Radio over Fiber Enabling PON Fronthaul in a Two-Tiered Cloud

Mémoire

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Résumé

Avec l'avènement des objets connectés, la bande passante nécessaire dépasse la capacité des interconnections électriques et interface sans fils dans les réseaux d'accès mais aussi dans les réseaux cœurs. Des systèmes photoniques haute capacité situés dans les réseaux d'accès utilisant la technologie radio sur fibre systèmes ont été proposés comme solution dans les réseaux sans fil de 5e générations. Afin de maximiser l'utilisation des ressources des serveurs et des ressources réseau, le cloud computing et des services de stockage sont en cours de déploiement. De cette manière, les ressources centralisées pourraient être diffusées de façon dynamique comme l'utilisateur final le souhaite.

Chaque échange nécessitant une synchronisation entre le serveur et son infrastructure, une couche physique optique permet au cloud de supporter la virtualisation des réseaux et de les définir de façon logicielle. Les amplificateurs à semi-conducteurs réflectifs (RSOA) sont une technologie clé au niveau des ONU(unité de communications optiques) dans les réseaux d'accès passif (PON) à fibres. Nous examinons ici la possibilité d'utiliser un RSOA et la technologie radio sur fibre pour transporter des signaux sans fil ainsi qu'un signal numérique sur un PON. La radio sur fibres peut être facilement réalisée grâce à l'insensibilité a la longueur d'onde du RSOA. Le choix de la longueur d'onde pour la couche physique est cependant choisi dans les couches 2/3 du modèle OSI. Les interactions entre la couche physique et la commutation de réseaux peuvent être faites par l'ajout d'un contrôleur SDN pour inclure des gestionnaires de couches optiques. La virtualisation réseau pourrait ainsi bénéficier d'une couche optique flexible grâce des ressources réseau dynamique et adaptée.

Dans ce mémoire, nous étudions un système disposant d'une couche physique optique basé sur un RSOA. Celle-ci nous permet de façon simultanée un envoi de signaux sans fil et le transport de signaux numérique au format modulation tout ou rien (OOK) dans un système WDM(multiplexage en longueur d'onde)-PON. Le RSOA a été caractérisé pour montrer sa capacité à gérer une plage dynamique élevée du signal sans fil analogique. Ensuite, les signaux RF et IF du système de fibres sont comparés avec ses avantages et ses inconvénients. Finalement, nous réalisons de façon expérimentale une liaison point à point WDM utilisant la transmission en duplex intégral d'un signal wifi analogique ainsi qu'un signal descendant au format OOK. En introduisant deux mélangeurs RF dans la liaison montante, nous avons

résolu le problème d'incompatibilité avec le système sans fil basé sur le TDD (multiplexage en temps duplexé) .

Abstract

With the advent of IoT (internet of things) bandwidth requirements triggered by aggregated wireless connections have exceeded the fundamental limitation of copper and microwave based wireless backhaul and fronthaul networks. High capacity photonic fronthaul systems employing radio over fiber technology has been proposed as the ultimate solution for 5G wireless system. To maximize utilization of server and network resources, cloud computing and storage based services are being deployed. In this manner, centralized resources could be dynamically streamed to the end user as requested. Since on demand resource provision requires the orchestration between the server and network infrastructure, a smart photonic (physical layer)PHY enabled cloud is foreseen to support network virtualization and software defined network.

RSOAs (Reflective Semiconductor Optical Amplifier) are being investigated as key enablers of the colorless ONU(Optical Network Unit) solution in PON (Passive Optical Network). We examine the use of an RSOA in radio over fiber systems to transport wireless signals over a PON simultaneously with digital data. Radio over fiber systems with flexible wavelength allocation could be achieved thanks to the colorless operation of the RSOA and wavelength reuse technique. The wavelength flexibility in optical PHY are inline with the paradigm of software defined network (SDN) in OSI layer 2/3. The orchestration between optical PHY and network switching fabric could be realized by extending the SDN controller to include optical layer handlers. Network virtualization could also benefit from the flexible optical PHY through dynamic and tailored optical network resource provision.

In this thesis, we investigate an optical PHY system based on RSOA enabling both analog wireless signal and digital On-Off Keying (OOK) transportation within WDM (Wavelength Division Multiplexing) PON architecture. The RSOA has been characterized to show its potential ability to handle high dynamic range analog wireless signal. Then the RF and IF radio over fiber scheme is compared with its pros and cons. Finally we perform the experiment to shown a point to point WDM link with full duplex transmission of analog WiFi signal with downlink OOK signal. By introducing two RF mixer in the uplink, we have solved the incompatible problem with TDD (Time Division Duplex) based wireless system.

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To my beloved parents and sister.

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I also want to thank Dr. Chul-Soo Park, who is a professional and responsible research scientist in our optical communication laboratory. Without his handling and maintenance of the equipments in our lab, I could not finish my experiment efficiently. I owe many thanks to our laboratory technician Mr. Philippe Chrétien for his promptly support and help in laboratory tools handling, engineering trouble shooting, inventory management and safety guidance.

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Avant-propos

Publications related to this thesis.

Chapter 4-6 contain the work that has been published on the conferences. Chapter 4 is a reprint of the following publication:

[1] A. T. Nguyen, **Zhihui Cao**, K. Lefebvre, and L. A. Rusch, "Full-duplex WiFi Analog Transmission in RSOA-based Radio-over-Fiber System with Wavelength Re-use," in *IEEE European Conference on Optical Communications (ECOC 2014)*, Cannes, September 2014.

The research topic is defined by Prof. Leslie Rusch. An Nguyen and Kim Lefebvre proposed the idea by utilizing RSOA to transport wireless analog signal. They already have done some experiment and characterization of the RSOA,however, only analog signal without any OOK transmission was demonstrated. I was responsible for the new experiment setup with the help of An Nguyen. An Nguyen was responsible for the transmitter and receiver side matlab code. Kim Lefebvre finished RSOA characterization before the new experiment. I carried out the experiment by changing the fiber length and optimizing the optical fiber link (power and polarization control). I performed the EVM/BER measurements. Prof. Leslie Rusch and Dr. An Nguyen provide valuable polishing on the paper text in Chapter 4.

Chapter 5 is a reprint of the following publication:

[2] **Zhihui Cao**, A. T. Nguyen, and L. A. Rusch, "Full-duplex WiFi Analog Signal Transmission with Digital Signal Downlink in Radio-over-Fiber System Employing RSOA-based WDM-PON Architecture," in *IEEE Conference on Microwave Photonics (MWP 2014)*, Sapporo, October 2014.

This experiment directly converted the wireless RF signal to an optical signal. I was responsible for the modification of the matlab code with the help of An Nguyen to generate dual services 802.11a OFDM signal. An Nguyen and I were responsible for the experiment setup. I wrote the first version of the paper, An Nguyen made a major revision on the paper. Prof. Leslie Rusch made the final revision and polishing on the paper.

Chapter 6 is a reprint of the following publication:

[3] **Zhihui Cao**, A. T. Nguyen, and L. A. Rusch, "Full-duplex Analog WiFi Transport over RSOA-based Wavelength-reused Digital Passive Optical Networks," in *IEEE International Conference on Communications (ICC 2015)*, London, June 2015.

The problem of our previous experiment was discussed by An Nguyen and I. We proposed a solution to dealing with the TDD compatible problem discussed in Chapter 6. I was responsible for the characterization of RF component and experiment setup. I performed the experiment by utilizing different order of modulation format with different fiber length. I was responsible for the EVM/BER measurement and results analysis. Finally I wrote the paper. Prof. Leslie Rusch provide valuable revision on the introduction and conclusion part.

Abbreviations

ADC	**A**nalog to **D**igital**C**onverter
BER	**B**it **E**rror **R**ates
BPF	**B**and**P**ass **F**ilter
CMOS	**C**omplementary **M**etal–**O**xide–**S**emiconductor
CO	**C**entral **O**ffice
CPRI	**C**ommon **P**ublic **R**adio **I**nterface
DAS	**D**istributed **A**ntenna **S**ystem
DAC	**D**igital to **A**nalog **C**onverter
DSB	**D**ouble **S**ide **B**and
DL	**DownL**ink
DSP	**D**igital **S**ignal **P**rocessing
E/O	**E**lectrical to **O**ptical
EPIC	**E**lectronic-**P**hotonic **I**ntegrated **C**ircuit
EAM	**E**lectro-**A**bsorption **M**odulator
EVM	**E**rror **V**ector **M**agnitude
FDD	**F**requency **D**ivision **D**uplex
FEC	**F**orward **E**rror **C**orrection
FDM	**F**requency **D**ivision **M**ultiplexing
FSAN	**F**ull **S**ervices **A**ccess **N**etwork
IoT	**I**nternet **o**f **T**ings
IF	**I**ntermediate **F**requency
IM-DD	**I**ntensity **M**odulation-**D**irect **D**etection
LAN	**L**ocal **A**rea **N**etwork
LTE	**L**ong **T**erm **E**volution
LSB	**L**ower **S**ide**b**and
LO	**L**ocal **O**scillator
LPF	**LowP**ass **F**ilter
M2M	**M**achine to **M**achine
MIMO	**M**ulti **I**nput and **M**ulti **O**utput

MAC	**M**edia **A**ccess **C**ontrol
MBH	**M**obile **B**ack**h**aul
MZM	**M**ach-**Z**ehnder **M**odulator
NG	**N**ext **G**eneration
O/E	**O**ptical to **E**lectrical
OFDMA	**O**rthogonal **F**requency **D**ivision **M**ultiplexing **A**ccess
OOK	**O**n **O**ff **K**eying
ODN	**O**ptical **D**istributed **N**etwork
ONU	**O**ptical **N**etwork **U**nit
OBSAI	**O**pen **B**ase **S**tation **A**rchitecture **I**nitiative
OSNR	**O**ptical **S**ignal to **N**oise **R**atio
PHY	**Phy**sical layer
PON	**P**assive **O**ptical **N**etwork
PDM	**P**olarization **D**ivision **M**ultiplexing
P2P	**P**oint to **P**oint
PAPR	**P**eak to **A**verage **P**ower **R**atio
QPSK	**Q**uadrature **P**hase **S**hift **K**eying
QAM	**Q**uadrature **A**mplitude **M**odulation
QoS	**Q**uality **o**f **S**ervice
RSOA	**R**eflective **S**emiconductor **O**ptical **A**mplifier
RoF	**R**adio **o**ver **F**iber
RAU	**R**emote **A**ntenna **U**nit
RF	**R**adio **F**requency
RRH	**R**emote **R**adio **H**ead
RTO	**R**ealtime **O**scilloscope
SDM	**S**patial **D**ivision **M**ultiplexing
SDN	**S**oftware **D**efined **N**etwork
SFDR	**S**pur **F**ree **D**ynamic **R**ange
SNR	**S**ignal to **N**oise **R**atio
SSB	**S**ingle **S**ide **B**and
SSBI	**S**ignal to **S**ignal **B**eating **I**nterference
SOA	**S**emiconductor **O**ptical **A**mplifier
SCM	**S**ub-**C**arrier **M**ultiplexing
SMF	**S**ingle **M**ode **F**iber
SMA	**S**ub**M**iniature version **A**
TDD	**Time** **D**ivision **D**uplex
TDM	**T**ime **D**ivision **M**ultiplexing
TWDM	**T**ime **W**avelength **D**ivision **M**ultiplexing

USB	**U**pper **S**ide**b**and
UL	**UpL**ink
VoIP	**V**oice **o**ver **I**P
VSG	**V**ector **S**ignal **G**enerator
WDM	**W**avalength **D**ivision **M**ultiplexing
WWAN	**W**ireless **W**ide **A**rea **N**etwork
WiFi	**W**ireless **F**idelity

Chapter 1

Introduction

1.1 Context and Motivation

1.1.1 Wireless Access Network Becomes Internet Traffic Bottleneck

Metro and access networks will continuously shoulder two $\sim$ three-fold network traffic (traffic only transmit in the metro and access network that bypass the longhaul links) compared to longhaul networks as shown in Fig 1.1 [24]. The traffic increase is mainly driven by the growing diversity of applications (cloud computing, storage, file sharing, web, data, Voice over IP (VoIP), mobile video and social networking etc.) and expanding proliferation of wireless devices(Wearable Devices, Wireless Sensor Devices, Smart phone, Tablet and Laptop etc.)[10]. Thus, wireless network will be in the dominate position to offload local Internet traffic to heterogeneous wireless devices. On the other hand, wired devices offloaded traffic will only account for less than 20 percent of the total Internet traffic in 2019 as shown in Fig 1.2.

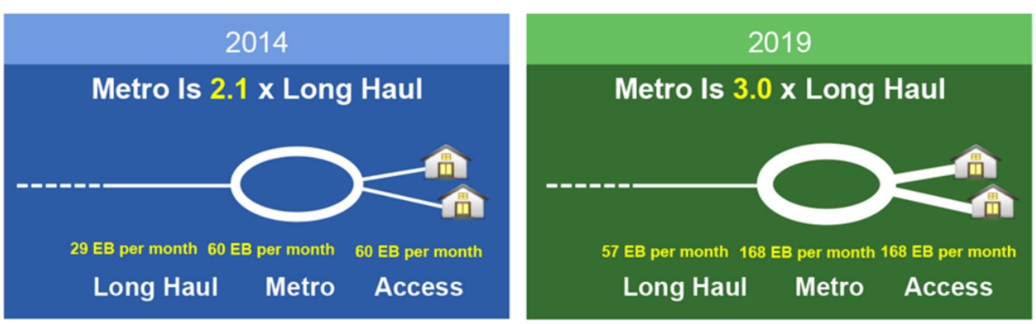


Figure 1.1: Longhaul, Metro and Access Network Traffic Forecast[24]

Cellular and wireless LAN (Local Area Network) as two complementary wireless access technologies are key for next generation wireless devices interconnection. Ultra-high data rates up to 10 Gbit/s are expected for wireless subscribed devices and emerging machine to machine (M2M) traffic. Continuous technology innovation and new spectrum exploration accelerate the pace of wireless technology evolution in the next decade.

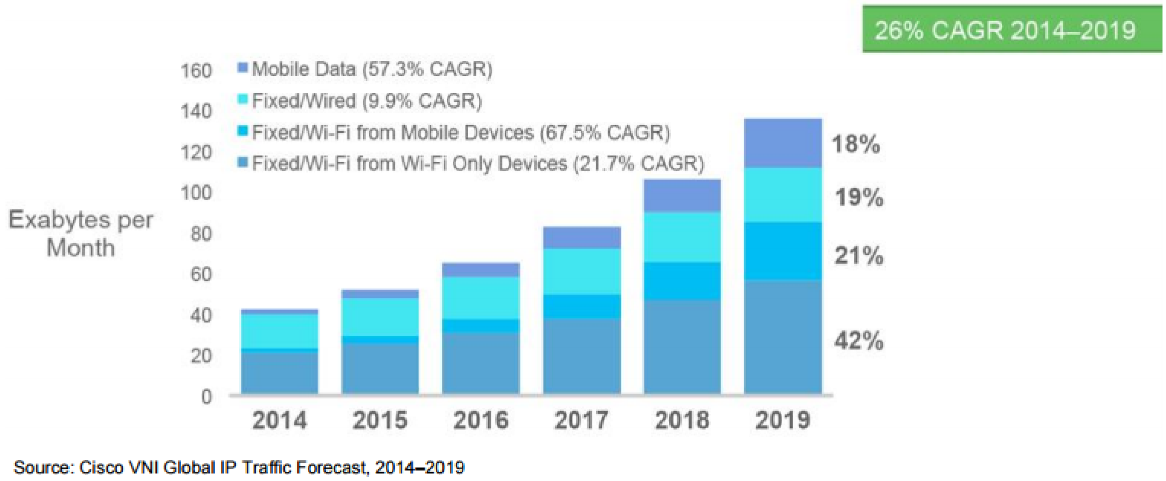


Figure 1.2: The Forecast of Wired and Wireless Internet Traffic Growth [24]

In cellular standards evolution, LTE (Long Term Evolution)-Advanced has been proposed to flexibly utilize the available spectrum to maintain throughput rates exceed 1 Gbit/s [47, 13]. Carrier aggregation, diversity MIMO (Multiple-input and Multiple-output) and multi point coordination technologies are studied as the candidate proposal for LTE-Advanced. In 802.11 family, relying on higher order OFDM (Orthogonal Frequency Division Multiplexing) modulation and Multi-user MIMO technology, 802.11ac could operate up to 1300Mbit/s in 80MHz channel in 5GHz band. While 802.11ad defines a new physical layer to operate in the 60GHz millimeter spectrum to provision upto tens Gigabit capacity [50].

Heterogeneous network with cell densification could be the prototype of future wireless network to enhance end user experience. Small cells (femtocell, picocell microcell) as the complement to macro cells provide higher throughput to user-intensive areas and it leaves the legacy infrastructure untouched. Meanwhile, for future millimeter wave compatibility, small cell is necessary due to high propagation loss of millimeter wave.

The bandwidth demand of cellular and wireless LAN further spurs high capacity fronthaul/backhaul network. Optical fiber is a promising and suitable transmission media to meet the increasing capacity requirements. Although the microwave is now the dominant backhaul technology worldwide (60%), it lacks the support for future network architecture. With the need to interconnect massive high capacity heterogeneous small cell nodes distributed in large area with low latency requirements, microwave may suffer from high loss and delay comparing to optical fiber.

SDN (Software defined network) and virtualization are two key concepts for current and next generation wired and wireless network architectures originally designed for copper networks and electronic switch and router nodes. As optical transport and access network has been widely deployed to replace the copper based links, SDN and virtualization are penetrating into optical PHY layer. SDN relies on the separation and centralization of network control logic and processing functionality. Virtualization tries to partition and share the physical resource in multi-dimensions. This research extends these concepts of SDN into the edge of the core network. In particular we examine how virtualization could be exploited in an optical fronthaul of wireless services over traditional passive optical network.

1.2 Radio over Fiber as An Enabler for Smart Edge

Access networks located at the edge of core or metro network provides the connection between the end users and transport network. Optical fiber as the prevailing solution for next generation fixed access network has been adopted and deployed worldwide. Meanwhile, optical link based next generation gigabit wireless fronthaul and backhaul network has also been demonstrated [5, 43, 70]. Radio over fiber as the enabling technique bridges the wireless and optical world. For orchestration with transport network, the virtualization should also be introduced into radio over fiber system.

Wireless virtualization technique unifies the hardware platform and lowers the operational cost in heterogeneous AP (access point)deployment scenario. DAS (Distributed antenna systems) utilizing RoF (radio over fiber) could further simplify the deployed AP. As shown in Fig 1.3, all the signal processing and virtualization functions could be reallocated to the CO (central office), where the CO houses the smart edge of the network. The simplified AP only includes the RF (Radio Frequency) front end and O/E, E/O components. Multi virtualized wireless technologies could be implemented as individual instances in the cloud like CO. The RoF link distribute different traffic flows to targeted antennas or antenna groups. The virtualization in optical access network is illustrated in Fig 1.4. The resource virtualization pool could be seen as the abstraction layer of the underlying radio over fiber PHY which hides the physical details and maps the physical resources to software handlers.

Resource virtualization could be done in multi-dimensions utilizing different physical layer multiplexing methods like FDM (frequency division multiplexing), TDM (time division multiplexing), PDM (polarization division multiplexing) and SDM (spatial division multiplexing). The orchestration of the virtual machines in data center and network virtualization could be seen as mapping the virtual flows to respective network resources according to the application requests. The optical PHY transmission parameters are self-configured according to the services.

The author in [12] experimentally demonstrates the first implementation of OpenFlow enabled flexible provision of 150 Mbps 4G mobile overlaying 10 Gbps PON (passive optical network) architecture in Fig 1.5. The OpenFlow controller platform with extension to include the physical layer transmitter wavelength information. The wavelength planner (λ planner) is responsible for assign proper wavelength to uplink and downlink transmitter through controlling

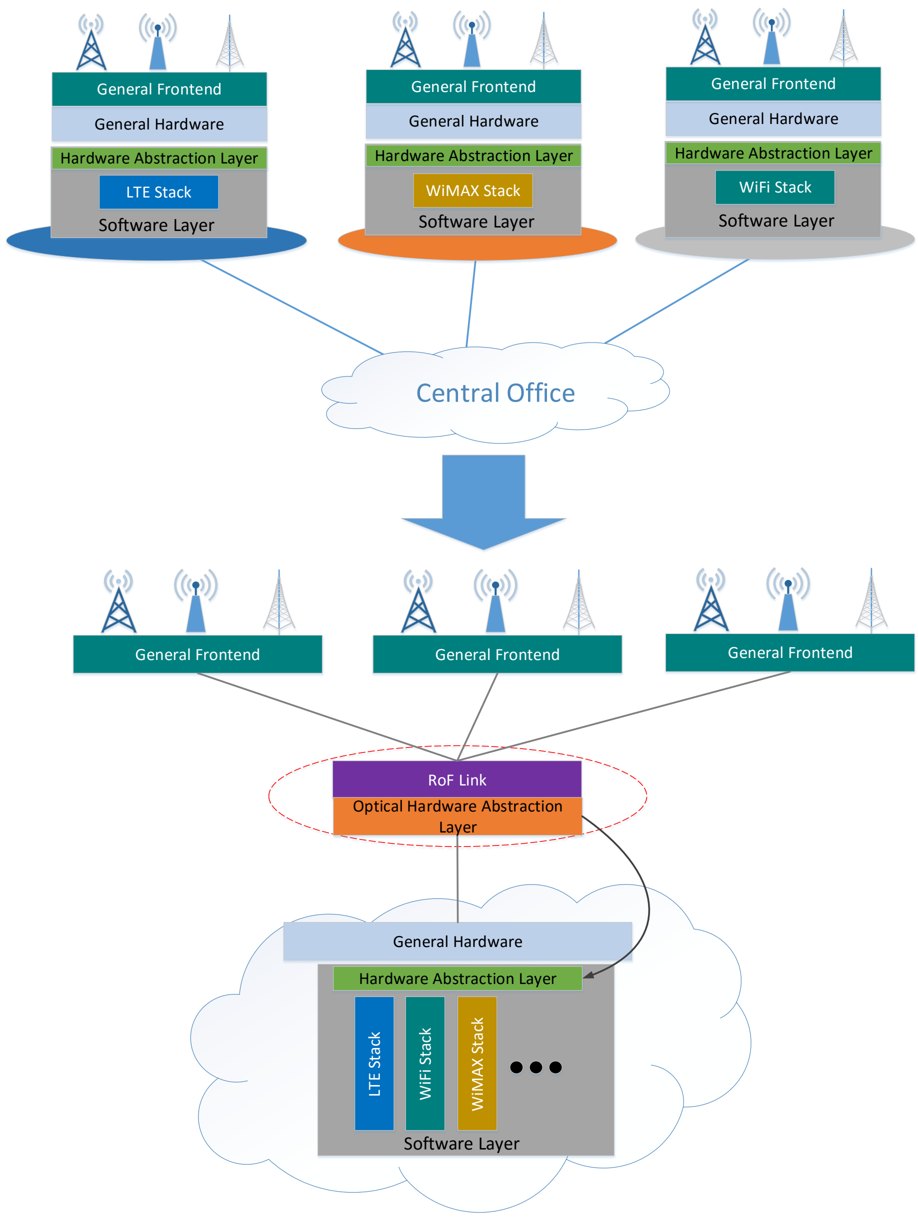


Figure 1.3: RoF link as the fronthaul/backhaul of cellular/wireless access network

the tunable laser. According to the bandwidth requests from different OpenFlow switch port, channel spacing between the downlink OOK and OFDM signal could be determined. Thus the transmitter is configured with specified optical wavelength to avoid the overlap. The optical spectrum is virtualized and dynamically provisioned to fixed digital OOK and wireless analog OFDM signal. Since the passive optical splitter in PON system is transparent to optical wavelength, so wavelength multiplexing could be a viable way to overlay wireless traffic over legacy PON infrastructure.

Based on the same principle, [62] proposes an OpenFlow enabled fixed optical access network

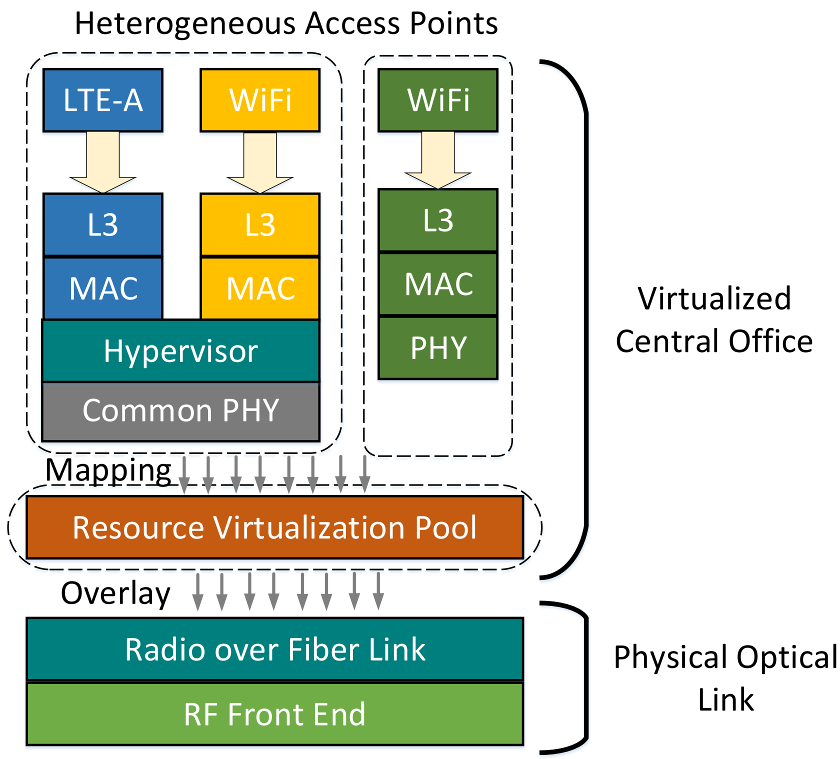


Figure 1.4: Virtualization in Radio over Fiber Link

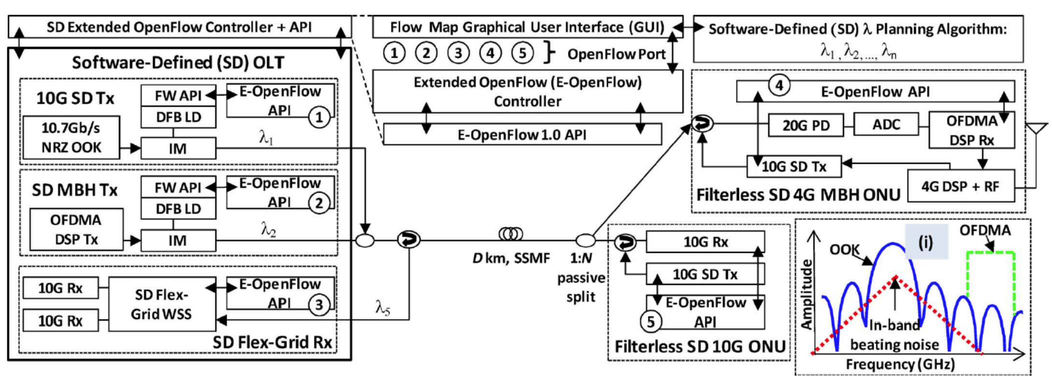


Figure 1.5: Proposed OpenFlow-based flex-grid -flow architecture for 4 G 150 Mb/s per-cell OFDMA MBH overlays onto legacy PON [12]. FW:firmware, WSS:wavelength selective switch

based on TWDM (Time-Wavelength Division Multiplexing) PON architecture in Fig 1.6. Different from [12], each transmitter is pre-assigned a wavelength according to the WDM grid. Different service requests are mapped to multiple predefined optical-electrical transmitter through an OpenFlow electrical switch. The mapping could be dynamically modified by OpenFlow controller resulting the flexibility in the optical link. Each ONU (Optical Network Unit) is assigned with fixed wavelength group. The service load could reach any target ONU by change the mapping in electrical switch to link the requested service to a specified wave-

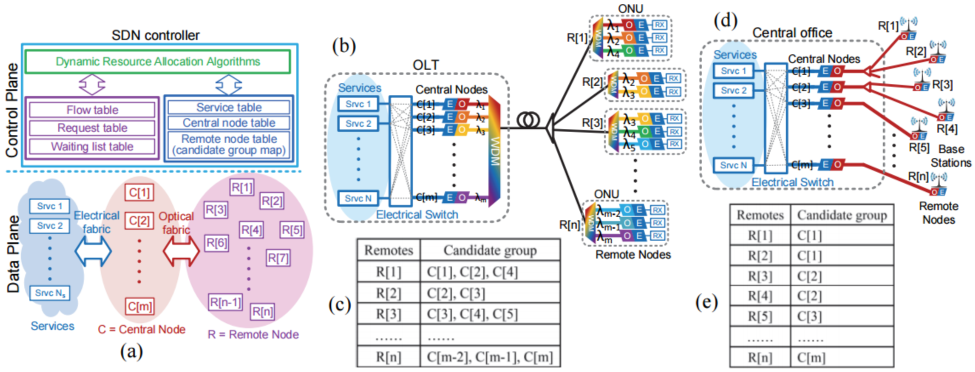


Figure 1.6: (a, left) Proposed SDN-based access network virtualization architecture; (b, center, top) tunable-λ WDM-PON implementation instance of the virtualization architecture of (a); (c, center, bottom) Candidate group map for the instance in (b); (d, right, top) Fixed-λ hybrid point-to-point implementation instance of the virtualization architecture of (a); (e, right, bottom) Candidate group map for the instance in (d)[62].

length.For the fixed λ architecture, multi-antennas are mapped to the same wavelength with different physical links, the time slot is actually sliced to allow different service loads accessing the antennas.

Software defined optical access networks are starting to emerge, and new virtualization methods are proposed to slice the optical resources with the advanced exploration of multiplexing dimensions in optical fiber like mode multiplexing(multi-mode fiber), spacial multiplexing (multi-core fiber) and orbital angular momentum multiplexing. These concept and pioneer work will light the path for programmable photonic devices design. Combining with silicon photonics, the programmable CMOS and photonic integrated circuit provides the most cost effective and promising solution for optical access network.

1.3 Radio over Fiber overlays Next Generation PON

In order to support network virtualization for multi-services overlay, next generation PON should be scalable to new service models and compatible with legacy PON system as shown in Fig 1.7. WDM technology as the key enabler has been introduced in next generation (NG) PON 2 proposed by FSAN (full services access network) [26]. NG PON 2 reuses the power splitter based ODN (optical distributed network) deployed for Gigabit-PON, XG-PON1 to overlay new services. To meet high bandwidth requirement for fixed residential applications, NG PON 2 provides aggregated 40Gbps downlink transmission rate, adopting 4 DWDM (Dense WDM) channel with each operating at 10Gbps. For uplink, 10Gbps is achieved with each λ channel line rate at 2.5Gbps. Different line rates are drafted in NG PON 2 with symmetrical uplink and downlink 10Gbps and 2.5Gpbs for each WDM channel. Aggregated TWDM PON shown in Fig 1.9, could be able to communicate with the TWDM ONU. Wavelength tunable

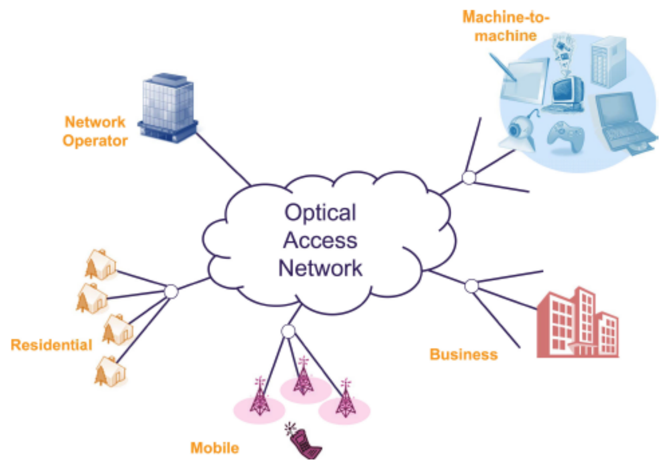


Figure 1.7: Multi Services Support in NG PON 2 [39]

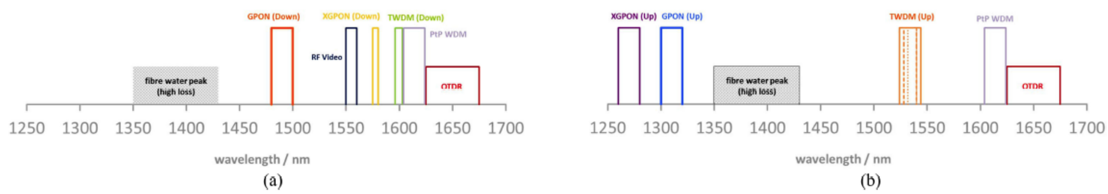


Figure 1.8: Wavelength Spectrum Plan for NG PON 2 and Legacy PON (a)Downlink;(b)Uplink[39]

transmitter and receiver is expected for a cost effective colorless ONU. Legacy PON is stacked to coexist with TWDM PON system. The wavelength plan for NG PON 2 and legacy PON system is depicted in Fig 1.8. Wavelength plan facilitates the filtering and customer premises components. For uplink, three different bands are defined to allow multiple ONU with different laser drifting range. The channel spacing for uplink TWDM PON adapts to 50GHz 100GHz and 200GHz. While eight channels are aggregated with 100GHz fixed WDM channel spacing for TWDM PON downlink.

In Fig 1.9, point to point WDM (P2P WDM) overlay is defined in NG PON 2 which could be seen as the reserved virtual optical channel for extended services. P2P WDM supports different classes line rates range from 1Gbps to 10Gbps. With the reserved shared spectrum plan, P2P WDM could be deployed overlay the legacy PON and NG PON 2 system. For flexible spectrum utilization, the expanded spectrum plan allows the P2P WDM to use the spectrum reserved for other PON systems where legacy PONs are not deployed. As shown in Fig 1.8, shared spectrum of P2P WDM is not fixed assigned to uplink or downlink. A photonic wireless fronthaul should be compatible with WDM PON architecture to overlay NG PON 2 architecture. Since the reserved spectrum for P2P WDM is limited, to better utilize the resource, wavelength reuse technique is adopted to share a single wavelength for uplink

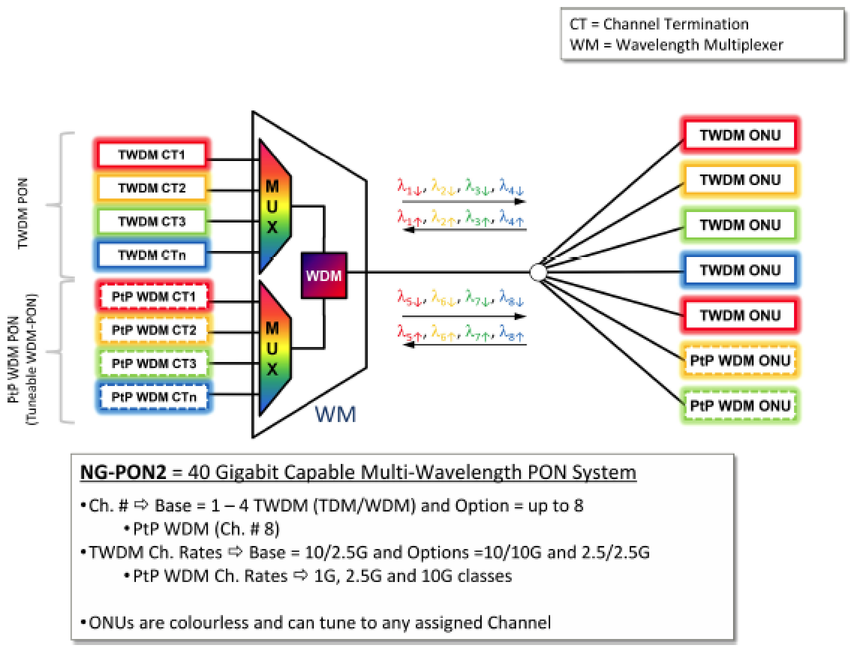


Figure 1.9: NG PON 2 Architecture based on TWDM [39]

and downlink.

By slicing the physical ODN with the granularity based on λ, multi-services could overlay the same ODN infrastructure without influencing each other. However, fixed grid WDM system is an inefficient way to fully utilize the spectrum due to the large excess guard band assigned in each WDM channel and static bandwidth allocation. For the wireless backhaul application, a fine granularity virtualization solution should be proposed to further partition the bandwidth inside a single WDM window.

For radio over fiber application, analog RF signals are aggregated and transmitted over high capacity fiber link to extend the coverage of emerging bandwidth demanding wireless applications. In order to reduce the deployment cost of RoF system, photonic link based DAS is proposed. The RAU (remote antenna unit) could be further simplified. The power demanding digital processing function could be reallocated in the CO, only O/E, E/O and RF front end are kept in the RAU as depicted in Fig 1.10.

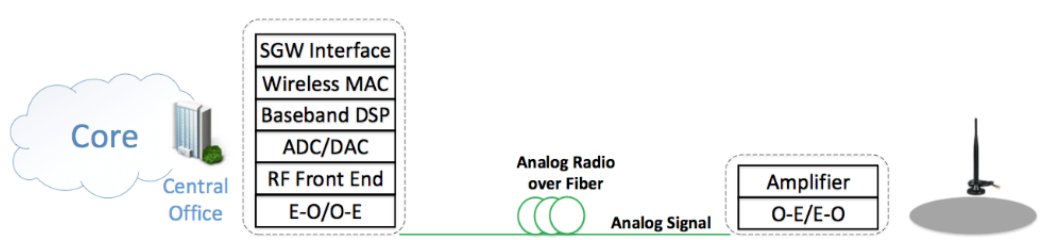


Figure 1.10: Distributed Antenna System based on Analog Radio over Fiber Link

1.4 Organization of the Thesis

The thesis is divided into 7 chapters: In this chapter,we reviewed virtualization in next generation network architecture has been reviewed. In chapter 2, relevant optical physical layer transmission technologies are reviewed, including radio over fiber transport techniques, digitized/analog radio signal over fiber solution, next generation PON architecture. MIMO provision methods in the RoF DAS are also been compared. Chapter 3 presents a brief overview of the work on analog radio over fiber adopting wavelength reuse with RSOA. Chapter 4 to 7 are reprints of the publications of our work. Full duplex analog WiFi transmission with downlink OOK in RSOA based WDM PON system is investigated experimentally. RF and IF (Intermediate Frequency) over fiber performance are compared. Due to the high electrical to optical conversion efficiency, IF outweighs RF as our solution to distribute WiFi signal. Finally, we show a transparent physical layer design to support wireless transmission by introducing up and down mixer in CO and RAU. Experiments are performed to show its capability to transparently transmit uplink and downlink WiFi signal at the same frequency. The experiment shows the successful transmission of virtualized WiFi signal over the fiber utilizing analog subcarrier multiplexing and wavelength-reuse. Chapter 8 gives the conclusion of the thesis.

Chapter 2

Literature Review

Fiber wireless system bridges the wireless and optical world covering photonic generation of wireless signal, transport methods and network deployment etc. In this chapter, we review the relating physical layer transmission technologies including analog/digital radio transmission and distribution, emerging PON architecture for future wireless convergence and distributed antenna system based on radio over fiber technology.

2.1 Analog Vs Digital Radio over Fiber

There are two main ways to transport analog radio signal in the fiber which results in two different system architectures: digital and analog radio over fiber system. We will compare the pros and cons of these systems in this section.

Transporting analog radio signal from the CO to multiple RAUs significantly simplified the RAU architecture and power consumption. The downlink optical signal is directly translated to analog radio through photodetector, meanwhile the uplink optical signal is obtained through analog electrical optical modulator [45, 37]. Thus, power hungry ADC/DAC (analog-to-digital/digital-to-analog converters) is stripped out from the RAU hardware.

The RAU simplification comes at the cost of shortened transmission distance limited by the reduced dynamic range of analog fiber link. The nonlinearity mainly comes from the electrical to optical conversion. Backoff is adopted to squeeze wireless signal with high dynamic range(80$\sim$90dB) into a dynamic limited optical modulator($\sim$ 30dB) which leads to under utilization of launched wireless power[19]. A high Optical SNR (Signal to Noise Ratio) is required due to the noise sensitive nature of analog signal at the receiver [1]. The situation gets worse as wireless system evolution since even higher PAPR (peak to average power ratio) is expected as the next generation wireless system employing higher order OFDM and wider channel bandwidth. Nonlinearity becomes the main concern for analog radio over fiber system design [59].

To form a linear analog radio photonic link, linearization schemes using digital signal processing have been widely investigated [49, 48, 2, 46]. Linearization techniques consists of a series of compensation methods that could be implemented at the receiver and transmitter side. Pre-distortion [49, 48, 2] algorithm is implemented at the transmitter to distort the transmit signal before it launched to the fiber link. Typically, training symbols are required to get transfer curve of the system before pre-distortion and post-distortion. Nonlinear polynomial serials have been used to model the system, [49] proposes a complex-reduced multi-band pre-distortion algorithm based on volterra serials with significant improvement of nonlinear suppression and EVM reduction. While for post compensation, adaptive digital filters are normally utilized at the receiver side. For analog radio over fiber system, Asymmetrical compensation is normally adopted where pre-compensation is done for the downlink while post-compensation. No DSP is required in the RAU thanks to centralized signal processing in this asymmetrical architecture [20].

An analog based connection would also have an impact on feasible architecture options for the optical distribution network. For analog radio over fiber system compatible with frequency multiplexing may not work with time division multiplexing signalling since no buffer and scheduler at the RAU to handle digital signal multiplexing [45].

Many of the problems associated with analog modulation could be circumvented if it is possible to first digitize the information signal and then transport it digitally. Therefore, radio over fiber taking advantage of the digital optical link by using ADC and DAC have attracted more attention in recent years. With more and more low cost ADC/DAC spurring the interest in digitized radio over fiber links become available due to mature semiconductor technologies [31, 44]. Fig 2.1 compares the dynamic range performance of an analog and digital optical link as a function of link length [34].

The pink and blue curves in Fig 2.1 demonstrate the accumulated dynamic range with the fiber length for digital and analog fiber link respectively. Dynamic range is defined as the ratio of the strongest and weakest launched signal power that could be detected without distortion. As the fiber extending, analog radio over fiber link suffers from the dynamic range reduction. While, a constant dynamic range is maintained to certain fiber length in digital radio over fiber link. When the received power could not be detected by the receiver, a sharp roll off emerges as shown in pink curve in Fig 2.1. Although the transmission distance could be extended effectively, the quantization noise and delay introduced by ADC/DAC could be seen as another limitation of digital radio over fiber system [33].

A direct digitized RF solution has been proposed by ADC Telecommunications [56], where ADC and DAC functionalities are located both in base transceiver station site and remote unit for up and down links. However, in direct digitized radio over fiber link (shown in Fig 2.2 right), extremely high sampling rate ADC and DAC are required for radio signal at higher RF

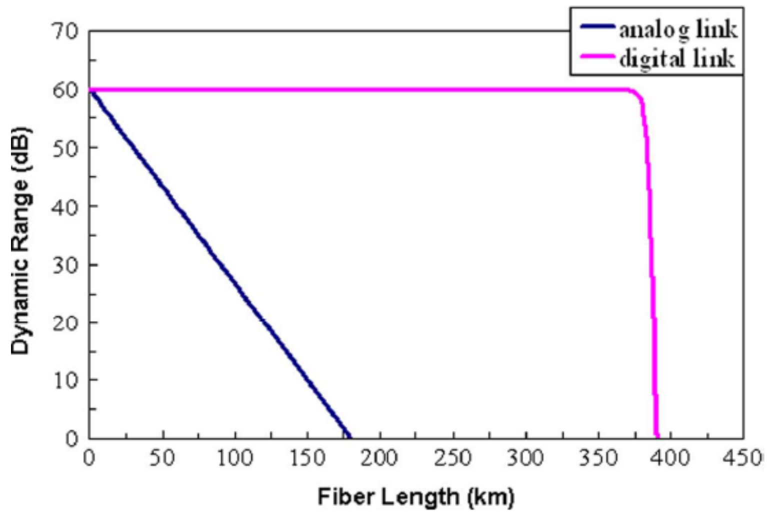


Figure 2.1: Dynamic range along with RoF link length incorporating analog and digital link [33]

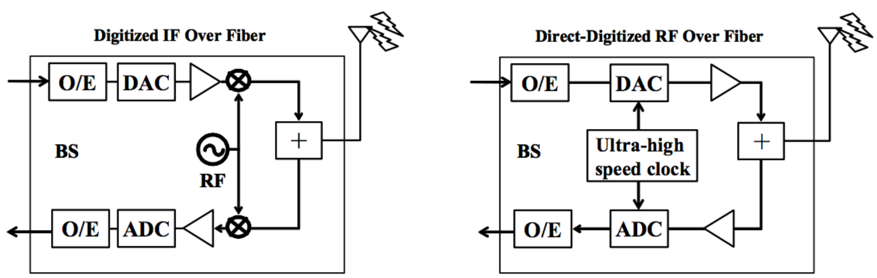


Figure 2.2: RAU configurations for digital optical links [66]

carrier, and it severely increases the implementation cost and difficulty. The digitized IF over fiber approach (shown in Fig 2.2 left) greatly decreases the sampling rate of the DAC/ADC with the help of RF mixer[60, 66]. Thus, the performance of digital radio over fiber link largely relies on the DAC/ADC technology.

Utilizing bandpass sampling technique, a minimal set of hardware components is needed in the transceiver of the base station, leaving all signal processing functions to be located in the central office [44, 66]. The sampling rate of the ADC could be significantly reduced using bandpass sampling technique. Meanwhile a baseband copy of the signal could be extracted through a low pass filter. The RF mixer is no longer need in such a setup. The signal could be reconstructed according to classic bandpass sampling theory as long as the sampling rate is at least twice of the information bandwidth[58].

Fig 2.3 illustrates the implementation of digital radio over fiber link using bandpass sampling technique. To accurately reconstruct the signal and prevent any spectral aliasing, the sampling rate for bandpass sampling should strictly follow the rules given in [64]. In the uplink

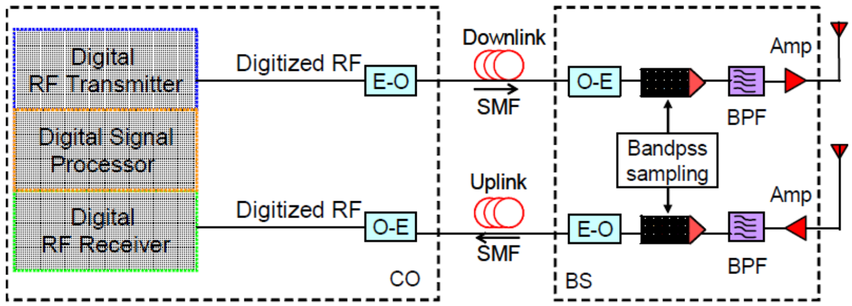


Figure 2.3: Bandpass sampling based Digitized RoF [66]

transmission, the RF wireless signal received at the base station is sampled and quantized by the ADC with a sampling rate setting according to bandpass sampling theory. After transmission in the fiber, the received signal in central office is reconstructed by a DAC with an electrical bandpass filter. Although the sampling rate is reduced using bandpass sampling, the bandwidth of the ADC/DAC is still demanding which has to work up the carrier frequency of the RF signal to be processed.

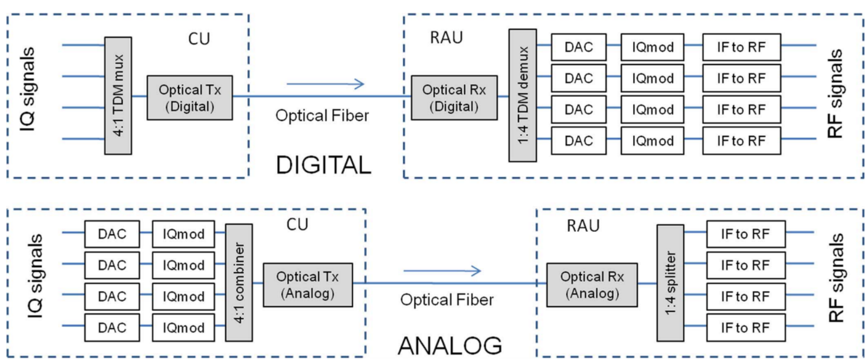


Figure 2.4: Simplified layouts of analog and digital transmission link options (downlink direction only). The shaded boxes denote the components which differ between the two options.[59]

Another constrain of the digital radio over fiber link is the scalability. The digitized process converts the multi-level analog signal into binary bits which largely expands the signal bandwidth. The binary bits from different antennas then are multiplexed in time domain resulting a prohibited high bit rate optical link [61]. The optical PHY layer could not afford such a high bit rate link cost effectively. The scalability issue hinders the digital radio over fiber system deployed in dense cell environment.

CPRI (Common Public Radio Interface) [54] and OBSAI (Open Base Station Architecture Initiative) [25] are two proposed specifications that defines standard digital electrical optical interface and line rate between digital base station containing the baseband processing functions and a RRH (remote radio head) containing the radio functions of a traditional base station [27]. From the analysis in [22, 54], the minimum optical bandwidth is 6.144 Gbps supporting 100 MHz LTE signal transmission with sampling rate of 153.6 MHz and 20 bits resolution. As shown in Fig 2.4, the optical PHY layer operates at 24 Gbps consisting four 100MHz LTE signal. The optical line rate already exceeds the CPRI specification line rate with upto 12 Gbps [54]. Digital radio over fiber system leads to a low spectral efficient optical PHY layer which requires expensive high bandwidth optical transceivers. Comparing to analog radio over fiber system where low cost optical components could be utilized, the cost of deploy digital radio over fiber link will be prohibitive high when connecting of thousands small and femto cells.

2.2 Baseband, IF and RF Radio over Fiber

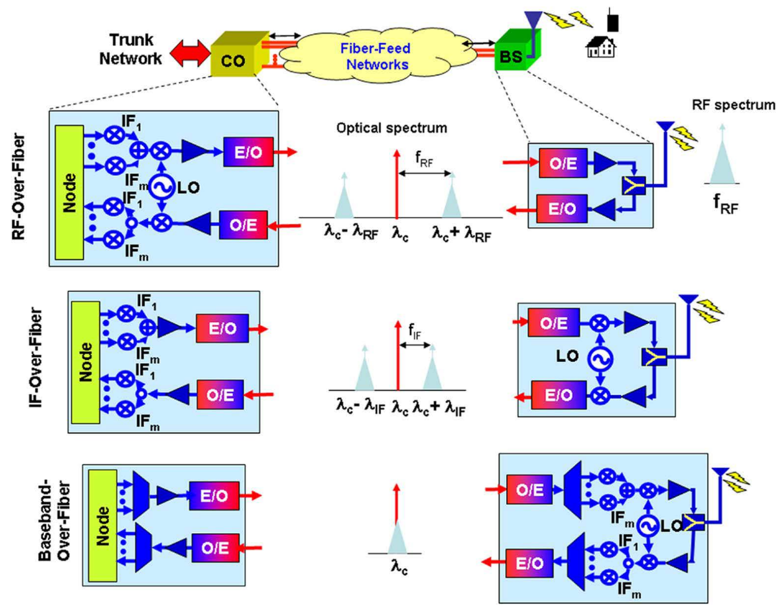


Figure 2.5: Different kind of RoF link configurations.[33]

Radio over fiber is realized by modulating the optical carrier by RF signals belonging to wireless networks. Different fiber link configurations could be employed to distribute radio signal using radio over fiber depicted in Fig 2.5. The simplest scheme for transport RF radio signal over fiber is to directly modulate the radio signal with optical carrier without any frequency translation at the remote antenna unite as shown in Fig 2.5 as RF-Over-Fiber. In this configuration, the RF radio signal is externally modulated on the optical sub-carrier $f_c \pm f_{RF}$ resulting an optical double side band signal. Upon detection at the remote antenna unit, the radio signal could be recovered via direct detection using a photodetector with bandwidth of f_{RF}. A simple remote antenna unit design could be realized using RF over fiber configuration with additional benefits of centralized control, independence of the air-interface and also enabling multi-band wireless operation. However, the simplicity comes at the cost of the high modulation bandwidth requirement on the E/O modulator and photodetector. On the contrary, baseband over fiber scheme relaxes the bandwidth constrain of the component at the cost of the complex design in remote antenna. IF over fiber is a trade-off scheme between the bandwidth constrain and complexity[34, 33] .

The drawback of intensity modulated double side band signal is easy destroyed by the fiber chromatic dispersion at the receiver. At the receiver, each side band beats with the optical carrier, thereby generating two beat signals which constructively interfere to produce a single component at the RF frequency. However, if the signal is transmitted over fiber, chromatic dispersion causes each spectral component to experience different phase shifts depending on the fiber-link distance, modulation frequency, and the fiber-dispersion parameter. These phase shifts result in relative phase differences between the carrier and each side band, and produce a phase difference in the two beat signals at the RF frequency, which results in a power degradation of the composite RF signal. When the phase difference is π, complete cancellation of the RF signal occurs. As the RF frequency increases, the effect of dispersion is even more pronounced and the fiber-link distance severely limited[21, 53].

Dispersion effects can be reduced further and almost totally overcome by eliminating one side band to produce an optical carrier with SSB (single-side band) modulation. Side band cancellation effect could introduce power fluctuation at the receiver after the photodetector. Eq 2.1 shows the relations of the received RF power and chromatic dispersionD_{cd}, fiber lengthL_{fiber}, optical wavelength(λ_0) and RF carrier frequency f_{RF}.

$$P_{receivedRF} \propto cos^2\left[\frac{\pi D_{cd} L_{fiber} \lambda_0^2 f_{RF}^2}{c}\right] \tag{2.1}$$

For $f_{RF} = 2.4GHz$ and $5GHz$, the received power fluctuation is demonstrated in Fig 2.6. For 2.4GHz/5GHz wireless signal the dispersion limited transmission distance are 120km and 50km respectively (for received RF power decreased 20% as the comparison). For the typical distance of 20km between the CO and RAU, DSB signal introduced dispersion could be ignored. For larger network coverage and longer distance, the dispersion will dominate as fiber length increases and as in RF carrier power grows.

Utilizing IF over fiber solution could greatly improve the transmission length and at the same time decrease the modulation bandwidth requirement of the modulator. Optical SSB has been previously demonstrated with baseband digital transmission to overcome fiber dispersion, whereby an optical filter was used to suppress one of the side bands [67].

2.3 Wavelength Reuse Technique and Reflective Uplink Modulator in PON

Remote optical wavelength seeding simplifies the ONU design and management, since no tunable laser source is needed in the ONU. The uplink wavelength assignment and management is done centrally in the OLT. For a better utilization of the optical spectrum, wavelength

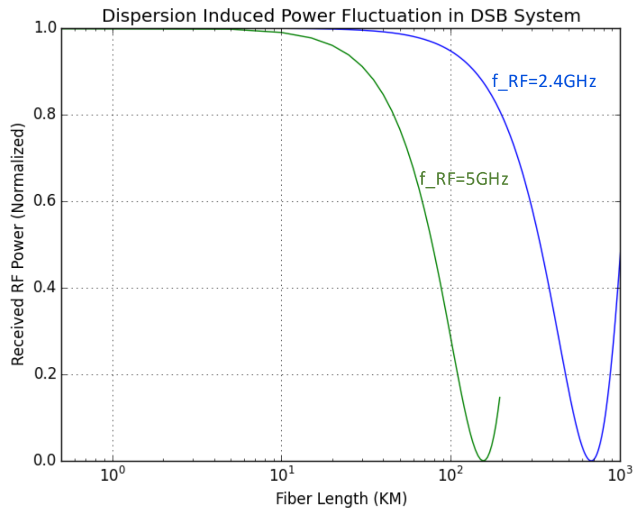


Figure 2.6: Dispersion Limited DSB (double side band) Signal Transmission Distance $D_{cd} = 16ps/nm/km$, $\lambda_0 = 1550nm$

reuse technique is explored to share the same optical wavelength for downlink and uplink data transmission. The uplink signal quality is determined by the suppression or isolation of the downlink signal. Various methods have been proposed to realize uplink and downlink isolation using one wavelength. Utilizing intensity modulation in downlink and phase modulation in uplink respectively is one way to encode data along different dimensions of the optical wavelength [6]. In [7], the downlink OOK signal is pre-coded using 8b10b to generate frequency notches. The uplink signal is allocated with respect to the spectrum notches to avoid overlapping with the downlink OOK signal. The Reflective SOA's gain suppression effect is investigated to effectively erase the downlink intensity modulated signal in [55, 30]. The gain curve of the RSOA increases nonlinearly with the input optical power. By operating the RSOA in the nonlinear gain region (by adjusting the input optical power or bias current), the input modulated optical signal pattern could be well suppressed. Thus the uplink signal could be remodulated on the 'cleaned' optical carrier. This in-band uplink and downlink multiplexing leads a high spectrum efficiency, however, it always suffers from rayleigh backscattering noise and the residual downlink signal[18].

To eliminate the rayleigh backscattering noise, it is better to assign the downlink and uplink signal within different optical sub-bands. [65] propose a wavelength reuse method with backscattering noise mitigation where USB (upper sideband) and LSB (lower sideband) are utilized for downlink and uplink transmission respectively as shown in Fig 2.7. In IM-DD (Intensity Modulation-Direct Detection) OFDM system, a guard band is normally reserved for the reception of the OFDM signal using direct detection which is called offset OFDM. The guard band is adopted to accommodate the SSBI (signal to signal beating interference) after

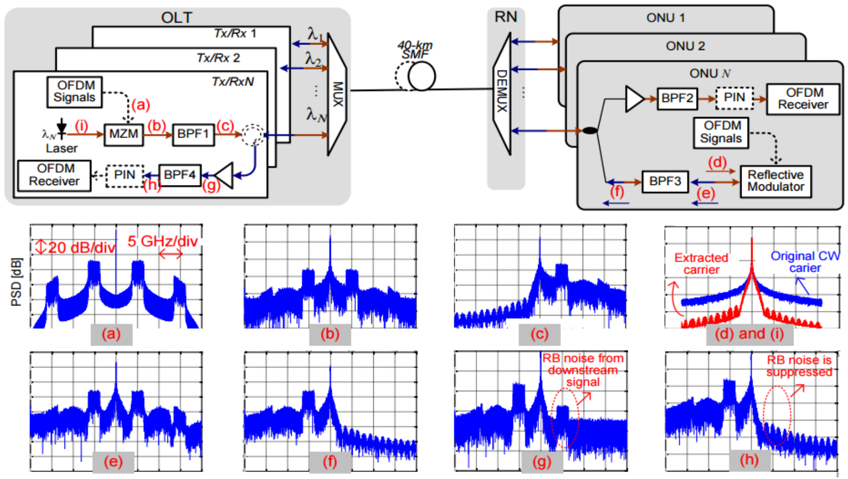


Figure 2.7: Rayleigh Backscattering Mitigation with Optical Sideband Reuse [65]

the direct detection process. In [16], the author proposes to utilize the guard band of the offset OFDM for uplink baseband transmission.

Since wavelength reuse needs to route the downlink optical carrier back into the uplink direction, reflective modulator provides much benefits in such a loopback structure. The simplified architecture eliminate the adoption of circulator which is hard to integrate with the modulator. RSOA as the typical reflective uplink modulator with extra gain is attractive for remodulation. While, the low modulation bandwidth (typical 3dB bandwidth 1.2 GHz) hinders the further application of the RSOA. R-EAM-SOA is an integrated component comprising EAM (electro absorption modulator) and SOA (semiconductor optical amplifier) [55]. It provides decent modulation speed and also extra gain for the uplink.

2.4 Multi-user MIMO provision in RoF-DAS

As we mentioned in chapter 1, next generation wireless communication system will be deployed with multi antennas in small cells. MIMO technology, which made its first broad commercial appearance in 802.11n systems, is now gaining substantial momentum in WWAN (Wireless Wide Area Network) with the launch of 4G LTE and 5G networks.

The use of MIMO necessitates the transport of several radio channels between the central office and the remote antenna units at exactly the same radio carrier frequency. There are several options for providing this functionality: 1) using separate radio over fiber links on separate optical fibers (SDM); 2) using separate radio over fiber links on the same fiber but on separate optical wavelengths (WDM); 3) using the same radio over fiber link where each channel is frequency translated to a separate IF (SCM); 4)using the same radio over fiber link where each channel is modulated on the same optical carrier with orthogonal polarization state. (PDM).

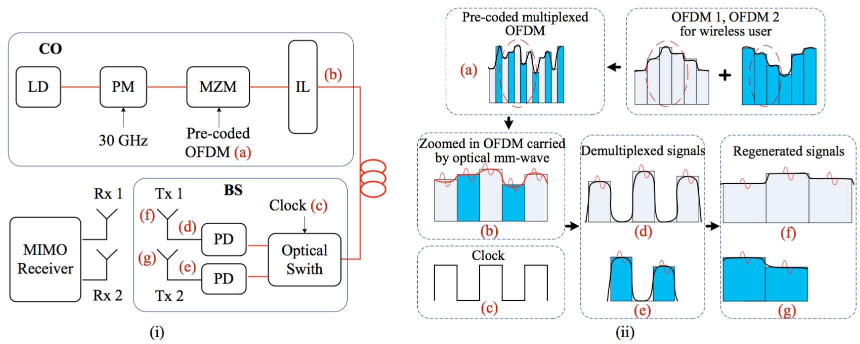


Figure 2.8: System diagram of the proposed 2x2 MIMO-OFDM MMW RoF system. (ii) Signals at different locations in radio over fiber testbed as indicated in (i). [69]

Approaches for transmitting MIMO signals over DAS have been proposed[8, 52]. WDM technique proposed in [8] requires multiple optical transmitter and receiver for each MIMO wireless service, while optical SCM (sub-carrier multiplexing) in [52, 71], frequency shifting approached in [9] and phase quadrature double side band frequency translation technique proposed in [36] need multiple number of LO (local oscillators) , mixers, electrical amplifiers and narrowband band pass filters depending on the number of MIMO antennas at a given wireless frequency. Multi mode fiber has also been demonstrated to support MIMO provision in radio over fiber[23] . But multi-mode fiber have not been used worldwide comparing to the deployed single mode fiber . Polarization multiplexing to transport MIMO signal over fiber has been experimentally demonstrated for 2×2 MIMO only[32, 35, 38]. MIMO with more than 2 antennas has not been widely investigated yet.

A flexible and scalable radio over fiber system has been demonstrated using $2{\times}2$ MIMO millimeter-wave signals based on optical TDM technique[69]. Two independent QPSK (quadrature phase shift keying)-OFDM signals at 60 GHz are multiplexed in time domain and demultiplexed by an optical switch as depicted in Fig 2.8. Although, it comply with today's TDM PON system, the clock needed at the RAU to extract different MIMO signal is demanding.

Chapter 3

Experiment Investigation of RSOA based Radio over Fiber WDM PON Adopting Wavelength-reuse

3.1 General Objective and proposed solutions

The general objective of the project is shown in Fig 3.1. Our proposed solutions are summarized with common features and variation configuration also described in Fig 3.1. For the different experiment setups we apply different SCM solutions to accommodate WiFi signal with RSOA.

3.2 Milestones,Objectives and Conclusions

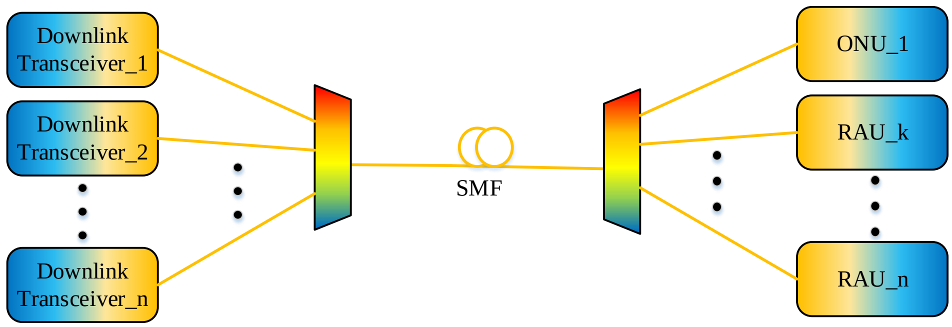
3.2.1 Experiment-1 Referring to Chapter 4

First we evaluate the performance of the RSOA as a optical wireless interface. Uplink and downlink spectrum allocation is presented as depicted in Fig 3.2. The SFDR of the RSOA is experimentally measured. The relationship between the injection power, RSOA bias current and uplink WiFi signal EVM (Error Vector Magnitude) is experimentally characterized. No OOK signal transmission in uplink and downlink. Only full-duplex WiFi signal transmission is evaluated in both uplink and downlink.

3.2.2 Experiment-2 Referring to Chapter 5

But for a simplified RAU [1] design, we hope the RAU could interface with the WiFi signal without any frequency translation. That is the motivation for the experiment setup in Fig 3.3.

[1]The RAU could provide extra wireless access function compared to ONU which could only support residential access. We use the RAU to emphasize the add-on wireless function to the ONU.



WDM PON Architecture

Objective:

Design an optical PHY layer supporting and enabling virtualized wireless back haul.

Proposed Solutions :

Prerequisite Constraints	1. Based on WDM PON architecture; 2. RSOA based RAU with uplink and downlink share the same laser source from CO; 3. OOK downlink and/or uplink.
Objective	4. SCM for wireless signal at RF carriers or an intermediate frequency (IF).

Figure 3.1: Project Objective and Proposed Solution.

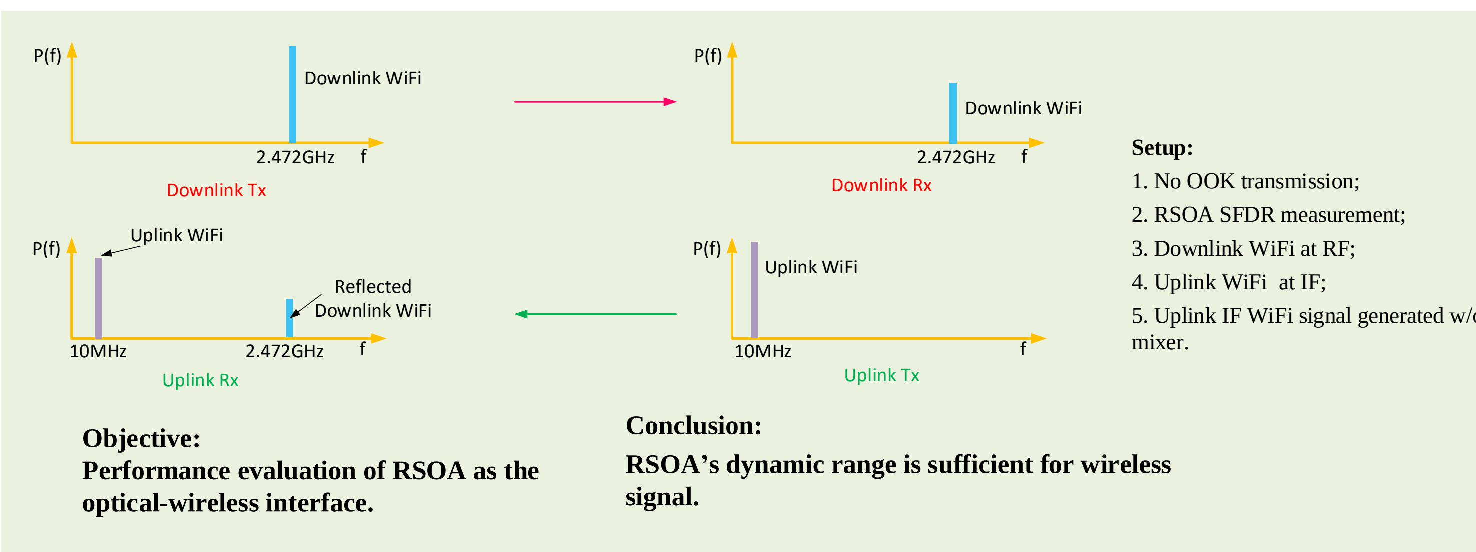


Figure 3.2: Different Uplink and Downlink schemes investigation-1 [40]

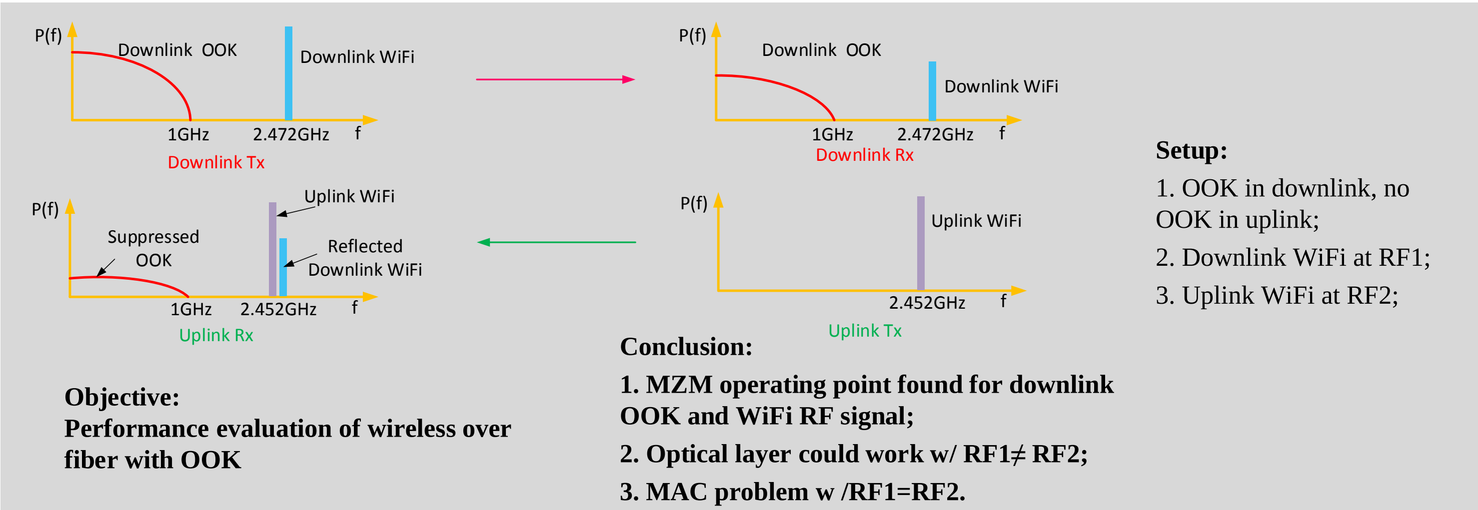


Figure 3.3: Different Uplink and Downlink schemes investigation-2 [3]

The downlink signal is comprised of OOK and WiFi signal (at RF1 wireless carrier). No OOK signal in the uplink direction. The uplink WiFi signal is placed at RF2 wireless carrier. Both the OOK and WiFi signal quality is evaluated with different fiber length.

Since the WiFi MAC mostly operates in TDD mode, we can expect an incompatible problem in Fig 3.3's setup. The reflected downlink signal will arrive the uplink receiver before the uplink signal which would violate the MAC protocol. The incompatibility issue originates from the optical layer re-modulation scheme. We solve the optical layer incompatible problem in experiment 3 by introducing mixer in the RAU and CO.

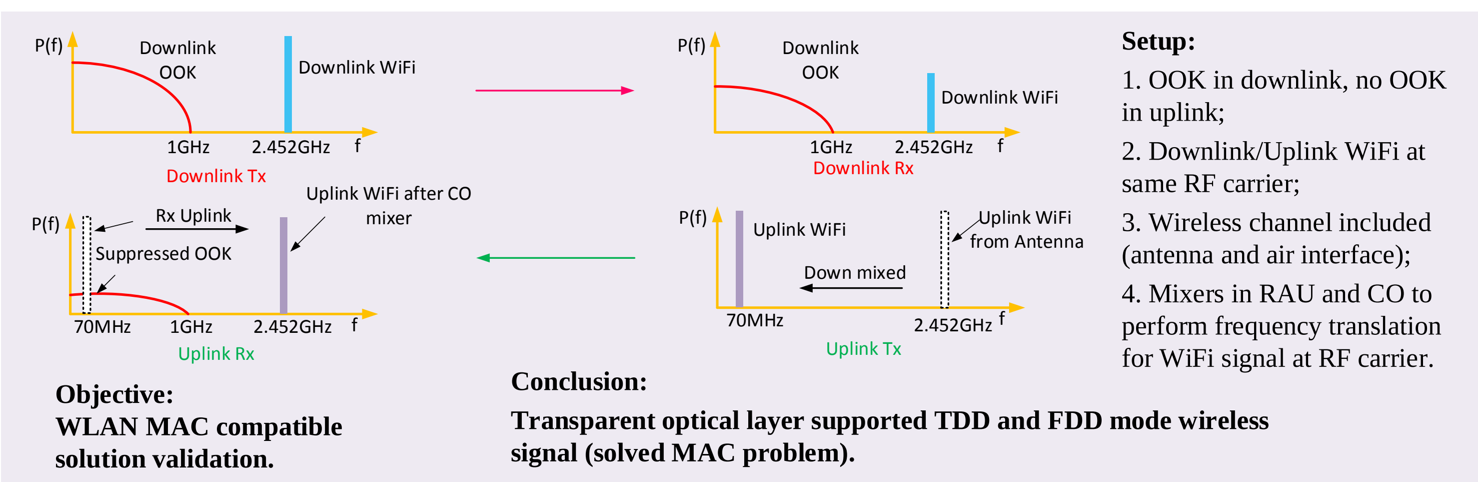


Figure 3.4: Different Uplink and Downlink schemes investigation-3 [4]

3.2.3 Experiment-3 Referring to Chapter 6

In Fig 3.4, the uplink and downlink WiFi signal at same wireless RF carrier are transmitted in the link simultaneously. OOK transmission is only in the downlink. No OOK transmission in the uplink. The mixer in the RAU first down-convert the uplink WiFi signal at RF carrier to IF, and then to drive the RSOA. When the uplink signal arrives the CO receiver, the IF WiFi signal is first detected and then up-convert to the original wireless RF carrier. In this setup, the wireless interface is also integrated. The downlink signal after detected at the RAU is transmitted by the antenna and received by antenna linked to the RTO.(Realtime Oscilloscope) Vice versa for the uplink.

Chapter 4

Full-duplex Analog WiFi Transmission in WDM-PON System

4.1 Introduction

Previously [29, 28, 41], we proposed an RSOA-based WDM PON architecture to support RoF technology. Utilizing the saturation effect of RSOA, we demonstrated that a single and multi-service analog WiFi OFDM uplink signal can be transmitted full-duplex with a properly controlled OOK downlink signal over 80 km and 20 km standard single mode fiber (SMF), respectively. The bit error rates (BERs) of downlink and uplink signal were below 1×10^{-9} for OOK signal, and below pre-forward error correction (pre-FEC) level of 1×10^{-3} for OFDM signal. The ability of this architecture to support full duplex analog WiFi signal has not been demonstrated and investigated.

The experimental setup is shown in Fig 4.1. A continuous wave generated by high power tunable laser (Cobrite-DX1) is first modulated by the Mach-Zehnder modulator (MZM) driven by a 2.4 GHz RF WiFi OFDM signal. The laser power is tuned to 15 dBm at 1550 nm. We set the MZM bias at 0.5 V_π so that higher downlink RF power could be launched without nonlinearity distortion. Under this condition the average launched power is 7 dBm after MZM. Then the downlink optical signal is fed into the SMF through a circulator. After propagating in the fiber, an optical filter is used to emulate 100 GHz spacing WDM DUX/MUX component which could filter out the out-of-band noise and route the downlink signal to the target RAU.

A 3-dB splitter in each RAU splits the incoming signal in two paths. One path goes to the receiver consisting of a 10 GHz PIN photo-diode, electrical amplifier, a 2.4 GHz band pass filter (BPF), and a 10 GHz, 40 GSa/s real time oscilloscope (RTO) used to capture data for offline processing of error vector magnitude (EVM) and BER. The other path leads to a polarization controller before injecting to the RSOA (SOA-R-OEC-1550nm CIP). The polarization controller maximizes the input power to the RSOA as it is polarization sensitive

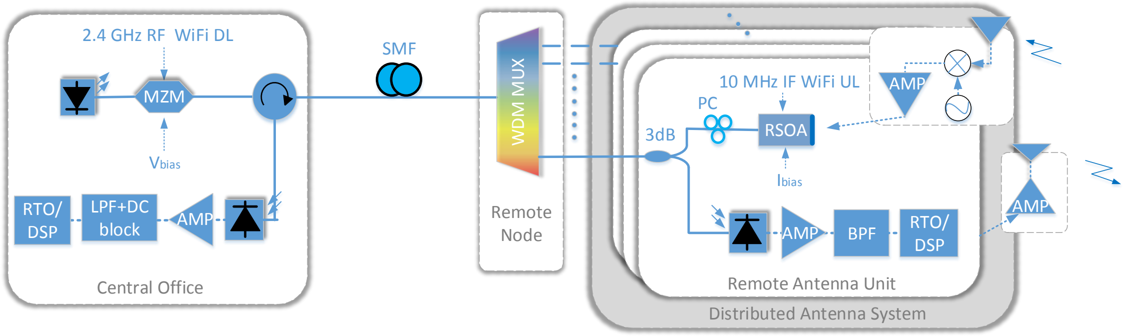


Figure 4.1: Experiment setup to implement WiFi full duplex transmission. AMP: amplifier, LPF: low pass filter,BPF: band pass filter

(20 dB).

The downlink light is re-modulated in the RSOA with the uplink OFDM WiFi signal at 10 MHz IF and transmitted back to the CO in the same fiber. When the uplink signal reaches the CO, a 3 GHz 8 GSa/s RTO is used after the PIN, electrical amplifier, 2 MHz low pass filter and DC block to acquire only the AC components of the uplink signal.

The WiFi OFDM signal uses the 802.11a frame structure with the desired modulation format (QPSK, 16QAM or 64QAM). No FEC is used for the data payload. Due to equipment availability, one vector signal generator (VSG) is used to generate each RF signal. The WiFi signal was created offline with a 10 MHz carrier and uploaded to the VSG. The RF uplink signal was output via the VSG 100 MSa/s DAC. For the downlink, the signal was routed to the internal VSG mixer for upconversion to 2.4 GHz. No effort was made to synchronize the two signals temporally or in frequency; they were naturally desynchronized by the internal mixer and disparate cabling.

4.2 RSOA Characterization

As the majority of nonlinearity in the RoF system comes from the optical modulator, we investigate the nonlinear tolerance when using an RSOA as an wireless/optical interface. We show the SFDR of the RSOA to be compatible with WiFi signals. Due to the wireless channel, a large linear dynamic range is required in the RoF link, especially in the uplink. Because the simple RAU design rule is only responsible for the E/O conversion without any processing function. It has been observed that indoor pico-cells the radio signals can fluctuate by 40-50 dB and outdoor microcells this fluctuation can be as high as 80-90dB [17, 63]. We first examine the SFDR character of the RSOA serving as E/O modulator in the RAU [19]. A second effect of concern is erasure of the downlink RoF signal by the RSOA and remodulation of the downlink carrier with a new RoF signal. We measure the EVM when factors such as:

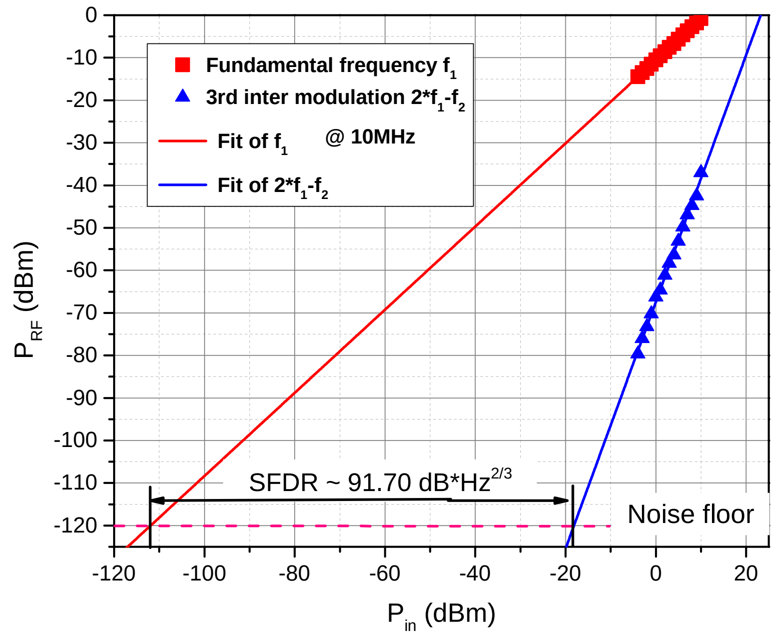


Figure 4.2: SFDR measurement of RSOA at IF Band.

RSOA bias current, injection power and RF swing voltage, are varied independently.

The SFDR is measured using two 1 MHz-spaced sine tones for baseband modulation of the RSOA used in our experiment. The third order inter-modulation power is measured and plotted in Fig 4.2. Extrapolating measured data, we find the SFDR to be $91.7dB \times Hz^{2/3}$ above our measurement noise floor, which is comparable to the $91dB \times Hz^{2/3}$ requirement of wireless signals [11].

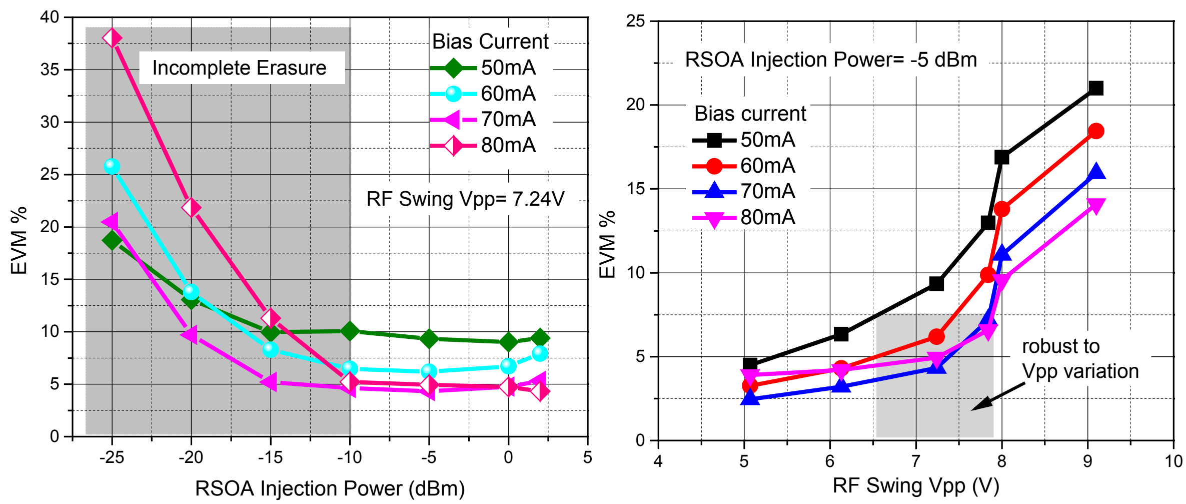


Figure 4.3: EVM variation with respect to the Injection Power (left), and RF swing voltage (right)

In B2B (shown in Fig 4.1), for an RF Vpp swing fixed at 7.24 V, we observe EVM performance when varying the RSOA injection power as shown in the left of Fig 4.3. Clearly EVM is best at greater injected power, when we have deepest saturation, and hence the best erasure of the downlink signal. The grey zone has insufficient saturation. Greater bias current gives best EVM outside the grey zone. At 80 mA, although the gain is higher, the ASE noise from the RSOA also increases explaining the poorer EVM compared to 70mA outside the grey area. We next fix the injection power to -5 dBm and vary Vpp, see the right of Fig 4.3. The grey zone shows increased tolerance to larger RF swing voltage biased at 80 mA as opposed to 50 mA, i.e. increased dynamic range.

Fig 4.4 shows the OSNR at bias current 50 mA and 80 mA with -25 dBm injection. The signal gain variation is limited to 1 dB, however, the noise floor climbs up 6 dB leading to a 5 dB deterioration in OSNR. Which is compliant with the behaviour observed in Fig 4.3 grey zone.

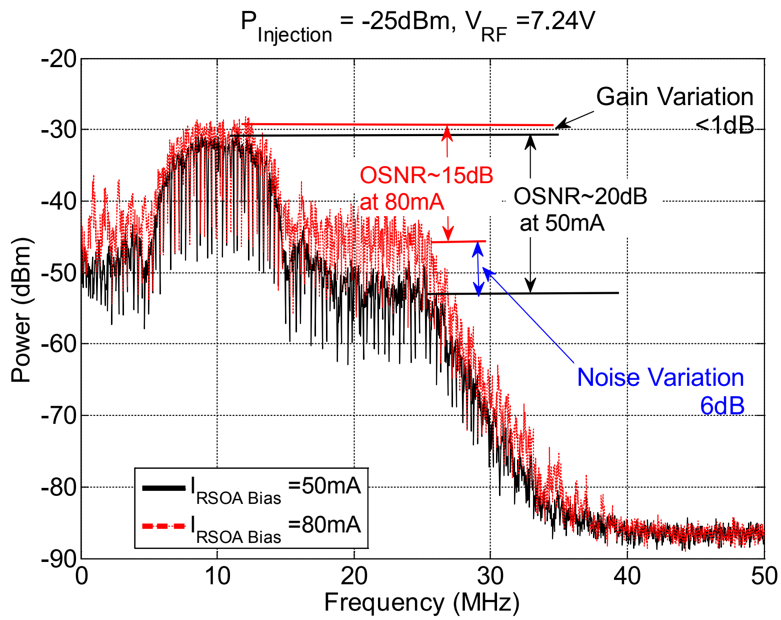


Figure 4.4: Spectrum at different bias current

4.3 Experiment Results and Discussion

Then we experimentally demonstrate the transmission of full-duplex analog WiFi uplink and downlink at 10 MHz IF and 2.4 GHz RF, respectively. The BER is below FEC-threshold for 64QAM for transmissions of up to 20 km single mode fiber.

We run transmissions experiments by changing the fiber lengths and modulation formats in Fig 4.1. The RSOA is biased at 70 mA with 7.24 V RF modulation, providing the best trade-off per our previous characterizations. EVM is plotted in Fig 4.5 left versus fiber length, with BER estimates (over 10^6 bits) are written next to markers; dashed lines are for uplink, solid for downlink. FEC thresholds are indicated for each modulation format. For fiber

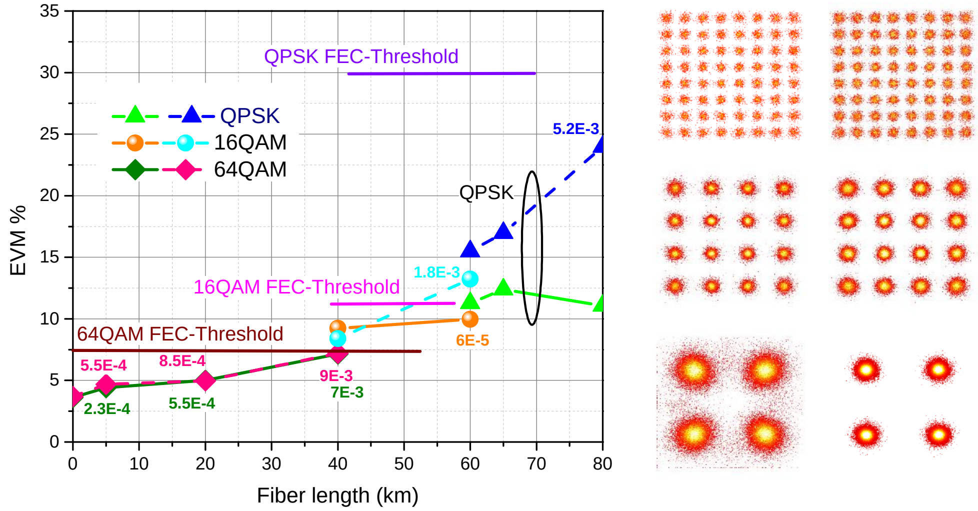


Figure 4.5: EVM/BER of WiFi uplink and downlink with different modulation modes

length between 20 km and 40 km, an injection power of 5 dBm to 10 dBm can be achieved by increasing the launched power at the CO. Therefore, below 40 km downlink and uplink have comparable performance. Beyond 40 km, however, attenuation cannot be completely compensated. For 64QAM (diamond markers), transmissions below 20 km respect the FEC threshold; note uplink and downlink curves are superimposed. At 16QAM, 50 km can be achieved, while QPSK has good performance even beyond 80 km. At the right of Fig 4.5, uplink (left column) and downlink (right column) received constellations are presented for the fiber lengths indicated.

Chapter 5

Full duplex Analog WiFi Transmission with Digital Downlink OOK in Wavelength-reused WDM PON System

5.1 Introduction

In this section, we experimentally demonstrate bidirectional analog WiFi signal transmission in a digital WDM-PON system. Our solution is compatible with a single optical feeder fiber and customer premises units employing RSOAs. The downlink optical carrier is modulated which both baseband 1 Gb/s OOK data and a WiFi signal in the 2.4 GHz band. The optical signal is split, with part going to reception and part reflected by the RSOA and modulated with an uplink WiFi signal.

In previous chapter 4, due to the RSOA limited bandwidth of 1.2 GHz, down conversion was proposed to convert the standard wireless signal from its RF carrier to an IF before UL transmission. To reduce system complexity, especially at the RAUs, we propose directly modulating the RSOA with the passband analog signal. The uplink WiFi signal is in the 2.4 GHz band (no frequency translation).

At the BER threshold of 2×10^{-3} before FEC, we achieve the transmission link up to 20 km (64-QAM), 30 km (16-QAM), and 40 km (QPSK). In all cases, the 1 Gb/s digital downlink signal is error-free.

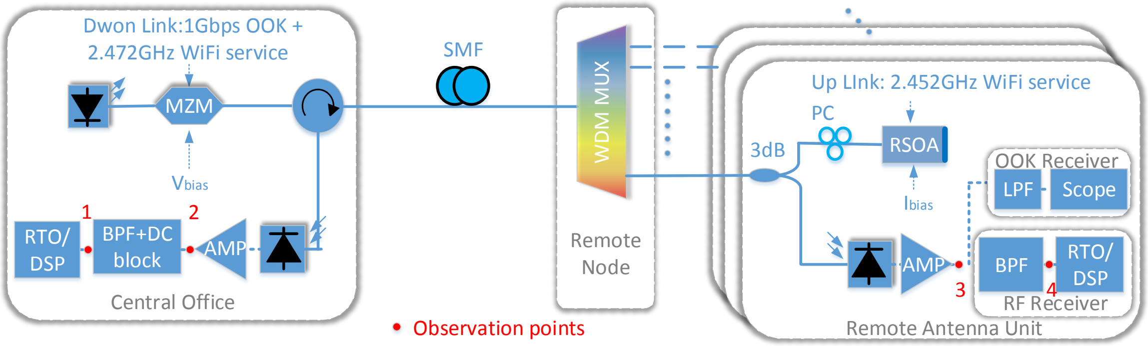


Figure 5.1: Experiment Setup for Full Duplex WiFi Transmission and OOK Downlinks

5.2 Experiment Setup Description and Disscussion

Fig 5.1 depicts the experimental setup. There are some modifications based on the setup in Fig 4.1. In the CO, a MZM modulates a continuous wave light from a tunable laser operated at 1550 nm with 15 dBm optical power. The DL electrical signal driving the MZM is generated by combining a 1 Gb/s non-return-to-zero OOK from a bit pattern generator with a WiFi signal from a programmable vector signal generator. The OOK signal carries random data from a pseudo-random binary sequence pattern of $2^{31} - 1$ bits, and its spectrum is shaped by a 980 MHz LPF. The downlink OFDM WiFi signal covers a bandwidth of 10 MHz centered at 2.472 GHz (channel 13 in IEEE 802.11a stand-ard). An optical circulator routes DL signals into the fiber, and directs the UL signal from the fiber to the receiver.

The DL signal propagates through the SMF and reaches the WDM demultiplexer which acts as a distributing node. At the RX, the DL signal is converted to electrical signal by a 10 GHz PIN, amplified by a trans-impedance amplifier and filtered for proper reception. The DL-OOK signal is filtered by a 1.5 GHz low-pass filter and captured by a 10 GHz sampling scope. The DL-WiFi signal is filtered by a 22 MHz BPF at 2.472 GHz and acquired by a 40 GSa/s RTO and passed to offline digital signal processing (DSP) done with MATLAB. The optical signal going to the RSOA is reflected, amplified and used as the carrier for UL-WiFi signal.

The RSOA is driven by a bias current of 70 mA and modulated by a 10 MHz UL-WiFi signal which has a 4 V_{p-p} voltage swing. The UL-WiFi signal is located at 2.452 GHz (channel 9 in the IEEE 802.11a standard). To highlight the full-duplex operation, we presume the WiFi transmission is in frequency division duplexing (FDD) mode where UL and DL signals occupy different channels. In practice, for WiFi standard particularly, TDD is normally utilized, but for experi-mental convenience we use FDD. We discuss below how sys-tem performance in TDD mode should be superior to our results. The UL optical signal propagates toward the CO and directed to the RX by the circulator. There it is captured and processed in the same manner as the DL-WiFi, with the ap-propriate BPF and DSP.

The operating point of the TX MZM plays a key role in de-termining UL-WiFi performance. The RSOA suppresses the DL modulation when saturated, thus cleaning the reflected car-rier and improving the signal-to-noise-ratio for the UL sig-nal. However, the saturation is controlled by the average opti-cal input power since the driving current is fixed. The output optical power at the CO MZM will vary when changing the bias point; thereby affecting the RSOA input power.

In previous work we transmitted only DL-OOK signals, so we could raise the bias point to reduce the OOK swing to have high out optical power. We sacrificed DL-OOK performance (to an acceptable limit) to support UL-WiFi transmission over 80 km of SMF. In the case of mixed OOK and WiFi signals for DL, we cannot do the same. We vary three factors (the bias voltage, the OOK swing and the WiFi swing) to find a combi-nation to support UL-WiFi transmission. The voltage swings of the OOK and WiFi signals are 1.4 and 0.8 V_{p-p} respectively. As the V_π parameter of the MZM is about 5 V, and the bias point is controlled at the quadrature point, the combined voltage of the OOK and WiFi signal falls squarely inside the linear region of the MZM. Under this condition, the average optical power after the MZM is 5 dBm.

5.3 Results and Remarks

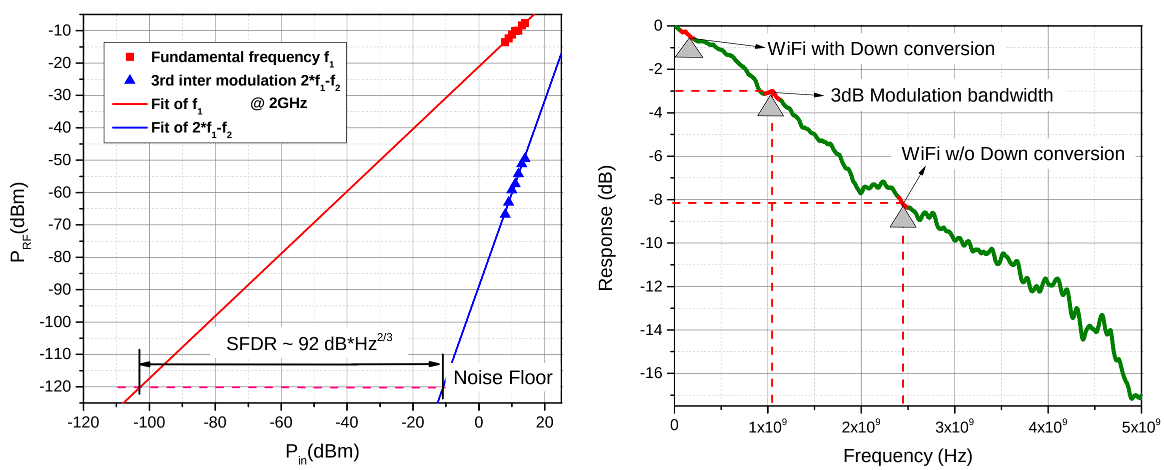


Figure 5.2: SFDR measurement and frequency response of the RSOA

In order to secure the UL-WiFi transmission, we perform an SFDR measurement for the RSOA at the 2 GHz band. The vector signal generator generates two sinusoidal tones at 2 GHz and 2.01 GHz, and the output RF power is swept. We connect the RSOA to a 3-dB 1×2 coupler on which one input receives a continuous wave optical carrier and the other is connected to a photo-diode for receiving the reflected optical signal. The O-E converted signal is measured by an electrical spectrum analyzer and the fundamental and the 3rd order components are recorded. Fig 5.2 (left) shows the evolution of the powers of the two tones; the measured SFDR is 92 $dB \times Hz^{-2/3}$, close to the requirement for WiFi transmission (94 $dB \times Hz^{-2/3}$).

As the electrical frequency response of the RSOA is limited around 1.2 GHz, the UL-WiFi signal has its electrical power reduced by the low-pass filtering effect, resulting in a low E-O conversion efficiency. We use a mixed-signal vector network analyzer to measure the frequency response of the RSOA, presented in Fig 5.2 (right). The UL-WiFi signal may suffer up to 8 dB attenuation when it is located at 2.4 GHz band comparing to baseband modulation (10 MHz).

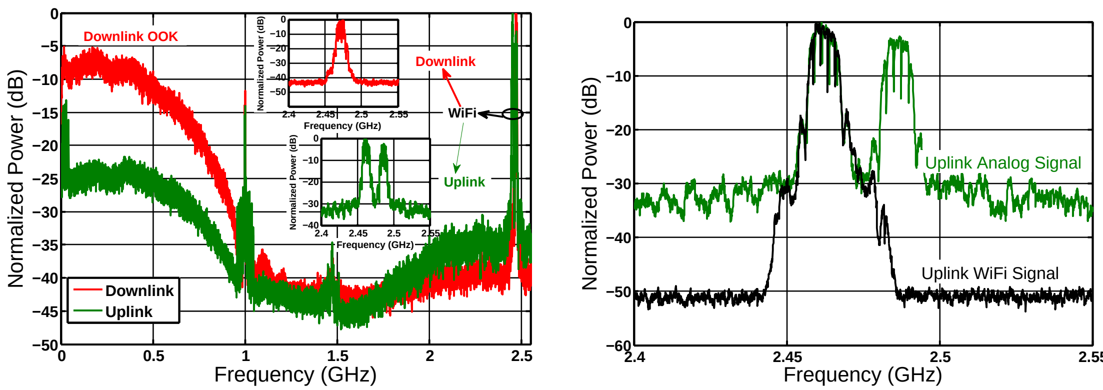


Figure 5.3: Uplink and Downlink Spectrum at observation point left:2,3; right:1,2.

The electrical spectra of the DL and UL signal are depicted in Fig 5.3 (left). The DL spectrum (red) shows the 1 Gb/s OOK and the WiFi at 2.472 GHz while the UL one (green) shows a suppressed OOK and two WiFi services at 2.572 and 2.452 GHz respectively. The RSOA is well known for its high-pass filter effect; it erases the baseband DL modulation whose cut-off frequency is 500 MHz. While the DL-OOK modulation is suppressed quite effectively, the DL-WiFi remains clearly visible. Fig 5.3 (right) shows a zoomed-in UL spectrum on which the DL-WiFi and UL-WiFi are visible. The filtered UL-WiFi spectrum (black) is normalized for easy viewing with the full UL spectrum (green).

Note that the UL-WiFi spectrum is around 5 dB higher than that of the DL-WiFi. At the CO, the DL-WiFi signal does not modulate the optical carrier at 100 % modulation depth; we choose a level permitting the UL-WiFi signal to exploit deeper modulation, thus improving its SNR. Nonetheless, the UL-WiFi performance is worse than that of the DL-WiFi sig-nal. The UL-WiFi signal suffers from a much noisier carrier; also, the received photocurrent is shared with the reflected DL-WiFi signal. With MAC layer enforcement of TDD signaling, the UL-WiFi and DL-WiFi would share the same frequency, but never be present simultaneously. In this case, the UL-WiFi performance would improve due to the purer optical carrier and stronger received electrical power. However, we expect a potential problem with TDD mode due to the fact that the RSOA reflects back the DL signal before the UL signal is transmitted, and that can cause a misunderstanding by the CO. Fortunately, the fiber length is normally fixed, the round trip time is known in advance. Therefore with a proper time delay management the CO can neglect the reflected DL signal.

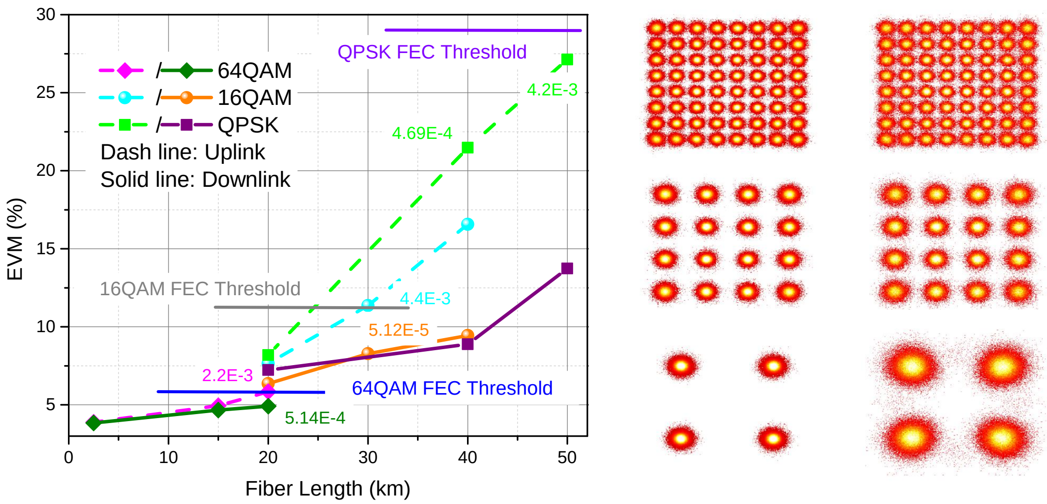


Figure 5.4: EVM of OFDM WiFi signal Uplink at 2.452 GHz Downlink at 2.472 GHz(left);Constellation for (from top to bottom) 20 km, 30 km and 40 km downlink (left) and uplink (right).

The results for the transmission experiment are presented in Fig 5.4 (left). The WiFi signals (either UL or DL) are captured by a broadband RTO using a passband sampling technique at a sampling rate of 200 MSa/s. The standard DSP procedure for data recovery is used: baseband down conversion, down-sampling, filtering, frame synchronization, frequency offset rejection, channel estimation/equalization, and finally de-modulation. EVM is calculated from the equalized constellation and BER is counted from the de-modulated data.

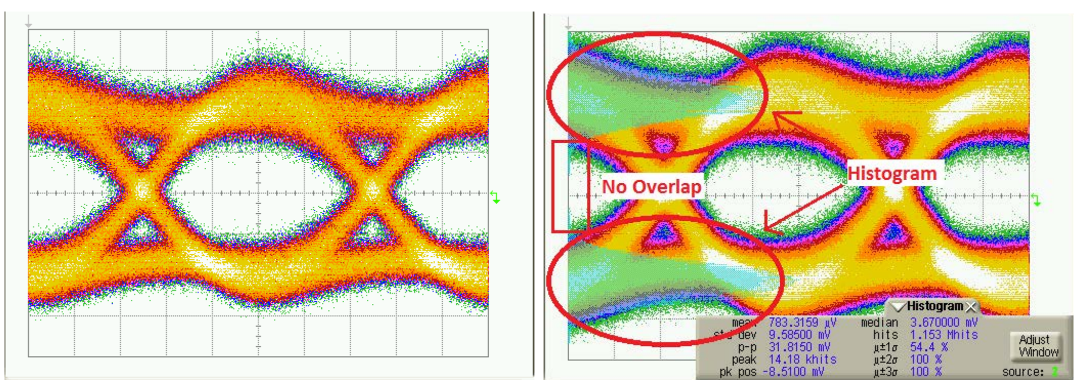


Figure 5.5: Eye diagram of downlink OOK signal 20 km (left); 40 km (right)

The WiFi signal is generated based on the IEEE 802.11a standard. We presume the convolutional code CC(171,133) rate 2/3 is used to encode the data, and soft decision Viterbi decoding scheme is used for recovery. With that assumption, we define a pre-FEC BER around 3×10^{-3} as the acceptance threshold for the performance of WiFi signals. At distances below 20 km, the DL and UL WiFi performance is similar. At longer distances, the UL-WiFi performance de-grades very quickly. The maximum reachable distance for 64-QAM is around 20 km. For 16-QAM and QPSK modulation modes the transmission distance are 30 km and 40 km respectively. In Fig 5.4 (right), we also show example constellations of the UL-WiFi signal (left) and the DL-WiFi signal (right) for 64-QAM (20 km), 16-QAM (30 km) and QPSK (40 km). Unlike the DL-WiFi constellation diagrams which are quite uniform across all symbols, the UL-WiFi constellation dia-grams show some nonlinear noise distribution. This can be due to the combination of RSOA nonlinearity, DL crosstalk on a noisy carrier and interference from the DL-WiFi signal due to imperfect filtering. These impairments could be greatly mitigated by employing a wide band, enhanced linear RSOA[14].

In all cases, the DL-OOK signal is error-free. We report in Fig 5.5 the eyediagram and the histogram of "1" and "0" levels of the DL-OOK signal after 40 km of transmission. A clear open eye is achieved and the 3-minute accumulated histogram shows no overlapping between "1" and "0" level, indicating error-free performance.

Chapter 6

Transparent Full-duplex Radio over Fiber Link Incorporating up/down Conversion Board

6.1 Introduction

In chapter 4 we have investigated the possibility to transmit full duplex WiFi uplink and downlink at IF and RF respectively in WDM PON system [42]. To reduce system complexity [68], especially at the RAUs, we propose directly modulating the RSOA with the passband analog signal in chapter 5. However, the RSOA could not work with 5 GHz band signal or higher without down mixing due to its bandwidth limitation. For further wireless standard seeks to utilize bandwidth in higher frequency band (mm-Wave etc.) which consume more bandwidth resource of the modulator. By down converting the narrow band wireless signal from RF to IF band within the 3-dB modulation bandwidth of the RSOA ($0 \sim 1.2$ GHz), the E/O conversion efficiency could be significantly increased. So it is reasonable to introduce the low cost and less complex mixer in the RAU and CO. And also, the down mixing function could let us to flexibly rearrange the spectrums when the antenna receives multi-service signals from different users [41].

Additionally, as we mentioned a MAC layer compliant to TDD standard has the uplink and downlink WiFi sharing the same frequency, but are never present simultaneously. Fiber transmission will lead to the RoF downlink WiFi signal being reflected back by the RSOA before the RoF uplink WiFi signal is transmitted, violating the TDD assumption. The time delay introduced could be dealt with in the MAC layer, albeit with greater MAC complexity. Introducing the up/down mixing function in the CO and RAU, in addition to improving fiber reach, would solve the timing problem by separating the optical WiFi signals in the frequency domain. The TDD problem is described in Fig 6.1.

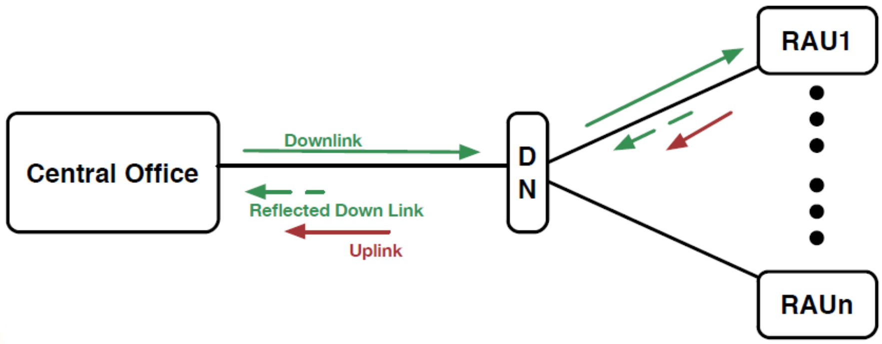


Figure 6.1: Reflected Downlink violate the TDD MAC signalling

In this section, we experimentally demonstrate a transparent optical physical layer architecture adopting up/down mixer in RSOA based wavelength reuse WDM PON system with wireless interface. We experimentally measure the SFDR and the frequency response of the RSOA and analyze its impact on the analog modulated optical signal. Full duplex analog WiFi with downlkink OOK are successfully transmitted over 20 km fiber and 1 meter wireless path with required performance. EVM is measurd for the RoF signal and an error free eye is measured for the downlink OOK signal.

6.2 IF vs RF Transmission Performance Comparison

The spectral allocation of uplink and downlink plotted in Fig 6.2 (right) is the spectrum observed at point (a) and (b) in the experiment setup. At CO the uplink received WiFi signal always accompany with suppressed OOK singal and reflected downlink WiFi signal. The uplink singal to noise ratio is determined by the suppression and erasing effect inside the RSOA. The RSOA suppress the downlink modulation when saturated, thus cleaning the reflected optical carrier and is modulated by the uplink signal.

In the our previous study, we transmitted OOK signal in the downlink only, so we could raise the bias point to reduce the OOK swing to obtain a high optical power at the RAU. In another word, we sacrifice the more robust OOK performance to trade for a high signal to noise ratio uplink WiFi signal supporting transmission over 80 km of SMF. Whereas this is not the case when the downlink signal mix OOK and WiFi. The downlink WiFi signal easily get distorted by the transmitter nonlinearity when we raise the operating point to improve the uplink performance. We trade off the downlink WiFi modulation depth with uplink performance. So that we can let the uplink signal to exploit deeper depth while the downlink WiFi signal with less modulation depth of the optical carrier. Nonetheless, the uplink WiFi signal performs worse than the downlink WiFi signal. The uplink WiFi signal suffers from a much noisier carrier; also, the received photo current is shared with the reflected downlink WiFi signal which further lower the signal to noise ratio of the uplink WiFi signal.

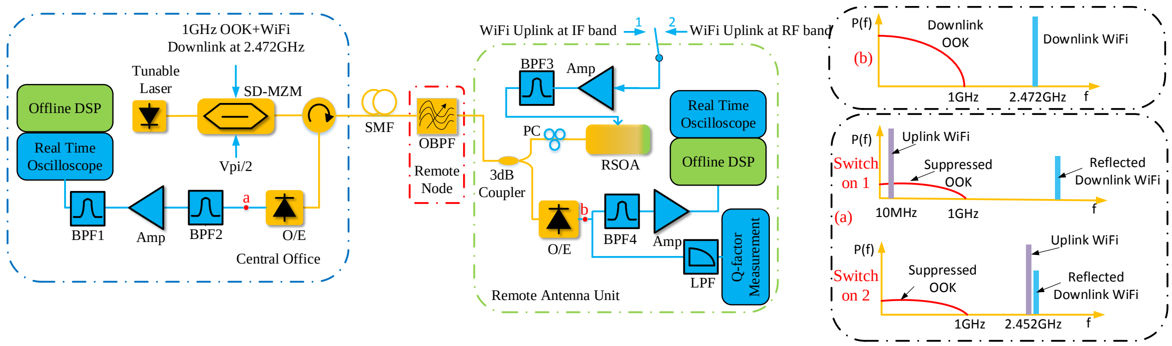
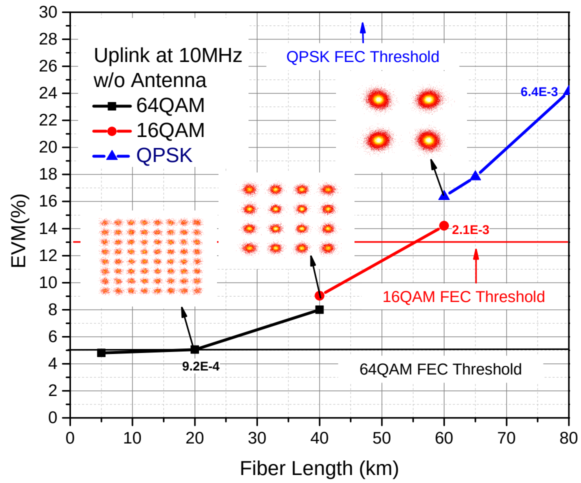


Figure 6.2: Experiment setup for comparing IF and RF options for optical transport and spectrum allocation.

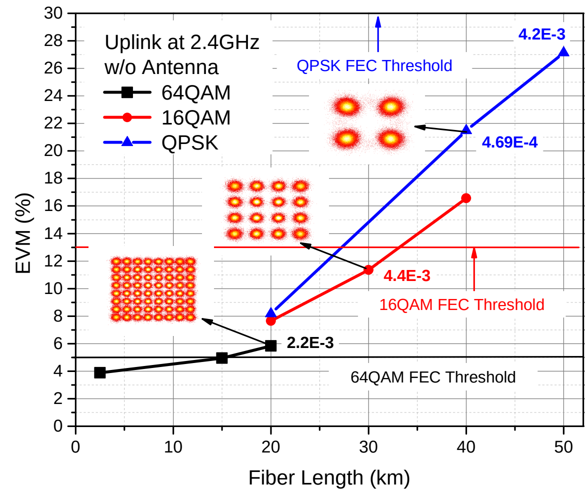
The experiment setup and spectrum arrangement are depicted in Fig 6.2. The switch in the RAU in Fig 6.2 is used to select uplink WiFi signal located at IF/RF (10 MHz/2.452 GHz) band separately. The uplink WiFi signal is amplified and filtered by the respective IF/RF centered BPF (BPF3) to suppress amplifier noise. The downlink signal is transmitted and received with the same manner in Section 5. The electrical uplink signal is captured and processed in the same manner as the downlink WiFi signal, with appropriate BPF (BPF1 and BPF2) and DSP. The full-duplex operation is with frequency division duplexing mode where uplink and downlink signal occupy different channels.

The experiment is operating with downlink OOK and full duplex WiFi transmission. As to full-duplex transmission , the uplink is always the constrain of the fiber reach. We only present the uplink transmission performance in Fig 6.3. EVM is calculated from the equalized constellation and BER is counted from the demodulated data. The WiFi signal is generated based on the IEEE 802.11a standard. We presume the convolutional code CC(171,133) rate 2/3 is used to encode the data, and soft decision Viterbi decoding scheme is used for recovery. With that assumption, we define a pre-FEC BER around 2×10^{-3} as the acceptance threshold for the performance of WiFi signals. Using the results in [51], we map the BER threshold to EVM as marked in the figure with black (64QAM), red(16QAM) and blue (QPSK) line.

With the uplink WiFi signal at 10 MHz carrier, the supported fiber length is 20 km (64QAM), 40 KM (16QAM) and 60 KM (QPSK) below the FEC-threshold. The insets depict the constellation at the respective fiber length for different modulation format. When we choose the uplink WiFi signal mixed with 2.452 GHz RF carrier, the fiber could only reach 15 km (64QAM) 20 KM (16QAM) and 40 km (QPSK) due to the low pass filter effect of the modulation curve. From the analysis above , it is naturally to draw the conclusion that IF over fiber is the best candidate with improved E/O conversion efficiency in RSOA. Then we introduce up/down mixer in the CO and RAU separately, the full duplex WiFi signal at same frequency is transmitted co-currently with downlink OOK signal through fiber and wirless channel.



(a) Uplink WiFi at IF band



(b) Uplink WiFi at RF band

Figure 6.3: Fiber Length vs EVM Comparison.

6.3 Full-duplex WiFi Transmission with Up/Down Mixer and Antennas

In our experiment we demonstrate our scheme could support uplink and downlink wireless WiFi signaling at the same frequency. The experimental setup and captured spectra are depicted in Fig 6.4 and Fig 6.5.

The downlink WiFi signal is filtered by a 2.452 GHz BPF (BPF4 in Fig 6.4) and sent to the antenna after being boosted by another amplifier. The antenna is omni-directional (HPBW / H: 360°, V: 15°) with 8 dBi gain on the 2.4 GHz band [57]. The downlink WiFi signal is received by an antenna at a distance of 1 meter. The signal is acquired by a 40 GSa/s real-time oscilloscope (RTO). Offline digital signal processing (DSP) is performed in MATLAB. The downlink optical signal is reflected, amplified and erased by the RSOA and reused as the uplink carrier.

Two up/down converter board (ADL5801) is used at the CO and RAU to up/down convert the uplink IF and downlink RF WiFi signal. The ADL5801 uses a high linearity, doubly balanced, active mixer core with integrated local oscillator buffer amplifier to provide high dynamic range frequency conversion from 10 MHz to 6 GHz. The mixer benefits from a proprietary linearization architecture that provides enhanced input IP3 performance when subject to high input levels. We utilize the integrated input power detector to adaptively control the bias to optimize the input linearity and SSB noise figure [15].

The two local oscillators, Lo1 and Lo2, originate from the same sinusoidal generator and oscillate at 2.382 GHz with 11 dBm power. The power level to the ADL5801 is well maintained between -35 dBm and -40 dBm to avoid saturation in the amplifier embedded in the ADL5801. The input 2.452 GHz WiFi signal is first down converted to 70 MHz as depicted in Fig. 6.4 bottom (c). The local reference frequency and residual intermodulation products are further filtered out by BPF2 (63 MHz to 77 MHz); the IF band signal is then amplified to drive the RSOA with an electrical swing around 1.5V_{pp}.

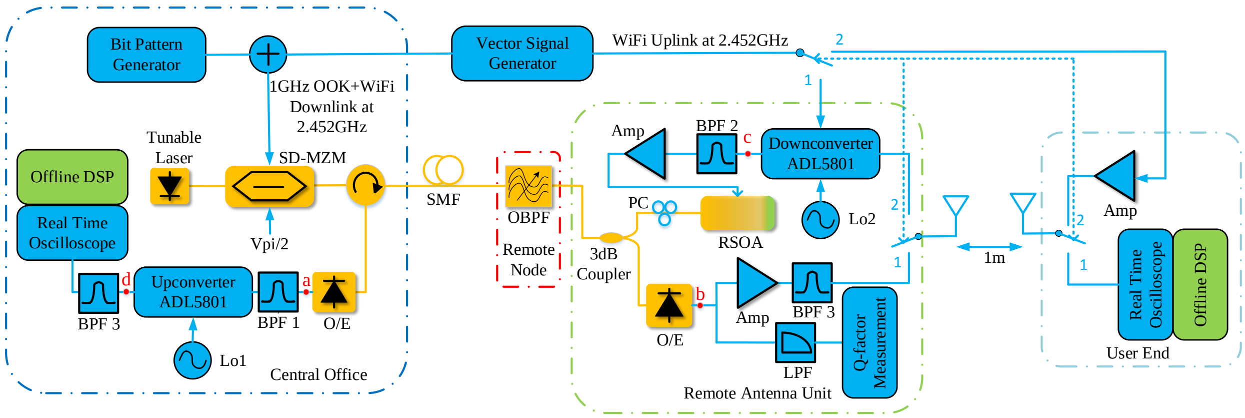


Figure 6.4: Experiment Setup and Spectrums at the Respective Points

Due to equipment availability, two switches are employed. In switch position one we monitor the performance of the downlink RoF signal, while the uplink RoF signal is only present for full duplex optical operation. The downlink WiFi signal is transported optically, routed to an antenna, transported wirelessly, and then captured by an RTO to assess performance of the RoF downlink at the mobile user. The performance of the WiFi uplink (which is never transported wirelessly) is not monitored. In switch position two the WiFi uplink is transmitted wirelessly, the received signal from the antenna drives the RSOA, after fiber transmission the uplink RoF WiFi signal is captured by an RTO to assess performance of the uplink at the CO.

Use of the switches assures that all optical transmissions are full duplex. As we are not assessing the wireless channel, the use of half duplex in the wireless domain is unimportant.

The receiver at the CO sees the downlink WiFi with suppressed downlink OOK signal and the reflected WiFi signal simultaneously. BPF1 (63 MHz to 77 MHz, same as BPF2) extracts the uplink WiFi signal at IF frequency (center 70 MHz) and attenuates the out-of-band noise. The uplink WiFi is contaminated by the downlink suppressed OOK signal and Rayleigh back-scattering noise.

The mixer at the CO upconverts the IF WiFi signal, as seen in the spectrum at Fig 6.5 , back to the original RF band 2.452 GHz. In this way, the physical optical infrastructure is transparent to the wireless signal. Due to the use of a double sideband mixer, the signal is output to a bandpass filter (BPF3 center 2.452 GHz) before being sampled by the RTO. We observe a leakage IF signal after the upmixer when we set the input power to the mixer around

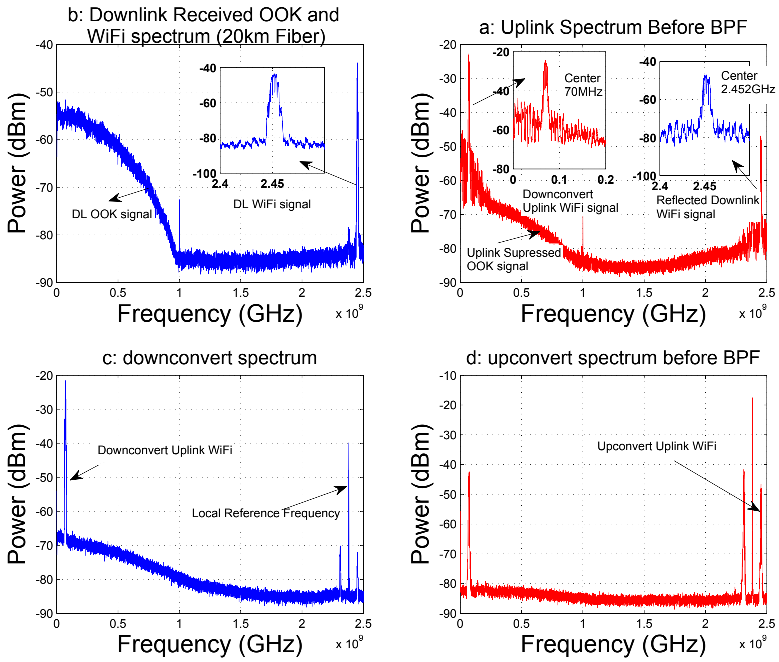
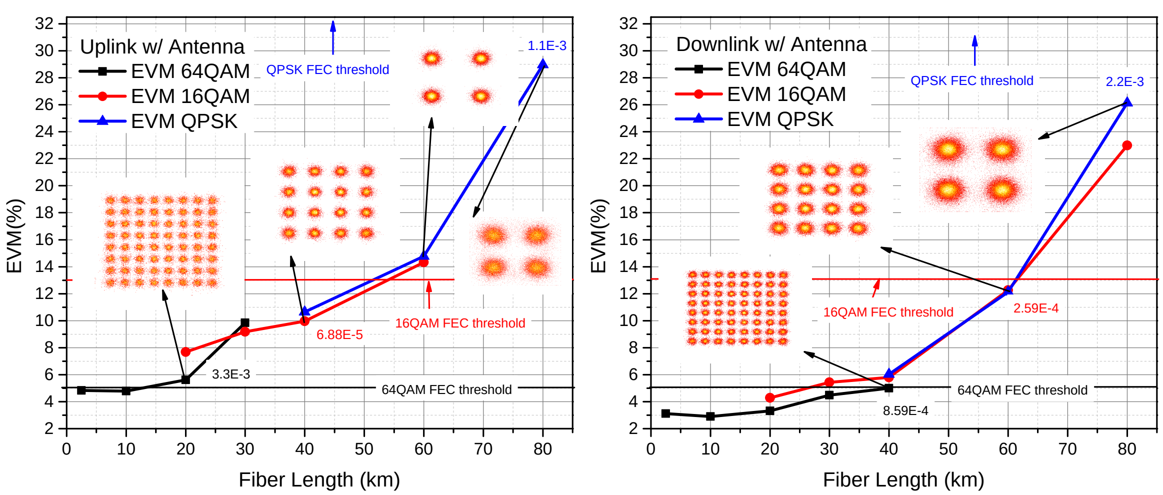


Figure 6.5: Captured Spectrums at the Respective Points

-20 dBm (above the suggested value -35 dBm). The downlink OOK and WiFi signal spectrum is shown in Fig. 6.5 (d).



(a) Uplink with 1m wireless channel

(b) Downlink with 1m wireless channel

Figure 6.6: Downlink and Uplink Transmission Performance and Constellation.

The WiFi transmission performance over full duplex fiber link and half duplex wireless link is recorded in Fig. 6.6. The uplink EVM and BER is calculated with the switch in position two and presented in Fig. 6.6(a). The uplink WiFi is amplified and sent from the user end. After

1 meter propagation in the air, the signal is received by the antenna at RAU and transformed to optical signal. Using the technique in [51], we map the BER threshold to EVM as marked in the figure with black (64QAM), red(16QAM) and blue (QPSK) line.

When the switch is in position one, the uplink WiFi signal goes directly to the downmixer at the RAU and the antennas are invoked for downlink transmission and reception. Results are presented in Fig. 6.6 (b). After 40 km single mode fiber the BER of 64QAM downlink WiFi signal is still below the FEC threshold whereas the uplink WiFi is outage over 20 km fiber. The constellation is inserted at the maximum supported fiber length for different modulation formats. With the limitation of the uplink, the fiber could reach 15 km (64 QAM), 40 km (16 QAM) and 60 km (QPSK) with full duplex WiFi in the fiber and half duplex transmission over the air interface.

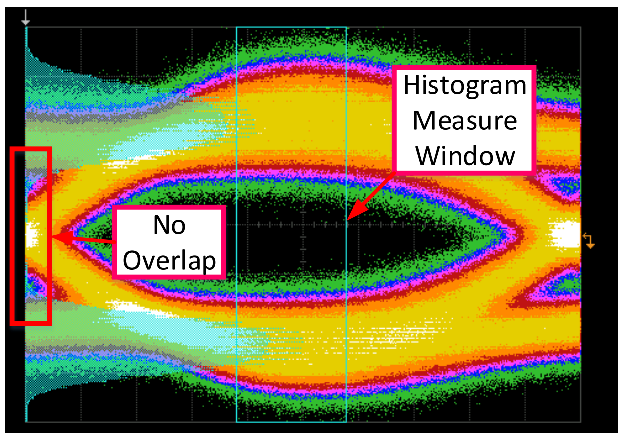


Figure 6.7: Eye diagram and histogram of downlink OOK signal.

The downlink OOK signal performance is also evaluated in Fig. 6.7. The eye diagram and histogram of "1" and "0" levels of the OOK signal after 20 km of transmission is accumulated for 3 minutes. The clear open eye and non overlapped histogram between "0" and "1" levels are achieved, indicating error-free performance. We are restricted by the low efficient and high noise PIN , the OOK is undetectable with the fiber longer than 20 km.

6.4 Conculsion

We analyse and experimentally demonstrated the challenge of using RSOA as the E/O interface in the RAU in RoF DAS adopting WDM PON architecture. In full duplex transmission scenario, we compare the uplink transmission performances adopting IF or RF mixed uplink WiFi signal. IF scheme is more robust to fiber length than the RF scheme. Although the IF scheme add extra complex to the RAU, the improved E/O conversion efficiency and transparent physical layer support make it the only available candidate. Furthermore, we show the feasibility of the WiFi and OOK transmission over the wireless interface and fiber. The results show a full duplex support in the fiber link for wireless interface complying with TDD or FDD mode.

Chapter 7

Conclusion

In this thesis our first contribution is to experimentally demonstrate the possibility of adopting RSOA in radio over fiber system as the reflective E/O modulator. The RSOA has been proved to be capable of handling the high dynamic range wireless signal. The SFDR and frequency response of the RSOA has been characterized experimentally. Then RF and IF radio over fiber scheme are also experimentally compared. To balance between simplicity and scalability of the RAU in RoF system.

In order to achieve a simple RAU architecture, the RSOA is modulated with RF wireless signal at 2.4GHz in the uplink. The RSOA's frequency response put a limitation on the maximum output optical power launched into the fiber. Thus the system reach is severely restricted by the uplink signal power. Higher modulation bandwidth is desired for the optical modulator at the RAU when interfacing with other wireless services. Apparently, the scalability is limited for this kind of RAU design. Especially, when high frequency radio spectrum are multiplexed at the RAU. The simplicity relies on a high end optical modulator. Since the wireless signal are mostly narrow bandwidth signal, so down convert the wireless signal to IF band at the RAU could be an efficient way to utilize the RSOA modulation bandwidth. Thus IF over fiber system performance is demonstrated. The RSOA with 1.2GHz modulation bandwidth could accommodate IF band wireless signal with upto hundreds MHz bandwidth. Low cost optical modulator could be adopted at the RAU with extra complexity due to the mixer circuit.

The second contribution of the paper is that we experimently demonstrate the advantage and disadvantage of an RSOA based radio over fiber system. A transparent optical PHY design supporting analog wireless and digital OOK transportation utilizing wavelength reuse is proposed. A laser free and colorless RAU design is achieved by using RSOA. Thanks to the saturation effect of the RSOA uplink signal could share the laser source with the downlink. Laser free and colorless RAU greatly increase the flexibility and decrease the cost of the system. For transparency, the optical PHY radio over fiber system could be compatible with TDD based wireless system like WiFi, WiMax etc. The RSOA could provide extra gain for the uplink optical signal which is important in wavelength reused system. While, the RSOA's limited bandwidth could not afford the uplink digital signal transmission. On the other hand RSOA's footprint and power consumption make it less appealing than silicon photonics devices. For the collaboration work, we only demonstrate the preliminary possibility by seamless integrating optical PHY with virtualized wireless AP. The orchestration between the optical layer and wireless AP has not been investigated and demonstrate yet. And this will light the way for future research.

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