UNIVERSIDADE DO ALGARVE

DYNAMIC FREQUENCY ASSIGNMENT FIBER-WIRELESS ACCESS NETWORKS

Sérgio Elísio da Cunha Sabino

Master Dissertation in Informatics Engineering

Work done under the supervision of:
Prof. Doutor Álvaro Barradas

2014

UNIVERSIDADE DO ALGARVE

DYNAMIC FREQUENCY ASSIGNMENT FIBER-WIRELESS ACCESS NETWORKS

Sérgio Elísio da Cunha Sabino

Master Dissertation in Informatics Engineering

Work done under the supervision of:
Prof. Doutor Álvaro Barradas

2014

Statement of Originality

DYNAMIC FREQUENCY ASSIGNMENT FIBER-WIRELESS ACCESS NETWORKS

Statement of authorship: The work presented in this thesis is, to the best of my knowledge and belief, original, except as acknowledged in the text. The material has not been submitted, either in whole or in part, for a degree at this or any other university.

Candidate:

____

(Sérgio Elísio da Cunha Sabino)

NETWORKING

Work done at Research Center of Electronics Optoelectronics and Telecommunications (CEOT).

To my mother: Rosalina Jopela

Acknowledgements

Firstly I thank my advisor Professor Doctor Álvaro Barradas for his dedication, suggestions, encouragement and remarkable guidance during the elaboration of this dissertation.

I address my especial thanks to Professor Doctor Noélia Correia. Thank you very much for all your attentions, ideas and suggestions. We are so privileged at research center of electronics optoelectronic and telecommunications (CEOT) laboratory to have someone like you supporting all the students when needed.

I'd like to thanks José Coimbra, also member of CEOT laboratory for his assistance and encouragement.

I thank very much Camões- Instituto da Cooperação e da Lingua, Portugal for the opportunity to take this Master course.

I thank all professors from MEI (Mestrado em engenharia informática) courses, those who contributed to my education.

I thank my all family members for their support during this master course, particularly to my brother Rui Sabino. Thank you for being present whenever I needed your help.

A special acknowledgement to Valentina Asquini. "Grazie mille per tutte i consigli e supporto".

Finally I'd like to thank my mother Rosalina Jopela for the educations and support she always gave to me.

Abstract

This dissertation focuses on the Fiber-Wireless (FiWi) access networks, more specifically on the problem of assigning frequencies to maintain connectivity and acceptable standards of service quality in face of changes in the pattern of traffic flows in the network. Mainly realized on radio and fiber technologies, these networks form an hybrid architecture comprising an optical section and a wireless section that provides a feasible paradigm for high bandwidth and ubiquity at new access network areas. In these FiWi scenarios, in particular when multi-radio and multi-channel configurations are used, an effective frequency assignment should be done to radios so that higher throughput and low delay can be obtained and the best of such architectures is achieved. However, traffic conditions may change over time, meaning that radio channel configurations may be outdated and new reconfigurations can be done to improve network performance. To cope with the increasing demand for bandwidth, fiber to the home/premises/building (FTTX) technologies were massively deployed at the back-end. These technologies are characterized by the huge bandwidth capacity and the absence of active devices on the network plant, which is an advantage for power saving. On the other hand, at the front-end, wireless mesh networks (WMN) are expected to provide mobility and converge different wireless technologies to provide high-speed and huge bandwidth connectivity to the end user. In this dissertation, the frequency reassignment problem in the context of FiWi access networks is discussed and a state-of-art on the subject is proposed. Also, two methodologies for frequency reconfiguration planning are proposed along with their mathematical formalization, and are evaluated by simulation. In one of the strategies, NBR, the algorithm prioritizes channel assignment according to the relative position of nodes and their gateways, while in the other, RBR, nodes are processed as their routes toward the gateways are traversed. A discrete event simulation model to evaluate the performance of the proposed frequency reassignment algorithms was developed using OMNeT++ framework. Simulation results showing that RBR is the algorithm that better exploits channel reconfigurations are presented and discussed.

Keywords: Fiber-Wireless Access Networks, Wireless Mesh Network, Frequency Assignment

algorithm, Frequency Reassignment Algorithm, Network Simulation.

Resumo

Esta dissertação foca-se nas redes de acesso Fiber-Wireless (FiWi), mais especificamente no problema da atribuição de frequências necessária à manutenção de conectividade e de padrões aceitáveis de qualidade de serviço perante alterações na dinâmica de tráfego que circula na rede. Combinando tecnologias de rádio e de fibra óptica, estas redes formam uma arquitetura híbrida, composta por uma seção óptica e uma seção wireless, que se afirma como paradigma viável para os requisitos de largura de banda e omnipresença das novas redes de acesso. Nestes cenários FiWi, especialmente quando são usadas configurações muiti-rádio e multi-canal, torna-se necessário efetuar uma atribuição eficaz de frequências aos rádios para que valores elevados de throughput e de baixo atraso possam ser obtidos, e o melhor desempenho da arquitetura seja alcançado. No entanto, a dinânica do tráfego pode mudar ao longo do tempo, o que significa que uma determinada configuração de canais pode estar desatualizada e novas reconfigurações possam ser feitas para melhorar o desempenho da rede. Para lidar com a crescente demanda por largura de banda tecnologias FTTX (Fiber to the home/premises/building) têm sido massivamente implementadas na secão óptica. Estas tecnologias são caraterizadas pela sua enorme largura de banda e pela ausência de dispositivos ativos na rede, o que é uma vantagem para a economização de energia. Por outro lado, espera-se que na seção óptica as redes sem fio em malha (WMN) possam proporcionar mobilidade e ver convergir várias tecnologias “sem fios” que providenciem maior largura de banda e conetividade ao utilizador final. Nesta dissertação, o problema de reafetação de frequências no contexto das redes de acesso FiWi é discutido e o seu estado de arte apresentado. Além disso, duas novas metodologias para a planificação da reconfiguração de frequências são propostas juntamente com as suas formalizações matemáticas, e são avaliadas por simulação. Uma das estratégias, NBR, prioriza a afetação de frequências de acordo com a posição relativa dos nós e respetivas gateways, enquanto que na outra, RBR, os nós são processados à medida que as suas rotas vão sendo percorridas em direção as gateways. Um simulador de redes FiWi para a avaliação dos algorítmos de reafetação também foi desenvolvio usando a framework OMNeT++. Os resultados das simulações mostram que o RBR é aquele que melhor explora a reconfiguração de canais.

Palavras chave: Redes de Acesso Híbridas Fiber-Wireless (FiWi), Redes Sem Fio em Malha (WMN), Alocação de Frequências, Realocação de Frequências, Simulação de Redes.

Contents

Statement of Originality **ii**

Acknowledgements **v**

Abstract **vi**

Resumo **viii**

Nomenclature **xiv**

1 Introduction **1**

1.1 Motivation and Scope 1

1.2 Objectives 1

1.3 Contributions 2

1.4 Dissertation Outline 2

2 Fiber-Wireless Access Network Overview **3**

2.1 Introduction 3

2.2 Optical Access Networks 4

2.2.1 Passive Optical Network (PON) 4

2.3 Wireless Access Networks 9

2.3.1 Wireless Mesh Network (WMN) 10

2.4 FiWi Access Network 12

2.5 Summary 14

3 Frequency Reassignment in FiWi Access Networks **15**

3.1 Introduction 15

3.2 Frequency Assignment State-of-Arte and Related Works 17

3.3 Mathematical Formalization of Frequency Reassignment Problem 19

3.3.1 Assumptions and Notation 19
3.3.2 FiWi-RTR Problem Formalization 21
3.3.3 FiWi-RTR Problem Formalization with Network Disconnection Avoidance 22
3.4 Algorithmic Approach for Frequency Reconfiguration 24
3.4.1 The Methodology 24
3.4.2 Suitability of the Reconfiguration Process 25
3.4.3 Heuristic Algorithms 26
3.5 Summary 32

4 FiWi Simulation Model 35
4.1 Introduction 35
4.2 Network Simulator 36
4.2.1 OLT 36
4.2.2 WRouter 37
4.2.3 WRGateway 38
4.2.4 ClientNode 39
4.3 Summary 40

5 Experiments and Results 41
5.1 Performance Analysis 41
5.1.1 Parameters 42

6 Conclusions and Future Work 49
6.1 Conclusion 49

References 50

List of Publications 56

List of Figures

2.1 Optical back-end section. 5
2.2 Downstream traffic. 5
2.3 Upstream traffic. 6
2.4 A typical logically point-to-point WDM-PON (*adapted from* [1]). 8
2.5 Infrastructure WMN [2]. 10
2.6 Hybrid WMN [2]. 11
2.7 Radio and fiber architecture 13

3.1 FiWi network used to illustrate algorithms. 29
3.2 Illustration of NBR algorithm. 30
3.3 Illustration of RBR algorithm. 32

4.1 Modules relation in the simulation model. 35
4.2 Simulation Model Network Topology. 36
4.3 OLT and NED code snippet. 37
4.4 Wireless Router and NED code snippet. 38
4.5 ONU/Gateway and NED code snippet. 39
4.6 ClientNode and NED code snippet. 39

5.1 Performance analysis for traffic load equal to 10% of the channel capacity; (a) Average throughput; (b) Average end-to-end delay; (c) Average queue size. . 44
5.2 Performance analysis for traffic load equal to 20% of the channel capacity; (a) Average throughput; (b) Average end-to-end delay; (c) Average queue size. . 45
5.3 Performance analysis for traffic load equal to 30% of the channel capacity; (a) Average throughput; (b) Average end-to-end delay; (c) Average queue size. . 46
5.4 Performance analysis for traffic load equal to 40% of the channel capacity; (a) Average throughput; (b) Average end-to-end delay; (c) Average queue size. . 47
5.5 (a) Average throughput; (b) Average end-to-end delay; (c) Average queue size. 48

List of Tables

5.1 Unchangeable parameters 42
5.2 Non-permanent parameters 42
5.3 Info Related to Matrices 44

Nomenclature

Abbreviations

3G	Third Generation
4G	Fourth Generation
10G-EPON	10 Gigabit EPON
AOP	Active Optical Network
AP	Access Point
ATM	Asynchronous Transfer Mode
AWG	Arrayed Wave Guide
BK	Backoff
BPON	Broadband Passive Optical Network
BS	Base Station
CM	Cable Modem
CO	Central Office
CTS	Clear to Send
CW	Contention Window
DCF	Distributed Coordination Function
DSL	Digital Subscriber Line
DFA	Dynamic frequency assignment
EPON	Ethernet PON
ESS	Extended Service Set
FA	Frequency Assignment
FiWi	Fiber-Wireless
FSAN	Full Service Access Network
FTTB	Fiber To The Building
FTTC	Fiber To The Cabinet

FTTH	Fiber To The Home
FTTX	Fiber To The Premises
GPON	Gigabit PON
HFC	Hybrid Fiber-Coax
HFA	Hybrid Frequency Assignment
IEEE	Institute of Electrical and Electronics Engineers
ILP	Integer Linear Program
IP	Internet Protocol
IPTV	Internet Protocol Television
ITU-T	International Telecommunications Union, Telecommunication Standardization Sector
LOS	Line-of-Sight
MAC	Media Access Control
MIMO	Multi-Input Multi-Output
NED	Network Description
NBR	Node-Based Reconfiguration
NG-GPON	Next-generation 10 Gigabit Ethernet PON
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONT	Optical Network termination
ONU	Optical Network Unit
PCF	Point Coordination Function
PHY	Physical
PON	Passive Optical Network
QoS	Quality of Service
RAU	Remote antenna unit
RBR	Route-Based Reconfiguration
RE	Reach Extender
RF	Radio Frequency
R&F	Radio and Fiber
RoF	Radio over Fiber
RP	Reconfiguration Process
RTR	Reconfiguration Time Reduction

RTS	Request to Send
SAA	Static Assignment Algorithm
SFA	Static Frequency Assignment
SFNet	San Francisco Network
STA	Subscriber stations
TDMA	Time Division Multiple Access
TDMA-PON	Time Division Multiple Access PON
TFR	Traffic Flow Rule
UWB	Ultra Wideband
VoD	Video on Demand
WDM	Wavelength Division Multiplexing
WDM-PON	Wavelength Division Multiplexing PON
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Networks
WR	Wireless Router
WRR	Weighted Round Robin
XG-PON	10 Gigabit GPON

Sets

$\mathcal{G}$	Represents a graph of FiWi access network
$\mathcal{N}$	Set of mesh wireless nodes including gateways
$\mathcal{L}$	Set of reachability wireless links
$\mathcal{C}$	Set of available channels

Set elements

$\mathcal{W}$	A wireless node $\in \mathcal{N}$
$\mathcal{G}$	A gateway node $\in \mathcal{G}$
l	A link $\in \mathcal{L}$
c	A channel $\in \mathcal{C}$

Variables

r_w	Route adopted by node $w \in \mathcal{W}$
R_n	Number of radios available in a node n
D_w	Traffic demand of a wireless node $w \in \mathcal{W}$
B	Bandwidth
$\beta_{n,c}^{OLD}$	Old frequency assignment
$\beta_{n,c}$	New frequency assignment
$\delta_w^{l,c}$	Route usability
α	Channel congestion factor
$\theta_{n,c}$	Monitor the channel variation
$\sigma_w^{l,c}$	Monitor the route availability
h_{r_w}	Number of hops of route r_w
w^+	Successor of the node w toward the gateway
$\mathbf{F}^c$	Time division matrix of channel $c \in \mathcal{C}$
$\mathbf{R}$	Frequency assignment matrix
A	Associative array
Π	List of nodes for processing

CHAPTER 1

Introduction

1.1 Motivation and Scope

The bandwidth requirements of the telecommunication network users increased rapidly during the last decades [3]. FiWi access networks have been pointed as a promising approach to support a plethora of future and emerging broadband services and applications on the same infrastructure by converging optical access technologies at the back-end and wireless access technologies at the front-end [4][5].

Within the frame of this dissertation more emphasis will be placed at the front-end technologies, where wireless nodes are configured in a mesh topology forming a WMN. In this WMN nodes may be equipped with multiple radio interfaces operating in multiple orthogonal frequencies aiming to provide higher network throughput. Therefore, in multi-radio WMNs, higher network throughputs exist if an effective frequency assignment to radio interfaces is done. However, frequency assignments may become outdated after network traffic changes, which eventually may reduce the network throughput. Thus a channel reconfiguration process capable of maintaining the network connectivity, keep the QoS acceptable and increase throughput is desirable. The main motivation for this work is to study FiWi access networks and develop an algorithm able to find the best frequencies to be assigned to radios, starting from an initial frequency assignment setup, so that the network can adapt to changing traffic conditions without loosing performance.

1.2 Objectives

The objective of this work is to study an effective way to plan the reassignment of frequencies at the wireless mesh front-end. New frequency assignments should adapt to recent network traffic distributions, allowing throughput and QoS to be improved, while avoiding network disruption.

It includes the following tasks:

- Analysis of FiWi access networks;
- Development of a simulation model for a FiWi access network;
- Proposal of frequency reassignment algorithms;
- Evaluation of the proposed algorithms.

1.3 Contributions

The main contributions of this work include the following:

- Presentation of the state-of-art on FiWi access networks with emphasis on the frequency assignment problem.
- A simulation model for a FiWi access networks available for future work.
- Two frequency reassignment algorithms developed, tested and evaluated.
- Two articles were produced from this dissertation, one submitted to the CISTI 2014 and another submitted to the computer network journal (Elsevier).

1.4 Dissertation Outline

In this dissertation there are 6 chapters organized as follows:

Chapter 1 introduces the subject, presents the motivation, and the scope of this work. The objectives are also stated in this chapter and main contributions are refereed.

Chapter 2 provides an overview of FiWi access networks, visits some related work, and the main technologies involved in FiWi access architecture are described.

chapter 3 presents the state-of-art of the frequency assignment strategies. Two reassignment algorithms and their respective mathematical formalization are presented and discussed.

Chapter 4 presents the FiWi simulation model, developed under OMNeT++ framework. In this chapter the models components of the model are described and their functionality is explained in detail.

Chapter 5 analyses and discusses the simulation results of the proposed algorithms.

Chapter 6 concludes this dissertation and states some considerations for future work.

CHAPTER 2

Fiber-Wireless Access Network Overview

2.1 Introduction

The fast growth of the bandwidth demand from subscriber application and emerging services such as video on demand (VoD), Internet protocol (IP) telephony, online gaming, or full-duplex video-conferencing, has led to intensive research in the access network. Current copper-based access network technologies such as digital subscriber line (DSL), hybrid fiber-coax (HFC) and cable modem (CM) do not meet the bandwidth requirements for these emerging services. Therefore, optical fiber-based networks such as fiber to the home/fiber to the premises (FTTH/FTTP) are being deployed to cope with the ever increasing need of huge bandwidth. In FTTX networks, fiber is brought (close) to the end user, to a place denoted by X where a discontinuity between the optical fiber and some other, either wired or wireless, transmission medium occurs [6]. Due to their low attenuation, and huge bandwidth, passive optical networks (PONs) are widely deployed to realize cost-effective FTTX access networks [7][8]. Moreover, PONs are able to provide lower network deployment and maintenance costs as well as longer distances than current DSL and HFC networks [9]. Wireless broadband access networks have attracted a great deal of attention from research as well due to their low implementation costs and mobility support [10][11]. There are three main technologies that have been successfully employed for wireless access networks worldwide: Wireless fidelity (WiFi), Worldwide interoperability for microwave access (WiMAX), and Cellular Network. Generally a radio using one of these standards is configured to operate on a single channel. Researchers in [12][13][14] and recently [15][16] agree on the usage of multiple radios operating at different channels to increase the performance of WMNs. In this case, frequency channels should be carefully assigned to radios in order to reduce interference and effectively contribute throughput improvement of global network performance.

Optical access networks offer huge amount of bandwidth and wireless access networks offer mobility and ubiquity. The idea of combining these two networks is very attractive since it would allow the exploitation of the complementary benefits of both technologies. This led to the FiWi network proposal where optical and wireless technologies form a common integrated infrastructure capable of supporting upcoming applications and services while offering seamless mobility to clients [10].

The remainder of this chapter is structured as follows: Section 2.2 presents the optical access networks architectures. The currently adopted standards and technologies are also discussed in this very section. Section 2.3 covers wireless access networks, their adopted standards and technologies. Section 2.4 addresses the most implemented technologies for FiWi architectures on the access side and their main design challenges, and finally Section 2.5 summarizes this chapter.

2.2 Optical Access Networks

Basically, three architectures may be deployed for fiber access networks [7][17]: Point-to-point architectures, active star architecture leading to active optical networks (AON) and passive star architecture leading to passive optical networks (PON). In a point-to-point architecture, all subscribers are connected to the central office (CO) via dedicated fibers. Many fibers are needed, which entails high first installation costs, but also provides the ultimate capacity and the most flexibility to upgrade services for subscribers individually. In AON, a single fiber carries all traffic to an active node close to the subscriber premises. Only a single feeder fiber is needed, and a number of short branching fibers to the subscribers, which reduces costs; but the active node needs powering and maintenance. In contrast to an AON, in a PON the active node is replaced by a passive optical power splitter/combiner that feeds the individual short branching fibers to the subscriber premises. Besides technical performance, economic considerations play a key role in deciding for a particular architecture [7]. Among these architectures PONs are widely deployed as FTTX access networks, and they are discussed in detail in the following section.

2.2.1 Passive Optical Network (PON)

PONs are generally characterized by the absence of active components, with the exception of the premises where the optical line termination (OLT) and the optical network unit/optical network termination (ONU/ONT) are placed. However, a PON can also include a reach extender (RE), which contains active components, when long distance between the OLT and the ONU is required. These can be deployed in several topologies such as bus, ring and tree, being the former the most adopted PON topology, as shown in Figure 2.1. In this case transmission occurs between an OLT, located at CO, and multiple ONUs located at subscriber premises. The OLT and ONUs are connected via one or more inexpensive passive splitters deployed as part of the fiber optical cable plant as aforementioned, mostly in point to multipoint configuration, with splitting factors 1:16, 1:32, 1:64 or more, according to International Telecommunication Union - telecommunication standardization sector (ITU-T) Recommendation G.671 [18].

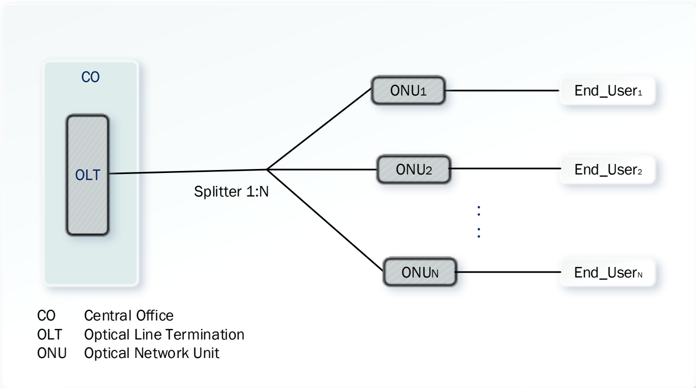


Figure 2.1: Optical back-end section.

Concerning how traffic flows inside PON trees, in the downstream (OLT to ONU) traffic is broadcast to all ONUs using a splitter. Then, based on each ONU's media access control (MAC) address, ONUs extract the traffic addressed to them discarding additional traffic as shown in Figure 2.2.

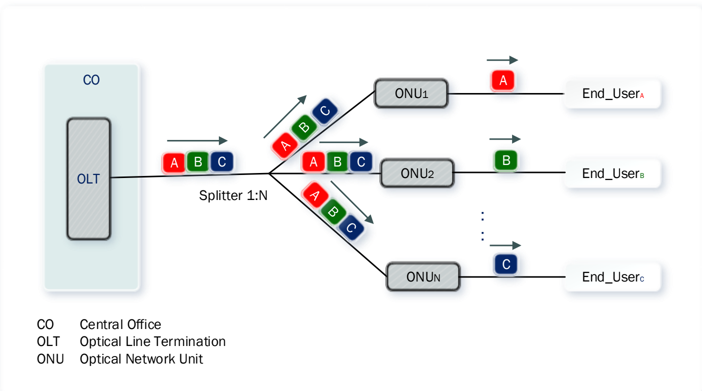


Figure 2.2: Downstream traffic.

For the upstream (ONU to OLT) it should be seen as a multipoint to point network where time division is required [19], and there is no direct communication between ONUs, as depicted in Figure 2.3.

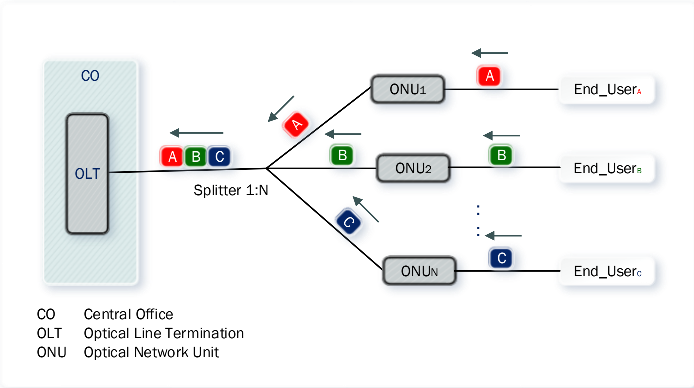


Figure 2.3: Upstream traffic.

Time division multiple access (TDMA) techniques are commonly used for that purpose but, for network capacity and scalability increase, wavelength division multiple access (WDMA) techniques can also be used. In TDMA-PON systems, the bandwidth is shared in time domain, where each ONU has its specific time slot to transmit data packets. Transmission time slots are synchronized by OLT, which send grants to ONUs instructing them when to send packets. The basic fiber infrastructure carries a single upstream wavelength channel and another single downstream wavelength channel. As the ONUs are sharing the capacity of the OLT, the average capacity per ONU decreases as the number of ONUs grows. This marks a drawback to TDMA-PONs when network scalability is required [7]. The full service access network (FSAN) group was founded in the earlier 1995 for the development of optical access network standards capable of delivering a full set of narrowband and broadband telecommunication services. Broadband passive optical network (BPON) was the first one to be proposed, then followed by two other variants so far widely used, namely the Gigabit PON (GPON) and Ethernet PON (EPON).

- BPON is based on asynchronous transfer mode (ATM) and is also referred to as asynchronous transfer mode passive optical network (APON). The transfer rate in BPON is specified as 155.52 Mbps according to ITU-T G.983 series recommendations [20].

- GPON is specified by ITU-T G.984 series [21][22][23][24], the normal bit rate is specified to 2.488 Gbps downstream traffic and 1.244 Gbps for the upstream. It comprises an additional downstream wavelength for distribution of analog video service. The network supports up to 60 km reach, with 20 km differential reach between ONUs, and a minimum supported passive splitting ratio of 1:16, 1:32, or 1:64 way split.

- EPON is a PON that carries all data encapsulated in Ethernet frames, based on the IEEE 802.3ah standard [25] providing bidirectional 1 Gbps links and offering a splitting ratio up to 1:64. A 1490 nm wavelength is used for downstream and 1310 nm for upstream, with 1550 nm reserved for future extensions or additional services, such as analog video broadcast.

In September 2009 the IEEE completed the standardization of next-generation 10 Gigabit Ethernet PON (NG-EPON) [26]. It extends the EPON and offers a tenfold leap in bandwidth up to 10 Gbps in the access network while providing core protocol compatibility with the current 1G-EPON system, supports symmetric 10 Gbps downstream and upstream and asymmetric 10 Gbps downstream and 1 Gbps upstream data rates [27]. Standardizations efforts have already been initialized in the ITU-T to specify the 10 Gigabit capable PON (XG-PON). The FSAN community has commissioned a study on defining possible smooth migration scenarios from the current Gigabit-class PON systems toward the next-generation passive optical networks (NG-PON), and their technical requirements [28][29]. The outcomes of this study previews two potential candidate system architectures [28]:

- NG-PON1 supports coexistence with GPON on the same optical distribution network (ODN) and is viewed as a midterm upgrade. ODN is defined as the fiber plus the splitter(s) deployed between OLT and ONUs.

- NG-PON2 has no requirements in terms of coexistence with GPON on the same ODN and is considered as a long-term proposal.

The WDM-PON is considered to be the next evolutionary solution for a simplified and future-proofed access system that can accommodate exponential traffic growth and "bandwidth-hungry" new applications. WDM-PON mitigates the complicated time sharing and power budget issues in TDM-PON by providing point-to-point optical connectivity to multiple end users through a dedicated pair of wavelengths [30]. In a general WDM-PON architecture a passive wavelength router is used to replace the passive splitter in the PON fiber plant. As a result, each OLT-ONU pair gets a dedicated and permanent wavelength assignment requiring two transmitter/receiver pairs to form a point-to-point link as shown in Figure 2.4. The passive wavelength router located at the remote node is realized by arrayed wave guide grating (AWG) or a set of thin film filters (TFF)s. An AWG can operate over multiple free spectral ranges, permitting use of the same device for both downstream and upstream transmission, and an ONU can operate at a rate up to the full bit rate of the wavelength channel and without facing resource competition among them.

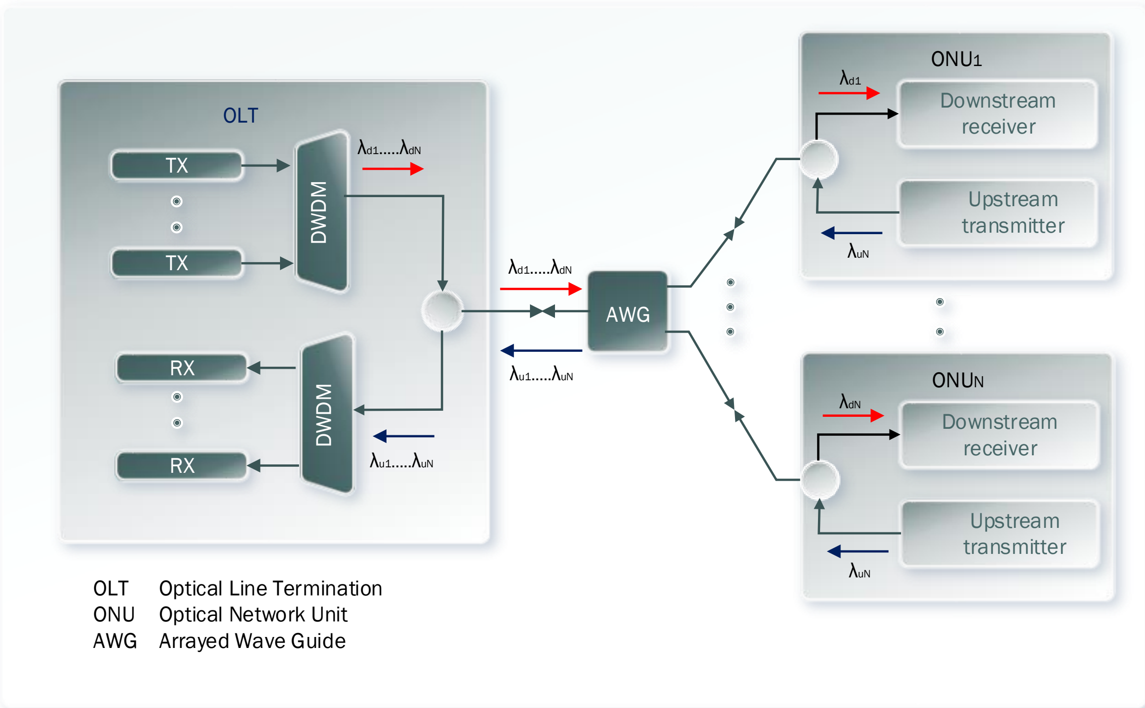


Figure 2.4: A typical logically point-to-point WDM-PON (*adapted from* [1]).

WDM-PONs can also be combined with additional TDMA techniques in particular those already used by the EPON and GPON standards. This leads to hybrid WDM/TDMA-PONs and improves scalability by allowing splitting ratios of up to 1:1000. PONs using standard WDM techniques, particularly broadband amplification, can also support enhanced distances in the range of 100 km. This leads to the concept of active PONs, which could play an important role in future metro access and back-end convergence scenarios [31] . These hybrid systems can be classified as static and dynamic WDM/TDMA-PONs as detailed in [32], where:

- Static WDM/TDMA-PON is defined as a PON system in which several wavelengths can be used in each direction to realize communication between the OLT and a number of ONUs, each wavelength can be shared by several ONUs, and the wavelength(s) assigned to an ONU remain unchanged from installation until disconnection. The optical branching device is typically a power splitter, or a combination of a power splitter and a wavelength filter/router.

- Dynamic WDM/TDMA-PON is defined as a PON system in which several wavelengths can be used in each direction to establish communication between the OLT and a number of ONUs, each wavelength can be shared by several ONUs, and ONU wavelength assignment can be dynamically changed during communication/operation.

2.3 Wireless Access Networks

Wireless networks consist of a number of nodes which communicate with each other over a wireless channel [33]. There are many broadband wireless access technologies [34]. Wi-Fi technologies such as IEEE 802.11 b/g and IEEE 802.11a standards, providing 3 and 12 non-overlapping channels respectively, and WiMAX IEEE 802.16 standard are generally deployed as the main technologies for the wireless part of the FiWi access networks [6]. WiFi are characterized by the use of unlicensed frequency band (2.414–2.484 GHz), and the MAC layer uses distributed coordination function (DCF) as the default technique to access the transmission medium. In DCF subscriber stations (STAs) associated with the AP use their radio interfaces for sensing if a channel is available. If the channel is not in use, the source STA sends its data to the destination STA through the associated access point (AP). If more than one STA try to access the channel simultaneously a collision occurs. In order to avoid collisions carrier sense multiple access/collision avoidance (CSMA/CA) mechanism is used [35]. An alternative medium access technique is point coordination function (PCF) in which data transmission can be done ether in centralized mode, where the AP polls each STA in a round-robin fashion, or in contention-based mode, which works similarly to DCF. In addition, the Request To Send (RTS)/Clear To Send (CTS) mechanism is applied to solve the hidden node problem [34]. IEEE 802.11 b/g can reach data rates up to 11/54 Mbps.

IEEE 802.16 standard was initially established to operate in the frequency band of 10-66 GHz and maximum transmission range of 50 km, providing up to 75 Mbps data rate line-of-sight (LOS) connections in both point-to-multipoint and mesh modes. The standard specifies the radio interface, including the MAC and physical PHY (layers), of broadband access. The key development in the PHY layer includes orthogonal frequency-division multiplexing (OFDM), in which multiple access is achieved by assigning a subset of sub-carriers to each individual user [36]. The 802.16e amendment added support for mobile users in a range of 5-15 Km with maximum theoretical rates up to 30 Mbps.

WMN is an access emerging technology for wireless access networks in which several different wireless technologies are expected to converge. In fact, in this context, technologies such as WiFi based WLANs, 3G/4G cellular systems and WiMAX can be used together to provide high-speed and huge bandwidth connectivity to the end user.

2.3.1 Wireless Mesh Network (WMN)

WMN is a fully wireless network that employs multi-hop ah-hoc networking techniques to forward traffic to/from the Internet [14][37]. WMN are gaining significant momentum as an inexpensive way to provide last-mile broadband Internet access [38][39]. There are two types of nodes in a WMN: mesh routers and mesh clients. Mesh routers are fixed and dedicated nodes which build a wireless backbone for mesh clients. A mesh client may work as a router for a mesh networking, but their hardware platform and software may be much simpler than those for mesh routers [2]. In the context of a FiWi network, the traffic flows toward the ONU through multiple paths. There are three main types of architectures of WMNs: infrastructure, client and hybrid. In an infrastructure WMN architecture, see Figure 2.5, a router has no mobility. It performs mesh functions such has routing and configurations, acting as a network gateway.

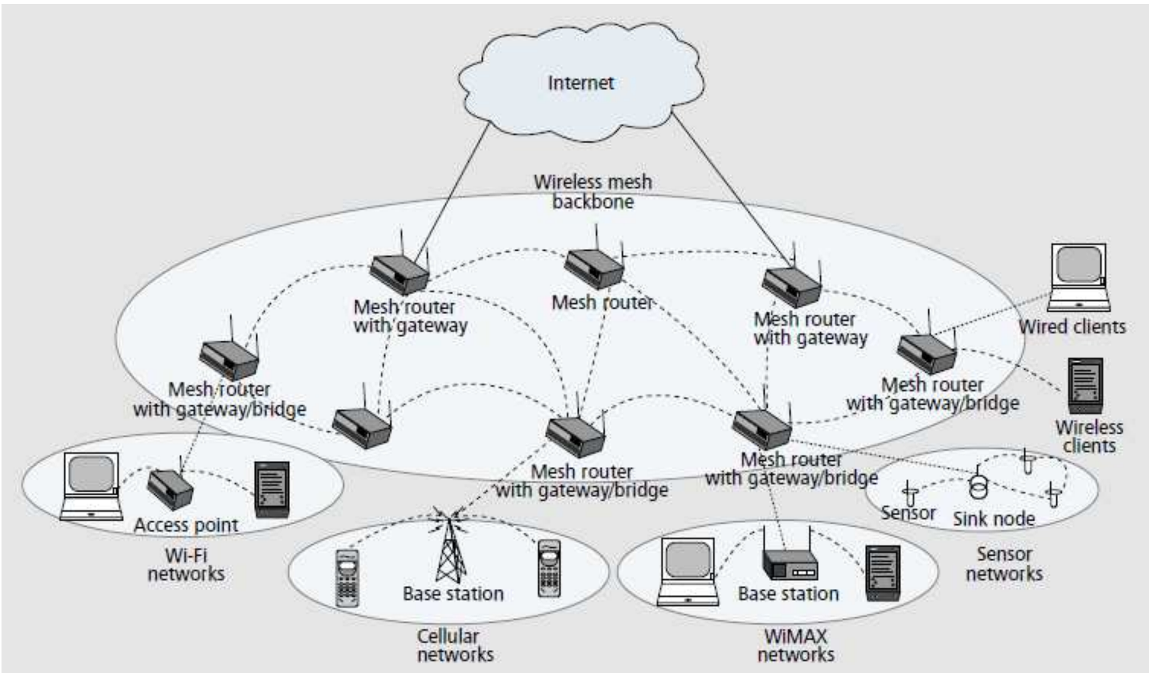


Figure 2.5: Infrastructure WMN [2].

In a client WMN architecture, client nodes perform mesh and gateway functions among themselves, acting as a conventional ad hoc network. Finally, in a hybrid WMN architecture both infrastructure and client meshing are combined as depicted in Figure 2.6.

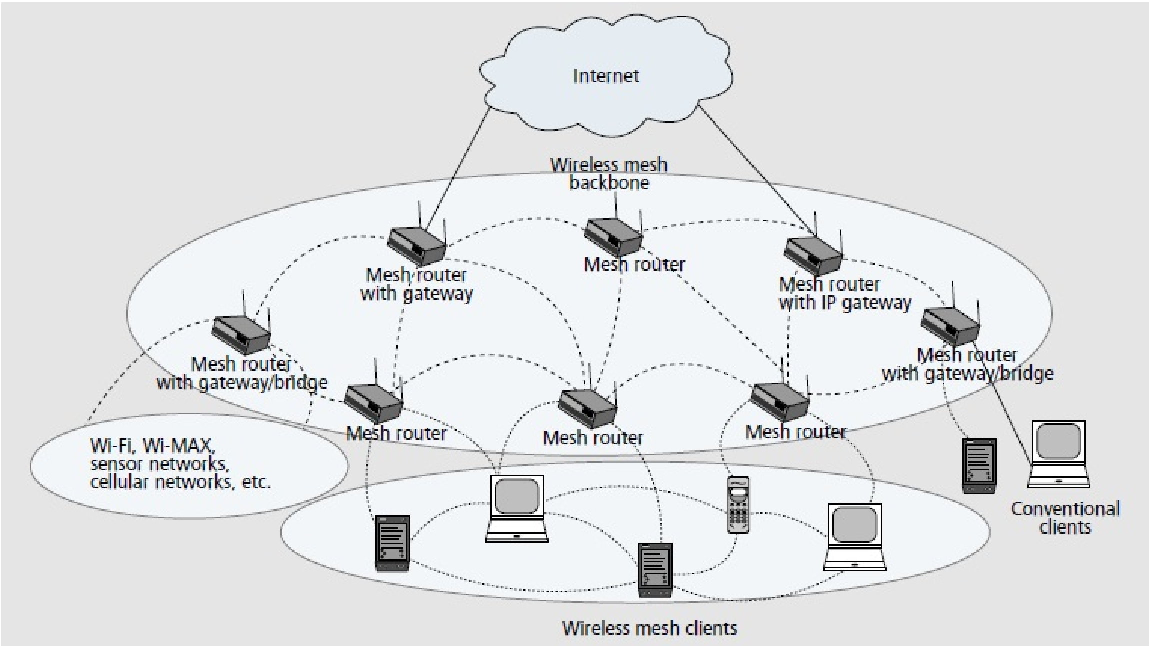


Figure 2.6: Hybrid WMN [2].

Although multi-radio and multi-channel WMNs are envisaged as one of the key components in the converged networks of the future [14], there are still some critical constraints that affect their performance. New technologies and protocols in the PHY layer, MAC protocols, and routing protocols are required to optimize the performance of WMNs. In the PHY layer, smart antenna, multi-input multi-output (MIMO), ultra wideband (UWB), and multichannel interface systems are being explored to enhance network capacity and further enable wireless gigabit transmission [8].

Given the increase demand for mesh networks, a task group was formed in 2004 to define the Extended Service Set (ESS) mesh networking standard based on IEEE 802.11 standard [8]; IEEE 802.11s amendments should be focused on multi hop routing, MAC enhancements, security, and general topics.

2.4 FiWi Access Network

FiWi access networks aim to integrate optical fiber and wireless networks technologies together by providing the strong features of both, such as huge capacity and stable transmission from optical fiber domain, and the flexibility offered by wireless access domain. This combination brings as outcome a reduction on the cost and complexity of the network implementation. FiWi networks are realized by deploying two main technologies: radio-over-fiber (RoF) and radio-and-fiber (R&F) technologies. In RoF, radio frequencies (RF) are carried over optical fiber links between the CO and multiple low-cost remote antenna units (RAUs) in support of wireless application, such as WLANs [40]. In RoF architecture the CO takes the control of all access to the optical and wireless media. Experimentally, it was demonstrated that RoF networks are capable to reach 50 Km of optical fiber range. However, inserting an optical distribution system in wireless networks may have a major impact on the performance of media access control MAC protocols. The additional propagation delay may exceed certain time-outs of MAC protocols and the network performance would become worse [9]. This technology basically relies on modulation techniques to realize a FiWi access network that are fully exploited here [41][42]. A different approach is taken in R&F architectures, where the control of optical and wireless media is decentralized. By using two different MAC protocols, a translation must be done at the interface of optical and wireless segments by an appropriate optical-wireless device, such as the optical network unit-base station (ONU-BS). As a consequence, wireless MAC frames do not have to travel along the optical fiber to be processed at the CO by the optical line termination (OLT), but simply traverse their associated access point (AP) and remain in the wireless network, thus avoiding the negative impact of fiber propagation delay on the network performance [9][43][44].

This work consider a R&F based FiWi access networks represented by architecture having sections. A FiWi architecture typically includes at the optical section a PON technology such as EPON or GPON, in a tree topology with one or more OLTs as the root. At the wireless section a WMN generally composed by IEEE 802.11 and IEEE 802.16 standards is a typical choice. Figure 2.7 depicts a deployment of a R&F architecture for a FiWi access network infrastructure at University of California (UC) Davis integrating Ethernet passive optical network technology (EPON) and an IEEE 802.11g standard WLAN-based WMN [5].

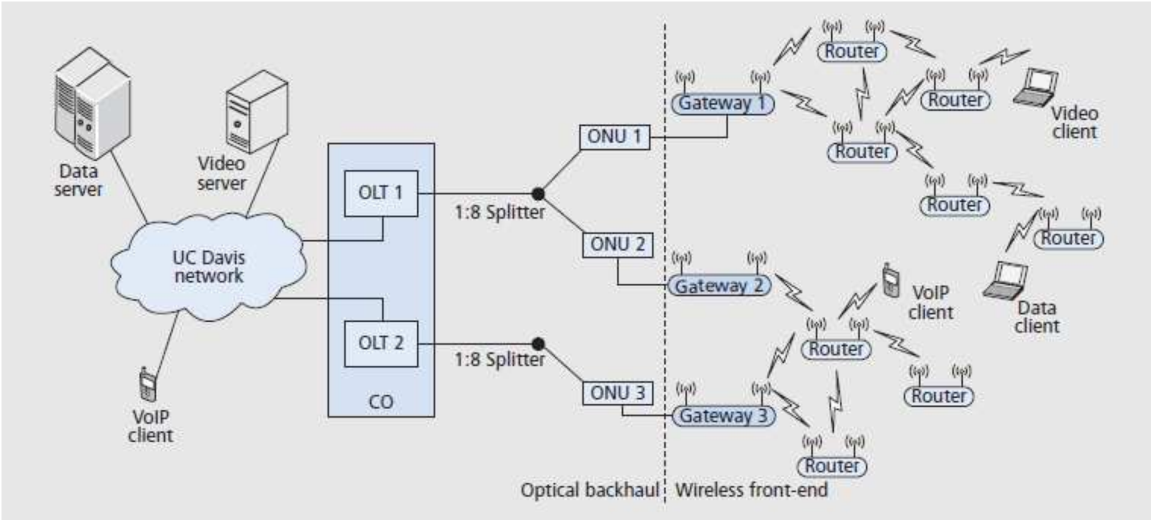


Figure 2.7: Radio and fiber architecture-R&F [9].

The integration of optical and wireless technologies is the most promising solution for the access bottleneck in communication network [4]. However, there are still some technological challenges. One first challenge is to seamlessly converge optical and wireless technologies as they are ruled by different protocols. For instance in [45], the author propose the convergence of EPON and IEEE 802.16 (WiMAX) network by mean of a module (termed Virtual ONU-BS) placed between an ONU and a WiMAX BS to serve as bridge between the two technologies. Also, QoS in FiWi access networks should be kept acceptable. However, designing a QoS algorithm in such heterogeneous environment where applications and services have different QoS requirements still a challenging problem. Moreover, the level of provided QoS largely depends on the performance of the implemented routing and resource management algorithms, including bandwidth allocation and FA algorithm with absolute or relative QoS assurances [9]. Research work has been carried out in designing various QoS algorithms which improve specific aspects of the system [46][47]. A QoS architecture of integration of GPON and WiMAX is proposed in [46]. A recent work by [47] presented an algorithm that can be used for planning and design of QoS considering energy saving in a FiWi access networks. The proposed algorithm finds the proper way of putting into sleep/awaking mode the devices in the network, so that energy consumption is reduced while packet delay is kept under threshold. Routing information and channel assignment at FiWi access network front-end are important and challenging problems as well. Authors in [48] present a proactive routing algorithm termed DARA (delay-aware routing algorithm) which has the objective of minimizing the average of the packet delay in the wireless front-end of a FiWi access network.

As the contribution to this challenging issues the following chapter covers the problem of assigning frequencies to nodes equipped with multiple radios in multi-channel environment.

2.5 Summary

This chapter provides an overview of FiWi access networks and visits some related work. It presents optical and wireless access networks, and their currently adopted standards and technologies. Two main technologies, RoF and R&F involved to realize FiWi access networks are presented and, finally, some design challenging issues are addressed. In this dissertation, FiWi access networks with a mesh front-end are the main focus of study.

CHAPTER 3

Frequency Reassignment in FiWi Access Networks

3.1 Introduction

FA in a multi-radio WMN aims to assign frequencies to radios in a way that interference between transmissions is minimized, increasing the network throughput. A taxonomy of frequency assignment can be found in [14], where three main strategies are presented, namely, a static frequency assignment (SFA) strategy, dynamic frequency assignment (DFA) strategy and hybrid frequency assignment (HFA) strategy. In SFA frequencies are assigned to radios either permanently or for long time intervals with respect to the radio switching time. Static assignment can be further classified into two types:

Common frequency assignment: in this case radio interfaces of each node are all assigned a common set of channels. This approach has a main benefit of ensuring that connectivity of the network is the same as that of a single channel assignment approach.

Varying frequency assignment: in this approach, radio interfaces of different nodes may be assigned to a different set of channels. Therefore, there is a possibility that the length of the routes between nodes may increase. Also, unless the interface assignment is done carefully, network partitions may arise [14][49].

DFA is strategy in which channels are constantly updated to provide better performance,meaning that radio interfaces should have the ability to switch from one channel to another. It is a key property that can be exploited to utilize all the available channels, even when the number of radio interfaces available is significantly lower than the number of available channels [49][50]. However, the key challenges involve channel switching delays (typically on the order of milliseconds in commodity 802.11 wireless cards), and the need for coordination mechanisms for channel switching between nodes [14]. In HFA [51] some radios receive static assignments while others use dynamic assignments.

Some researchers [52] argue that the taxonomy presented above fail to capture the main factors that affect the network performance. Therefore, in their perspective, FA scheme classification should be based on connectivity, minimal interference, and flow patterns, three aspects that can have the following implications: Although schemes based on connectivity have the advantage of being simpler, they do not have a satisfactory performance. In strategies that consider minimizing interference among neighboring nodes, in most cases, when links carry more traffic they would be assigned more bandwidth. If bandwidth and the traffic load did not match, it would result in congestion and increasing packet loss rate. The flow-based channel assignment strategies mainly consider the flow pattern of the traffic, a suitable characteristic for the networks where traffic is directed to/from the Internet such as WMN. However, such strategies can not minimize the network interference between neighboring nodes, thus seriously affecting the capacity of the mesh network. An hybrid approach considering both minimizing interference and flow pattern, which can greatly improve the network performance, is presented in [53].

A FA strategy classification that best suits to FiWi access networks and is able to capture and evaluate the network performance can be found in [54]. These FA schemes are classified into two categories: centralized or distributed. For the centralized approaches, a central control (in FiWi networks OLT may performs this task) is assumed and has complete knowledge about the mesh network. Thus, the formulated FA problem can be solved at a single place. After the result of FA is calculated, it is distributed to the nodes of the network.

For the distributed approaches, no central control is assumed and each node runs its own copy of the algorithm for channel assignment.

Frequency assignment should be done also having QoS into consideration. In this dissertation frequency assignment is studied in the context of FiWi networks where traffic flows toward the ONUs. That is, in these networks traffic either flows from a wireless router source to an ONU, or vice versa, while in traditional WMNs both source and destination can belong to the wireless mesh. Therefore, the approaches for FiWi networks and traditional WMNs are different since this must be taken into consideration.

In this chapter the problem of reassigning frequencies to radios in a multi-radio and multichannel FiWi access network is addressed. Here, the terms frequency strategy and frequency algorithm are used interchangeably. A survey on previous work related with this subject will help us in addressing their main issues while presenting the state-of-art.Finally two new frequency reassignment strategies will be proposed.

The next section provides the FA the state-of-art; Section 3.3 presents the mathematical formalization of the frequency reassignment; Section 3.4 presents the proposed algorithms and, finally, Section 3.5 summarizes this chapter.

3.2 Frequency Assignment State-of-Arte and Related Works

Several strategies for the FA problem in a multi-radio multi-channel WMN have been proposed in the literature [14][55][56][57]. Nevertheless, it is still a challenging issue that has been proven to be NP-hard [58]. This is also why most of the FA works presented employ heuristic techniques to perform this task. The FA problem can actually be divided into two sub problems: Firstly, in *neighbor-to-interface binding*, is determined which interface a node uses to communicate with each of its neighbors. In this context of multi-channel multi-radio mesh networks, connectivity should be kept in mind when doing frequency assignment so that neighboring nodes that need to communicate are assigned a common channel. This is in contrast with cellular network [59], where the goal is to share channels among base stations in neighboring cells and reuse them across distant cells. Secondly, in *interface-to-channel binding*, to determine which radio channel a network interface should use.
The main constraints that FA algorithm needs to satisfy can be summarized as follows [55]:

- The number of distinct channels that can be assigned to a WMN node is bounded by the number available radios.
- Two nodes that communicate with each other directly should share at least one common channel.
- The raw capacity of a radio channel within an interference zone is limited.
- The total number of non-overlapped channels is fixed.

There are some research work such as in [60][61] that proposes MAC protocols to perform channel assignment that require changes to IEEE 802.11 standards, this approaches have disadvantages because they cannot be deployed by using commodity hardware. In [14] authors propose a FA scheme called MesTiC which stands for mesh-based traffic and interference aware channel assignment. It is a static, rank-based, polynomial time greedy algorithm for centralized channel assignment, which visits every node once. Here each node is assigned a rank which is computed on the basis of its link traffic characteristics, topological properties, and number of radios on a node. Topological connectivity is ensured by a common default channel deployed on a separate radio on each node, which can also be used for network management. The channels to a node are assigned based on its rank, the higher ranked node will be assigned a channel of least interference. The traffic/load should be known from the beginning, as it is used as input to evaluate the rank of each node in the network. A fully distributed FA algorithm that can adapt to traffic load dynamically is presented in [55]. A multi-channel WMN architecture (called *Hyacinth*) is proposed, having each node equipped with multiple 802.11 radio interfaces. First *neighbor-to-interface binding* mapping is determined. For the FA to take place, particular radio interfaces (termed DOWN-NICs) have to estimate the usage status of all the channels within its interference neighborwood. In this architecture, each node periodically exchanges its channel usage information with all its neighbors within its interference range. The aggregated traffic load of a particular channel is estimated by summing up the loads contributed by all interfering neighbors that are using the channel. The total load of a channel is a weighted combination of the aggregated traffic load and the number of nodes using the channel. Based on the per-channel total load information, a WMN node determines a set of channels that are least-used in its vicinity. The Priority of a WMN node is equal to its distance in hops from the gateway. When a WMN node performs channel assignment, it restricts its search to those channels that are not used by any of its interfering neighbors with higher priority. Because traffic pattern and, thus, channel load can evolve over time, the *interface-to-channel binding* mapping is adjusted periodically. The architecture used in this scheme requires an higher number of radios than other surveyed strategies which is a disadvantage. The authors in [62] proses a flow-aware channel assignment scheme in the context of wireless-optical broadband access network. This scheme aim to balance load among different channels to minimize contention based on the flows on the link. The authors considered in their approach the fact that wireless nodes at front-end are equipped with different number of radios and they formulated this problem as an Integer Linear Program (ILP) and solved it using a standard solver such as CPLEX.

These surveyed studies make frequency planning from scratch without taking into consideration the previous assignment done. In this dissertation another step forward is taken and an approach for frequency reconfiguration planning in FiWi networks while avoiding network disconnection is proposed.

3.3 Mathematical Formalization of Frequency Reassignment Problem

When planning the reassignment of frequencies at the front-end of FiWi networks one has to take into consideration the recent traffic distribution across the network, so that throughput can be maximized when adopting the new frequencies. This goal alone, however, may become impracticable as too many reassignments can be triggered for a small network throughput increase. Traffic also varies over time meaning that recent frequency assignments may quickly become outdated. A more realistic approach should try to minimize the required frequency reassignments for node congestion prevention when the traffic scenario changes. This problem, called reconfiguration time reduction (RTR) problem, is defined as follows for FiWi networks:

Definition 1 (FiWi-RTR Problem)**.** *Given a FiWi access network find the front-end frequency reassignment, involving the smallest number of frequency changes, and routing of traffic demands that keeps QoS acceptable by preventing node congestion.*

When evaluating node congestion one can use as channel capacity a fraction of the actual channel capacity. The fraction to be considered depends on the burstiness of traffic and resulting queueing delays, and QoS concerns.

3.3.1 Assumptions and Notation

A FiWi network can be represented by a directed graph $\mathcal{G}_{\mathcal{F}}(\mathcal{N}, \mathcal{L}, \mathcal{I})$, where $\mathcal{N}$ is a set including both mesh wireless nodes and gateways while $\mathcal{L}$ is the set of wireless reachability links available at the front-end. Mesh wireless nodes[1] will be denoted by $\mathcal{W}$ and gateways by $\mathcal{G}$, both included in $\mathcal{N}$. Every wireless node needs a route toward one of the gateways/ONUs in order to send/receive traffic. A route r_w adopted by node $w \in \mathcal{W}$ toward gateway $g \in \mathcal{G}$ can be defined as a sequence of nodes $(w, w_{i_1}, w_{i_2}, ..., g)$ where every pair of adjacent nodes can communicate, ensuring connectivity between front and back ends. Note that although directed routes are considered for an easier formalization of the problem, in practice any route can be used for upstream and downstream transmission.

Interference between links is given by $\mathcal{I}$: $\mathcal{I}_{l,l'} = 1$ indicates that link l' is at the interference range of l, meaning l and l' can not transmit simultaneously if using the same channel. For that

[1] Gateways not included.

to be possible, time division is required. The interference model considered is the one used in [63] where, considering a specific link l, it is assumed that link l' can interfere with l, not able to transmit on the same channel at the same time, if and only if $n_1 = s(l')$ or $n_2 = d(l')$ is at the interference range of $n_3 = s(l)$ or $n_4 = d(l)$, $\forall n_1, n_2, n_3, n_4 \in \mathcal{N}$:

$$\begin{aligned} d_{n_3,n_1} < (1+\kappa)T_{n_3} \text{ or } d_{n_3,n_2} < (1+\kappa)T_{n_3} \\ \text{or } d_{n_4,n_1} < (1+\kappa)T_{n_4} \text{ or } d_{n_4,n_2} < (1+\kappa)T_{n_4} \end{aligned} \tag{3.1}$$

where $s(l)$ and $d(l)$ denote the source and destination nodes of link $l \in \mathcal{L}$, respectively, d_{n_i,n_j} is used to denote the distance between n_i and n_j, T_{n_i} is used to denote the transmission range of the radio in n_i, and $\kappa \geq 0$ is the increase of the interference range over the transmission range. For simplicity it is assumed $\kappa = 0$. That is, the transmission and interference ranges are considered to be the same.

The set of available channels at wireless devices will be denoted by $\mathcal{C}$ and the number of radios available at node $n \in \mathcal{N}$ will be denoted by R_n. The total upstream and downstream traffic demand of wireless node $w \in \mathcal{W}$ will be denoted by D_w while each channel is assumed to have B of bandwidth. As previously stated, B can be a fraction of the actual channel capacity for higher QoS achievement.

In the following sections two mathematical formalizations of the FiWi-RTR problem are discussed. The first one is basically related with the core of the problem, which is to reduce the number of required reconfigurations, and therefore reconfiguration time, while the second one is an improvement to ensure that the network will not become disconnected when reconfiguring frequencies. That is, a smooth transition from the old frequency assignment to the new one is ensured by leaving some links unchanged. The old frequency assignment will be embedded in $\beta_{n,c}^{OLD}$, $\forall n \in \mathcal{N}, \forall c \in \mathcal{C}$, and is given as input, while the new frequency assignments will be stored in $\beta_{n,c}$ variables, $\forall n \in \mathcal{N}, \forall c \in \mathcal{C}$. Therefore, we are interested in minimizing the difference between $\beta_{n,c}^{OLD}$ and $\beta_{n,c}$. It is assumed that the number of the radios available per node do not change. The variables will be the following:

$\delta_w^{l,c}$ One, if the route of wireless router $w \in \mathcal{W}$, toward the optical section, is using link $l \in \mathcal{L}$ on channel $c \in \mathcal{C}$, zero otherwise.

$\beta_{n,c}$ One, if node $n \in \mathcal{N}$ (mesh wireless router or gateway) operates on channel $c \in \mathcal{C}$, zero otherwise.

α Channel congestion factor, a real value in the interval [0, 1[.

The α factor will be used to reduce the channel congestion, as it will become more clear next.

3.3.2 FiWi-RTR Problem Formalization

$$\text{Minimize} \sum_{n \in \mathcal{N}} \sum_{c \in \mathcal{C}} |\beta_{n,c}^{OLD} - \beta_{n,c}| + \alpha \tag{3.2}$$

This objective function minimizes the number of frequency reconfigurations (difference between $\beta_{n,c}^{OLD}$ and $\beta_{n,c}$, $\forall n \in \mathcal{N}, c \in \mathcal{C}$) and minimizes the congestion related factor α, improving QoS if possible. That is, the lowest possible number of reconfigurations, not violating the capacity of channels (see expression (3.8)) will be found and then, if multiple solutions exist, the one providing the smallest α (smallest congestion impact) will be chosen.

– Route flow conservation:

$$\sum_{l \in \mathcal{L}: s(l)=w} \sum_{c \in \mathcal{C}} \delta_w^{l,c} = 1, \ \forall w \in \mathcal{W} \tag{3.3}$$

$$\sum_{l \in \mathcal{L}: d(l) \in \mathcal{G}} \sum_{c \in \mathcal{C}} \delta_w^{l,c} = 1, \ \forall w \in \mathcal{W} \tag{3.4}$$

$$\sum_{l \in \mathcal{L}: s(l)=w'} \sum_{c \in \mathcal{C}} \delta_w^{l,c} - \sum_{l \in \mathcal{L}: d(l)=w'} \sum_{c \in \mathcal{C}} \delta_w^{l,c} = 0, \quad , \forall w, w' \in \mathcal{W} : w' \neq w \tag{3.5}$$

These constraints ensure that mesh wireless nodes have a route toward a gateway/ONU.

– Radio channel assignment:

$$\beta_{n,c} \geq \frac{\sum_{w \in \mathcal{W}} \sum_{l \in \mathcal{L}: s(l)=n} \delta_w^{l,c} + \sum_{w \in \mathcal{W}} \sum_{l \in \mathcal{L}: d(l)=n} \delta_w^{l,c}}{|\mathcal{L}|}, \quad , \forall n \in \mathcal{N}, \forall c \in \mathcal{C} \tag{3.6}$$

$$\sum_{c \in \mathcal{C}} \beta_{n,c} = R_n, \forall n \in \mathcal{N} \tag{3.7}$$

Expression (3.6) ensures that a channel, at some node, is assigned to a radio if a route requires it. Expression (3.7) ensures that the number of radios used at a node is equal to the available radios at that node.

– QoS guarantees:

$$\sum_{w \in \mathcal{W}} \sum_{l' \in \mathcal{L}: \mathcal{I}_{l,l'}=1} \delta_w^{l',c} \times D_w \leq B \times \alpha, \ \forall l \in \mathcal{L}, \forall c \in \mathcal{C} \tag{3.8}$$

This expression ensures that the load of interfering links, using time division when transmitting, does not exceed the bandwidth available at channels. That is, interference between links, given by $\mathcal{I}$, is being accounted for time division. The value of B, a fraction of the actual channel capacity, must be defined according to the highest level of congestion that is acceptable.

– Binary and continuous variables:

$$\delta_w^{l,c}, \beta_{n,c} \in \{0, 1\}; 0 \leq \alpha < 1. \tag{3.9}$$

3.3.3 FiWi-RTR Problem Formalization with Network Disconnection Avoidance

A network may become temporarily disconnected when switching from a currently active frequency assignment to a new one. To avoid such grim situation extra constraints should be added to the formulation previously discussed, so that a set of links ensuring traffic flow remain unchanged from the previous frequency assignment to the new one. Two extra variables need to be introduced:

$\theta_{n,c}$ One, if the assignment of channel $c \in \mathcal{C}$ to node $n \in \mathcal{N}$ (wireless router or gateway) has changed from previous frequency assignment to the new one, zero otherwise.
$\sigma_w^{l,c}$ One, if there is a route for wireless router $w \in \mathcal{W}$, including link $l \in \mathcal{L}$ operating at channel $c \in \mathcal{C}$, using the set of effective links that do not change from the previous assignment to the new.

Assuming that expression (3.2) is the same as having:

$$\text{Minimize} \sum_{n \in \mathcal{N}} \sum_{c \in \mathcal{C}} \theta_{n,c} + \alpha \tag{3.10}$$

$$\theta_{n,c} \geq \beta_{n,c}^{OLD} - \beta_{n,c}, \forall n \in \mathcal{N}, \forall c \in \mathcal{C} \tag{3.11}$$

$$\theta_{n,c} \geq \beta_{n,c} - \beta_{n,c}^{OLD}, \forall n \in \mathcal{N}, \forall c \in \mathcal{C} \tag{3.12}$$

the extra constraints required to ensure traffic flow using a set of unchanged links, to be added to the RTR formulation discussed in the previous section, will be:

– Route flow conservation using unchanged links:

$$\sum_{l \in \mathcal{L}: s(l) = w} \sum_{c \in \mathcal{C}} \sigma_w^{l,c} = 1, \ \forall w \in \mathcal{W} \tag{3.13}$$

$$\sum_{l \in \mathcal{L}: d(l) \in \mathcal{G}} \sum_{c \in \mathcal{C}} \sigma_w^{l,c} = 1, \ \forall w \in \mathcal{W} \tag{3.14}$$

$$\sum_{l \in \mathcal{L}: s(l) = w'} \sum_{c \in \mathcal{C}} \sigma_w^{l,c} - \sum_{l \in \mathcal{L}: d(l) = w'} \sum_{c \in \mathcal{C}} \sigma_w^{l,c} = 0, \quad , \forall w, w' \in \mathcal{W} : w' \neq w \tag{3.15}$$

$$\sum_{w \in \mathcal{W}} \sum_{l \in \mathcal{L}: s(l) = n} \sigma_w^{l,c} \leq (1 - \theta_{n,c}) \times \beta_{n,c}^{OLD} \times |\mathcal{L}| \times |\mathcal{W}|, \forall n \in \mathcal{N}, \forall c \in \mathcal{C} \tag{3.16}$$

This last expression ensures that routes, built by variables $\sigma_w^{l,c}$, use unchanged links only.

– Radio channel assignment:

$$\beta_{n,c} \geq \frac{\sum_{w \in \mathcal{W}} \sum_{l \in \mathcal{L}: s(l) = n} \sigma_w^{l,c} + \sum_{w \in \mathcal{W}} \sum_{l \in \mathcal{L}: d(l) = n} \sigma_w^{l,c}}{|\mathcal{L}|}, \quad , \forall n \in \mathcal{N}, \forall c \in \mathcal{C} \tag{3.17}$$

– Binary variables:

$$\sigma_{w}^{l,c}, \theta_{n,c} \in \{0,1\}. \tag{3.18}$$

The optimizer is able to choose a small set of links to ensure connectivity since no limitation of hops are imposed to these routes.

3.4 Algorithmic Approach for Frequency Reconfiguration

The formalizations previously discussed help us to understand the problem but are too hard to solve. For this reason a reconfiguration process, which will serve as a basis for the development of the two heuristic algorithms, is discussed next.

Before discussing the reconfiguration process, some notation and assumptions need to be clarified. As previously, let the graph $\mathcal{G}_{\mathcal{F}}(\mathcal{N}, \mathcal{L}, \mathcal{I})$ represent a FiWi network, where $\mathcal{N}$ is a set including both mesh wireless nodes and gateways/ONUs, $\mathcal{L}$ includes wireless reachability links and $\mathcal{I}$ provides information about interference between any two links. For the following discussion assume:

- *Radios and Channels*: Node $n \in \mathcal{N}$ has R_n radios available, all radios being able to tune to one of the frequency channels in $\mathcal{C}$.
- *Traffic Demand*: For traffic demand the vector **d** $= \{d_1, d_2, ..., d_{|\mathcal{W}|}\}$ of integer values, representing relative traffic demands, is used. For example, if node w_i has twice the demand volume of node w_j then $d_{w_i} = 2 \times d_{w_j}$.
- *Shortest Paths*: The route that a mesh wireless node $w \in \mathcal{W}$ will take toward gateway $g \in \mathcal{G}$, denoted by $r_w = (w, w_{i_1}, w_{i_2}, ..., g)$, is assumed to be one of the shortest paths. That is, $h_{r_w} = min_{r'_w}(h_{r'_w})$, where $h_{r'_w}$ denotes the number of hops of route r'_w toward a gateway. This route is defined using the reachability links, given as input, and never changes. The node that succeeds node w in route r_w, toward the optical section, will be denoted by w^+.

3.4.1 The Methodology

The goal in this section is to define general rules that will serve as a basis for the development of heuristic algorithms for frequency reassignment in FiWi networks. The network can not disconnect during reconfiguration, frequency changes must be minimized, and higher throughput and QoS must be assured. For this to be achieved the following can be assumed:

1. At the old frequency assignment, there is at least one effective link operating at some channel $c_i \in \mathcal{C}$ that connects w and w^+, meaning that $\beta_{w,c_i}^{OLD} = \beta_{w^+,c_i}^{OLD} = 1$.
2. For traffic flow on a set of effective links, and assuming that $\mathcal{C}_w = \{c_i : \beta_{w,c_i}^{OLD} = \beta_{w^+,c_i}^{OLD} = 1\}$, $w \in \mathcal{W}$, the following traffic flow rule (TFR) can be assumed:
   (a) if $d_w \leq |\mathcal{C}_w|$, then each traffic unit of d_w will be using one of the effective links (w, w^+); traffic units will be flowing through different channels;
   (b) if $d_w > |\mathcal{C}_w|$, then at least $\lfloor \frac{d_w}{|\mathcal{C}_w|} \rfloor$ traffic units of d_w will be using one of the effective links (w, w^+); traffic units will be evenly distributed by all channels.

Having this in mind the following frequency reconfiguration process (RP), to be adopted by the heuristic algorithms discussed next, can be defined:

1. For each $w \in \mathcal{W}$, consider (w, w^+). Choose a channel $c_i \in \mathcal{C}$ such that $\beta_{w,c_i}^{OLD} + \beta_{w^+,c_i}^{OLD} = 2$ and mark it as unchangeable.
2. Form a list including all wireless nodes using some ordering criteria.
3. For each w in list, assign channels to unmarked radios of pairs of nodes (w, w^+) by descending order of $\beta_{w,c_i}^{OLD} + \beta_{w^+,c_i}^{OLD}$, $c_i \in \mathcal{C}$, while making traffic flow allocation using TFR.

3.4.2 Suitability of the Reconfiguration Process

Preposition 1. *Applying the RP approach to a FiWi graph $\mathcal{G}$ avoids network disconnection, minimizes frequency reconfigurations and distributes traffic across the network improving throughput and QoS.*

Proof: The first step of the RP ensures that the network will always be connected throughout the execution of reassignments. This is so because each node will have at least one channel in common with its successor, which was also included in the old frequency assignment that provided connectivity. Such channels are marked as unchangeable at this first step. A node will have more than one of such unchangeable channels in cases where $(w_k, {w_k}^+)$ operates on channel $c_i \in \mathcal{C}$, $(w_l, {w_l}^+)$ operates on channel $c_j \in \mathcal{C}, c_i \neq c_j$, and $w_k = {w_l}^+$. Thus, it is possible to state that Step 1 is equivalent to determining values for $\sigma_w^{l,c}$ variables in the FiWi-RTR problem with disconnection avoidance. Moreover, channels marked as unchangeable in Step 1 ensure communication between any pair of nodes.

The third step of the RP minimizes the number of frequency reassignments as channel assignments are made by descending order of $\beta_{w,c_i}^{OLD} + \beta_{w^+,c_i}^{OLD}$, meaning that the values for $\theta_{n,c}$ variables will be the smallest possible and the objective function (3.10) is minimized. Traffic is also distributed across the network by applying TFR.

3.4.3 Heuristic Algorithms

In the following section two heuristic algorithms, called node-based reconfiguration (NBR) and route-based reconfiguration (RBR), are proposed based on the discussed reconfiguration process. These include an initialization step that is similar to both algorithms. Two types of matrices must be populated during algorithm execution and the two algorithms basically differ in the way they are populated. The matrices are:

- *Node Clustering Matrices*: A matrix $\mathbf{F}^c$, with $|\mathcal{N}|$ columns and K rows, is defined for each $c \in \mathcal{C}$. Columns refer to nodes while rows refer to groups of nodes able to transmit in parallel, called *group of independent nodes*. Rows will be added to $\mathbf{F}^c$ as the algorithms evolve and at the end of its execution K basically provides a time division or bandwidth allocation planning. A node may appear in many groups according to its local demand and demand that it has to forward from other nodes. A cell $\mathbf{F}^c_{kn}$, where $k \in \{1, ..., K\}$ is a row and $n \in \{1, ..., |\mathcal{N}|\}$ is a column, may include one of the states:
  - USED (U), means that node n belongs to group k, for transmission using channel c.
  - CONFLICT (C), means that node n is not in group k, for transmission using channel c, due to an interference conflict.
  - FREE (F), means that information about node n in group k has not been filled yet.

  The algorithms will try to fill rows with as many nodes as possible so that the number of groups of independent nodes is the smallest as possible. Groups/rows in a specific matrix $\mathbf{F}^c$ will compete for bandwidth, and require time division at frequency channel c, because they are not independent.

- *Frequency Assignment Matrix*: A matrix $\mathbf{R}$, of size $|\mathcal{N}| \times |\mathcal{C}|$, also needs to be defined to store radio frequency assignment where $\mathbf{R}_{nc} = 1$ indicates that node $n \in \mathcal{N}$ operates at channel $c \in \mathcal{C}$, $\mathbf{R}_{nc} = 0$ otherwise. During the operation of both algorithms it is required that $\sum_{c=1}^{|\mathcal{C}|} \mathbf{R}_{nc} <= R_n, \forall n \in \mathcal{N}$.

3.4.3.1 Initialization Step

Both heuristic algorithms discussed next execute an initialization step that is as follows. Create $\mathbf{F}^c$ with a single row, $K = 1$, and $|\mathcal{N}|$ columns, $\forall c \in \mathcal{C}$, and initialize all cells to FREE. Create $\mathbf{R}$ with $|\mathcal{N}|$ rows and $|\mathcal{C}|$ columns and initialize it with 0s. Mark unchangeable frequency channels as follows:

for *each* $n \in \mathcal{N}$ **do**
    for *each* $c \in \mathcal{C}$ **do**
        if *(*$\beta_{n,c}^{OLD} + \beta_{r_n^+,c}^{OLD} == 2$*)* **then**
            $\boldsymbol{R}_{nc} = 1;$
            $\boldsymbol{R}_{r_n^+ c} = 1;$
            break;
        end
    end
end

Algorithm 1: Initialization Step

The order in which the nodes are traversed might influence the efficiency of this step. Nodes having a single radio, if any, should be processed first.

3.4.3.2 Node-Based Reconfiguration (NBR) Algorithm

Nodes more close to the ONUs are processed first.

Step 1 - Build list of nodes for processing following the algorithm 2.

While A is an associative array indexed by a depth key, which indicates how far node w is from an ONU, Π is a list where nodes more close to the ONUs will appear first. Thus, harder frequency assignments will be done first. Harder in the sense that nodes nearer the ONUs have to forward more traffic from others, meaning that the frequencies assigned to them have more impact on network performance.

Step 2 - The algorithm 3 (see end of chapter) defines NBR groups of independent nodes:

Step 3 - Assign frequencies to free radios according to the frequencies used by succeeding nodes (neighbours on the route toward the optical section), so that the nodes in question share

```
A = {} /* associative array indexed by depth key */;
for each w ∈ W do
    depth = h_{r_w};
    i = w;
    repeat
        /* insert i, in associative array A, d_w times */;
        for j = 1 to d_w do
            A(depth) ← i;
        end
        i = r_i^+;
        depth − −;
    until depth = 0;
end
Π = {} /* list of nodes for processing in Step 2 */;
for depth = 1 to Length(A) do
    Π = Π + A(depth);
end
```

Algorithm 2: Associative array

one or more frequencies.

Every node will be able to communicate as radio assignment is done only if there is at least one neighbour tuned to the same frequency (line 6 of Step 2). The more load (local and foreign traffic) a node has the more rows/groups, of the time division matrices, it will get due to the way Π was built. Frequency reconfigurations are minimized since similarity with old frequency assignment is privileged (line 4 of Step 2).

3.4.3.3 Route-Based Reconfiguration (RBR) Algorithm

Nodes are processed as their routes toward the optical section are traversed.

Step 1 - Building groups of independent nodes following the procedure in algorithm 4 (see end of chapter).

Step 2 - Assign frequencies to free radios according to the frequencies used by succeeding nodes (neighbours on the route toward the optical section), so that the nodes in question share one or more frequencies.

Instead of building a Π list, this algorithm goes through the routes used by wireless nodes to forward traffic toward the optical section, to make the assignment of nodes to rows/groups of time division matrices. This way frequency assignment is done as routes are traversed and frequency assignment in a certain area will be influenced by the demand requests of many nodes. Similarly to the previous algorithm every node will be able to communicate and frequency reconfigurations are minimized.

3.4.3.4 Illustration of Algorithms

Based on FiWi network of Figure 3.1, the NBR and RBR algorithms are illustrated in Figures 3.2 and 3.3, respectively. For simplicity the routes of nodes 6 and 7 are not displayed, as these nodes have no demand and do not forward traffic from other nodes. The frequencies shown near the nodes are the old frequencies, stored in β^{OLD}. Note that this small network is suitable for illustration purposes and not much parallel transmission will occur. Note also that, for clarity in illustration, the initialization step common to both algorithms is skipped. Concerning NBR algorithm every element of Π will be processed and tables are filled as follows:

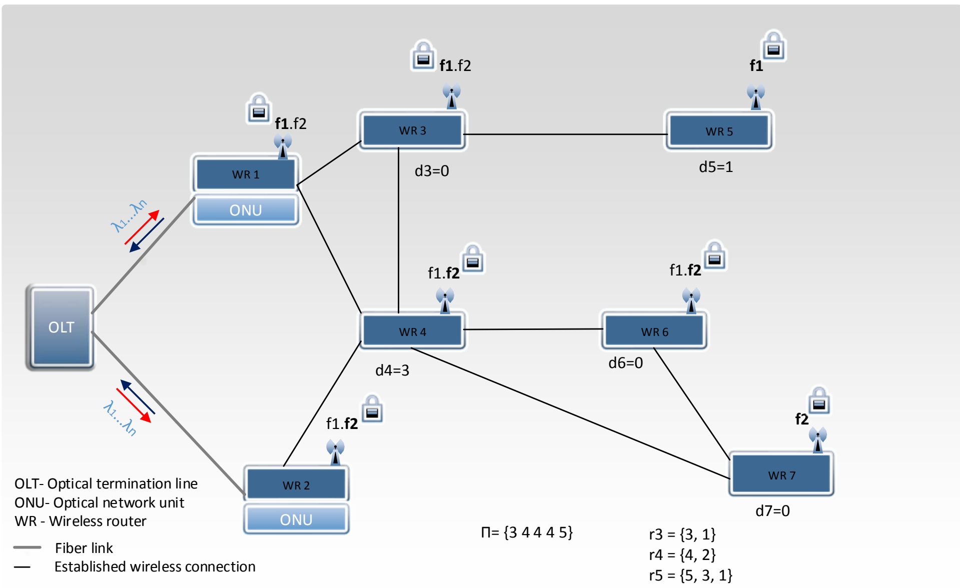


Figure 3.1: FiWi network used to illustrate algorithms.

1. Node 3 at Π list is processed. The table of frequency 1 is filled since this was one of the frequencies previously assigned to nodes 3 and its succeeding node. Time slot is labelled USED (U) for node 3 and CONFLICT (C) for the others.

2. Node 4 is the next one in Π list. Table of frequency 2 is filled since this was one of the frequencies previously assigned to nodes 4 and its succeeding node. Time slot is labelled USED (U) for node 4 and CONFLICT (C) for the others.

3. Node 4 is the next one in Π list. A first attempt to fill table of frequency 2 is done, as this was one of the frequencies previously assigned, but no FREE (F) cell for node 4 is found at any existing row. Table of frequency 3 is filled since this is also a frequency previously assigned to nodes 4 and its succeeding node. Time slot is labelled USED (U) for node 4 and CONFLICT (C) for the others.

4. As frequencies 2 and 3 have been assigned to the radios of node 4, by previous steps, only these frequencies will work when processing node 4, the next element in Π list. The existing rows of frequency tables 2 and 3 have no FREE (F) cells for node 4 and, therefore, an extra row is added to all tables, which is then filled at table of frequency 2.

5. Node 5 is the next node in Π list. A first attempt to fill table of frequency 2 is done, since it is the previously assigned frequency, but no row with a FREE (F) cell for node 5 exists in this table. This means that the other tables will be sought for a FREE cell. If such cell is found a reconfiguration at node 5 is required to switch from frequency 2 to the new one, otherwise an extra row must be added to the tables. Since a FREE (F) cell was found when searching table of frequency 1, USED (U) and CONFLICT (C) are filled accordingly.

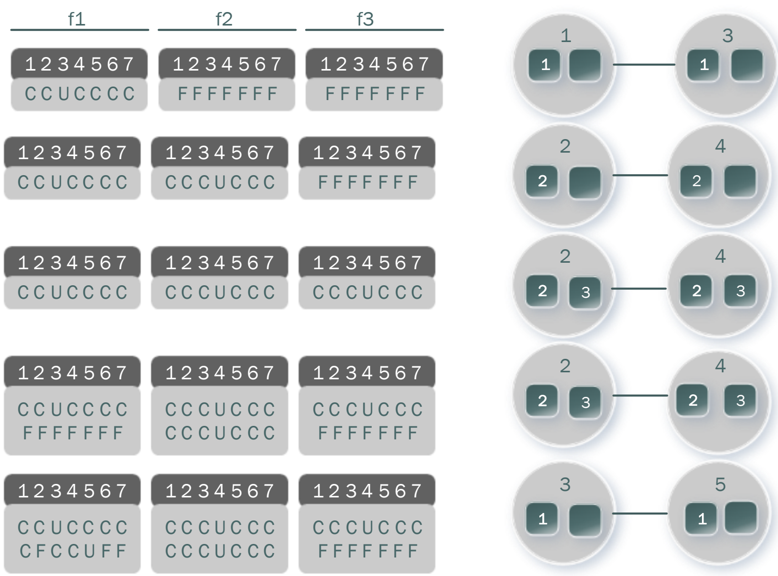


Figure 3.2: Illustration of NBR algorithm.

Concerning RBR algorithm, where nodes with demand are processed as routes are traversed, tables are filled as follows:

1. Node 4 is processed. The existing row of frequency 2's table is filled, since this was one of the old frequencies previously assigned to nodes 4 and its succeeding node, and was marked as unchangeable. The row is labelled USED (U) for node 4 and CONFLICT (C) for the others. The demand of node 4 decreases from 3 to 2.

2. Node 5 is processed. Since this node has a single radio working on frequency 1, and the existing row has a FREE (F) cell for node 5 at this frequency, the row will be labelled USED (U) for node 5 and CONFLICT (C) for the interfering nodes. The demand of node 5 decreases from 1 to 0.

3. Node 3 is processed, as this is an intermediate node on the route from node 5 to the optical section. Tables of frequencies 1 and 2 are scanned, since these are old assigned frequencies, but no FREE (F) cell for node 5 exists in these tables. Frequency 3 is then searched and a FREE (F) cell is found at the existing row. This row is labelled USED (U) for node 3 and CONFLICT (C) for the others. Nodes 1 and 3 will have one of their radios reconfigured to frequency 3.

4. Node 4, the one still with demand, is processed. As no FREE (F) cell for node 4 exists in any of the tables, an extra row is inserted. The existing row of frequency 2's table is filled, since this was one of the old frequencies previously assigned to nodes 4, and its succeeding node, and was marked as unchangeable. The row is labelled USED (U) for node 4 and CONFLICT (C) for the others. The demand of node 4 decreases from 2 to 1.

5. Node 4, the one still with demand, is processed. After looking at frequency 2's table, which has no FREE (F) cell for node 4, frequency 1's table is filled and labelled USED (U) for node 4 and CONFLICT (C) for the others. The demand of node 4 decreases from 1 to 0.

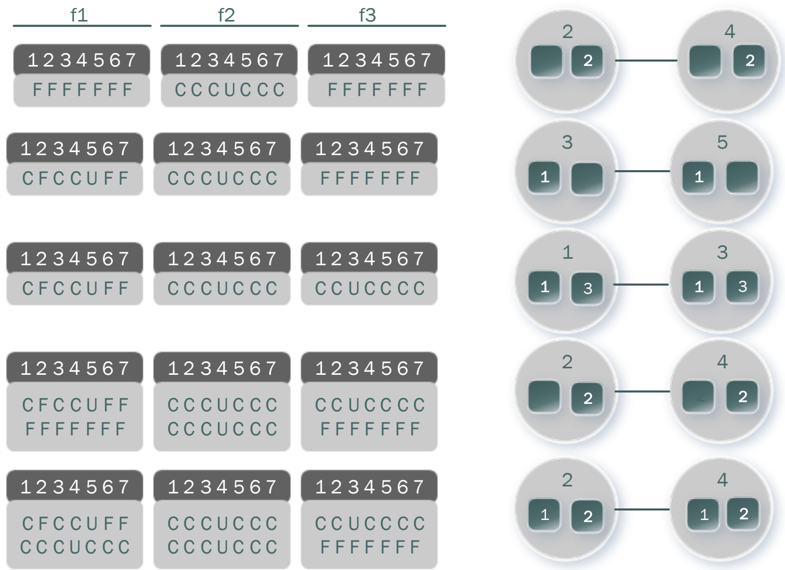


Figure 3.3: Illustration of RBR algorithm.

3.5 Summary

In this chapter the state-of-art on the frequency assignment problem was presented. The problem of reassigning frequencies to radios was discussed and demonstrated. Two frequency reconfiguration algorithms were proposed along with their mathematical formalization. The following chapter will present the simulation model that was developed for performance evaluation of the presented algorithms.

```
for each $w \in \Pi$ do
    $assigned$ =FALSE;
    for $i = 1$ to $K$ do
        for each $c \in \mathcal{C}$ in descending order of $\beta^{OLD}_{w,c} + \beta^{OLD}_{w^+,c}$ (unchangeable channels first) do
            /*test availability and if $w$ and its successor either operate on $c$ or have a radio available*/
            if ($\mathbf{F}^c_{iw}$ == FREE) $\wedge$ ($\mathbf{R}_{wc} == 1 \vee \sum_{c'=1}^{|\mathcal{C}|} \mathbf{R}_{wc'} < R_w$) $\wedge$ ($\mathbf{R}_{w^+c} == 1 \vee \sum_{c'=1}^{|\mathcal{C}|} \mathbf{R}_{w^+c'} < R_{w^+}$) then
                /*mark interference conflicts*/;
                for each $l \in \mathcal{L}$ such that $\mathcal{I}_{l,(w,w^+)} == 1$ do
                    $\mathbf{F}^c_{is(l)}$=CONFLICT;
                    $\mathbf{F}^c_{id(l)}$=CONFLICT;
                end
                $\mathbf{F}^c_{iw^+}$=CONFLICT;
                /*include $w$ in group $i$ of frequency $c$*/;
                $\mathbf{F}^c_{iw}$=USED;
                /*assign frequency to radios*/;
                $\mathbf{R}_{wc} = 1$;
                $\mathbf{R}_{w^+c} = 1$;
                $assigned$ =TRUE;
                break;
            end
        end
        if assigned then
            break;
        end
        if (!assigned $\wedge$ $i == K$) then
            AddRow($\mathbf{F}^c$), $\forall c \in \mathcal{C}$;
            $K++$;
        end
    end
end
```

Algorithm 3: NBR group of independent nodes

while *(*$\exists w$ *such that* $d_w! = 0$*)* **do**
    for *each* $w \in \mathcal{W}$ *with* $d_w! = 0$ **do**
        $assigned$=FALSE;
        $j = w$;
        repeat
            for $i = 1$ *to* K **do**
                for *each* $c \in \mathcal{C}$ *in descending order of* $\beta^{OLD}_{j,c} + \beta^{OLD}_{j^+,c}$ *(unchangeable channels first)* **do**
                    /**test availability and if* j *and its successor either operate on* c *or have a radio available**/
                    if $(\boldsymbol{F}^c_{ij} ==$ FREE$) \wedge (\boldsymbol{R}_{jc} == 1 \vee \sum_{c'=1}^{|\mathcal{C}|} \boldsymbol{R}_{jc'} < R_j) \wedge (\boldsymbol{R}_{j^+c} == 1 \vee \sum_{c'=1}^{|\mathcal{C}|} \boldsymbol{R}_{j^+c'} < R_{j^+})$ **then**
                        /**mark interference conflicts**/;
                        for *each* $l \in \mathcal{L}$ *such that* $\mathcal{I}_{l,(j,j^+)} == 1$ **do**
                            $\mathbf{F}^c_{is(l)}$=CONFLICT;
                            $\mathbf{F}^c_{id(l)}$=CONFLICT;
                        end
                        $\mathbf{F}^c_{ij^+}$=CONFLICT;
                        /**include* j *in group* i *of frequency* c*/;
                        $\mathbf{F}^c_{ij}$=USED;
                        /**assign frequency to radios**/;
                        $\mathbf{R}_{jc} = 1$;
                        $\mathbf{R}_{j^+c} = 1$;
                        assigned=TRUE;
                        break;
                    end
                end
                if *assigned* **then**
                    break;
                end
                if *(!assigned* $\wedge\ i == K$*)* **then**
                    AddRow($\mathbf{F}^c$), $\forall c \in \mathcal{C}$;
                    $K++$;
                end
            end
            $j = j^+$;
        until *(*$j == NULL$*)* /* *end of route* */;
        $d_w - -$;
    end
end

Algorithm 4: RBR group of independent nodes

CHAPTER 4

FiWi Simulation Model

4.1 Introduction

This chapter describes the adopted approach to build a network model, in which the proposed algorithms could be tested and evaluated by simulation. The model was developed using OMNeT++, an object-oriented library and framework for building network simulators [64], with the appellative of being open-source for academic use. To describe the structure of simulation model using OMNeT++, one should use the NED language. NED, which stands for Network Description, lets the user declare simple modules, and connect and assemble them into compound modules. Simple modules, that are the active modules, have their behaviour defined by code written in C++ programming language. They can be grouped into compound modules unlimited number of hierarchy levels. The whole model, called "network" in the OMNeT++ framework is itself a compound module. Figure 4.1 is used here to show the relation between the NED modules in the network.

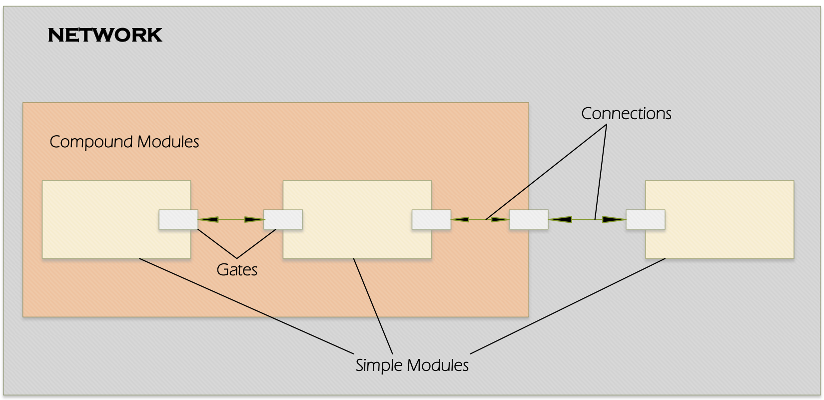


Figure 4.1: Modules relation in the simulation model.

Modules are connected via gates and interact by passing messages through the gates. Messages may carry arbitrary data structure, including any packets for network communication. Compound module may be organized in order to construct a network devices such as routers, switches, access points, etc.

The topology used in simulation is the one in Figure 4.2, taken from [11] and represents the San Francisco WOBAN (called “SFNet”). It is assumed that all the ONUs are connected to a single OLT. The architecture of the model components is described in the following sections.

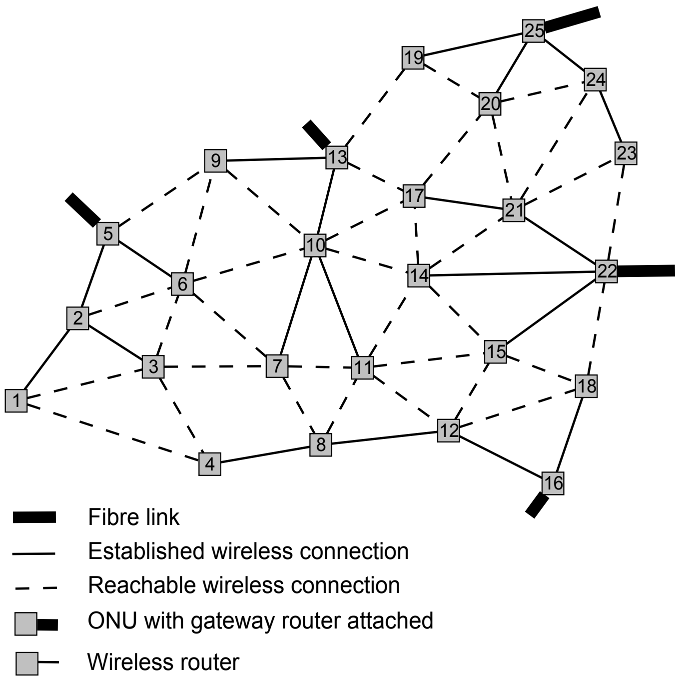


Figure 4.2: Simulation Model Network Topology.

The remainder of this chapter describes the following modules of our network simulator: Section 4.2.1 describes the **OLT**, **manager** and **sink**; Section 4.2.2 presents the **networkLayer** and **nic** submodules from the **WRouter**; Sections 4.2.3 and 4.2.4 describe submodules **onu** and **app** from **WRGataway** and **ClientNode** respectively.

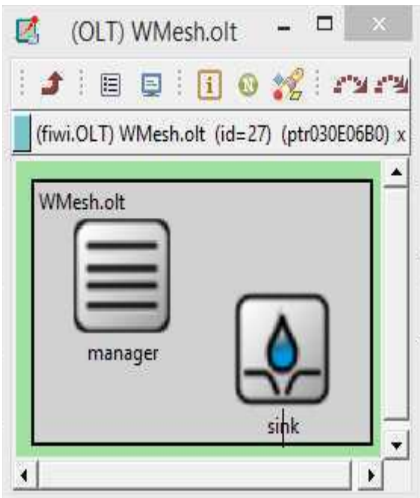
4.2 Network Simulator

4.2.1 OLT

The internal structure of the OLT, presented in Figure 4.3, is basically composed of two simple modules one of which, the manager, is of utmost importance. The functionalities of these submodules can be described as follows:

- The **manager** implements the heuristics (NBR and RBR) proposed above and, therefore, is responsible for the most critical functionalities related with network set-up and operation. It holds information about the nodes' adjacency and interference. The frequency assignment matrix $\mathbf{R}$, and node clustering matrices $\mathbf{F}^c$, for each frequency, are also held in this submodule. During initialization all matrices are set to zero, all existing radios are registered, the assigned frequencies to radios are also registered in the frequency matrix, and links are established based on the adopted transmission ranges. After one of the NBR or RBR finishes execution the simulation model is ready to drive the flow of packets arriving from the traffic generators on no-gateway nodes at the front end.

- **sink** is simply a submodule where each packet life cycle ends and data for statistical analysis is collected.




```
package fiwi;

module OLT
{
    parameters:
        @display("i=device/server");
        int address;
        double posX;
        double posY;
        @display("p=$posX,$posY");
    gates:
        inout inAndOut[];

    submodules:
        sink: Sink {
            @display("p=102,58");
            gates:
                onu[sizeof(inAndOut)];
        }
        manager: Manager {
            @display("p=36,32");
        }
    connections:
        for i=0..sizeof(inAndOut)-1 {
            sink.onu[i] <--> inAndOut[i];
        }
}
```

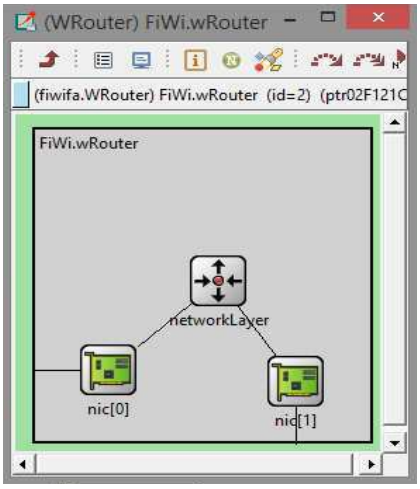
Figure 4.3: OLT and NED code snippet.

4.2.2 WRouter

This is a module from which the **ONU/Gateway** and the **ClientNode** modules are derived. Its internal structure is shown in Figure 4.4 with submodules addressing the functionalities of the network and data link layers considered relevant in the scope of this work.

- **networkLayer**, responsible for finding the next hop toward the destination whenever a packet arrives.

- **nic**, models a network adapter, and stores the assigned frequency that might result into a wireless effective link if a neighbour uses such frequency.



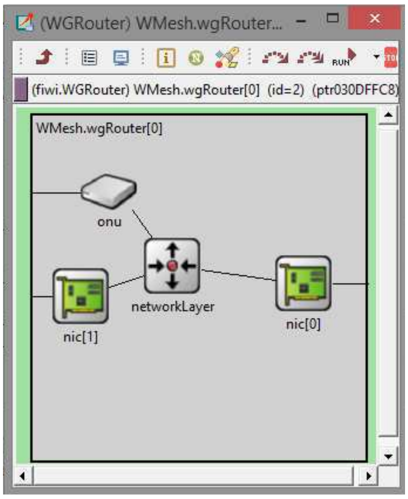

```
package fiwi;
module WRouter
{
    parameters:
        @display("i=abstract/router;bgb=235,245");
        int address;
        int numOfNodes = default(6);
        int numRadios = default(3);
        double posX; // object horizontal positioning
        double posY;// object vertical positioning
        @display("p=$posX,$posY");
    gates:
        inout Radio[numRadios*numOfNodes];
    submodules:
        networkLayer: NetworkLayer {
            @display("p=98,107");
            gates:
                to_nic[numRadios];
        }
        nic[numRadios]: NIC {
            gates:
                Nic[numOfNodes];
        }
    connections allowunconnected:
        for i=0..numRadios-1 {
            networkLayer.to_nic[i] <--> nic[i].upperLayer;
        }
        for i=0..numRadios-1, for j=0..(numOfNodes-1) {
            nic[i].Nic[ j ]  <--> Radio[ j+i*numOfNodes];
        }
}
```

Figure 4.4: Wireless Router and NED code snippet.

4.2.3 WRGateway

This module models wireless gateways of the FiWi access network and its internal structure is illustrated in Figure 4.5. It is an extension of **WRouter** module with one additional submodule, **onu**. Assuming in this simulation a compound ONU/Gateway architecture, each packet arriving at this module is directly forwarded toward the **onu**.

- **onu** is responsible for forwarding each packet to the OLT.

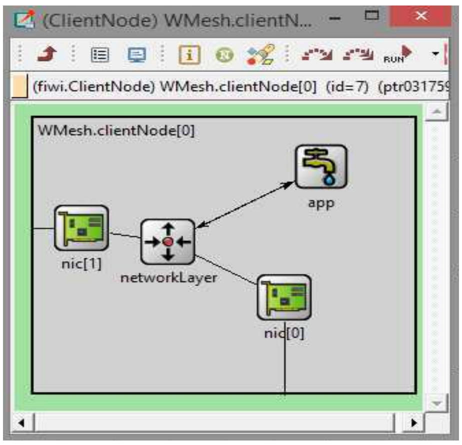



```
package fiwi;

module WGRouter extends WRouter
{
    parameters:
        @display("i=abstract/accesspoint");
    gates:
        inout to_ONU[ ];
    submodules:

        onu: ONU {
            @display("p=54,54");
        }
    connections:
        networkLayer.onu <--> onu.gateway;
        onu.olt <--> to_ONU++;
}
```

Figure 4.5: ONU/Gateway and NED code snippet.

4.2.4 ClientNode

This module is also an extension of **WRouter** and models a wireless mesh node which may generate traffic and transmit packets during its granted time slot in a TDMA fashion. It also may receive packets from other wireless mesh nodes in its vicinity and forward them. In its internal structure, shown in Figure 4.6, it extends the **WRouter** by adding one extra submodule:




```
package fiwi;

module ClientNode extends WRouter
{
    parameters:
        @display("i=device/accesspoint;bgb=278,237");
    submodules:
        app: App {
            @display("p=210,42");
        }
    connections:
        networkLayer.localOut --> app.in;
        networkLayer.localIn <-- app.out;
}
```

Figure 4.6: ClientNode and NED code snippet.

- **app** is responsible for the traffic generated by each wireless mesh node and this traffic generation can be parameterized to typify a certain demand.

4.3 Summary

This chapter presented the simulation model and described the main functionalities of each simple and compound modules. In the following chapter simulation results are shown and discussed.

CHAPTER 5

Experiments and Results

5.1 Performance Analysis

In order to compare the performance of both algorithms NBR and RBR, and their improvement over a no-reconfiguration scenario the simulation model presented in the previous chapter was used taking into account the following aspects: As IEEE 802.11 technologies are widely spread and inexpensive, its assumed a 802.11-based behaviour at the front-end nodes using its default medium access technique DCF that employs CSMA/CA MAC protocol. For channel collision avoidance, 802.11 specifies that stations must choose a random backoff (BK) in the range (0,CW-1), where CW stands for contention window which is in units of a defined time slot. The CW is initially equal to CW_{min}, doubles at each retransmission and can not exceed CW_{max}. Implementations define $CW_{min} = 16$ or $CW_{min} = 32$ and $CW_{max} = 1024$. As stated in [65], a small CW_{min} can be suitable under light traffic conditions, as packet loss will be small, but as network traffic load increases the throughput rapidly decreases due to an increase in packet loss. This is more serious in multi-hop wireless networks than in single-hop.

The main issue that needs to be taken into consideration, in order to incorporate IEEE 802.11 behaviour when evaluating the proposed frequency reassignment algorithms, is that there will be periods of time when channels will not be used due to backoff. Also, nodes will send packets in batches.The way node clustering matrices have been built allow us to simulate this behaviour as follows: the nodes of a group/row, able to transmit in parallel, are allowed to transmit during a fixed period of time corresponding to BK packet transmissions; the groups/rows are scheduled in a round robin way. Thus, whenever nodes are allowed to transmit and have no packets, or have just a few, the channel will not be utilized. Nodes will also have to wait to be able to transmit.

5.1.1 Parameters

In the simulation there are some parameters that remain constant, presented in Table 5.1, and there are others which vary throughout the performed experiments according to different traffic pattern at front-end nodes. It is assumed that only three channels can be used, e.g. channels 1, 6, and 11 of 802.11b/g standards.

Parameters	Value
Simulation time	600 s
Number of radios/node	2
Channel capacity	54 Mbps
Packet size (average)	625 bytes
BK	64

Table 5.1: Unchangeable parameters

The packet size parameter presented in Table 5.1 follows a normal distribution and the aforementioned non-permanent parameter is the packet inter-arrival time, which follows an exponential distribution in each scenario. Traffic pattern on access network may be consulted here [66]. To mimic different and asymmetric traffic demands, 4 scenarios (a, b, c, d) were obtained. Here, a scenario is referred to a set of 10 nodes randomly chosen at front-end which are expected to generate 4 times more traffic than the others, and these random nodes use different seeds for traffic generation. To evaluate the performance of the algorithms, these 4 scenarios were submitted to 10%, 20%, 30% and 40% of traffic load. Table 5.2 shows the inter- arrival time for each traffic load.

Parameter	Load			
Inter-arrival time	10%	20%	30%	40%
demand=4	0.001	0.005	0.00033	0.00025
demand=1	0.005	0.0025	0.0017	0.00125

Table 5.2: Non-permanent parameters

Concerning the old frequency assignment, β^{OLD} values, it is assumed that all nodes have their two radios tuned to the same frequency channels, first and second channels available, a common approach adopted for full connectivity between nodes in the transmission area of each other.

A static assignment algorithm denoted SAA is used as a reference to evaluate the performance of NBR and RBR. Based on the network topology and node location as shown in Figure 4.2, all nodes could directly communicate with their neighbours in case of sharing a common channel, which leads to high interference and consequently the need of time division. SAA is assumed to be the source of β^{OLD} values, and, as aforementioned, the radios in each node are tuned to two static orthogonal channels and are the same for all nodes at front-end. A total number of 5 gateway nodes are used to connect to the wired network with a single OLT.

NBR and RBR algorithms may include or not the initialization step discussed in section (3.4.3.1). NBR(Y) or NBR(N) means NBR including or excluding initialization step respectively, the same for RBR(Y) and RBR(N).

The total simulation time was 600 s and the following performance parameters were analysed:

1. NBR and RBR throughput increase over the no-reconfiguration case (SAA)
2. Number of frequency reconfigurations
3. Average end-to-end packet delays
4. Average size of queues

Figure 5.1 presents the performance of the algorithms with respect to different scenarios at 10% of traffic load. Firstly it allows to observe that the performance of each algorithms vary according to a certain scenario, having some of them performing better in some scenarios and relatively worse in others. Concerning to throughput all algorithms apart of RBR(Y) and RBR(N) show some similarities on their behaviour at this load.

The average time to deliver traffic is considerably lower when performing RBR(Y) and RBR(N) algorithm than the others, and supporting this, the average queue sizes presented by this algorithm are also lower. When increasing the network traffic load to 20% as show in Figure 5.2, we may observe that the reconfiguration did not cause noticeable effects between throughput of SAA, NBR(Y) and NBR(N) algorithms, though still giving a considerable advantage for RBR(N) and RBR(Y). RBR maintain low average queue size as well as low average end-to-end for packets delivery, which means that RBR takes better advantage of the available frequencies, increasing parallel transmission, even if traffic pressure is low because packets stay less time in queues, thus reducing the end-to-end delay.

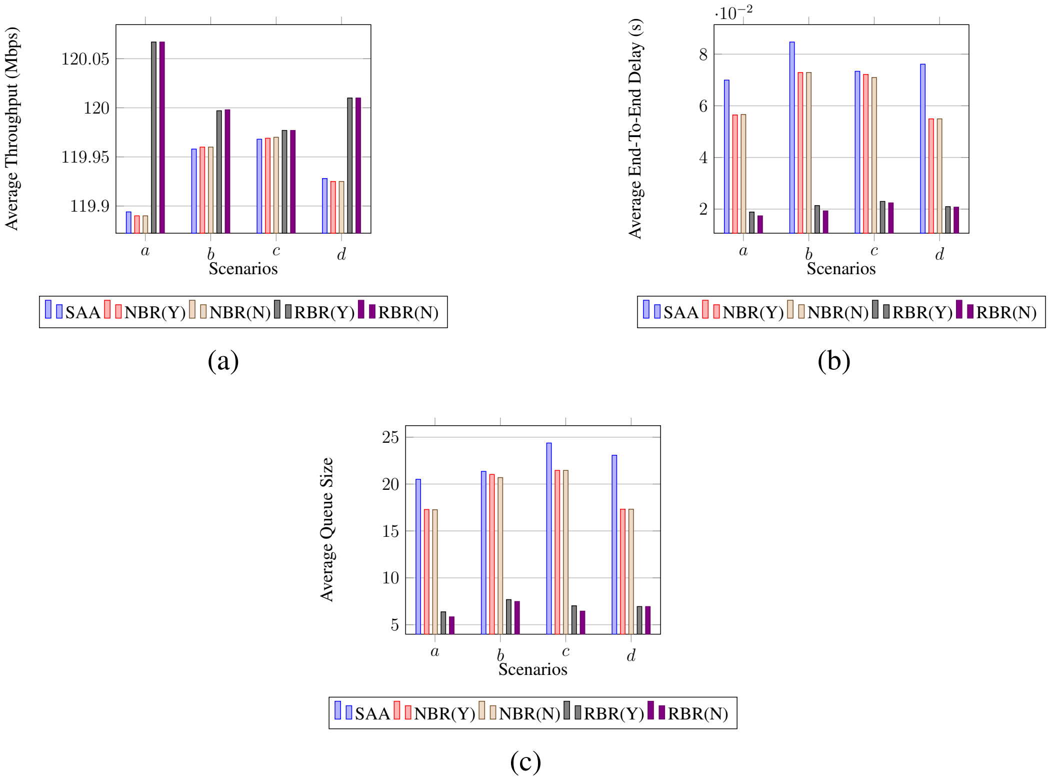


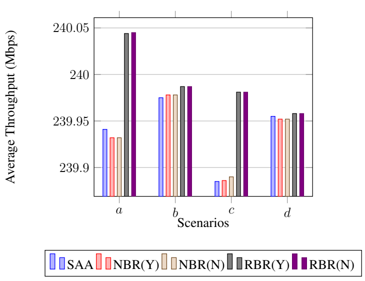
Figure 5.1: Performance analysis for traffic load equal to 10% of the channel capacity; (a) Average throughput; (b) Average end-to-end delay; (c) Average queue size.

Results from experiments where the pressure of traffic is increased to 30% and 40% of the channel bandwidth are presented in Figures 5.3 and Figure 5.4 respectively. The throughput, end-to-end delay and average queue size do not change when the initialization step is inserted or removed, meaning that introducing this step into algorithms, for network disconnection avoidance, will not penalize performance results. At this load, it is noticeable the NBR performance improvement over SAA, meaning that reconfiguration is fully exploited when load is high.

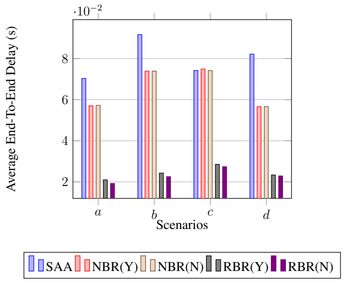
Algorithm	Avg Nr. of Rows in Node Clustering Matrix	Avg Nr. of Reconfigurations
SAA	18.25	-
NBR(Y)	16.25	5
NBR(N)	16.25	8.5
RBR(Y)	13	12
RBR(N)	13	12

Table 5.3: Info Related to Matrices

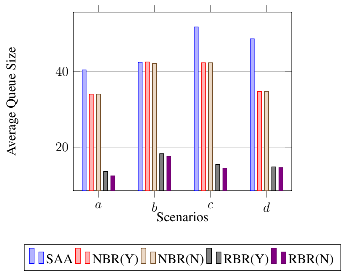
Table 5.3 includes information related with the node clustering and frequency assignment matrices. The first column shows the number of rows, K, inserted during algorithm execution



(a)



(b)

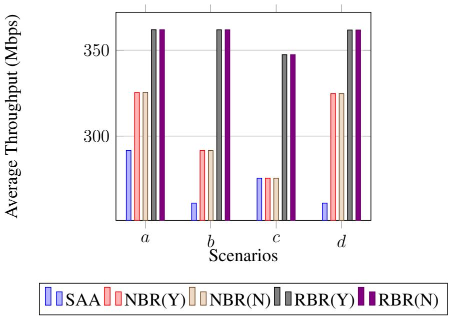


(c)

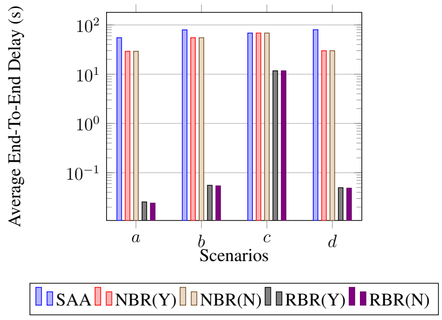
Figure 5.2: Performance analysis for traffic load equal to 20% of the channel capacity; (a) Average throughput; (b) Average end-to-end delay; (c) Average queue size.

while the second column shows the number of radio reconfigurations, also done during algorithm execution (difference between the old and the new frequency assignment). Results show that the RBR was in fact able to reduce time division, increasing parallel transmission, as the number of rows in the clustering matrices is lower when compared with the other algorithms. These values do not change when the initialization step is inserted or removed. Concerning the number of radio channel reconfigurations, NBR makes less reconfigurations than RBR. This increases when the initialization step is not performed, since all radio channels can be changed. RBR makes more reconfigurations to be able to increase parallel transmission, as previously stated. That is, RBR makes more reconfigurations than NBR but these have the nice purpose of increasing parallel transmission, improving throughput and delay. RBR shows no difference in the number of reconfigurations when the initialization step is included or removed, while in the NBR the extra reconfigurations seem not to be productive since it has no effect on throughout and delay.

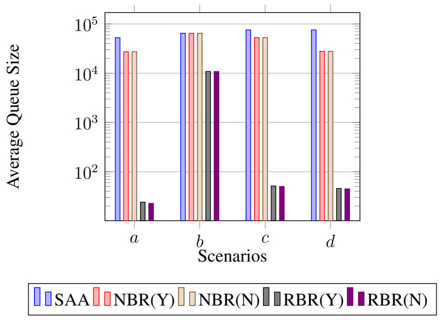
In global terms, the network presents a better performance and the QoS perceived by users increases when the RBR algorithm is used. This statement may be confirmed if we look at behaviour of the parameter being evaluated through different load, as depicted in Figure 5.5. We can clearly observe that, in fact, at low loads such as 10% to 20% there is a relative performance



(a)



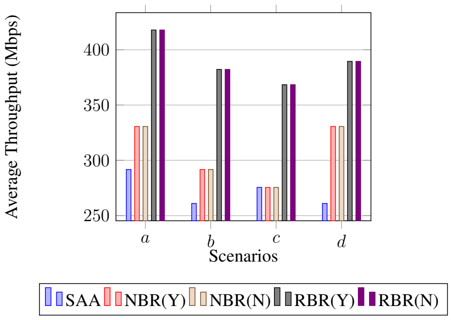
(b)



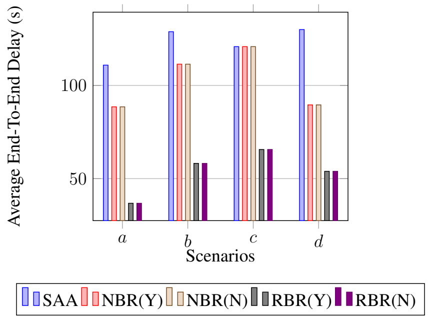
(c)

Figure 5.3: Performance analysis for traffic load equal to 30% of the channel capacity; (a) Average throughput; (b) Average end-to-end delay; (c) Average queue size.

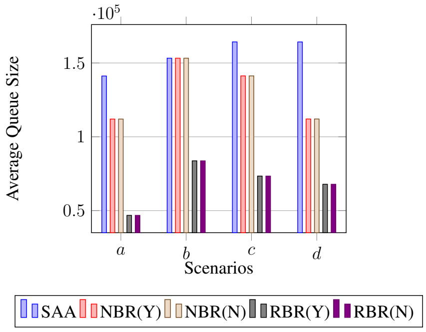
similarities among the algorithms and that similarities are disrupted when the load is above 20%.



(a)

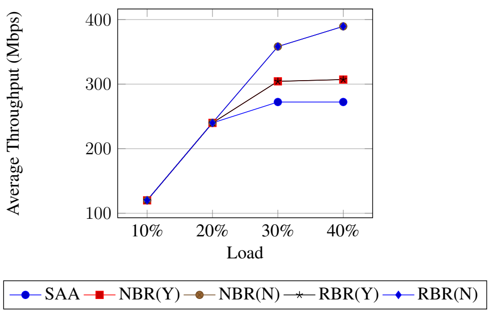


(b)

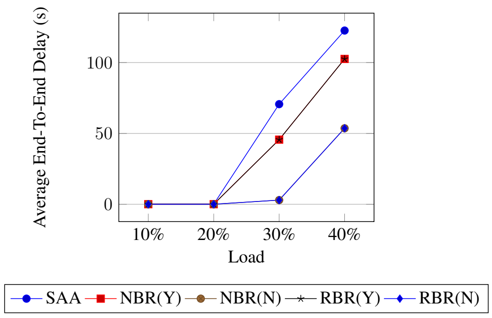


(c)

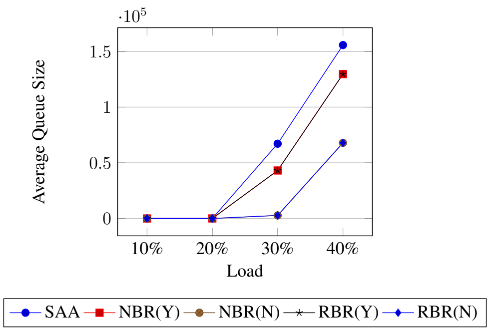
Figure 5.4: Performance analysis for traffic load equal to 40% of the channel capacity; (a) Average throughput; (b) Average end-to-end delay; (c) Average queue size.



(a)



(b)



(c)

Figure 5.5: (a) Average throughput; (b) Average end-to-end delay; (c) Average queue size.

CHAPTER 6

Conclusions and Future Work

6.1 Conclusion

This dissertation provides an overview of FiWi access networks, a technology that is suited to embrace a plethora of future and emerging broadband services and applications in a single infrastructure. Starting with a presentation of the technology and an update on the state of the art of the frequency assignment problem, this dissertation is mainly focussed on the front-end of the FiWi access network, where wireless nodes are equipped with one or more radios and are able to operate in a multi-channel environment.

To follow the main goal of this work, two algorithms termed NBR and RBR which stands for node based reconfiguration algorithm and route based reconfiguration algorithm respectively, were proposed along with their mathematical formalization to be used in the planning of frequency assignment in FiWi access networks.

A simulation model, using OMNeT++ framework, to analyse the performance of the strategies being proposed was developed, for which it is worth noting the importance of simple modules which are the active components of the model, and implement the desired behaviour of a network component.

Results show that the two proposed algorithms have advantages over static approaches, but the RBR is the one that provides the best performance, by carefully planning frequency assignment so that more parallel transmission, and less time division occurs.

In this dissertation, the simulation model uses the shortest path to route packets towards gateway as stated in section 3.4. For future work, it could be interesting to investigate on routing protocols that could better exploit the routing mechanisms in a WMN environment.The order in which nodes are processed during algorithm execution and the initialization step could be explored since there is no defined criteria.

References

[1] N. Ansari and J. Zhang, *Media Access Control and Resource Allocation: For Next Generation Passive Optical Networks*. Springer, 2013.

[2] X. Akyildiz, Ian F and Wang, "A Survey on Wireless Mesh Networks," no. September, pp. 23–30, 2005.

[3] R. Q. Shaddad, A. B. Mohammad, S. M. Idrus, A. M. Al-hetar, and N. A. Al-geelani, "Emerging optical broadband access networks from tdm pon to ofdm pon," *RN*, vol. 3, p. 4, 2012.

[4] Y. Luo, T. Wang, S. Weinstein, M. Cvijetic, and S. Nakamura, "Integrating optical and wireless services in the access network," in *National Fiber Optic Engineers Conference*. Optical Society of America, 2006.

[5] P. Chowdhury, B. Mukherjee, S. Sarkar, G. Kramer, and S. Dixit, "Hybrid Wireless-Optical Broadband Access Network(WOBAN) : Prototype Development and Research Challenges," no. June, pp. 41–48, 2009.

[6] M. Maier, N. Ghazisaidi, and M. Reisslein, "The audacity of fiber-wireless (fiwi) networks," in *AccessNets*. Springer, 2009, pp. 16–35.

[7] T. Koonen, "Fiber to the Home/Fiber to the Premises: What, Where, and When?" *Proceedings of the IEEE*, vol. 94, no. 5, pp. 911–934, May 2006. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1634534

[8] N. Ghazisaidi, M. Maier, and C. M. Assi, "Fiber-Wireless (FiWi) Access Networks : A Survey," no. February, pp. 160–167, 2009.

[9] N. Ghazisaidi and M. Maier, "Fiber-Wireless (FiWi) Access Networks: Challenges and Opportunities," no. February, pp. 36–42, 2011.

[10] T. Tsagklas and F. Pavlidou, "A survey on radio-and-fiber fiwi network architectures," *IEEE Journal of Selected Area in Communiations (JSAC)*, pp. 18–24, 2011.

[11] S. Sarkar, S. Dixit, and B. Mukherjee, "Hybrid wireless-optical broadband-access network (woban): a review of relevant challenges," *Lightwave Technology, Journal of*, vol. 25, no. 11, pp. 3329–3340, 2007.

[12] N. Correia, J. Coimbra, and G. Schutz, “Multi-radio hybrid wireless-optical broadband access networks,” PTDC/EEA-TEL/71678, Tech. Rep., 2006.

[13] A. Reaz, V. Ramamurthi, and S. Sarkar, “Flow-aware channel assignment for multi-radio Wireless-Optical Broadband Access Network,” *2008 2nd International Symposium on Advanced Networks and Telecommunication Systems*, pp. 1–3, Dec. 2008. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4937807

[14] H. Skalli, S. Ghosh, S. Das, L. Lenzini, and M. Conti, “Channel Assignment Strategies for Multiradio Wireless Mesh Networks :,” no. November, pp. 86–93, 2007.

[15] Y. Chen, N. Xie, G. Qian, and H. Wang, “Channel assignment schemes in Wireless Mesh Networks,” *2010 Global Mobile Congress*, pp. 1–5, Oct. 2010. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5634623

[16] F. Kaabi, S. Ghannay, and F. Filali, “Channel Allocation and Routing in Wireless Mesh Networks : A survey and qualitative comparison between schemes,” 2010.

[17] D. Breuer, F. Geilhardt, R. Hulsermann, M. Kind, C. Lange, T. Monath, and E. Weis, “Opportunities for next-generation optical access,” *Communications Magazine, IEEE*, vol. 49, no. 2, pp. s16–s24, 2011.

[18] ITU-T_G671, “Transmission characteristics of optical components and subsystems:TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS,” 2012.

[19] International Telecommunication Union-Itu, *Optical fibres cables and Systems, ITU-T Manual 2009*, 2010.

[20] ITU-T_G983.1, “Broadband optical access systems based on Passive Optical Networks (PON):TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS),” 2005.

[21] ITU-T_G984.1, “Gigabit-capable passive optical networks (GPON): General characteristics:TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS,” 2008.

[22] ITU-T_G984.2, “Gigabit-capable Passive Optical Networks (GPON): Physical Media Dependent (PMD) layer specification:TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS,” 2003.

[23] ITU-T_G984.3, “Gigabit-capable Passive Optical Networks(G-PON): Transmission convergence layer specification:TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS,” 2008.

[24] ITU-T_G984.4, "Gigabit-capable Passive Optical Networks (G-PON): ONT management and control interface specification:TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS," 2008.

[25] IEEE, *IEEE 802.3ah Standards*, 2004, vol. 2004, no. September.

[26] "Carrier sense multiple access with collision detection (csma/cd) access method and physical layer specifications-amendment: Physical layers specifications and management parameters for 10 gb/s passive optical networks," 2009.

[27] K. Tanaka, a. Agata, and Y. Horiuchi, "IEEE 802.3av 10G-EPON Standardization and Its Research and Development Status," *Journal of Lightwave Technology*, vol. 28, no. 4, pp. 651–661, Feb. 2010. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5371994

[28] J.-I. Kani, F. Bourgart, A. Cui, A. Rafel, M. Campbell, R. Davey, and S. Rodrigues, "Next-generation pon-part i: Technology roadmap and general requirements," *Communications Magazine, IEEE*, vol. 47, no. 11, pp. 43–49, 2009.

[29] Y. Luo, X. Zhou, F. Effenberger, X. Yan, G. Peng, Y. Qian, and Y. Ma, "Time- and Wavelength-Division Multiplexed Passive Optical Network (TWDM-PON) for Next-Generation PON Stage 2 (NG-PON2)," *Journal of Lightwave Technology*, vol. 31, no. 4, pp. 587–593, Feb. 2013. [Online]. Available: http://apps.webofknowledge.com/full_record.do?product=UA&search_mode=GeneralSearch&qid=1&SID=S2j6nOlCg2AnLM6FgG1&page=1&doc=8

[30] G.-K. Chang, A. Chowdhury, Z. Jia, H.-C. Chien, M.-F. Huang, J. Yu, and G. Ellinas, "Key Technologies of WDM-PON for Future Converged Optical Broadband Access Networks [Invited]," *Journal of Optical Communications and Networking*, vol. 1, no. 4, p. C35, Aug. 2009. [Online]. Available: http://www.opticsinfobase.org/abstract.cfm?URI=JOCN-1-4-C35

[31] K. Grobe and J.-P. Elbers, "PON in Adolescence : From TDMA to WDM-PON," no. January, pp. 26–34, 2008.

[32] J.-i. Kani, "Enabling Technologies for Future Scalable and," vol. 16, no. 5, pp. 1290–1297, 2010.

[33] P. Gupta and P. R. Kumar, "The Capacity of Wireless Networks," vol. 46, no. 2, pp. 388–404, 2000.

[34] M. S. Kuran and T. Tugcu, "A survey on emerging broadband wireless access technologies," *Computer Networks*, vol. 51, no. 11, pp. 3013–3046, 2007.

[35] IEEE802.11std, "IEEE Standard for Local and Metropolitan Area Networks Specific Requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," 1999.

[36] B. Li, Y. Qin, C. P. Low, and C. L. Gwee, “A survey on mobile wimax [wireless broadband access],” *Communications Magazine, IEEE*, vol. 45, no. 12, pp. 70–75, 2007.

[37] C. B. Raffaele and G. E. O. Marco, “Mesh Networks : Commodity Multihop Ad Hoc Networks,” no. March, pp. 123–131, 2005.

[38] R. Karrer, A. Sabharwal, and E. Knightly, “Enabling Large-scale Wireless Broadband : The Case for TAPs,” pp. 1–6.

[39] P. Bhagwat, B. Raman, and D. Sanghi, “Turning 802.11 Inside-Out ,” 1994.

[40] B. L. Dang and I. Niemegeers, “Analysis of ieee 802.11 in radio over fiber home networks,” in *Local Computer Networks, 2005. 30th Anniversary. The IEEE Conference on*. IEEE, 2005, pp. 744–747.

[41] Z. Jia, J. Yu, G. Ellinas, and G.-K. Chang, “Key enabling technologies for optical–wireless networks: optical millimeter-wave generation, wavelength reuse, and architecture,” *Lightwave Technology, Journal of*, vol. 25, no. 11, pp. 3452–3471, 2007.

[42] M. Medeiros, R. Avo, P. Laurencio, N. Correia, A. Barradas, H. da Silva, I. Darwazeh, J. Mitchell, and P. Monteiro, “Radio over fiber access network architecture employing reflective semiconductor optical amplifiers,” in *ICTON Mediterranean Winter Conference, 2007. ICTON-MW 2007.* IEEE, 2007, pp. 1–5.

[43] N. Ghazisaidi, M. Scheutzow, and M. Maier, “Survivability Analysis of Next-Generation Passive Optical Networks and Fiber-Wireless Access Networks,” vol. 60, no. 2, pp. 479–492, 2011.

[44] H. T. Win and A.-S. K. Pathan, “On the Issues and Challenges of Fiber-Wireless (Fi-Wi) Networks,” *Journal of Engineering*, vol. 2013, pp. 1–11, 2013. [Online]. Available: http://www.hindawi.com/journals/je/2013/645745

[45] K. Yang, S. Ou, K. Guild, and H.-H. Chen, “Convergence of ethernet pon and ieee 802.16 broadband access networks and its qos-aware dynamic bandwidth allocation scheme,” *Selected Areas in Communications, IEEE Journal on*, vol. 27, no. 2, pp. 101–116, 2009.

[46] Y. Luo, N. Ansari, T. Wang, M. Cvijetic, and S. Nakamura, “A qos architecture of integrating gepon and wimax in the access network,” in *Sarnoff Symposium, 2006 IEEE.* IEEE, 2006, pp. 1–4.

[47] G. Schutz and N. Correia, “Design of qos-aware energy-efficient fiber-wireless access networks,” *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 4, no. 8, pp. 586–594, 2012.

[48] S. Sarkar, H.-H. Yen, S. Dixit, and B. Mukherjee, “A novel delay-aware routing algorithm (dara) for a hybrid wireless-optical broadband access network (woban),” *Network, IEEE*, vol. 22, no. 3, pp. 20–28, 2008.

[49] P. Kyasanur and N. Vaidya, "Routing and interface assignment in multi-channel multi-interface wireless networks," *IEEE Wireless Communications and Networking Conference, 2005*, vol. 4, pp. 2051–2056, 2005. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1424834

[50] K. Xing, X. Cheng, L. Ma, and Q. Liang, "Superimposed code based channel assignment in multi-radio multi-channel wireless mesh networks," in *Proceedings of the 13th annual ACM international conference on Mobile computing and networking*. ACM, 2007, pp. 15–26.

[51] K. N. Ramachandran, E. M. Belding-Royer, K. C. Almeroth, and M. M. Buddhikot, "Interference-aware channel assignment in multi-radio wireless mesh networks." in *INFOCOM*, vol. 6, 2006, pp. 1–12.

[52] Y. Chen, N. Xie, G. Qian, and H. Wang, "Channel assignment schemes in wireless mesh networks," in *Mobile Congress (GMC), 2010 Global*. IEEE, 2010, pp. 1–5.

[53] P. Bahl, R. Chandra, and J. Dunagan, "Ssch: slotted seeded channel hopping for capacity improvement in ieee 802.11 ad-hoc wireless networks," in *Proceedings of the 10th annual international conference on Mobile computing and networking*. ACM, 2004, pp. 216–230.

[54] W. Si, S. Selvakennedy, and A. Y. Zomaya, "An overview of channel assignment methods for multi-radio multi-channel wireless mesh networks," *Journal of Parallel and Distributed Computing*, vol. 70, no. 5, pp. 505–524, 2010.

[55] A. Raniwala and T.-c. Chiueh, "Architecture and Algorithms for an IEEE 802 . 1 1 -Based Multi-Channel Wireless Mesh Network," vol. 00, pp. 2223–2234, 2005.

[56] H. Skalli, L. Lenzini, and M. Conti, "Traffic and interference aware channel assignment for multi-radio Wireless Mesh Networks Technical report , 2006," 2006.

[57] A. P. Subramanian, H. Gupta, S. R. Das, and J. Cao, "Minimum Interference Channel Assignment in Multiradio Wireless Mesh Networks," vol. 7, no. 12, pp. 1459–1473, 2008.

[58] A. Raniwala, K. Gopalan, and T.-c. Chiueh, "Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 8, no. 2, pp. 50–65, 2004.

[59] I. Katzela and M. Naghshineh, "Channel assignment schemes for cellular mobile telecommunication systems: A comprehensive survey," *Personal Communications, IEEE*, vol. 3, no. 3, pp. 10–31, 1996.

[60] A. Nasipuri, J. Zhuang, and S. R. Das, "A multichannel csma mac protocol for multi-hop wireless networks," in *Wireless Communications and Networking Conference, 1999. WCNC. 1999 IEEE*. IEEE, 1999, pp. 1402–1406.

[61] N. Jain, S. R. Das, and A. Nasipuri, "A multichannel csma mac protocol with receiver-based channel selection for multihop wireless networks," in *Computer Communications and Networks, 2001. Proceedings. Tenth International Conference on*. IEEE, 2001, pp. 432–439.

[62] A. Reaz, V. Ramamurthi, and S. Sarkar, "Flow-aware channel assignment for multi-radio wireless-optical broadband access network," in *Advanced Networks and Telecommunication Systems, 2008. ANTS'08. 2nd International Symposium on*. IEEE, 2008, pp. 1–3.

[63] A. Barradas, N. Correia, J. Coimbra, and G. Schütz, "Load adaptive and fault tolerant framework for energy saving in fiber–wireless access networks," *Journal of Optical Communications and Networking*, vol. 5, no. 9, pp. 957–967, 2013.

[64] A. Varga and R. Hornig, "An overview of the omnet++ simulation environment," in *Proceedings of the 1st international conference on Simulation tools and techniques for communications, networks and systems & workshops*, ser. Simutools '08. ICST, Brussels, Belgium, Belgium: ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2008, pp. 60:1–60:10. [Online]. Available: http://dl.acm.org/citation.cfm?id=1416222.1416290

[65] L. Zhang, G. Wang, and W. L. Dong, "Adaptive contention window adjustment for 802.11-based mesh networks," in *Wireless Communications, Networking and Mobile Computing, 2008. WiCOM'08. 4th International Conference on*. IEEE, 2008, pp. 1–4.

[66] X. J. Hei and L. Cheung, *Access Networks: 4th International Conference, AccessNets 2009, Hong Kong, China, November 1-3, 2009, Revised Selected Papers*. Springer, 2010, vol. 37.

List of Publications

Journals

1. S. Sabino, N. Correia, G. Schütz and A. Barradas, "Planning the Reassignment of Frequencies in Fiber-Wireless Access Networks", submitted to computer network journal (Elsevier).

Conferences

1. S. Sabino, N. Correia and A. Barradas, "Frequency Assignment in Multi-Channel and Multi-Radio FiWi Access Networks", accepted to CISTI'2014 (Iberian Conference on Information Systems and Technologies).