Next let us find which design method is better to our demands. The center frequencies of OFDM signal's subcarriers, the nearest one to the notched band are about 2050MHz and 2260MHz, and the far left and far right RF signal is located at 2100MHz and 2160MHz, so the transition band of notch filter must locate between the two signals. The filter order is 200, and we choose the stop band depth of notch filter to be about 19dB at 2100MHz and 2160MHz. Table. 2 shows the magnitude responses, phase responses and design conditions of three different types of notch filters designing by Matlab filter design tool.

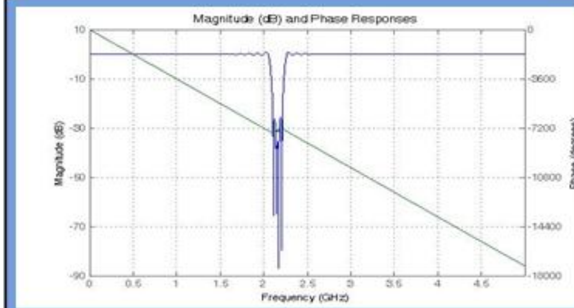
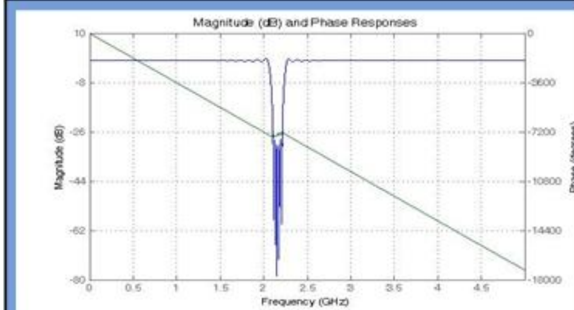
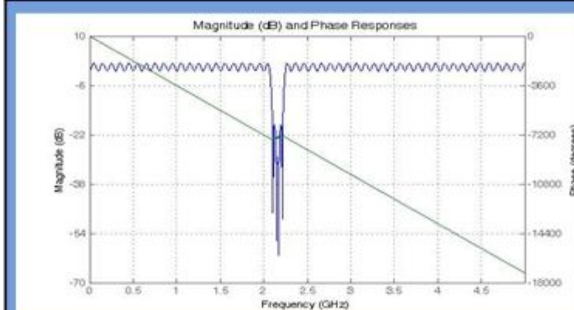
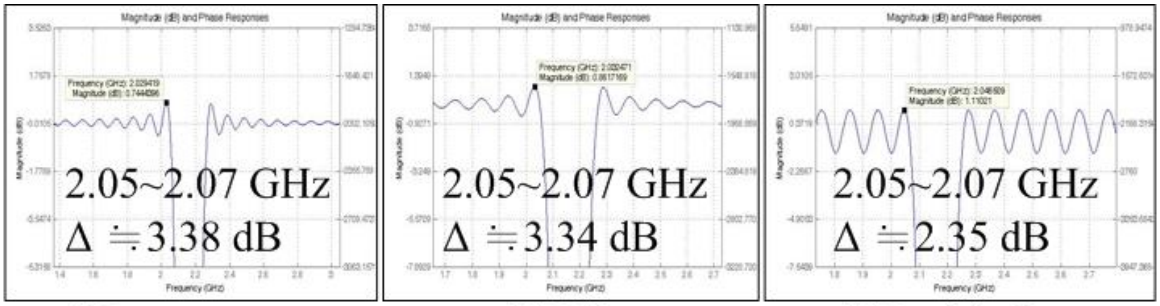
Magnitude and Phase Responses	Design Conditions of Filter
	Method：Kaiser window order：200 Attenuation： At 2.1 GHz ≒19.3dB At 2.16 GHz ≒35.3dB At 2.22 GHz ≒18.4dB
	Method：Least-square order：200 Attenuation： At 2.1 GHz ≒19dB At 2.16 GHz ≒31dB At 2.22 GHz ≒18.9dB
	Method：Equiripple order：200 Attenuation： At 2.1 GHz ≒19dB At 2.16 GHz ≒29dB At 2.22 GHz ≒18.9dB

Table. 2 Magnitude responses, phase responses and design conditions of three different types of notch filters

Figure. 19 shows notch filter's ripple, the largest shock range of ripple in the pass band is between 2.05~2.07GHz, and the magnitude ripple makes the signal distortion. We observe that the ripple shape of Least-square method designed notch filter (Figure. 19 (a)) is almost as same as Kaiser window method designed notch filter (Figure. 19 (b)), and equiripple method designed notch filter (Figure. 19 (c)) has the smallest in-band ripple, but its ripple is equal large in the entire pass-band of notch filter.



(a)Least-square (b)Kaiser (b)Equiripple

Figure. 19 Notch filter's Ripple

In Figure. 20, I show the OFDM signal's SNR under different effects of notch filters. Note that let the power of RF signal be equal to OFDM signal. We can observe that the OFDM signal without adding notch filter encounters serious interference, especially for the SNR of subcarriers which is close to the notched band. In this case, the SNR of subcarriers is less than 10dB. After adding notch filter, all SNR of OFDM signals are over 16dB. Although the lowest SNR of OFDM signal's subcarrier, which adds the

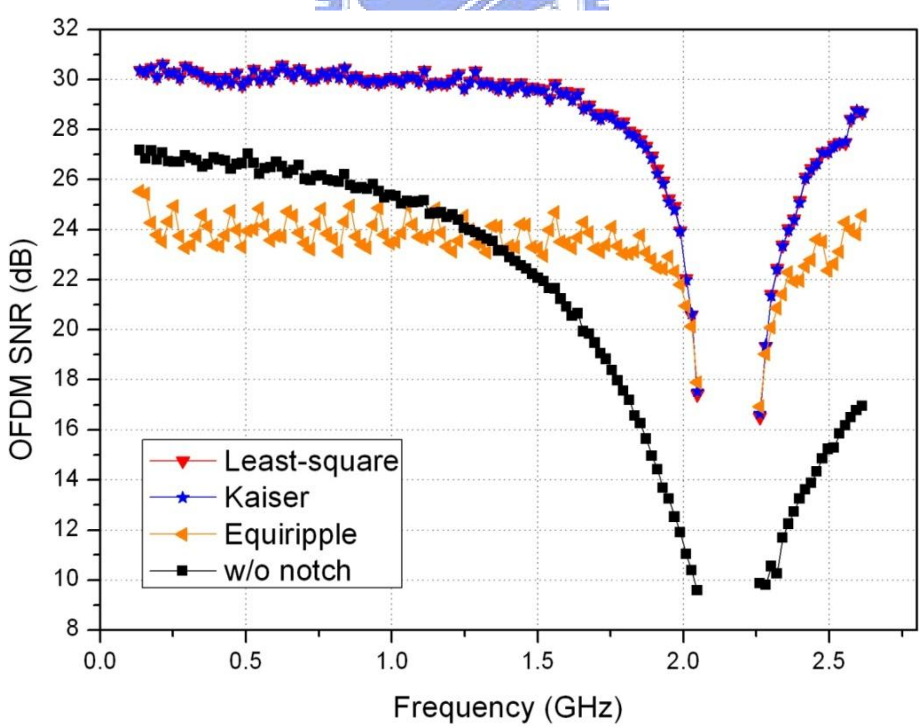


Figure. 20 OFDM signal's SNR under different notch filter

equiripple method designed notch filter, has the best performance among three types of notch filter, the equal large ripple in entire pass-band makes every subcarriers distorted. Some SNR of subcarriers, which are far away from the notched band, are even worse than the subcarrier before adding notch filter. And the performances of OFDM signal that adding Least-square method designed notch filter and adding Kaiser window method designed notch filter are almost the same. I choose the Kaiser window method designed notch filter to be used in our system. So in follow-up chapter, the notch filter represents for the Kaiser window method designed notch filter.

4.5 Improving the effect of notch filter by windowing method

In Figure. 20, we can observe another problem. If the OFDM signal's distortion is caused only by the ripple of notch filter, the OFDM signal's SNR should shock in a fix range. However, from the figure we can observe that the SNR of subcarriers, which are close to the notched band, are lower than other subcarriers. This is because the notch filter is not only removing the RF signal but also removing the side-lobe of OFDM signal. Traditional signal carrier signal uses a filter to shape the pulse of signal, so the signal's side-lobe is low. OFDM signal puts data in frequency-domain and executes IFFT to time domain directly, so the time-domain signal is composed by a series of square waves without pulse shaping. The series of square waves without pulse shaping makes the spectrum of whole signal gain high side-lobe. And the notch filter only removes one side of OFDM signal's side-lobe. It changes the shape of signal. The windowing method is just one of methods to reduce side-lobes of signal. After reducing the side-lobes of OFDM signal, the number of removed side-lobes becomes smaller, then the distortion caused by the notch filter can be improved.

CHAPTER 5 **Experimental results**

5.1 Experimental setup

Figure. 21 is the experimental setup which is constructed to test the upstream signal performance. The OFDM signal, which occupies about 0.1~2.6GHz bandwidth, was generated by an arbitrary waveform generator (AWG) with 10GHz sampling rate. The IFFT size is 512, from which 16QAM encoded 128 subcarriers are used for data transmission. The allocated radio band is 220MHz wide at frequency 2160MHz, which is wide enough to accommodate multiple wireless signals. Three 20MHz WiMAX RF signal at 2100MHz, 2160MHz, and 2220MHz, generated by AWG2, are used for upstream test. After the attenuators and directional coupler, OFDM and RF are combined to drive a 3dBm output power, 1540nm direct modulated laser module. For the direct link

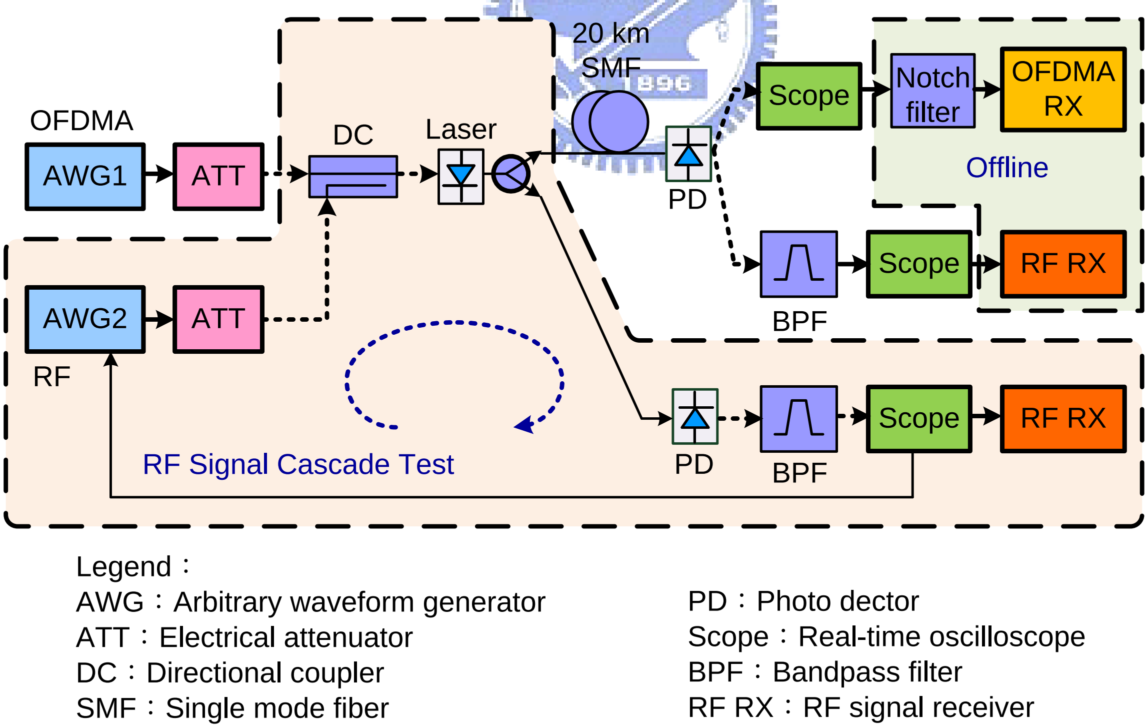


Figure. 21 Experimental setup

test, the combined signal reaches optical photoreceiver after 20km single mode fiber. Then a real-time scope captures the signal for offline signal demodulation. Before analyzing the OFDMA signal, we harness a 200MHz notch filter at 2160MHz to remove the RF signals before OFDM receiver and demodulate it. Also, before analyzing the RF signal, we harness a 40MHz bandpass filter at 2100MHz to keep the 2100MHz RF signal before RF receiver.

If we want to estimate the performance of RF signal after cascaded EOE conversions and accumulate interference from the OFDM signal, an offline recalculating loop experiment is required. As the graph shown in the lower part of the setup, it uses a splitter to generate a copy of signal, and we use a 220MHz BPF at 2160 to keep all RF signals before the optical photo receiver. Then a real-time scope captures and stores a section of waveform at 12.5GHz sampling rate in a file. The stored waveform is re-sampled to 10GHz by a DSP program and fed to the AWG2 for next loop transmission. For each loop, we load different OFDM signal to AWG1 so that each loop's interferences will not be correlated. In this way, we can emulate the accumulated interference that is imposed on RF signal from ONU1 to ONU32. The Figure. 22 clearly shows the photograph of the experimental setup.

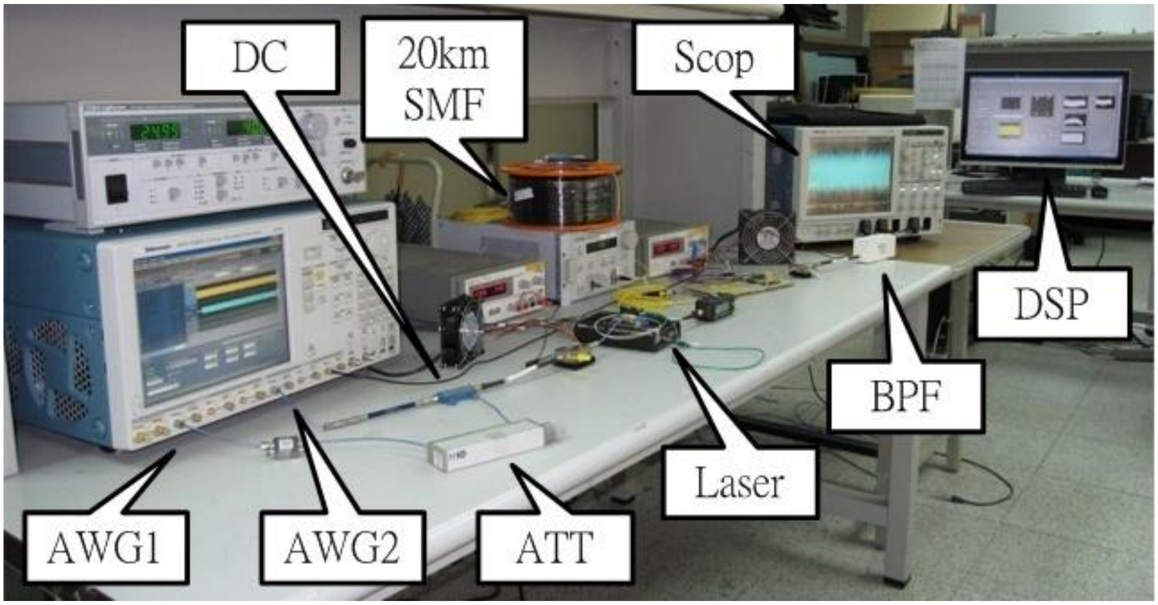


Figure. 22 Photograph of the experimental setup

To promote experimental efficiency, I firstly set up the digital signal processing tool by labview. This time-saving device includes numerous functions ranging from getting time domain data from real-time scope, demodulating the received data immediately, showing the constellation, SNR and coefficient of equalizer on the screen, to saving the demodulated information that are necessary for our experiment. In the process of experiment, the device can capture the data from real-time scope and demodulate it automatically so that we can save a lot of time, and analyze the result immediately.

5.2 Experiment result

We define some parameter at first. Power ratio (PR) means：

$$\mathrm{PR} = \frac{\text{Power of OFDM}}{\text{Power of RF}}\ (\mathrm{dB})$$

The origin OFDM data form, which turns off 10 subcarriers, we call it o0. And o3 means we turn off extra 3 subcarriers at the each side of the turnoff band, so there are 16 subcarriers which have been turned off.

Next I want to compare the subcarrier decreasing method with windowing method. Both of these two methods are bandwidth wasting, because the former should turn off the additional subcarriers and the latter should add extra guard interval. The following equation shows my desire to have the number of bandwidth waste in turnoff of additional subcarriers to be equivalent to its counterpart in the adding of guard interval ：

$$\frac{118}{(520+\mathrm{GI})\cdot\frac{1}{\mathrm{f_s}}}=\frac{118-2\mathrm{X}}{520\cdot\frac{1}{\mathrm{f_s}}}\ (\mathrm{data/s}\cdot\mathrm{symbol})$$

f_s ：Sampling frequency

GI：Guard interval

2X：Number of extra turnoff subcarrier

It means the transmited data per second per OFDM symbol need to be equal to both methods. To comapre windowing method with o3 which is 2X=6, we can calculate the equivalent GI=28. At following we add window with 28 GI points.

5.2.1 **Broadband signal result**

We firstly see the result of broadband OFDM signal. Figure. 23 shows three groups of the receiver sensitivity of OFDM signals. The first group is OFDM o0 signal without RF signal, the group, the base line, is only affected by the response of the component and instrument. Because the transmission power is constant, the power of OFDM signal should decrease when PR value increase. The BER curve in the picture below is divided into three curve lines rather than overlapped as one line because of the power reduction of OFDM signal. And we optimize the modulation index in a weakly clipping condition. We can see the receiver sensitivity of OFDM signal with PR=6 is about -15.5dBm. Note that the receiver sensitivity for BER=1×10^{-3} of OFDM signal, which is the error-free limit with FEC.

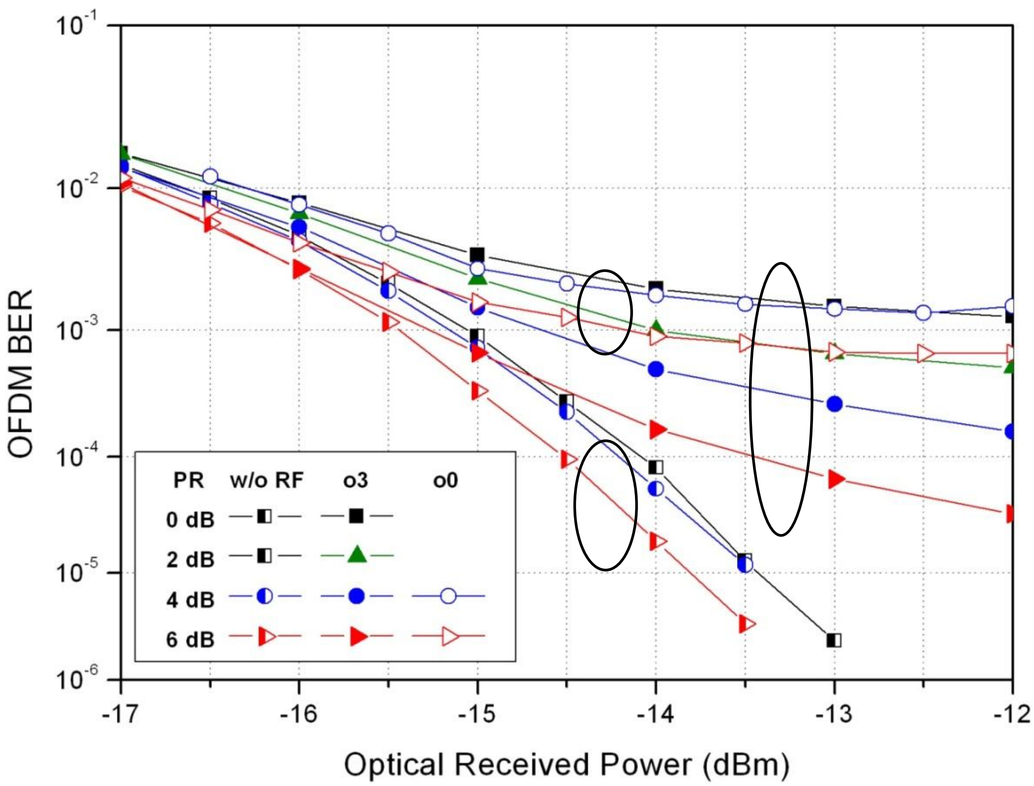


Figure. 23 BER curves of OFDM o0 with RF and without RF, and o3 with RF

The second and third group is o0 and o3 respectively. We can see all these lines have noise floor, they cannot achieve lower BER because of the interference from RF signal. o0 only has two lines for it cannot achieve the error-free limit when PR value is larger than 4 dB even though when PR=6dB, the line is close to the limit line so that it can't be done. So if the signal has no other improvements, it almost is invalid in this system. o3 uses subcarrier decreasing method, it turns off extra 6 subcarriers. The minimum PR value is 2 dB to maintain error-free condition. When PR=6 dB is not good enough, the BER is larger than 10^{-4} when the optical received power is smaller than -14dBm.

Figure. 24 shows the result that o0 add notches filter and window. We can see that the OFDM signal has a large improvement. Even when PR=0dB, it can still achieve BER

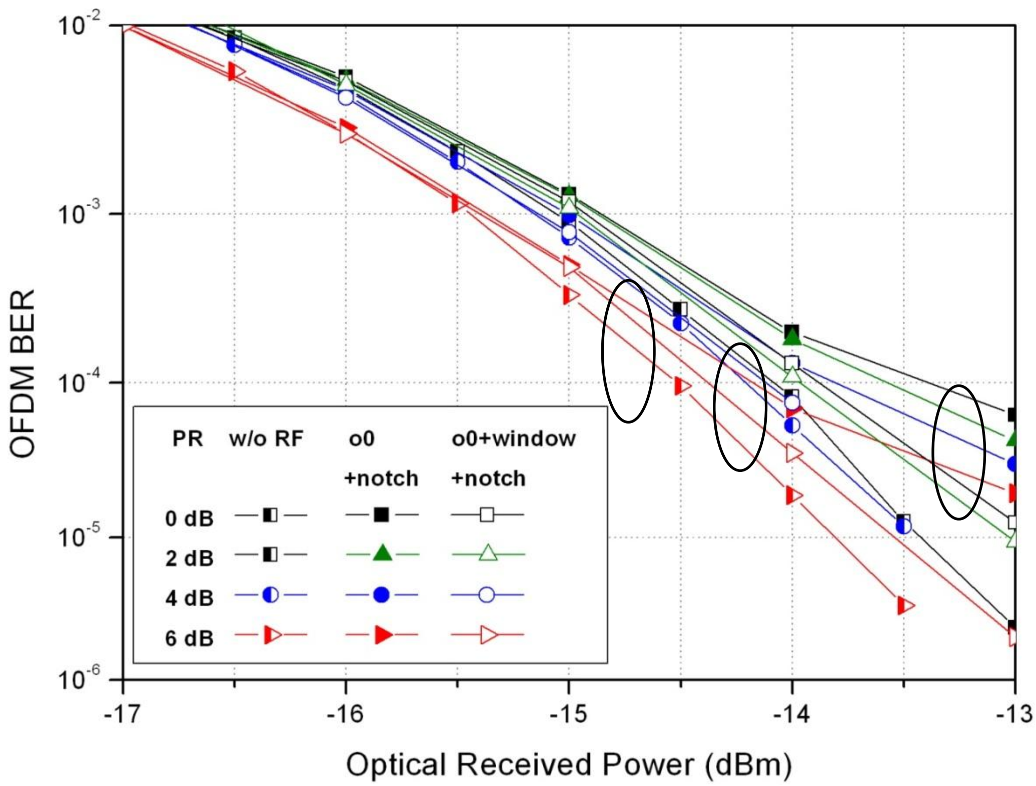


Figure. 24 BER curves of OFDM o0 signal with notch filter and window

which is smaller than 10^{-4} when optical received power larger than -13dBm. As I mentioned before, the windowing method can improve the distortion caused by notch filter. From this figure, we can see the lines, which add with notch filter and window, are all close to the origin line without adding the RF signals.

But the improvement of adding window is not very obvious; the notch filter is harmful to the subcarriers which are close to the notched band, so the window is used mainly in order to improve the subcarriers for closing to the notched band. Figure. 25 shows every subcarrier's SNR, which carries data of OFDM signal when PR=6 dB. Obviously, it is a better improvement that the SNR of the subcarriers are closed to the notched band. The SNR of the subcarrier, which has the most serious distortion, is promoting from 16.5dB to 18.4dB.

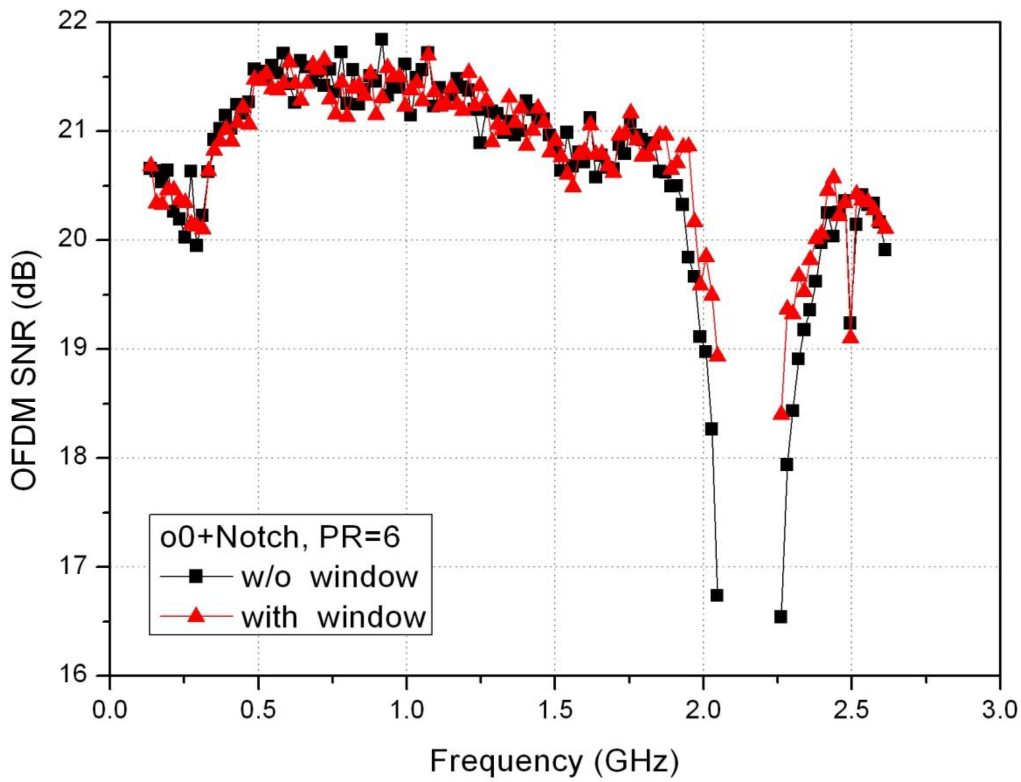


Figure. 25 Improving the distortion caused by notch filter by adding window

Figure. 26 shows the OFDM BER curves under different improving method, subcarrier decreasing method and windowing method. The o3 signal and the o0 signal with window have same spectral efficiency, we can know that the subcarrier decreasing method is better than windowing method. Both two method's performances are similar to the origin signal, and both of them can achieve BER which is smaller than 10^{-5} while optical receiver is over -13dBm. The sensitivity of o3 signal is -15.5dBm and the sensitivity of o0 signal with window is about -15.4dBm when PR=6dB.

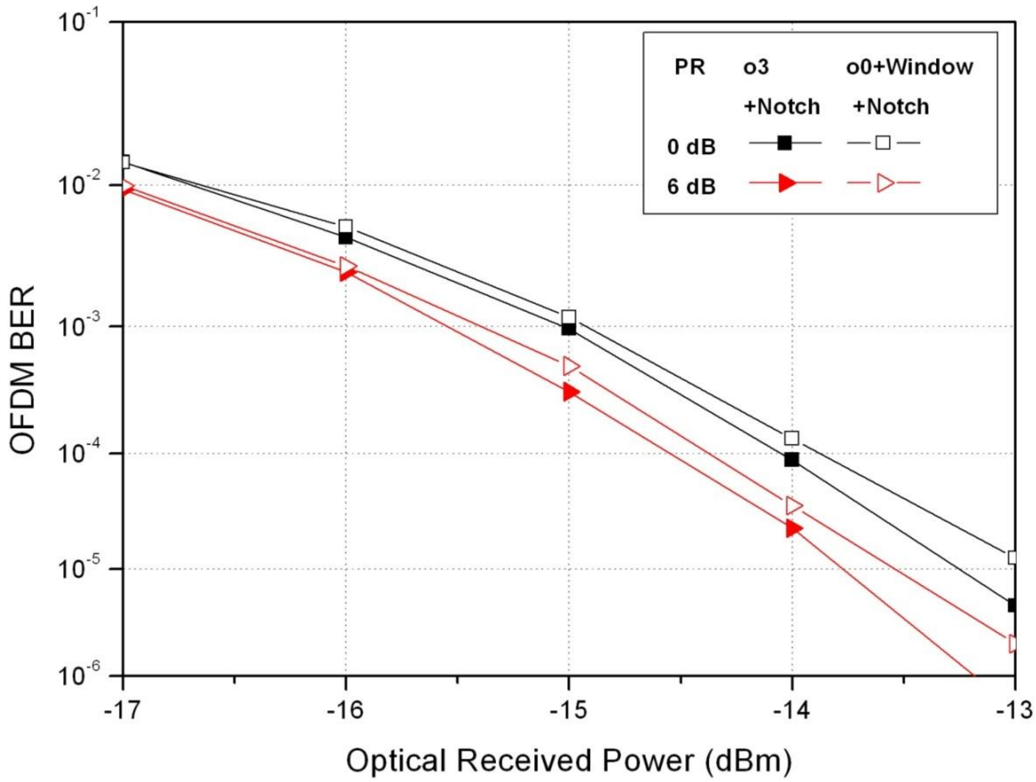


Figure. 26 OFDM BER curves under different improving method

The upstream OFDM signal is demodulated and regenerated at each ONU, so there is no noise accumulation issue, we can sacrifice some performance of OFDM to protect RF signal. But the last step for transmission is transmitting to OLT. It might pass through a long distance fiber. We choose the OFDM o0 to transmit through fiber and add notch filter before demodulation. Figure. 27 shows the OFDM BER curves after the 20km fiber transmission with different PR settings. The penalty is about 1.2dB after the 20km fiber transmission at PR=2~6dB. Even PR=0dB can achieve the error-free limit when optical received power is larger than -12dBm. From a signal with improving method in the previous result, we can know that o3 signal and o0 signal with window will have better performance after the 20km fiber transmission.

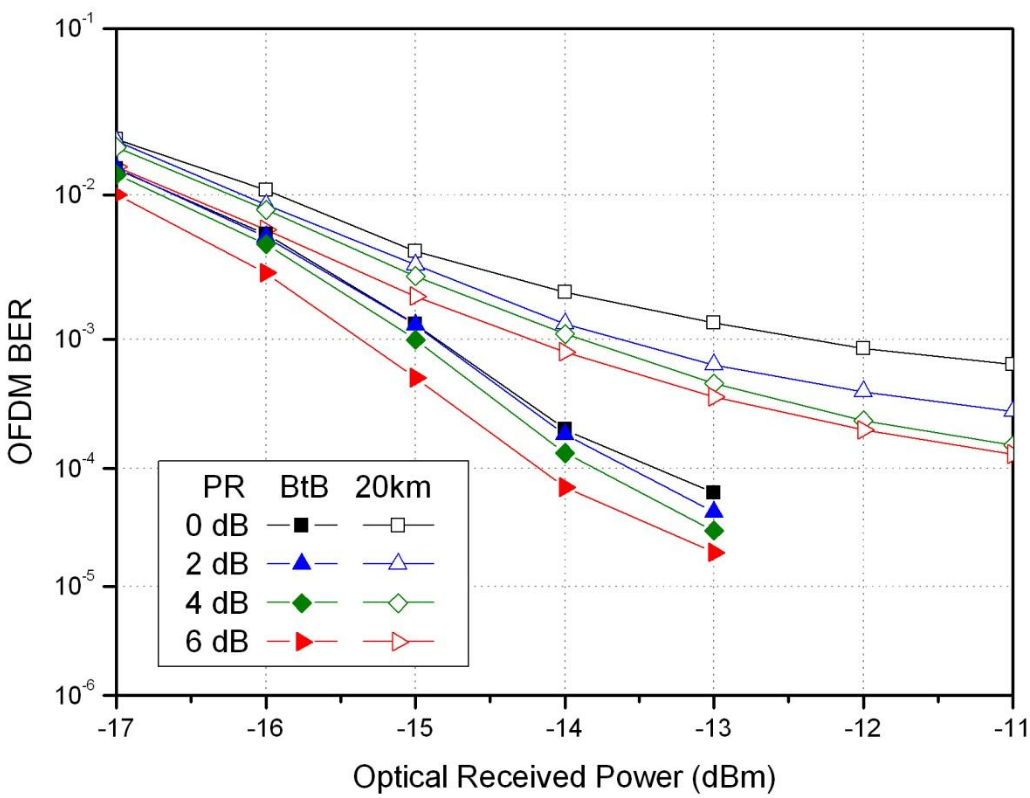


Figure. 27 OFDM BER curves after the 20km fiber transmission

5.2.2 **Wireless signal result**

In Figure. 28, we show the back to back SNR curves of 2100Hz RF signal with respect to the power ratio and the RF performance with windowing method promotion. o0 means RF signal transmits with OFDM o0 signal. Although we turn off 10 subcarriers for RF signal transmission, the OFDM's side-lobes still limits the RF signal's quality. We increase the optical received power from -15.5dBm to -13.5dBm, the SNR curve promotes 2dB, but when we increase the optical received power from -11.5dBm to -9.5dBm, the SNR curve only promotes 0.5dB. This is because when the optical received power is small, the main effect is from the optical receiver's noise. When optical received power is large enough, the main effect is from the interference of OFDM signal's side-lobes.

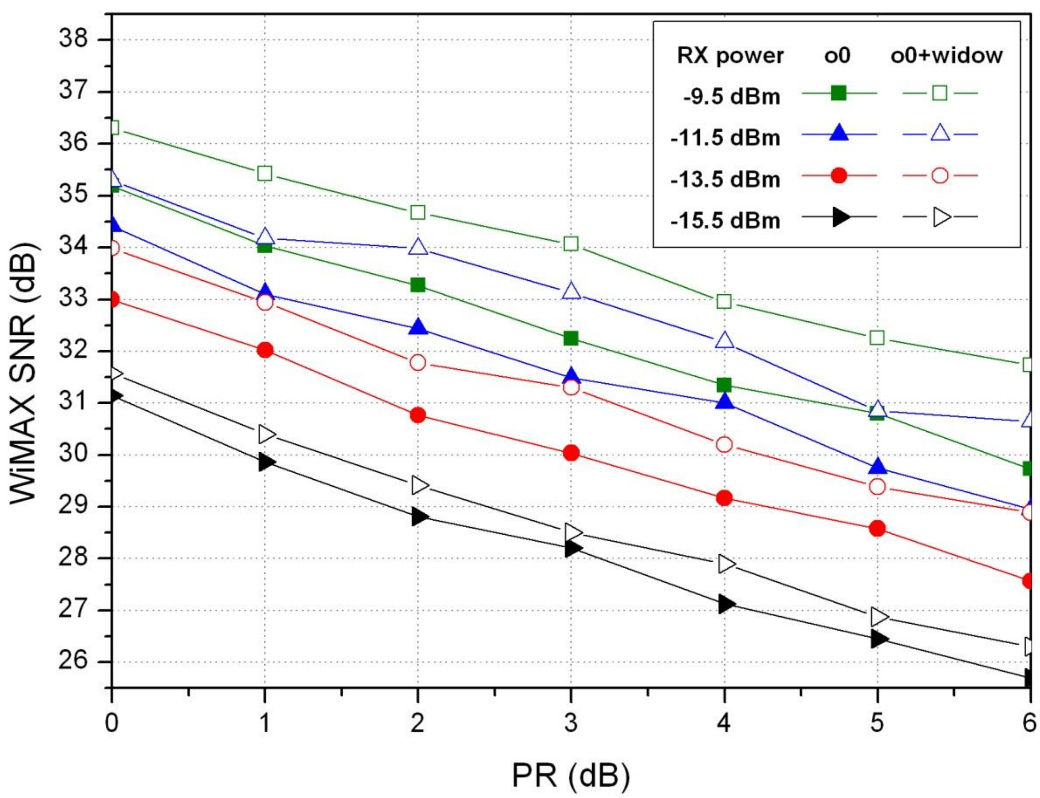


Figure. 28 RF signal's performance under different PR settings and the windowing method promotion

Next let us see the promotion after adding the window to OFDM signal. When optical received power is small, there is almost no promotion to the RF signal because the main noise is from the receiver. When optical received power is large enough, the side-lobes of OFDM signal is the main noise to RF signal, so we can see clearly the effect of windowing method, there is about 1.5dB promotion of SNR curve while optical received power at -9.5dBm.

In Figure. 29, we show the BER curves under two different promotion methods, subcarrier decreasing method and windowing method. We can see 2100MHz RF signal with these two methods has almost same SNR. It means the interference from OFDM signal is almost the same at 2100MHz under these two conditions.

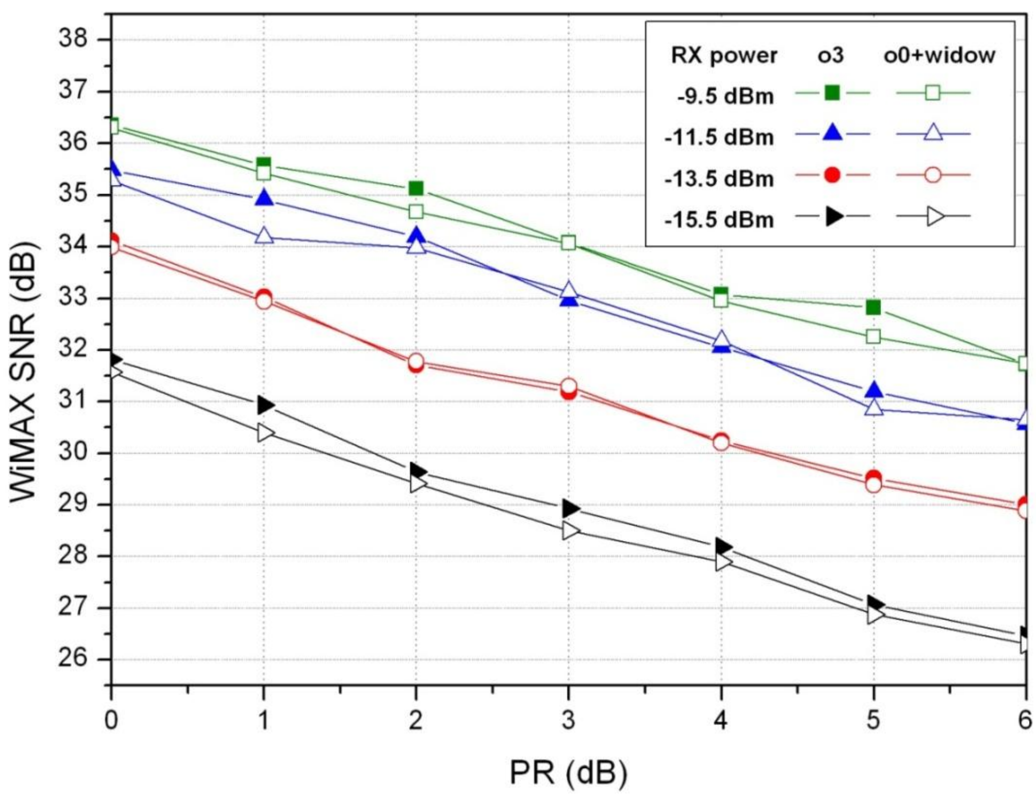


Figure. 29 RF signal's performance under two promotion method

In Figure. 30, we shows the spectrum of OFDM signal with two different promotion methods. The spectrum is captured by electrical spectrum analyzer. We can see that the side-lobe is almost the same at 2100MHz, and windowing method is better than subcarrier decreasing method at 2160MHz. The windowing method is to reduce the side-lobe. The farther away from the main-lobe, the more effective the reduction of the side-lobe would be. The subcarrier decreasing method just turns off more subcarriers, the side-lobe is still high. Although subcarrier decreasing method is simpler than windowing method, windowing method has more potential than subcarrier decreasing method. We may find better windowing method to reduce the side-lobe which is near the main-lobe. Or we can even combine the two methods, turning off some subcarriers and add extra guard intervals for window in order to achieve lowest side-lobe at the transmission band of RF signals.

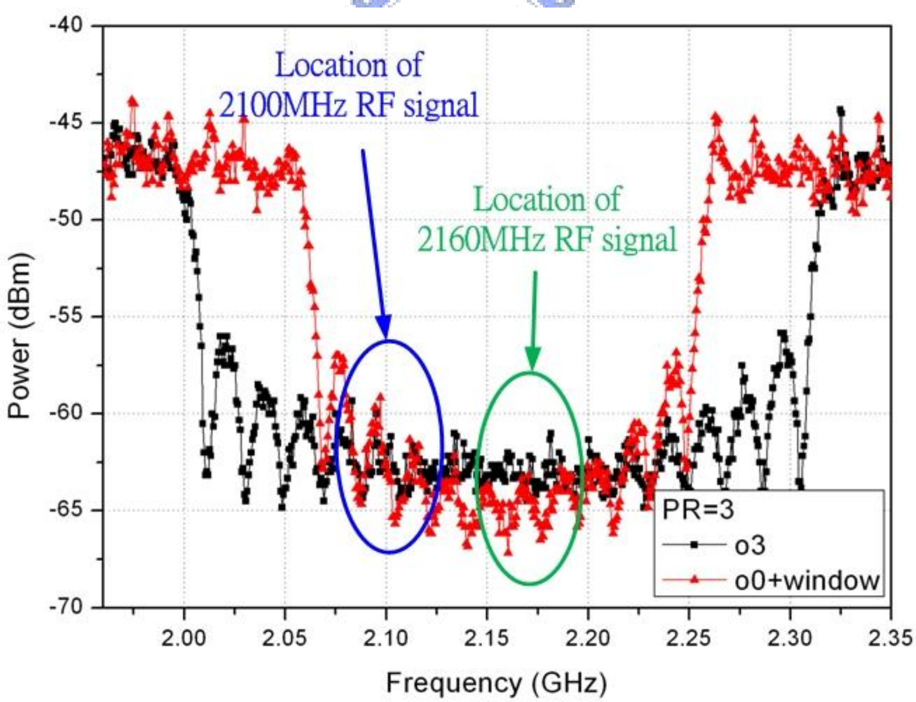


Figure. 30 Spectrum of OFDM signal with two different promotion method

In Figure. 31, we show the SNR curve of RF signal after 20km fiber transmission. Because the SNR of RF signal is linear to the change of PR value, we just choose four PR value to test the performance of RF signal. This is the test of transmitting RF signal from the last one ONU to the OLT. The penalty is about 1.5dB after 20km fiber transmission.

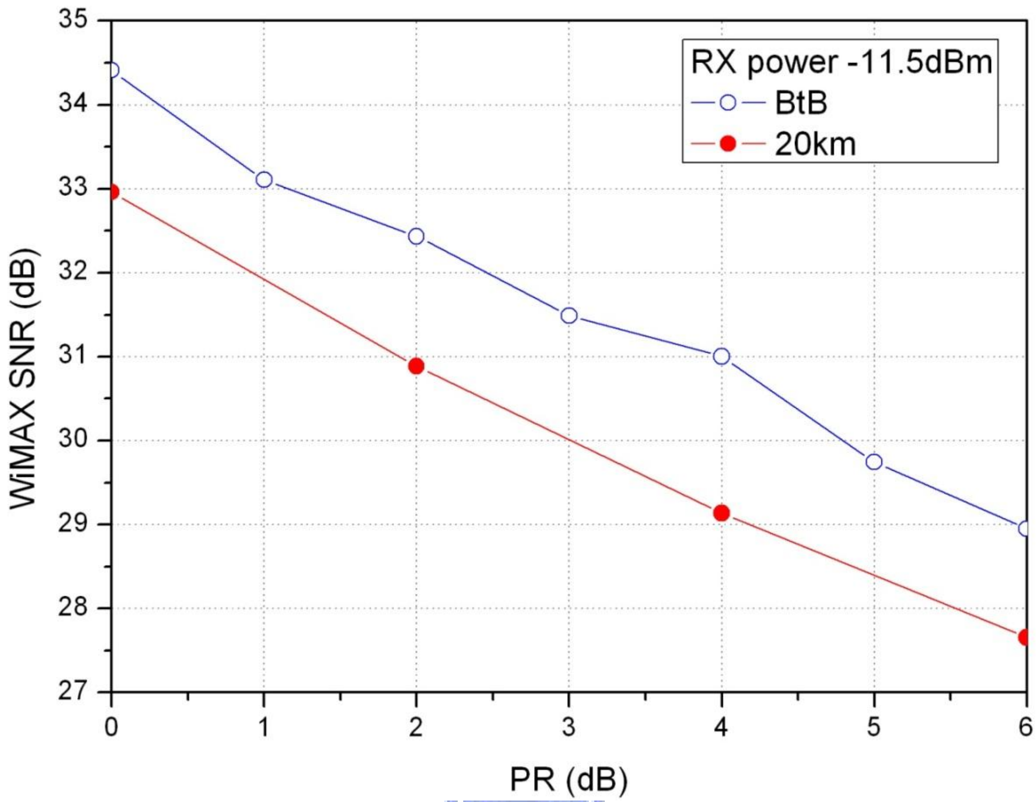


Figure. 31 RF signal's performance after 20km fiber transmission

5.2.3 **Cascading 32 ONU**

Finally, we test the RF signal's performance at every cascade ONU node. In Figure. 32, we show the RF signal's SNR after cascading 32 ONUs. The optical received power is fixed at -11dBm. As the ONU node number increases, the SNR of RF signal degrades because of the interference from OFDM signal's side-lobes. We could suppose that the noise added in every node is constant, so we can see the degraded range of SNR of RF signal is more and more small with the increase of node. If PR equals 1dB, the SNR of 2100MHz RF signal can still be over 16dB, which is the QPSK error-free bound after passing through 32 ONUs. And the performance of 2160MHz RF signal is better than 2100MHz RF signal.

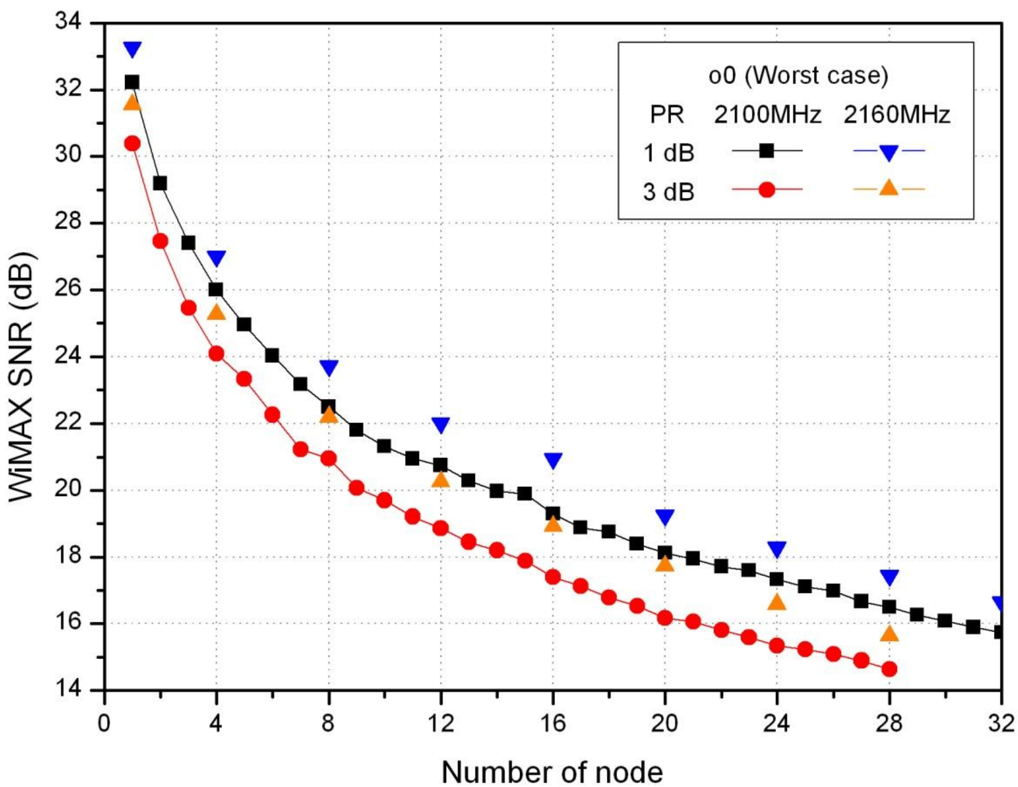


Figure. 32 RF signal's SNR after cascading 32 ONUs

CHAPTER 6 Conclusion

We propose a novel OFDMA hybrid access network architecture which integrates broadband and wireless service. It is a system that has high spectrum efficiency and high flexibility to allocate bandwidth. We analyze the interference between OFDM signal and wireless RF signal firstly. And then we propose two improved methods-- windowing method and turning off extra subcarriers method. The main goal of these methods is to improve RF signal by reducing the side-lobe at the transmission band of RF signal. With windowing method, there is approximately 1.5dB promotion of SNR curve when optical received power is at -9.5dBm. When windowing method and subcarrier decreasing methods share the same bandwidth-wasting condition, the effect of windowing method is as same as its counterpart of subcarrier decreasing method at 2100MHz as well as 2220MHz; however, the effect of windowing method is better than its counterpart of subcarrier decreasing method at 2160MHz. The penalty of RF signal is about 1.5dB after 20km fiber transmission. To improve the OFDM signal, we add notch filter before demodulating the signal in order to remove the RF signal. OFDM signal's receiver sensitive is less then -14.8dBm with notch filter. The windowing method not only can improve the RF signal but also can improve the distortion of OFDM which is caused by notch filter. The penalty of OFDM signal is approximately 1.2dB after the 20km fiber transmission at PR=2~6dB. The RF signal could exactly transmit through 32 ONUs when two conditions exist at the same time. Firstly, when it uses the OFDM o0 signal at the condition that PR equals 1dB. Next, optical received power equals -11.5dBm. So, the system could have more flexibility by executing windowing method or subcarrier decreasing method.

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