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Doctoral Dissertation

Dynamic Lightpath Provisioning Incorporating Four-Wave Mixing Induced Crosstalk and Modulation Format Conversion Interface

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To my family, whose life-long support and encouragement made it possible for me to become the woman I am.

" To my parents – *Dalila and Guillermo Olivo* –, who have been my role-models for hard work, persistence and personal sacrifices, and who emphasized the importance of education and instilled in me the inspiration to set high goals and the confidence to achieve them.

" To my brother – *Guillermo Alexander* –, who has been my emotional anchor through not only the vagaries of graduate school, but my entire life.

" To my sister – *Guidalys* –, my (childhood) beloved sister and eternal angel.

" To the Spirit of the Universe, who somehow fills me with a mysterious strength and hope, and leads me to believe that tomorrow will come not only with more challenging experiences but also with peace.

Adelys

Preface

Future optical networks are moving from static point-to-point connections towards dynamic wavelength routed networks using all-optical, reconfigurable switching nodes. By doing so, lightpaths are dynamically routed/switched entirely over the optical layer, eliminating current expensive electronic regenerators and enabling significant energy savings. However, the lack of optical-electrical-optical (O-E-O) transponders (i.e., transparency) makes it necessary to consider the degrading effects of the physical transmission of optical signals accumulated along the path. Previous work, consider mostly linear physical impairments during the wavelengths assignments scheme and only few incorporate nonlinear physical effects due to their complexity. The state-of-the-art in optical communication networks have enabled the increase of large capacity, high-speed data transmission and routing intelligence in the optical networks, and driving the need for an efficient strategy to face up the accumulation of physical impairments and to provide quality-enabled services. We proposed a new approach that takes into account the physical impairments during the entire path computation process, both wavelength assignment scheme and routing scheme, demonstrating by computer simulations of the impact on the network performance incorporating the physical impairments in the routing scheme. We had focused our study in the effects of four-wave mixing (FWM)-inducing crosstalk between the channels, which causes a fatal degradation in the teletraffic performance of wavelength-routed all-optical networks. In addition, none of the previous impairment routing studies has treated modulation format as an essential part of the impairment based routing strategy. In our study, modulation format conversion is taking into account as a technique to improve the network performance together with better utilization of the network resources while establishing the optical connection.

This dissertation introduces a study on dynamic lightpath provisioning towards the design on wavelength routed optical networks accomplishing physical impairment awareness (e.g., FWM-induced crosstalk) and enriching transparency in terms of bit rates and modulation format conversion interface using distributed impairment constraint based routing approach. The content of the dissertation is based on the research which I conducted during my doctoral course at the Department of Electrical, Electronics and Information Engineering, Graduate School of Engineering, Osaka University. The dissertation is organized as follows:

Chapter 1 is an introduction to the contents of the dissertation. It presents a general overview of the current state of optical networking including issues and challenges. A comprehensive description of the optical control plane is given, locating the routing controller and highlighting the main issue of dynamic provisioning of lightpath which form the motivation for the conducted research. The general architecture of wavelength-routed optical networks is described. Concepts as degree of transparency, impairment constraint based routing approach, routing and wavelengths assignments, intra- and inter-domain routing are introduced. The structure of the dissertation is explained at the end of this chapter.

Chapter 2 provides an overview of the issues found inside the physical layer related to the impairments of the optical networks addressing the details of the effects of FWM-induced crosstalk and its impact on the network performance of wavelength-routed optical networks. An analytical study of FWM and the basis of the calculation model used are described. Additionally the necessary fundamentals of on-off keying (OOK) and quadrature phase-shift keying (QPSK) modulation format are introduced.

Chapter 3 describes the novel designed impairment constraint-based routing algorithm. Covers wavelength-routed optical networks and focuses on lightpath computation encompassing physical impairment constraint, taking into account as a first instance FWM-induced crosstalk, as an important factor influencing the performance of high-bit-rate long-haul systems. In addition, an implementation to fast establishing the lightpath set up based on the advantages of a hybrid online/offline strategy is proposed.

Chapter 4 focuses on modulation format conversion feature interface, which has been added to the designed dynamic algorithm for high-bit-rate systems. By envisaged transparent modulation format conversion from 2-channels conventional OOK to QPSK in future wavelength-routed optical networks, we have proposed a novel FWM-induced crosstalk-aware dynamic RWA algorithm and have showed by numerical simulation that it can minimizes significantly the network blocking probability.

Chapter 5 summarizes the results of the preceding chapters and draws final conclusions of the dissertation. From all the obtained results, it is concluded that, the proposed FWM-induced crosstalk aware dynamic RWA with modulation format conversion has the feasibility to enrich the network performance, guarantee quality of services (QoS), increase scalability, and support transparency. Consequently, the proposed scheme is considered as one possible base to develop the network design framework for the future transparent optical communication networks.

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Osaka, Japan
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The present research has been carried out during my tenure of doctoral course at the Department of Electrical, Electronics and Information Engineering, Graduate School of Engineering, Osaka University, under the guidance of Prof. Ken-ichi Kitayama and Prof. Akihiro Maruta.

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Contents

List of Figures

Chapter 1

Introduction

Planning real world telecommunications networks is a task of growing complexity. The complexity results not only from the fact that the networks are large and functionally complex, subject to continuous technological evolution and growth, but also that network planning is a multidimensional techno-economic optimization problem.

Optical networks design draws an increasing amount of attention nowadays. Traffic demands in communication networks are growing rapidly, mainly due to data-centric applications. The major technology at hand that is promising to meet the high bandwidth demand is optical networking with wavelength division multiplexing (WDM). The technology of WDM splits the large bandwidth available in an optical fiber into multiple channels, each one operating at different wavelengths and at specific data rates, achieving a throughput of up to several hundreds of Gbits/s. The early deployment of WDM technology was in a point-to-point manner to ease fiber exhaustion. As more advanced systems, such as optical add/drop multiplexers (OADMs) and optical cross-connects (OXCs) (capable of routing and switching wavelengths), have matured, dense WDM (DWDM) has become a network-level technology. Therefore, efficient internetworking of higher-layer protocols, most notably internet protocol (IP) over DWDM networks, has become more important. The increasing complexities of optical networks, however, complicate the internetworking task. In particular, optical connection routing for channel setup is one of the major factors that affect optical network design and operation, and this is the global issue presented in the study of this thesis.

1.1 Optical networks, current trends and issues

Today's continuous increase of data traffic primarily reflects the progressively extending use of the new information and communication technologies in all the socio-economic segments of the developed and developing societies. The future user-friendly information society requires the implementation of optimized communication networks, the architecture and capacity of which depend both on the needs of each category of users and on the services which are provided to them.

Photonics research is seen as an agent in four main areas: 1) telecom/infotainment, 2) health care/life sciences, 3) environment/security and lighting, and 4) photonic devices relevant to the aforementioned areas. The strategic objectives for the first area include broadband for all, micro- and nano systems, advanced displays, and photonic functional components. In the second area, photonic technologies will be essential for non-invasive imaging, diagnostics and therapies. The third area includes solid-state lighting, optical sensors, and optical monitoring. And in the four area includes photonics devices that lead the trends of the previous areas. Photonics for telecom has been a strong driving force for new applications of photonics in the second and third areas; it is envisioned that the synergies between the areas can be further stimulated by the strategic priorities and actions of new research activities.

Therefore, some advances and perspectives of new services in photonic technology research are expected, and the general requirements they imply for the networks according to the presently commonly accepted technical assessments is a driven force of current research activities.

For instance, routing at so high bit rates for everybody put strong requirements on the metropolitan area networks (MAN) and wide area networks (WAN). The most noticeable demands are: fast reconfigurability up to 40 Gbit/s, very large node throughput (greater than 1 Tbit/s in the MAN and 10 Tbit/s in the WAN) and extremely high availability.

The implementation of such perspectives must be economically viable. The major part of the production costs is caused by capital expenditures (CAPEX) and operating expenditures (OPEX). Indeed, the technological research can contribute to the reduction of costs in a very effective way, especially at the nodes of the networks. Costs of a network node depend on its complexity. A reduced complexity can be achieved by the so called delayering, which means reduction of the protocol stack. The traditional protocol stack for IP services consists of 4 protocols (IP over Asynchronous Transfer Mode (ATM) over Synchronous Digital Hierarchy (SDH) over the optical layer). The major sustaining functions performed by the traditional layers are, high speed transmission and efficient fiber use on the optical layer, fast traffic protection and sub-wavelength multiplexing on the SDH/ synchronous optical networking (SONET) layer, service differentiation and traffic engineering on the ATM layer and finally packet forwarding and service features on the IP layer. Keeping in mind that the functions are important, not how they are organized in layers, the complexity strongly depends on the way these functions can be realized and organized thanks to the new technological advances.

The functions of the intelligent optical layer are realized by the optical control plane, which controls the optical layer, processes information from the monitoring, and communicates with the network management. For instance, performance monitoring is essential for the operators to ensure integrity of their network, and to enable service-level agreements with their customers. Intelligence in optical networks should enable the operator to meet emerging requirements such as: rapid automatic provisioning of connections, automatic topology recovery and network inventory, traffic engineering and fast optical restoration.

The objectives put forward by the vision of future applications and needs thus lead to strong technical requirements in the field of network architectures and solutions, systems and sub-systems for transmission and routing and in term of advanced components.

The past ten years have been very active in the field of research and development (R&D) on optical components and all-optical functionalities. Two important steps can be foreseen: the first is enhanced usage of the fiber spectral bandwidth including the channel bit-rate increase to 40 Gbit/s (or higher via optical time division multiplexing (OTDM)). This requires new amplifier specifications, new in-line control (polarization mode dispersion (PMD), regeneration, nonlinearities, etc.). The second is the introduction of enhanced optical transparency requiring OXCs and OADMs, optical signal processing and wavelength-agile components. In addition, new research concepts such as photonic crystals, and new materials such as polymers and organics, open new perspectives for future evolutions and future developments of better performing, more cost effective, and more compact devices.

The quest for higher capacity in MANs is solved by higher data rates and increased spectral density in WDM networks. The current trend is toward more complex and dynamic networks with dynamic reconfiguration and provisioning.

The WDM network relies on a number of wavelength selective or wavelength tuneable photonic components and subsystems. The OXC is the key building block of the WDM network; it may contain OADMs, which again may consist of wavelength selective switch (WSS) reconfiguration nodes, wavelength routers, wavelength converters, tuneable wavelength filters, etc. The challenge is to integrate many of these subsystems on a chip in a modular system that is upgradeable. At present the planar photonic crystal is the most promising technology for the realization of photonic integrated circuits with many functional elements. The WSS technology is highly scalable and can reduces network cost and enables new architectures in next generation DWDM networks.

The granularity problem will for a long time be solved by burst or packet switching based on optical-electrical-optical (O-E-O) conversion technology. In spite of an intense research activity to demonstrate true photonic packet switching, it may take a decade before it materialises in carrier networks on a larger scale. The crucial barrier to true photonic packet switching is the lack of an optical equivalent to the electronic buffer or random-access memory.

The major issue for the WAN, backbone and the global area network (GAN) is to cope with the large data capacity (1-10 Tbit/s) over very long distances (from hundreds to several thousands of kilometers for WAN and over 10,000 km for GAN, many of which are transoceanic). The nodes also serve as entry points to the MANs, and it is assumed that all signals will be fully regenerated at these entry points.

Innovations of the transport network requires:

- Increase of the single channel bit-rate (40 Gbit/s or more).
- Global (multi-wavelength) management of fiber chromatic dispersion, non-linearities, and PMD.
- Increase of the spectral efficiency through special modulation formats and introduction of forward error correction (FEC); (FEC can also be used for supervision of the optical links).
- Wideband amplification and introduction of Raman amplification.

The switching in the WAN and backbone area will be mainly performed on wavelength and waveband level, due to the highly aggregated traffic.

Throughout the network wavelength locking to the International Telecommunication Union (ITU) grid for sources and multiplexer channels is required. Tuneable sources and receivers are an important aspect of cost reduction and maintenance but require simple and stable wavelength allocation schemes.

The use of tuneable lasers may be supplemented by multi-wavelength light sources, which act as WDM channel generators. The WDM channels may be obtained by filtering the spectrum of a mode locked laser, which has the right repetition rate for the spectral comb to match the ITU grid. An alternative approach is to filter the broad spectrum generated by injecting high power light pulses into a nonlinear optical element. Special designs of photonic crystal fibers have proved to be very efficient nonlinear elements in this type of super-continuous (SC) light source [1,2].

The increase of the total in-line bit-rate imposes a strong demand on amplifiers. Dispersion and nonlinear effect management will require compensating fibers [3] while the use of spectral inversion techniques [4] will appear for specific links. In a longer term, the introduction of OTDM associated to WDM will allow higher bit rates (80-160 Gbit/s) per channel.

1.2 Degree of transparency in optical networks

The huge transport capacity of WDM technology has not been accepted to be fully used by current optical networks yet [5]. As the volume of IP traffic drastically changes time by time, a large portion of surplus transmission capacity is required to cope with this traffic change. Such inefficiency on the bandwidth usage is due to the use of expensive O-E-O transponders causing the electronic bottleneck.

Overall, optical networks can be opaque, translucent or transparent.

In opaque region of networks, each route connections encounter O-E-O conversion or regeneration at every intermediate node in the network. One advantage of opaque networks is that they decouple transmission from switching and prevent the accumulation of cascaded impairments along the signal path. Other benefits are the ability to convert wavelengths in a multivendor environment and do detailed performance monitoring. Nevertheless, the biggest drawback of such networks is the higher cost of the additional O-E conversions at the intermediate nodes. These costs comprise wavelength transponders and their related electronic control circuitries. Moreover, opaque networks are bit-rate-, protocol-, and format-dependent; hence, any hope of transparency to these attributes is lost.

As an alternative to both fully transparent and fully opaque networks, the translucent networks come to be placed in the middle on a range of transparency. In a translucent network, a signal from the source travels through the network "as far as possible" before its quality degrades, thereby requiring it to be regenerated at an intermediate node. The signal could be electrically regenerated several times in the network before it reaches the destination. A single hop in a translucent network could span one or more fiber links and may even span the entire source-destination route, under the right conditions. Previous study in [6] shows that, for medium-scale networks, where physical-layer characteristics are dominated by crosstalk and amplified spontaneous emission (ASE) noise, translucency can help to improve the overall network performance. For larger-scale networks, where impairments introduced by fiber nonlinearities and dispersion cannot be ignored, a higher degree of opacity may be needed to combat signal degradations is anticipate, but this is still an open problem for further research.

Conversely, in transparent networks there is no electronic signal regeneration or O-E conversion for an end-to-end optical lightpath. All-optical networks can support different bit rates, protocols, and modulation formats, and are therefore loosely termed future-proof. Since there is no O-E conversion in each node in the network, the total transmission time will be reduced. However, transparent networks still lack the detailed performance monitoring and distance advantage of opaque networks.

Future optical networks are moving toward overcoming these limitations and taking full advantage of the WDM technology. This is one of the main characteristics that drives our motivation to develop a dynamic lightpath provisioning coping with physical layer impairments during the process of optical channel set up.

All-optical networks will be achieved using all-optical switches (e.g., reconfigurable OADMs, namely, ROADMs, and/or OXCs) that switch/route connections (lightpaths) entirely within the optical domain (i.e., transparent networks). Therefore, the introduction of these switches allows to eliminate the need for O-E-O transponders, favoring the overall network's cost-effectiveness. However, this also results in losing the electrical regeneration signals, which in turn makes signal impairments accumulation due to fiber transmission (attenuation, dispersion, nonlinearities, etc.), optical amplification (ASE noise), and insertion losses and cross-talk introduced by optical elements.

Modern optical telecommunication and media services require rapid and flexible bandwidth allocation. The increasing reach of optical transmission systems and the introduction of new wavelength switching technologies has driven the evolution of backbone optical WDM networks towards all transparent networks. To efficiently cope with these requirements, the optical transport plane need to be upgraded to support the transparent transmission. As it has been aforementioned, transparency in an optical transmission is achieved when electronic forwarding is replaced with all-optical forwarding. Such a solution promotes scalability of the network because the forwarding in the optical domain alleviates the one-interface-per-channel requirement. Moreover, the introduction of transparency enables the flexibility in terms of signal bit rate as well as modulation format.

Albeit one of the key benefits of optically-switched networks is the transparency to bit-rate, protocol or modulation format, this is also one of the main obstacles when determining an optimum path through the network.

1.3 Wavelength-routed optical networks

There are two fundamental types of underlying network infrastructures based on how traffic is multiplexed and switched inside the optical network: circuit-switched and packet-switched. This dissertation focuses on the study of optical circuit-switched (OCS) network, i.e., the wavelength-routed optical network which is considered to be the candidate for the future wide-area backbone all-optical infrastructure. Some of the motivation for studying this type of network rest on the facts that it can provides services at much higher speeds, realizes higher capacities, improves link utilization and between others improves the bandwidth efficiency. However significant advances in technology are needed to make it practical, and there are some significant roadblocks to overcome.

Transparent wavelength-routed WDM networks consist of two types of nodes, shown in Figure 1.1. The photonic switching fabric and the edge or access-node. The photonic switching fabric: contains

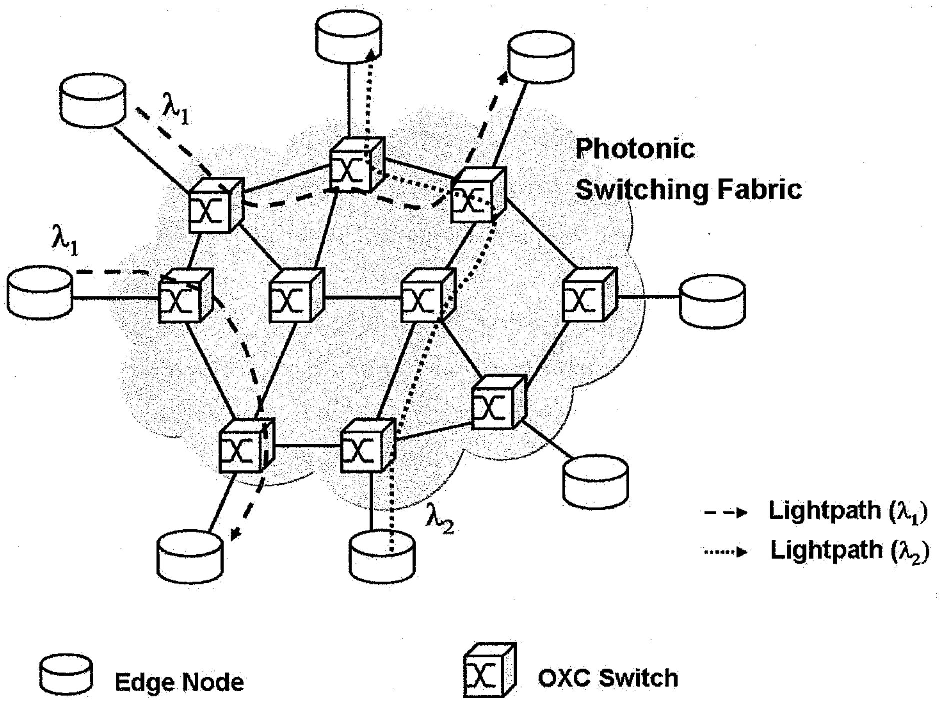


Fig. 1.1: Wavelength-routed optical network architecture.

optical switches or OXC connected by fiber links. The edge-node or access-node: provides the interface between non-optical end systems (such as IP routers, ATM switches, etc) and the optical core. Those are equipped with transceivers, which may be wavelength tuneable.

End-users (located between two edge-nodes in the network) communicate with one another via all-optical (WDM) channels, which are referred to as lightpaths or connections that may span more than one fiber link. Lightpaths are logical channels which provide an end-to-end connectivity in transparent networks without any intermediate electronics. In the absence of wavelength converters, a lightpath must occupy the same wavelength on each link in its route, a restriction known as the wavelength-continuity constraint. Given a set of connections, the problem of setting up lightpaths by routing and assigning a wavelength to each connection is called routing and wavelength assignment (RWA) problem. Our research focuses on dynamic traffic, in which a lightpath is set up for each connection request as it arrives, and the lightpath is released after some finite amount of time. One of the challenges involved in designing wavelength-routed networks with dynamic traffic demands is to develop efficient algorithm and protocols for establishing lightpaths. The algorithm must be able to select routes and assign wavelength to connections in a manner that efficiently utilizes network resources and maximizes the number of lightpath established.

Intelligent optical network management system allows carriers to set up new routes through the network in a matter of seconds or minutes, rather than the weeks or months it takes with legacy systems. In a transparent network a connection is set up to carry data traffic via an all-optical WDM channel or lightpath. Setting up and torn down a lightpath for a connection request by using an RWA technique [7] is known as connection provisioning. Dynamic connection provisioning is an important traffic-engineering problem for minimizing cost and for better utilizing network resources.

Routing in wavelength-routed network usually assumes that all the paths have adequate end-to-end signal quality [8]. This assumption is suitable for opaque networks, since O-E-O conversions regenerate the signal at every node along the route. Indeed, every data link between the optical switches (e.g., add-drop multiplexers) is isolated by O-E-O transponders. Thus, the objective of routing within opaque networks is to achieve an efficient utilization of the network resources (e.g., bandwidth) through the selection of both an spatial route (nodes, links) and an spectral route (wavelength) which minimizes the blocking of subsequent connection requests. This problem has been largely studied using RWA algorithms [9], which in its first stage deals with the design algorithms to route path that optimize the wavelength resources utilization. Nevertheless, the introduction of transparency imposes a new challenge on the lightpath provisioning, since the optical connections must remain entirely in the optical domain from the source to the destination nodes. As a result, transmission impairments accumulate while the signal travels, which causes that at the receiver the optical signal may not fulfill the stringent quality of service (QoS) required by the client, affecting the revenues of the network operator. One solution to face up this problem is to employ RWA algorithms that consider physical-layer effects besides network-layer issues in order to guarantee adequate end-to-end quality of the optical signal. These RWA algorithms are known as impairment constraint based routing (ICBR) or impairment-aware RWA (IRWA) [10, 11].

1.4 Control plane

In the context of wavelength-routed networks, the international telecommunication union (ITU), telecommunication standardization sector (ITU-T) automatic switched optical network (ASON) standard [12] describes the set of control plane components that are to be used to manipulate transport network resources in order to provide the functionality of setting up, maintaining, and releasing optical connections. Generalized multiprotocol label switching (GMPLS) is an implementation of the control plane that has been developed by the internet engineering task force (IETF) to facilitate the establishment of label switched paths (LSPs) [13], involving signaling, routing, and resource management functions and protocols. According to IETF definition, traffic engineering (TE) is concerned with performance and resource optimization of networks, in response to dynamic traffic demands and other stimuli like node and link failures. GMPLS implements all functional entities necessary for controlling an ASON, actually going beyond the pure optical domain and being capable of setting up LSPs in a variety of data plane technologies.

This control plane is seen by the industry as the most promising solution for introducing intelligence in future optical networks, it represents a common set of distributed functions and interconnection mechanisms (signaling and routing) that set up lightpaths dynamically with a required level of QoS. Distribution is widely considered as the best choice for handling dynamic connection requests [5], that

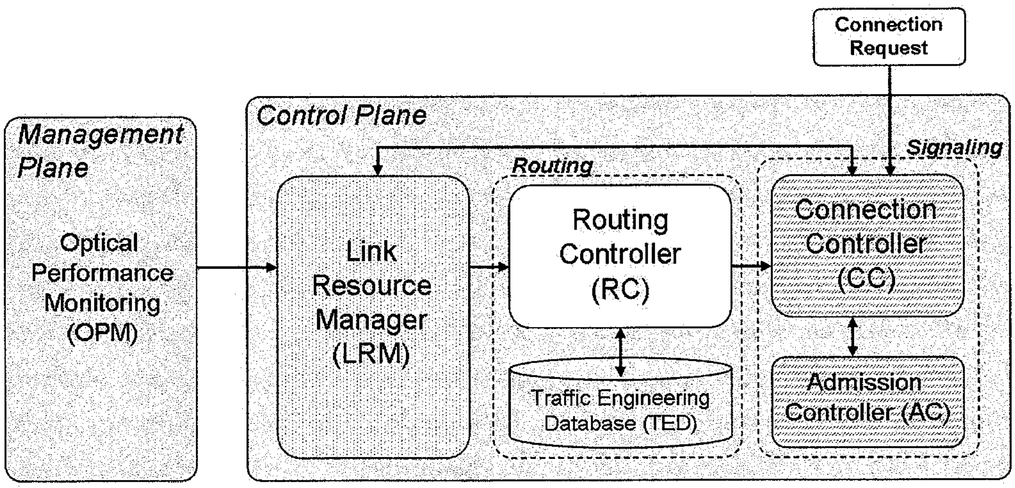


Fig. 1.2: Control plane of a distributed ASON/GMPLS-based architecture.

is, every network node is governed by a common control plane. In such scenario, path computation is driven by the source node of each connection request, which enhances the network scalability if one compares it with a centralized RWA model under the same dynamic traffic conditions.

Figure 1.2 depicts the ASON/GMPLS-based architecture of an control plane, which is constituted by four main elements, namely, the link resource manager (LRM), the connection controller (CC), the admission controller (AC), and the routing controller (RC). The LRM maintains an updated view of the local transport plane resources, the RC is for computing routes (RWA algorithm) and for disseminating resource and network topology information using a distributed routing protocol such as open shortest path first traffic engineering (OSPF-TE) [14], and the CC sets up, modifies and tears down lightpaths using a distributed signaling protocol as resource reservation protocol (RSVP-TE [15]). In particular, the AC element is responsible for informing the CC about whether the accumulated optical parameters are admissible by the connection being established. Therefore, if the accumulated parameters exceed an admissible value or threshold, further re-attempts shall try to follow a different path to set up the requested lightpath. The RC performs the source-initiated route computation for each requested lightpath by means of RWA algorithms. While in the distributed signaling approach these RWA algorithms only consider TE constraints and network resources, in the distributed routing approach new impairment-aware RWA algorithms shall be proposed for computing feasible end-to-end routes considering both TE and optical physical-link constraints [10].

Any change occurred within a node, that is (local) link attributes is reflected in the LRM. Thus, the LRM keeps track of any change over any attached local data link and informs the RC in order to flood (update) the network with such new information. This updated information will be used by the corresponding RWA algorithm on any node within the network. For this aim the updating/flooding procedure concerns the dissemination/broadcast of any variation suing a particular routing protocol (e.g., OSPF-TE). This information is then collected on each node in a repository referred to as traffic engineering database (TED) which is used to maintain an updated picture of not only its local net-

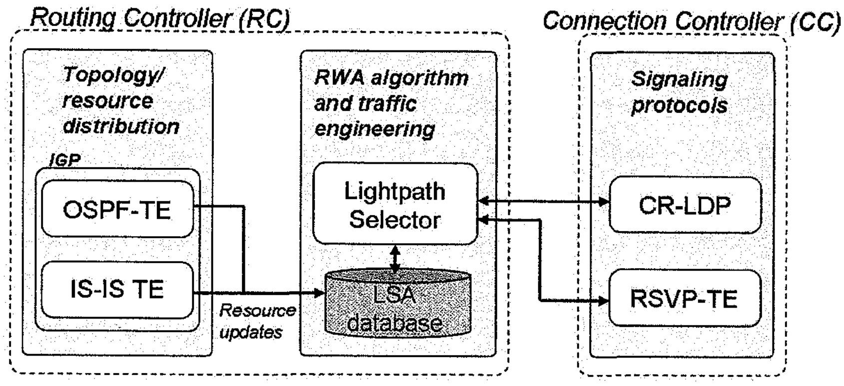


Fig. 1.3: GMPLS building blocks for lightpath routing.

work resources (i.e., adjacent data links) but also information related to remote links. Network-wide information stored in every TED serves as the input information for the RWA algorithms in order to compute optimal routes by using up-to-dated network-layer attributes. The use of ICBR algorithms in a distributed control plane requires that every node's TED be updated with physical-layer information within the network. For this aim, two main challenges need to be addressed within the considered distributed scenario: an on-line monitoring system and physical-layer extensions to existing routing protocols.

The scope of this dissertation lies inside the RC, and addresses the positive impact to the teletraffic network performance when physical impairments awarenesses are considering inside the dynamic establishing lightpaths process.

Figure 1.3 shows a view of lightpath routing and signaling processes using various building blocks of the GMPLS control plane. The interior gateway protocols (IGPs), such as open shortest path first (OSPF) and intermediate system to intermediate system (IS-IS), with extensions for optical and TE attributes, will allow nodes to exchange information about optical network topology, resource availability, and even policy information. This is done via properly defined link state advertisements (LSAs) that are maintained in an LSA/TE database. RWA algorithm is then used to select lightpaths subject to specified resource and/or policy constraints. Optical path computation algorithm makes use of the topology and resource information stored in the LSA/TE database. Once a lightpath is selected, the signaling protocol is invoked to set up the connection. Here, resource reservation protocol with TE (RSVP-TE) and/or constraint-based routing label distribution protocol (CR-LDP) are examples of signaling protocols used to signal a lightpath setup. The lightpath selector computes a lightpath for a given connection request with the objective of optimizing certain network wide parameters (e.g., network resource utilization). In general, lightpath computation is challenging due to the unique characteristics of optical networks.

Optical networks aim to support fast end-to-end optical lightpath setup and restoration, and generally there are three main components involved in setting up a channel (see the three main blocks in Fig. 1.3); Resource discovery: in resource discovery, state information of network resources such as network connectivity, link capacity, and special constraints is derived. Particularly, mechanisms used to disseminate the state information are specified. By and large, this is accomplished by extending conventional IGPs to carry additional optical resource information in their LSAs. Path selection: path selection is used to select an appropriate route through the intelligent optical network for the requested lightpath. It is implemented by introducing the concept of constraint-based routing which is used to compute paths that satisfy certain constraints, including constraints imposed by the operational environment and physical layer limitations. Path management: path management includes label distribution, path setup, path maintenance, and path revocation/ teardown. These functions are implemented through an appropriately extended signaling protocol, such as RSVP-TE or CR-LDP.

The above components of the control plane are separable and independent of each other, and the modularity allows the control plane to be implemented using a composition of best-of-breed subcomponents. This dissertation will mainly focus on lightpath routing, specifically on impairment-aware RWA.

1.5 Intra- and inter-domain routing

Internet routing can be uncoupled into two distinct planes, each of which has very different characteristics and goals, namely intra-domain routing and inter-domain routing.

On the one hand, intra-domain routing handles routing within a single network or administrative domain. Each administrative domain is free to choose the intra-domain routing protocol to be utilized within its network, according to its own preferences and needs. Two types of intra-domain routing protocols are available at present, that is link-state routing protocols and distance-vector routing protocols. Link-state protocols distribute the entire network topology to all routers within the domain, and the decision process to select the best path to reach any given destination inside this domain is based on Dijkstra's shortest path algorithm. Alternatively, in distance-vector routing protocols the routers lack of the entire network topology and the selection of the best path is based on the Bellman-Ford routing algorithm. At present, the most widely deployed intra-domain routing protocol is a link-state protocol, i.e., the OSPF [16].

On the other hand, across the administrative domain boundaries an inter-domain routing protocol is used in order to exchange reachability information, and to select the best path to reach any given destination according to each domain's specific policies and needs. In contrast to the intra-domain case, for inter-domain routing, the border gateway protocol (BGP) [17] is the standard routing protocol. BGP is a path-vector routing protocol, which for scalability reasons is only aware about the interconnections between the different administrative domains. In other words, BGP does not manage or exchange any kind of intra-domain information, so the internal state of the network in any administrative domain is not revealed by BGP. In summary, whereas intra-domain routing manages the selection of the best path within a single administrative domain, inter-domain routing is what holds the Internet as a single unit. Our research work copes with the intra-domain routing policy.

1.6 Physical impairments and modulation formats on the lightpath provisioning.

In dynamic allocation, a lightpath is created in response to a request for communication from a source to a destination by determining a path in the network and then allocating an usable WDM channel for every link fiber in the path. When the communication is over, the WDM channels used for this communication are reclaimed for future use in some other communication. The dynamic choice of wavelength ensures better wavelength utilization, therefore one important point in this research is that the provisioning design copes with dynamic lightpath demands, which overcome the drawbacks of static scheme designs but rise the complexity on algorithm constraints implementation. In a dynamic scheme, when allocating a lightpath for a new source-destination pair, all other lightpaths currently in use have to be considered. A dynamic scheme does not guarantee that communication from a source to a destination will always be possible. If the conditions for establishing a lightpath are not satisfied, the communication will be blocked. Clearly, in realistic situations, it is necessary to ensure that the probability that a communication is blocked is very low.

In a large number of previous works related to RWA, it is usually assumed that all routes have adequate signal quality. However, as the network size grows, a domain of transparency may be too large to ensure that all optical paths have adequate signal quality. Traditional routing approaches find a path that minimizes a certain cost parameter, such as the length of the connection. Most of the reported RWA algorithms assume that once an available path and wavelength have been identified, the connection is feasible. This may not be true in transparent optical networks using WDM, where the optical signal experiences and accumulates the effects of physical impairments associated with the transmission line and optical switching nodes, aggravated with the constant increasing on the system bit rate. In some cases, this results in unacceptable signal quality. Hence, ICBR is needed in order to ensure that the connections are feasible. To cope with this issue, it is necessary to consider not only the network-level conditions but also the equally important physical performance of the connection.

Various physical impairments unique to the optical network limit the optical reach, and also degrade the performance and QoS of the network, therefore it is important to cope with these issues especially from the routing process since it is expected to guarantee good signal quality of the optical channel without compromising the network performance and if possible to improve it. Impairments include various types of dispersion (e.g., chromatic, polarization), attenuation, ASE noise introduced by optical amplifiers, and nonlinear effects such as self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM), as impairments that arises from intra- or inter-channel crosstalk in multiplexers and demultiplexers. Although the Internet engineering task force (IETF) drat [8] provides a good overview of issues and framework for impairment routing, it lacks in implementation details.

Therefore, it becomes clearly that physical layer constraints should be included directly in the state information (and subsequent routing algorithms) and be taken into account by the routing algorithms when computing routes. The design of optical networks raises a number of issues depending on the switching paradigm, we will be dealing with circuit-switched networks, particularly with the

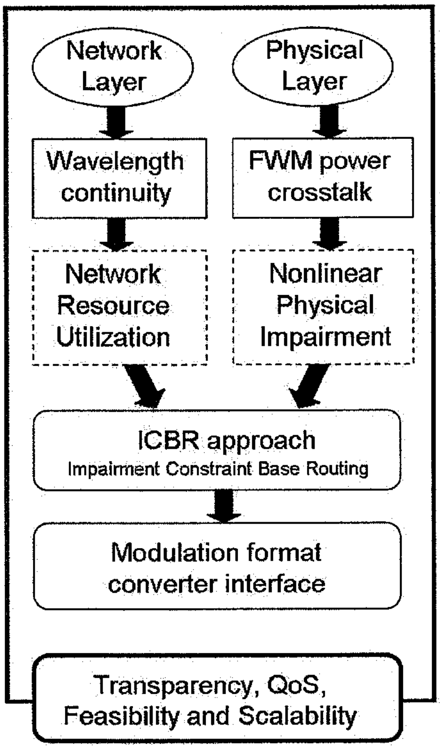


Fig. 1.4: Approach and goals in the current research.

wavelength-routed optical network as it has been mentioned above.

Although previous studies have investigated optical impairments in relation to optical transport systems, these studies tend to describe a fixed optical transmission link rather than a dynamic optical network path [18], or focus on linear impairments avoiding nonlinear impairments due to their complexities, except the studies in [19], and some others have included physical layer information only in the wavelengths assignment [20], or assuming a signaling approach [21].

Under dynamic lightpath demands, and through this study, it is expected to demonstrate that the physical layer impairment awarenesses should not be ignored inside the routing algorithm process as well as during the wavelengths assignment scheme, and a nonlinearity induced performance degradated factor as it is the FWM-induced crosstalk has been taken into account.

Additionally, none of the previous impairment routing studies has treated modulation format as an essential part of the impairment based routing strategy. However, transmission experiments have clearly shown that different modulation formats (e.g., DPSK) are affected unequally by various impairments [22–24].

Figure 1.4 summarizes the approach taken in this research and highlights the two main aspects as dynamic lightpath provisioning (coming from two different roads of layer nature: physical and network layer parameters) as well as given an inside on the modulation formats to be part of the lightpath establishing process. This volume gives the description on how this approach is carried out and how it affects and impacts the network performance in order to realize a better network realistic design and enrich transparency, QoS, feasibility and scalability in optical networks.

1.7 Organization of the dissertation

Within the general scenario described above, this dissertation has been organized as follows.

Chapter 2 provides the fundamentals of two main subjects, one is the physical impairment of FWM-induced crosstalk and the other is the main characteristics of the basic digital modulation formats. Details of the effects of FWM-induced crosstalk and its impact on the network performance of wavelength-routed optical networks is discussed, giving the reasons to adopt the FWM effect as a constraint for the dynamic lightpath provisioning. An analytical study of FWM and the basics of the power calculation of new waves generated are introduced. Also, the main digital modulation formats are described, providing benefits and drawbacks of each of their implementations.

Chapter 3 is devoted to describe the designed impairment constraint-based routing algorithm. This chapter focuses on dynamic lightpath computation encompassing physical impairments. A novel cost function is introduced with two natures of constraints: network and physical layers. The FWM-induced crosstalk is incorporated as an important factor that deteriorates drastically the performance of wavelength-routed optical networks and influences the design of high-bit-rate long-haul systems. Under a distributed approach the cost function is evaluated and the physical impairment is taking into account to both the routing and the wavelengths assignment processes. Extensive simulations are carried out to evaluate the performance in terms of blocking probability. Additionally, an implementation to fast establishing the lightpath set up based on the advantages given by a hybrid online/offline strategy is presented.

Chapter 4 focuses on modulation format conversion feature interface incorporated in the dynamic lightpaths establishing. By envisaged transparent modulation format conversion from 2-channels OOK to QPSK in future wavelength-routed optical networks a novel FWM-induced crosstalk aware dynamic RWA algorithm is demonstrated to minimize the blocking probability. Results gives a strong evidence of the advantages of taken into account modulation format conversion into the dynamic provisioning as well as the impact that this represented to the network performance, achieving in this way the goals defined at the initial stage of our research.

Chapter 5 summarizes the results of the preceding chapters and draws final conclusions of the dissertation.

Chapter 2

Fundamentals of Four-Wave Mixing and Modulation Formats

A general overview of the physical impairments in optical networks in given focusing in the impact of FWM crosstalk. The characteristics of FWM effect are explained and justified the reason why it is taken into account as one of the main constraints incorporated into the cost function of the routing algorithm. Details of the FWM products calculation are given. Principles of modulation formats as amplitude-shift keying (ASK), phase-shift keying (PSK), and frequency-shift keying (FSK) are addressed.

2.1 Introduction

A rigorous analysis of the physical effects on the performance of an optical network should require the simulation of the entire network for every possible configuration that the RWA algorithms may be taken into account. Such a task should require millions of hours of computation time. Hence, evaluation of the impairments accumulations of linear effects and the impairments of nonlinear effects separately is a practical approach.

In the case of wavelength-division multiplexing (WDM) systems, nonlinear effects can become important even at moderate powers and bit rates. At high bit rates such as 10 Gbit/s and above and at high transmitted powers, it is important to consider the effect of nonlinearities. Because of the large transmission distance involved, fiber dispersion and nonlinearity are important sources of performance degradation [25,26]. These effects are complex and interdependent, making simulation an appropriate tool for design and analysis [27].

Today, several impairments that were second- or third-order effects earlier began to emerge as first-order effects; this list includes nonlinear effects in fiber. Nonlinearities in optical fibers are caused by the physical effect called Kerr effect. The effect is a local change of the refractive index as a function of the overall propagating optical power. Kerr effect induces well know impairments on the propagating signal that can be classified as [28,29]: self phase modulation (SPM), i.e., the modulation of the phase of a signal induced by variation in time of the power of the signal itself; optical parametric gain (OPG), i.e., the transfer of power from a signal to the adjacent spectral components; cross-phase modulation (XPM), i.e., the modulation of the phase of a signal induced by variation in time of the overall power of the comb of WDM channels propagating in the fiber; four-wave mixing (FWM), i.e., the generation of spurious tones at new frequencies.

Here, we focus on crosstalk effects enhanced by FWM, and show that network design can alleviate the effects of crosstalk in all-optical networks. In the FWM, three light signals at different wavelength interact in the fiber to create the fourth light signal at a wavelength that may overlap with one of the light signals and interferes with the actual data that is being transmitted on that wavelength.

It turns out paradoxically that the higher the chromatic dispersion is, the lower the effect of fiber nonlinearities are. Chromatic dispersion causes the light signals at different wavelengths to propagate at different speeds in the fiber. This in turn causes less overlap between these signals, as the signals go in and out of phases with each other, reducing the effect of the FWM. The realization of this trade-off between chromatic dispersion and fiber nonlinearities stimulated the development of a variety of new types of single-mode fibers (SMFs) to manage the interaction between these two effects. These fibers are tailored to provide less chromatic dispersion than conventional fiber but, at the same time, reduce nonlinearities.

2.2 Four-wave mixing (FWM)-induced crosstalk

2.2.1 Impact of FWM in optical networks

In the early nineties, after the advent of the erbium-doped fiber amplifier (EDFA), fiber dispersion was the main obstacle in optical communication systems. Dispersion-shifted fibers (DSFs) were brought out as the solution and installation was widespread. Later, WDM was introduced to increase the utilization of the fiber bandwidth but in combination with DSFs, the performance turned out to be degraded due to FWM inducing crosstalk between the channels. This process is most efficient near the zero-dispersion wavelength, where the phase-matching condition is nearly fulfilled and sets limits to the launched channel power, the number of channels and the channel-spacing of the system. As there is already much DSF installed, this problem cannot be solved by dispersion management.

A few methods to alleviate the penalty due to FWM-induced crosstalk in DSFs have been proposed, as following:

1. Unequal channel spacing: the positions of the channels can be chosen carefully so that the beat terms do not overlap with the data channels inside the receiver bandwidth. This may be possible for a small number of channels in some cases, but needs careful computation of the exact channel positions.

2. Increased channel spacing: this increases the group velocity mismatch between channels. This has the drawback of increasing the overall system bandwidth, requiring the optical amplifiers to be flat over a wider bandwidth, and increases the penalty due to the stimulated brillouin scattering (SRS).

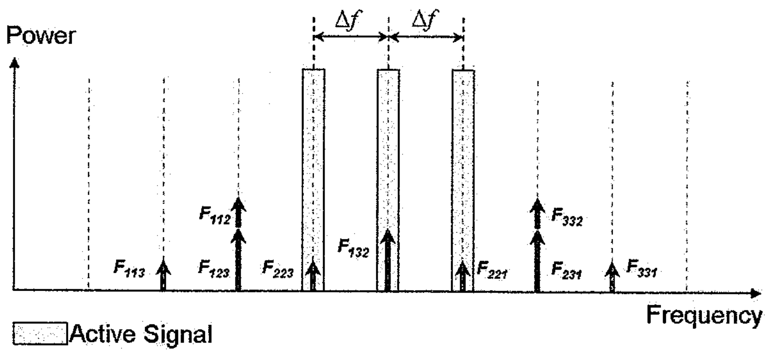


Fig. 2.1: Three copropagating equally-spaced channels with the generated products of frequencies f_{ijk} due to FWM crosstalk.

3. Using longer wavelengths beyond 1560 nm with DSF: even with DSF, a significant amount of chromatic dispersion is present in this range, which reduces the effect of FWM. The newly developed L-band amplifiers can be used for long-distance transmission over DSF.
4. Reducing transmitter power and the amplifier spacing will decrease the penalty.
5. If the wavelength can be demultiplexed and multiplexed in the middle of the transmission path, we can introduce different delays for each wavelength. This randomizes the phase relationship between the different wavelengths. Effectively, the FWM powers introduced before and after this point are summed instead of the electric fields being added in phase, resulting in a smaller FWM penalty.

However, increasing the channel spacing as well as utilizing unequal channel-spacing requires additional optical bandwidth. And due to the large amount of information (e.g., granularity on per wavelength basis) that need to be managed it is important to consider the effect of physical impairment during the lightpath establishment process, in particular the effect of the power crosstalk originated from FWM must be taken into account due to its fatal degradation in the teletraffic network performance of wavelength-routed optical networks.

The impairment constraint based routing (ICBR) approach has been proved beneficial for improving the performance, we used this technique in our research, and by introducing our novel implementation has been shown that it is possible to capture the state of detriment of the lightpath caused by FWM-induced crosstalk and avoid the set up of a lightpath that does not accomplish the requirement of QoS to assure an end-to-end optical connection.

2.2.2 FWM-induced crosstalk products calculation

The physical origin of FWM-induced crosstalk, and the resulting system degradation, can be understood by noting that FWM can generate a new wave at the frequency:

$$f_{ijk} = f_i + f_j - f_k, \tag{2.1}$$

whenever three waves of frequencies f_i , f_j and f_k $(i,j \neq k)$ copropagate in the fiber [28,30].

Depending on the individual frequencies, this beat signal may lie on or be very close to one of the individual channels in frequency, resulting insignificant crosstalk to that channel. In the case of equally spaced channels, most frequencies coincide with the existing channel frequencies and interfere coherently with the signals in those channels.

For a WDM transmission system with N channels, $(N \geq 3)$ with an equal frequency interval, this effect results in a large number of interfering signals equals to $(N(N-1)^2)$ corresponding to i, j, k varying from 1 to N in Eq.(2.1). In a system with three channels, for example, 12 interfering terms are produced, as shown in Fig. 2.1.

Interestingly, the effect of FWM depends on the phase relationship between the interacting signals. If all the interfering signals travel with the same group velocity, as would be the case if there were no chromatic dispersion, the effect is reinforced. On the other hand, with chromatic dispersion present, the different signals travel with different group velocities. Thus the different waves alternately overlap in and out of phase, and the net effect is to reduce the mixing efficiency. The velocity difference is greater when the channels are spaced farther apart (in systems with chromatic dispersion).

To quantify the power penalty due to FWM, we had used the results of the analysis from [31–34]. When there is no depletion of the propagating channels, the FWM power generated products of P_{FWM} or the power of the resulting new wave denotate as P_{ijk} in a link can be expressed as:

$$P_{ijk} = \frac{\eta}{9} D_{ijk}{}^2 \gamma^2 P_i P_j P_k e^{-\alpha L} L_{eff}{}^2, \tag{2.2}$$

where P_{ijk} is the FWM light power at the frequency f_{ijk}, the P_i , P_j and P_k are input light power of the f_i, f_j and f_k frequencies or powers of the mixing waves, η represents the dependence of the FWM efficiency on phase-mismatching. The term D_{ijk} is the degeneracy factor, which takes the values of $D = 3$ for $i = j$ and $D = 6$ for $i \neq j$. L represents the length of the link and α express the attenuation coefficients of the fiber.

The effective length L_{eff} is related to both of L and α through Eq. (2.3).

$$L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha}. \tag{2.3}$$

The nonlinear coefficient, γ can be calculated by Eq. (2.4):

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}, \tag{2.4}$$

where n_2, A_{eff} and λ are the fiber nonlinear refractive index, the effective fiber core area and the wavelength in vacuum, respectively.

The chromatic dispersion reduces the FWM efficiency, and we can model this by the parameter η which is given by

$$\eta = \frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2}\left[1 + \frac{4e^{-\alpha L}\sin^2(\Delta\beta \cdot L/2)}{(1 - e^{-\alpha L})^2}\right]. \tag{2.5}$$

η takes the maximum value of 1 for the phase matching factor $\Delta\beta = 0$, i.e., the phase-matching condition is satisfied. For on-off keying (OOK) signals, this represents the worst-case power at frequency f_{ijk}, assuming a "light-on" bit has been transmitted simultaneously on frequencies f_i, f_j and f_k.

The efficiency of the newly generated wave in the FWM process, denoted as η, goes down as the phase mismatch $\Delta\beta$ between the interfering signals increases.

The phase mismatch can be calculated as the difference in propagation constants between the different waves as:

$$\Delta\beta = \beta_i + \beta_j - \beta_k - \beta_{ijk} \tag{2.6}$$

The efficiency depends on the channel frequency separation, fiber chromatic dispersion D_c (dispersion slope $dD_c/d\lambda$), and the fiber length L, according to [34,35], as can be shown in Eq. (2.7):

$$\Delta\beta = \left(\frac{2\pi\lambda_0^2}{c}\right)(f_i - f_k)(f_j - f_k)\left[D_c + \left(\frac{\lambda_0^2}{2c}\right)\left(\frac{dD_c}{d\lambda}\right)\left[(f_i - f_0) + (f_j - f_0)\right]\right] \tag{2.7}$$

where c is the speed of light in vacuum, λ_k wavelength at frequency f_k and λ_0 the zero dispersion wavelength. Note that the efficiency has a component that varies periodically with the fiber length L as the interfering waves go in and out of phases.

FWM manifest itself as intra-channel crosstalk. The total crosstalk power for a given channel is given by Eq. (2.8):

$$P_{FWM} = \sum_{f_{ijk}} P_{ijk} \tag{2.8}$$

2.3 Digital modulation formats

As increasing data rates and reach drive development of a new generation of components, system designers face the challenges of minimizing the impact of impairments such as FWM. As a result, in recent months, research projects on alternative modulation have moved from the university laboratories to the telecommunication vendor's R&D departments. Deployment of new modulation methods has been unveiled. For instance, manufacturers have announced the roll out of systems based on return-to-zero as a building block of the next generation of 10-Gbit/s ultralong-haul systems. Differential PSK (DPSK) is another enabling technology that could help to push the limits further, but the obstacles delaying its deployment have more to do with economics than science.

Modulation formats suitable for long-haul transmission should have both a low OSNR requirement as well as a sound nonlinear tolerance. Since the invention of the EDFA made possible all-optical transmission over distances significantly longer than the length of spans between electronic regenerators, transmission line designers were confronted with a whole new design space. Parameters like dispersion, SPM, FWM, and optical noise became important.

The choice of digital modulation scheme will significantly affect the characteristics, performance and resulting physical realization of a communication system. There is no universal "best" choice of scheme, but depending on the physical characteristics of the channel, required levels of performance and target hardware trade-offs, some will prove a better fit than others. Consideration must be given to the required data rate, acceptable level of latency, available bandwidth, anticipated link budget and target hardware cost, size and current consumption.

The objective of this section is to review and examine the key characteristics and salient features of the main digital modulation schemes.

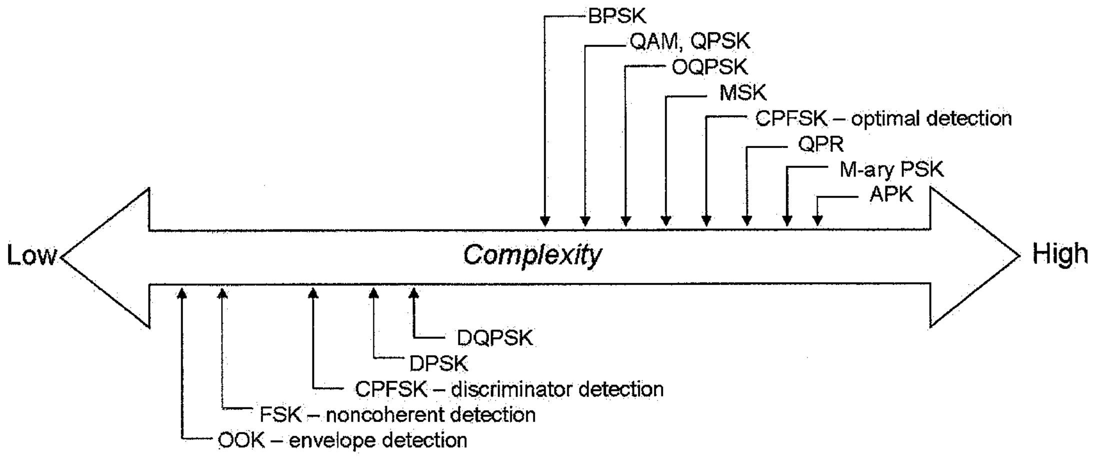


Fig. 2.2: Complexity in optical modulation formats.

2.3.1 Principles of modulation

In general, a laser semiconductor device (or semiconductor laser) generates a continuous photonic beam. However, as in its simplest mode of operation a semiconductor laser produces a continuous wave (CW) or beam of light, this beam carries no information other than frequency or wavelength. However, when the beam is modulated, then it could carry data at data rate of 40 Gbits/s, and higher modulation rates.

Modulation is the action of temporally altering one or more of the parameters of the photonic signal. In optical communications, such parameters are phase, frequency, polarization, and amplitude. When the phase is modulated, the method is called phase-shift keying (PSK); when the frequency is modulated, it is called frequency-shift keying (FSK); when the state of polarization is modulated, it is called state-of-polarization-shift keying (SoPSK) and when the amplitude is modulated, it is called amplitude-shift keying (ASK). The latter case includes the intensity modulation with direct detection (IM/DD) and the on-off keying (OOK) modulation methods. In optical communications, the modulation method plays a key role in the:

- Optical power coupled into the fiber
- Bit-rate limits
- Transportable amount of information per channel
- Dispersion limits
- Fiber-span limit
- Linear and nonlinear contributing effects
- Overall signal-to-noise ratio and bit error rate

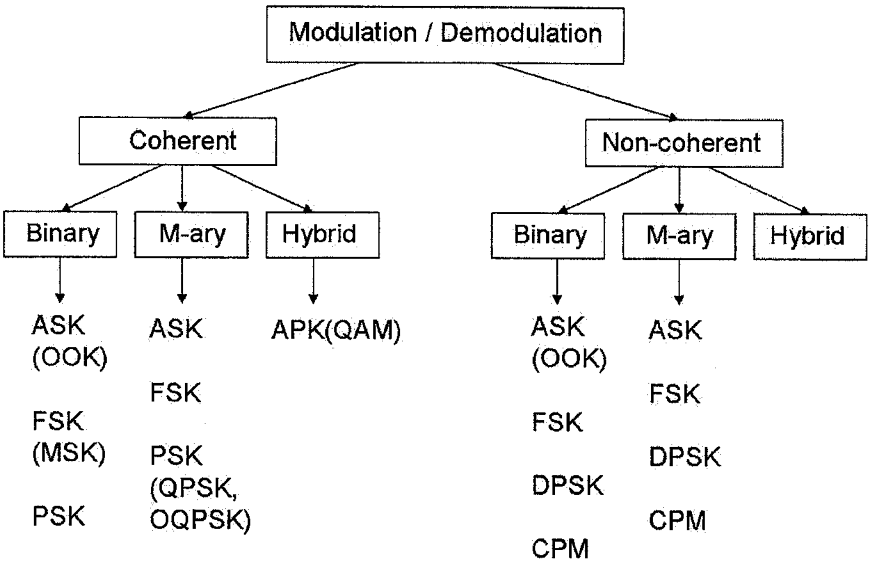


Fig. 2.3: Coherent and non-coherent MODEM methods.

- Reliability of signal detection and receiver penalty

The terms coherent and non-coherent are frequently used when discussing the generation and reception of digital modulation. When linked to the process of modulation the term coherence relates to the ability of the modulator to control the phase of the signal, not just the frequency. And with respect to the act of demodulation refers to a system that makes a demodulation decision based on the received signal phase. Fig. 2.3 shows a classification of modulation/demodulation formats according to coherent or non-coherent systems.

Among the scale measuring the complexity of different modulation formats listed in Fig. 2.2, there are three basic types of digital modulation techniques that are shown in Fig. 2.4 illustrating a binary pulse train and summarizing the basic modulation formats well-known as:

- Amplitude-Shift Keying (ASK)
- Phase-Shift Keying (PSK)
- Frequency-Shift Keying (FSK)

Amplitude-Shift Keying

The binary Amplitude-Shift Keying (ASK) signal is the same as On-Off Keying (OOK). While the term of on-off keying is used for IM/DD systems, ASK is the term commonly used for coherent optical communications.

The OOK modulation is an amplitude-modulation method. On and off states are represented by the presence or absence of light, the same as nonzero and zero amplitude, respectively. The modulating

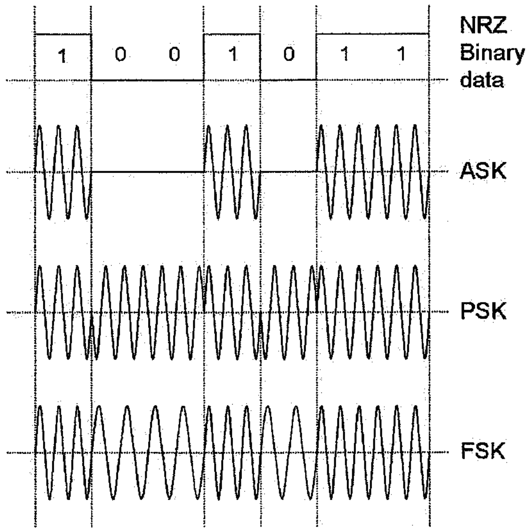


Fig. 2.4: Optical modulation formats.

signal closely resembles a square pulse that acts as a shutter on the laser beam, hence its name. The OOK method generates a stream of pulses that are then transmitted over the fiber. When the logic "one" is lighted for the full period ($T = 1/f$), this OOK is termed nonreturn to zero (NRZ), and when for a fraction of the period (such as 1/3 or 1/2), it is termed return to zero (RZ). As a consequence, NRZ modulation utilizes the full period as compared with RZ, which is a fraction of it. Thus, the energy within a NRZ bit is much more than the energy in a RZ bit, if everything else remains the same. This implies that either the NRZ signal can propagate to longer distances than the RZ or the NRZ power level can be lowered, for the same distance. OOK modulation can be used in both coherent and direct detection. However, coherent detection requires phase stability. As a consequence, the laser source cannot be directly modulated, as this may shift the signal phase and add chirp. To reduce this, the signal amplitude is modulated externally using a titanium-diffused $LiNbO_3$ waveguide in a Mach-Zehnder configuration or a semiconductor directional coupler based on electroabsorption multiquantum well (MQW) properties and structures. On the other hand, direct detection does not require stable phase; however, direct modulation may alter the spectral content of the source, which raises other issues.

In WDM optical communications, the carrier frequency is the electromagnetic wave in the infrared wavelength range (800 to 1620 nm). In single-wavelength transmission, selected wavelengths were used; 880 nm was used in multimode short-fiber applications and 1310 or 1550 nm in single-mode long-haul fiber applications. The OOK amplitude modulated carrier is expressed as:

$$f_c(t) = A \cdot a_m(t) \cos(\omega_c t) \tag{2.9}$$

where A is the amplitude of the OOK signal and $a_m(t)$ is 0 or 1 during an interval T, ω_c is the angular frequency of the optical carrier, and T is the signal duration that is also equal to the bit interval for the binary signal.

The Fourier transform of the OOK signal for $a_m(t) = 1$, using the frequency-shifting theorem, is expressed as:

$$F_c(\omega) = \frac{A}{2}[F(\omega - \omega_c) + F(\omega + \omega_c)] \tag{2.10}$$

For an initial baseband bandwidth B hertz (or $2\pi B$ rad/s), the modulated bandwidth is twice that, $\pm B$ hertz about the carrier, or $2B$ hertz. In other words, if the carrier spectrum is sliced into frequency channels, each slice must be at least $2B$ wide (in practice, it must be much wider to accommodate other effects). The OOK modulating method is also known as pulse amplitude modulation (PAM). In optical communications, we limit ourselves to the practical case of binary signals (two symbols, 0 and 1). However, studies have also analyzed M-ary signals (M symbols).

The two sidebands represent different wavelengths, which, because of dispersion phenomena, travel at different speeds and, thus, at different phases. Consequently, OOK modulation, under certain conditions, is expected to trigger certain interesting phenomena such as intersymbol interference and others.

ASK techniques are most susceptible to effects of nonlinear devices which compress and distort signal amplitude. To avoid such distortion, the system must be operated in the linear range, away from the point of maximum power where most of the nonlinear behavior occurs. Despite this problem in high frequency carrier systems, ASK is often used in wire-base radio signaling, either with or without carrier. ASK is also combined with PSK to create hybrid systems such as quadrature amplitude modulation (QAM) where both the amplitude and the phase are changed at the same time.

Phase-Shift Keying

This method modulates a light beam (the carrier) by changing the phase of the carrier (by 180 degrees) at the transition from logic "one" to logic "zero" and vice versa; that is, it shifts the phase by 180 degrees while the frequency and amplitude of the signal remain constant for all bits, thus appearing as a continuous light wave. There are two possible locations in the state diagram, so a binary one or zero can be sent. The symbol rate is one bit per symbol. For the same signal-to-noise ratio (SNR) and assumed ideal signal demodulation, binary PSK (BPSK) signal can achieve the lowest error probability.

The phase-shift keying signal is described as:

$$f_c(t) = \pm\ \cos\{\omega_c(t + \tau)\} \quad -T/2 \leq t \leq T/2. \tag{2.11}$$

The phase change in a phase modulator can be expressed by:

$$\delta\phi = (2\pi/\lambda)(\delta n)L_m \tag{2.12}$$

where the index change δn is proportional to applied voltage, V, and L_m is the length over which the index changes by the applied voltage, to the modulator.

For multilevel PSK, the change may be in increments of 45 degrees (8 levels). As a consequence, PSK requires a coherent carrier. A more common type of phase modulation is quadrature phase-shift-keying (QPSK). Quadrature means that the signal shifts between phase states which are separated by 90 degrees. The signal shifts in increments of 90 degrees from 45 to 135, -45, or -135 degrees.

Each of the four possible phases of carriers represents two bits of data. Thus there are two bits per symbol. Since the symbol rate for QPSK is half the bit rate, twice as much data can be carried in the same amount of channel bandwidth as compared to BPSK. This is possible because the two signals are orthogonal to each other and can be transmitted without interfering with each other. It is therefore a more bandwidth-efficient type of modulation than BPSK, potentially twice as efficient.

QPSK signal is an extension of the BPSK signal. Both of these are a type of M-ary signals. The process that describe the modulated signal in the polar coordinates is:

$$S_i(t) = A_c p_s(t) \cos\left(2\pi f_c t + \frac{2\pi i}{M}\right), \tag{2.13}$$

where $p_s(t)$ is the pulse shaping function. In digital phase modulation, the phase of the sinusoid is modified in response to a received bit. The changing phase is called the modulation angle. A sinusoid can go through a maximum of 2π phase change in one period. M quantized levels of 2π, to create a variety of PSK modulation. The variable is a number from 1 to M. The allowed phases are given by:

$$\textit{Modulation angles } \theta_i = \frac{2\pi i}{M} \tag{2.14}$$

M stands for the order of the modulation. $M = 2$, makes this a BPSK, $M = 4$ is QPSK, $M = 8$, 8PSK and so on.

Due to the lack of an absolute phase reference in direct-detection receivers, the phase of the preceding bit is used as a relative phase reference for demodulation. This results in differential phase-shift-keyed (DPSK) formats, which carry the information in optical phase changes between bits.

PSK is implemented by passing the light beam through a device that operates on the principle that, when a voltage is applied to it, its refractive index changes; this is known as electro-refraction modulation (ERM). Such devices are made with electrooptic crystals such as $LiNbO_3$, with proper orientation.

Frequency-Shift Keying

This exists in a great variety of forms, but in essence involves making a change to the frequency of the carrier to represent a different level. The binary signal can be conveyed by changing the frequency ω of the carrier at the transitions between logic "zero" and logic "one"; that is, it shifts the frequency while the amplitude of the signal remains constant for bits. At the transitions, the frequency changes by Δf, $f_0 + \Delta f$ for logic "1" and $f_0 - \Delta f$ for logic "0".

The total spectral bandwidth of an FSK signal is approximated to $2\Delta f + 2B$, where B is the bit rate and Δf the frequency deviation.

- When the deviation is large, $\Delta f >> B$, the spectral bandwidth approaches $2\Delta f$, and this case is known as wideband FSK.
- When the deviation is narrow, $\Delta f << B$, the spectral bandwidth approaches $2B$, and this case is known as narrowband FSK.

A frequency modulation index (FMI), defined by $\Delta f / B = \beta_{FM}$, distinguishes the two cases: wideband FSK has an FMI of $\beta_{FM} >> 1$ and narrowband FSK has an FMI of $\beta_{FM} << 1$.

FSK is achieved with electroacoustic Bragg modulators or with distributed-feedback (DFB) semiconductor lasers that shift their operating frequency when the operating current changes by a mere 1 mA. Thus, DFB semiconductor lasers make very good and fast coherent FSK sources with high modulation efficiency. FSK has the advantage of being very simple to generate, simple to demodulate. Significant disadvantages, however, are the poor spectral efficiency (SE) and BER performance. This precludes its use in this basic form from cellular and even cordless systems.

2.3.2 Principles of demodulation

Optical demodulating (or decoding) entails detecting the optical signal, converting it to electrical impulses, and retrieving binary coded information from the received modulated lightwave, based on one of the modulation formats described earlier:

- Detect optical amplitude level if amplitude shift keying (ASK or OOK) is used
- Detect phase change (from 0° to 180°) if BPSK is used
- Detect frequency change (from $f_0 - \Delta f$ to $f_0 + \Delta f$) if FSK is used

A metric of a good demodulator (or decoder) at the receiver is when the uncertainty of the received bits (1 or 0) is less than 1 bit per second per Hertz ($< 1 bit/s - Hz$); bit uncertainty may result in error bits. Optical communication systems are designed with a single-bit uncertainty (specified in ITU-T standards) of less than 10^{-12}. Thus, whatever demodulating method is used, it clearly impacts the demodulator design and its accuracy.

Coherent optical communication systems use different terminology from that in digital communications. Conventionally, an optical communication system is call "coherent" as long as there is optical signal mixing even without carrier recovery. Coherent heterodyne and homodyne detection techniques were initially developed for radio communications. In optical transmission, the term "coherent" indicates that a light source in the vicinity of the transmitted source is used as the local oscillator at the receiver. The local oscillator is expressed as:

$$C(t) = 2\cos(2\pi f_c t + \Theta) \tag{2.15}$$

where f_c and Θ are the expected local oscillator frequency and phase with respect to the incoming signal.

The aforementioned expression assumes an ideal monochromatic frequency f_c. However, in reality this is not the case as both the incoming optical signal and the optical oscillator are laser sources, presumably of the same wavelength. Therefore, the local oscillator must have a narrow spectral width that is comparable to the source. In addition, the local oscillator must have low-noise characteristics, otherwise the spontaneously emitted light adds to noise and the method is not practical. Therefore, the amplitude of the local oscillator in coherent receiver design is important. In IM/DD, the incoming signal is directly coupled into the detector, eliminating the coupler and the local oscillator.

Optical coherent methods with a stable coherent reference improve receiver sensitivity by 20 dB, allowing longer fibers to be used (by an additional 100 km at 1.55 μm). Although IM/DD detection and demodulation requires channel spacing on the order of 100 GHz, coherent techniques support spacing as small as 1-10 GHz, although currently they are not as popular.

OOK RZ and NRZ demodulators detect directly incident photons. The temporal density of photon fluctuation generates a temporal electrical fluctuation with similar amplitude plus some electrical noise added by the photodetector and receiver electronics. Then, the electrical fluctuation is low-pass filtered to remove high-frequency noise. The filtered signals are then sampled at an expected bit rate at a periodic instant and a threshold level that minimizes jitter and signal-level uncertainty. Thus, the density fluctuation of incident photons is interpreted as electrical logic "1" when it is above the threshold level or as logic "0" when it is below it. However, there are instances when the incident amplitude is ambiguous due to excessive attenuation, dispersion, noise, and jitter and an erroneous symbol (1/0 instead of 0/1) may be produced.

It should be noticed that a OOK NRZ signal provides photons for the full duration of the bit period, whereas a RZ signal does so for a percentage of the period, such as 33%, 40%, or 50%. The NRZ or RZ modulation, and the percentage is particularly important in ultrahigh bit rates such as 10 or 40 Gbit/s. For example, a 50% OOK 40 Gbit/s signal has logic "1" illuminated for 12.5 ps, whereas a 33% is illuminated for 8.3 ps. If all things are equal, this reduction is significant in the amount of received power, and, thus, in the received bit error rate. However, if the path is engineered correctly and the RZ peak power is higher, then RZ provides better noise isolation, so RZ improves the overall optical signal-to-noise ratio.

PSK demodulation is based on coherent detection. That is, in addition to the received optical signal, one or two local oscillators (optical frequencies) are required to interferometrically interact with the received optical signal and convert it to an amplitude modulated signal. That is, the received PSK signal, f_c, is mixed coherently with a locally generated laser light, f_{LO}, and since both are of the same frequency, they interact interferometrically. When both frequencies are in phase, there is constructive interference, and when they are opposite phase, destructive, and, thus (ideally), an OOK signal is generated. Since the accuracy of this method depends on the phase variation of the signal, phase stability and low noise are very critical. In FSK demodulation, the optical signal is passed through a narrow-band optical filter tuned to pass the frequency $f_1 = f_0 + \Delta f$ and reject the frequency $f_2 = f_0 - \Delta f$. Thus, the outcome is equivalent to an OOK modulated signal. Since the accuracy of this method depends on the frequency variation of the signal, no frequency shift (high-frequency stability) and low optical noise are very critical.

2.3.3 Current trends on modulation formats

PSK for fiber-optic data transmission first attracted significant attention around 1990. Most of these early experiments were focused on coherent optical communications [36, 37] with the main emphasis being the receiver sensitivity. For practical applications, however, PSK requires precise alignment of the transmitter and demodulator center frequencies, which was difficult to achieve at the low data rates in the early 1990s. With the advent and deployment of erbium-doped fiber amplifiers (EDFAs), the interest in PSK for optical transmission decreased noticeably, especially after the realization that nonlinear phase jitter limits the unregenerated transmission distance of a single channel PSK system and PSK was unlikely to outperform ASK [38]. Since then, research and development efforts have been mostly focused on ASK transmission format, particularly on OOK. There were relatively few reports of PSK studies, either experimental or numerical, between the mid-1990s and 2001. The capacity of fiber-optic transmission, on the other hand, increased dramatically during the same time period. The introduction of WDM for data transmission provided a new direction for increasing the system capacity, in addition to increasing the data rate per wavelength channel. For example, the channel data rate of commercially deployed systems has improved from 2.5 Gbit/s in the mid-1990s to 40 Gbit/s today, and the number of wavelength channels has reached , enabling a multi-terabit system in a single fiber. As a result, the spectral efficiency (SE) of fiber-optic communications has improved significantly, from a very low SE of single channel transmission around 1990 to 0.4 bit/s/Hz for the current commercial system, and even higher in research experiments. Concurrent to the rapid expansion of fiber capacity, the unregenerated reach of fiber-optic transmission has also increased dramatically, mainly driven by the desire to achieve a transparent all-optical network and ultimately reduce the cost of data transmission.

The advances in channel data rate, system SE, and reach dramatically altered the relative merits in performance and practicality between PSK and OOK. In contrast to the earlier systems, the increase in data rate relaxes the requirement for the frequency stability of the laser and the demodulator. Intuitively, the frequency jitter must be limited to a small fraction of the data rate, making PSK much more practical to deploy at high data rates such as 40 Gbit/s. Furthermore, signal degradations caused by fiber nonlinearity increase with increasing SE and reach. Thus, effects caused by fiber nonlinearity are vitally important for high-SE long-haul optical transmissions. Receiver sensitivity and tolerance to fiber nonlinearity are the most important considerations in a high-SE optical system.

PSK systems are not only superior in receiver sensitivity but also more tolerant to fiber nonlinearity, especially at a system SE of 0.4 or greater. There were research efforts on PSK between 2000 and early 2002 but the performances did not surpass that of conventional OOK, and in some cases either single-ended, instead of balanced, receivers were used or amplified spontaneous emission (ASE) noise was neglected in modeling. The conclusive evidence of PSK advantages in high-SE long-haul optical transmissions came in March 2002 [39], when a 4000-km-reach 2.56-Tbit/s system (64 channels at 40 Gbit/s) was experimentally demonstrated, easily doubling the reach of a conventional OOK system.

There is renewed excitement in PSK after a relatively quiet period of nearly ten years. Significant effort was devoted to coherent detections (i.e., heterodyne and homodyne detections) of PSK in the early 1990s; however, direct detection of differential PSK (DPSK) with a Mach-Zehnder delay interferometer (MZDI) is much more practical to implement at high data rate and only suffers a small penalty in receiver sensitivity. In addition, it was also realized that the return-to-zero (RZ) format further improved the practical implementation and nonlinearity tolerance of PSK [40]. Judging from the published literature in the last two years, RZ-DPSK is the focus of current research and development efforts.

DPSK has recently emerged as a promising alternative to conventional OOK in long-haul communication systems, as it can improve receiver sensitivity by a factor of 3 dB with balanced detection [40] and exhibit enhanced tolerance to fiber nonlinearity [22, 41]. In future photonic networks, OOK and

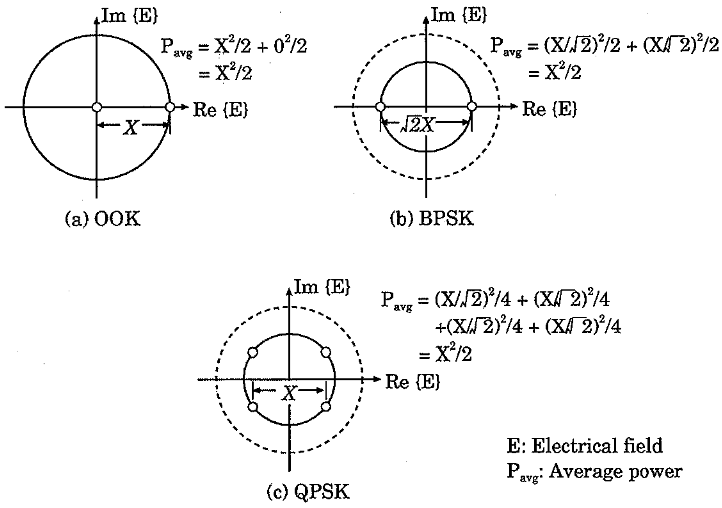


Fig. 2.5: Constellation diagram of OOK, BPSK and QPSK modulation formats.

PSK may be simultaneously used in different parts of the network, since the former is cost-effective for metro area networks while the latter is robust for long-haul backbone networks [42]. This has consequently spurred interest in format conversion from OOK to PSK which is needed at the intermediate node.

2.3.4 Comparison between OOK and PSK

OOK modulation has been a very popular modulation used in control applications. This is in part due to its simplicity and low implementation costs. OOK modulation has the advantage of allowing the transmitter to idle during the transmission of a "zero", therefore conserving power. The disadvantage of OOK modulation arises in the presence of an undesired signal. As the proliferation of control and data communication apparatus increases, so does the aggravation of not being able to communicate. Advances in optical and electronic components gave rise to optical communication systems employing advanced modulation formats with higher spectral efficiency, receiver sensitivity and resilience to nonlinear transmission impairments.

The modulation types can be graphically represented on a two dimensional ortho-normal plot, sometimes referred to as a signal space diagram or signal constellation, which is commonly used to study digital modulations. Fig. 2.5 shows the constellation diagrams of OOK, BPSK and QPSK modulation formats. It is instructive to graphically examine the different modulation formats in the complex plane of the E-field (i.e., the phasor diagram). Each data pulse is represented by a single point (or a vector connecting the origin to that point) in the phasor diagram, in which the radial direction represents the E-field amplitude and the angular direction is the E-field phase.

In contrast to conventional OOK, where the data are represented by either "0" or "1" shown in Fig. 2.5(a) BPSK essentially encodes the date as "1" or "−1" (i.e., 0- or π-phase shift), shown in Fig. 2.5(b). QPSK, which constellation is shown in Fig. 2.5(c), as BPSK can provide better spectral efficiency compared to OOK. A differential balanced receiver and a completely periodic intensity pattern are two major differences between BPSK and OOK. Not surprisingly, the advantages of PSK are mostly derived from these two characteristics.

The most obvious benefit of BPSK when compared to OOK is the approx. 3-dB-lower optical signal-to-noise ratio (OSNR) required to reach a given bit-error ratio (BER). This can be understood by comparing the signal constellations for OOK and BPSK, as shown in Fig. 2.5 (a) and (b), respectively. For the same average optical power, the symbol distance in BPSK (expressed in terms of the optical field) is increased by $\sqrt{2}$. Therefore, only half the average optical power should be needed for BPSK as compared to OOK to achieve the same symbol distance. Note, however, that this 3-dB benefit of BPSK can only be extracted using balanced detection. It has been demonstrated in [43] that the aprox. 3-dB advantage of DPSK in a linear channel disappears if only one of the two outputs of the delay interferometer is used and ignore the other, concluding that balanced detection is essential to achieve the 3-dB receiver sensitivity advantage in DBPSK.

Additionally, through simulations have been demonstrated that RZ-DPSK is more robust than OOK in terms of narrow-band optical filtering [44] and polarization-mode dispersion [45], especially when a balanced receiver is employed. Both issues are of practical importance in high-bit-rate and high-SE transmissions.

DPSK improves the tolerance to fiber nonlinearity in a high-SE system. DPSK significantly reduces the cross-phase modulation (XPM) effects in optical transmission. Because XPM depends only on the intensity profile of the pulses and is independent of the phases of the pulses (in contrast to FWM-induced crosstalk), and it should be able to eliminate the impairment caused by XPM by phase coding only.

While a large amount of timing jitter is present in the OOK transmission, DPSK completely eliminated such a pattern-dependent XPM penalty. It is more complicated when ASE noise is included for a practical system. Because the nonlinear transmission penalties differ considerably depending on the channel data rate.

The comparison between OOK and DPSK in terms of nonlinear transmission penalty at 10 Gbit/s involves a trade-off between single-channel SPM (in DPSK) and multichannel XPM (in OOK), and it is expected the relative transmission performance of DPSK when compared with OOK to improve as the SE of the system increases [46, 47]. Furthermore, the improvement in receiver sensitivity for DPSK with a balanced detection allows error-free transmission at significantly lower signal powers (even lower pulse energies), leading to additional reduction in nonlinear transmission penalty, which becomes more important in a high-SE system. When comparing low-SE DPSK and OOK transmissions [46], in a single channel transmission OOK clearly outperformed DPSK. In fact, even better "single" channel OOK performance can be obtained by increasing the signal power. The results for WDM transmission, however are markedly different. WDM DPSK performance is essentially the same as that of the single channel, while the performance of WDM OOK is significantly degraded. Clearly, the relative performance of DPSK improves at higher SE transmission. Indeed, DPSK is found to outperform OOK in 10 Gbit/s dense WDM systems with 0.4 SE by both numerical simulations [46] and experiments [47].

In contrast to 10 Gbit/s transmissions, strong pulse overlap usually occurs in 40 Gbit/s transmissions due to its four-times-reduced signal bit period (or 16-times-stronger dispersive effect). The main nonlinear effects are intrachannel FWM and XPM [48]. DPSK is found numerically to suffer less overall nonlinear penalty in pulse-overlapped 40-Gbit/s transmissions [49]. Due to the strong dispersive effect in 40-Gbit/s transmissions, the Gordon-Mollenauer effect is much reduced. Thus, the major nonlinear penalty in 40-Gbit/s DPSK is intrachannel FWM-induced nonlinear phase noise [49]. It is further found, through theoretical analysis and numerical simulations, that DPSK suffers less penalty from intrachannel FWM than OOK with the same average power due to the lower peak power of DPSK and a correlation between the nonlinear phase shifts experienced by any two adjacent bits [50].

Because the data information resides in the relative phase difference between adjacent bits, correlated phase shifts have no direct impact on the transmission performance. Thus, besides its 3-dB receiver sensitivity advantage over OOK, DPSK improves the tolerance to fiber nonlinearity under a strong intersymbol interference.

Using conventional OOK signals, 40-Gbit/s WDM transmission systems have achieved record distances due to such innovations as forward error correction, distributed Raman amplification, and new transmission fibers. The polarization multiplexing DPSK transmission can be used to double system capacity with only a small sacrifice in transmission distance [51].

Multilevel coding can significantly enhance the SE. The effective data rate of M-level coding is $log_2 M$ times the symbol rate. Thus, the SE of an M-level system is improved by a factor of $log_2 M$ when compared to a binary coding system at the same symbol rate. Although research in multilevel coding has a strong emphasis for achieving an SE of greater than 1/bit/s/Hz, there are other advantages by using multilevel coding even at SE of 0.8 or less. Because the high SE is achieved through multilevel coding, there will be no increase in sensitivity to chromatic and polarization-mode dispersion, adverse side effects typically associated with increasing the channel data rate. The main nonlinear penalty of DPSK transmission is the nonlinear phase jitter induced by ASE noise and SPM, which can be compensated by nonlinearity management scheme [43].

2.4 Conclusion

In this chapter, the fundamentals of FWM-induced crosstalk and modulation formats have been introduced. In the the first part of this section the effect of FWM-induced crosstalk has been described and the power calculation of FWM crosstalk products has been introduced. It can be concluded that with the increase of large capacity and the high-speed data transmission in transparent optical networks, become essential to consider the effect of FWM during the lightpath establishing process due to its fatal degradation in the teletraffic network performance of wavelength-routed optical networks. In the second part, the principles of modulation and demodulation formats for three basic types of digital modulation techniques as ASK, PSK, and FSK have been introduced, and the current trends on modulation formats, as well as a comparison between OOK and PSK has been addressed.

Chapter 3

FWM-Aware Dynamic Lightpath Provisioning

Dynamic routing and wavelengths assignment taking into account physical impairments in wavelength-routed optical networks is proposed via an ICBR approach. An algorithmic framework for lightpath computation is presented, highlighting the issue of wavelength continuity, network resources utilization and physical impairment (i.e., FWM crosstalk) in a transparent wavelength-routed network. Additionally, a fast computation establishment lightpath scheme with the advantages of offline/online technique is introduced.

3.1 Introduction

In transparent wavelength division multiplexed (WDM) networks with dynamically arriving connection requests, call blocking due to non-ideal physical-layer transmission media has attracted much research attention in the past few years. With the growing demand for enhanced network capacity, more and more channels are being carried in WDM networks, and the data rate per channel is fastly increasing. As a result, satisfying the quality of signal (QoS) transmission becomes increasingly difficult due to the aggravated physical-layer impairments.

The accumulation of impairments from end-to-end optical connections (lightpath) has become a fundamental issue in wavelength-routed optical networks. In a high-speed transmission system, the physical impairments become more prominent; causing a significant impact on the teletraffic performance of the network [52]. At the same time, the engineering of wavelength-routed networks is extremely complex; signal may originate at any node and terminate at any other. This requires designing the transmission equipment to support the worst case path. When the network is to be extended, all the equipment must be upgraded to support the new worst case path. This constrains the upgradability of the network, which can not exploit, for example, developments in broader amplifier bandwidth or narrower channel spacing as they become available. In this sense, network management is complicated in that there is not simple way to assure that signals entering or leaving a node are valid.

Extensive works have been done to introduce physical impairments into the RWA problem [9], and different approaches have been proposed [21, 53, 54]. However, most of the proposed approaches only deal with linear effects, and from the several factors that are affecting the network performance the nonlinear effects from optical fibers needs more attention. Additionally, previous works assume a signaling process [21], or are not based on a realistic model of physical impairments. Approaches as in [20] evaluate the four-wave mixing (FWM) crosstalk, estimating the signal degradation during the wavelength assignment process. However, few studies have dealed with performance evaluations considering the physical-layer constraint of FWM crosstalk incorporated into the network routing scheme, which can lead to a realistic network design and better network performance [19].

A new solution to estimate the network performance by incorporating physical constraints using a routing approach in the dynamic establishment of lightpath, evaluating one of the most severe problems for wavelength-routed networks in a dense WDM (DWDM) system, the FWM effect, is introduced. The influence of the FWM crosstalk into the system, had been studied theoretically and experimentally in [32, 33] and [55], showing that this effect greatly limits the system performance, imposing a severe limitation on the maximum launched power of individual WDM channel. Therefore, we developed a realistic network model by considering the FWM constraint of the signal degradation.

An algorithm which relates the system performance measurement (connection blocking probability) with the crosstalk due to FWM products generation has been developed, and a novel cost-function which satisfies the dynamic establishment of a lightpath with minimum cost for network resource utilization and minimum signal FWM-induced crosstalk degradation has been incorporated.

3.2 FWM-aware RWA model

The design algorithm is called FWM-aware RWA algorithm. It allows dynamic establishment of end-to-end lightpaths on demand, taking into account the available link capacity and level of FWM crosstalk, by updating the network states information stored in a novel cost function [56]. The cost function is evaluated and updated at generating a link state and the validity of the computed path under the implemented constraints (network resource utilization and FWM-induce crosstalk) is examined at the end of the calculation candidate path through the ICBR approach, if the computed candidate online path satisfies the permitted threshold guaranteeing in this way the signal quality, the candidate path is established, otherwise, it is rejected. The algorithm guarantees the QoS of the lightpath, by avoiding setup lightpaths that has been degradated by FWM crosstalk. The designed algorithm can be understood by following the flowchart shown in Fig.3.1.

3.2.1 Extension of FWM model calculation for multichannel systems

In a multichannel system, as each lightpath traverses h hops or links until it reaches its destination node, the accumulated FWM noise power at the destination node, P_{DN}, is the summation of all crosstalk

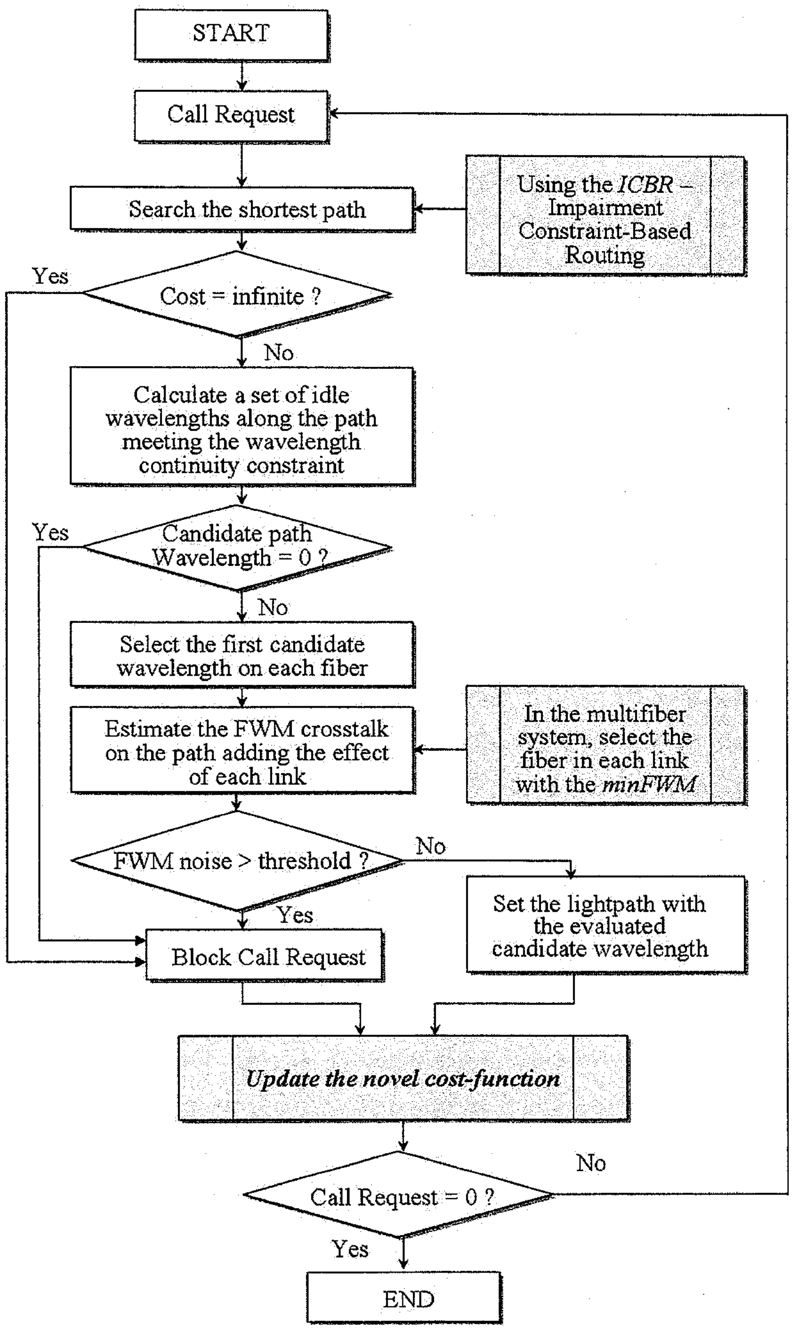


Fig. 3.1: Simulation Flow Diagram.

components along the lightpath [31, 57], which is expressed as:

$$P_{DN}(f_{ic}+f_{jc}-f_{kc})=\sum_{c=1}^{h}\sum_{f_{kc}}\sum_{f_{jc}}\sum_{f_{ic}}P_{FWM}(f_{ic},f_{jc},f_{kc}), \tag{3.1}$$

gathering the effect along its links by either a candidate or an active lightpath out of W wavelengths per link. The f_{ic}, f_{jc} and f_{kc} are the frequencies or mixing waves in a hop or link c. The FWM power generated products of P_{FWM}, can be calculated as in Eq. (2.2). This Eq.(3.1) is an extension of Eq.(2.8).

3.2.2 Novel cost function

In the ICBR FWM-aware RWA, two natures of constraint are taking into consideration. Both, utilization of network resources and physical impairment are taken into account to simulate realistic scenarios without compromising the network performance and moreover guaranteeing the signal quality (avoiding the effect of FWM crosstalk as has been addressed).

The novel cost function has been defined and expressed as Eq. (3.2):

$$C = \alpha \cdot \frac{F \times W}{\sum_{j=1}^{F} \sum_{i=1}^{W} w_{ij}} + \beta \cdot \frac{\overline{P}_{FWM}}{P_{th}}, \tag{3.2}$$

where the first term represents the resources utilization with α denoting the utilization weight factor, F and W the number of fibers and wavelengths per link, respectively, w_{ij} corresponds to the resource utilization state (set to 1 for idle, and 0 for occupied). The second term represents the FWM effect with β denoting the FWM weight factor, $\overline{P}_{FWM}$ represents the average power of the noise generated by FWM in all the idle wavelengths and P_{th} is the threshold power level, which allows or blocks the candidate lightpath according to the accumulated level of FWM crosstalk into the lightpath under evaluation. P_{th} will be determined base upon the request for the lightpath quality on demand.

According to this, the path with more network resources and the smaller effect of FWM crosstalk will be more likely to be selected. From Eq. (3.2) can be seen that the cost metric increases while more resources are occupied and the level of noise added by FWM crosstalk increases in a link state, several attempts occur to find the best result, and tentative lightpaths with a cost metric near to infinite have the lower percentage to be selected. The designed cost function ranks the feasible source-destination pair connection or lightpath used into the modified shortest path algorithm.

The cost function is evaluated and updated at generating a link state and the validity of the computed path under the implemented constraints is examined at the end of the calculation path through the ICBR approach, if the computed candidate on-line path satisfies the permitted threshold guaranteeing in this way the signal quality, the candidate path is established, otherwise, it is rejected.

3.2.3 Characteristics and assumptions of the system

The proposed algorithm is based on the following assumptions and sub-routines:

- The conventional On-Off Keying (OOK) modulation format has been assumed on account of simulating the large impact of FWM-induced crosstalk, compared with PSK modulation format.
- The generation of connection requests is governed by Poisson process with arriving rate equal to λ.
- A lightpath is held for an exponentially distributed time with a mean of unity after being established with service time equalt to $1/\mu$ (with μ as service rate), and the accepted connection request are provided a single path which is maintained for the whole connection lifetime.
- The sources and destinations of the calls are uniformly distributed over the set of nodes.

- The network performance is evaluated in terms of blocking probability, and the results are shown considering the overall offered load.
- The well-known shortest path routing strategy has been modified in order to create an impairment-constraint based routing using the cost function (3.2), initially the First-Fit (FF) wavelength assignment is implemented. In addition, some improvement of the algorithm is examined.
- When a connection request arrives to the network, a search for the set of idle wavelengths meeting the continuity constraint along the shortest path is carried out.
- The candidate wavelength is pre-inserted and the FWM for each fiber on each link (P_{ijk}) of the candidate path is estimated using Eq.(2.2). In each link, the fiber with the minimum noise FWM power is selected.
- The P_{DN} is calculated, for this purpose the calculation of the FWM products of each link that traverses the path (from source to destination) is added up.
- The FWM-induced crosstalk at the destination is compared with a fixed threshold. If the noise level of FWM is bigger than the set threshold, the call request is blocked, otherwise the candidate lightpath will be established. Note here that the threshold level depends on the modulation format of the optical signal.
- The FWM products are calculated by considering only the interactions between the co-existence lightpaths inside a link (the propagation of the previous link FWM generated products into the next link of the path were neglected.). The FWM-induced crosstalk calculation in a link is assumed to be an independent process from the previous link, and the effect of the FWM noise of each link is then gathered at the end of the candidate path. This assumption is justified because the generated FWM crosstalk powers are much smaller than the transmitted signal powers.

3.3 Numerical results and analysis

3.3.1 Simulations setup

Extensive simulations are carried out over different network topologies, which are shown in Figs. 3.2 and 3.3. Connection request were generated up to 500,000 calls. For each time simulation, the first 10,000 connection requests are used for network warm-up, and then the blocking probability are estimated [29, 58] for the subsequent 500,000 connection requests. Variations are introduced into the basic proposed algorithm. We proposed the following schemes:

1. *FWM-blind RWA:* this scheme computes all the connection requests and chooses a route and a wavelength based on the shortest path and the FF wavelength assignment. In the FF wavelength assignment scheme [9], all wavelengths are numbered. When searching for available wavelengths, a lower numbered wavelength is considered before a higher-numbered wavelength. The

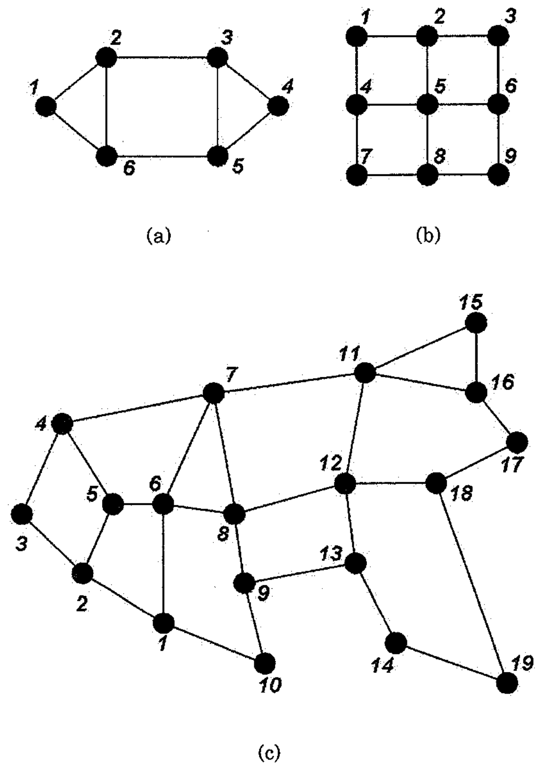


Fig. 3.2: Networks used in the simulation: (a) 6-node network, (b) 9-node network, and (c) 19-node National Science Foundation Network (NSFNet).

first available wavelength is then selected. This scheme is considered a basic traditional RWA algorithm. This strategy ignores the crosstalk-induced FWM.

2. *FWM-partially-blind RWA:* this scheme computes all the connection requests by selecting a route and a wavelength for each connection request based on the shortest path algorithm and the FWM-constraint FF wavelength assignment. After a route had been chosen, the first candidate wavelength meeting the wavelength-continuity constraint, is selected or blocked depending on the estimated FWM level degradation that it might experience after being inserted into the system. The algorithm ignores any direct relation of physical constraints with the route selection strategy.

3. *FWM-aware FF RWA:* this scheme computes all the connection requests based on impairment-constraint base routing (ICBR) by using the described novel cost function in Section 3.2.2 given by Eq. (3.2), and takes only the first candidate wavelength to evaluate their level of FWM power, if this lightpath satisfies the threshold to guarantee the quality of the signal, then the lightpath is accepted and established, if not then it is blocked. Results are shown in Figs. 3.5, 3.6 and 3.7 for different network topologies.

4. *FWM-aware minLambda RWA:* this scheme computes all the connection requests based on ICBR by estimating the cost function given by Eq. (3.2), and chooses the wavelength among all the candidate wavelength that gives rise to the smallest FWM crosstalk which has been calculated

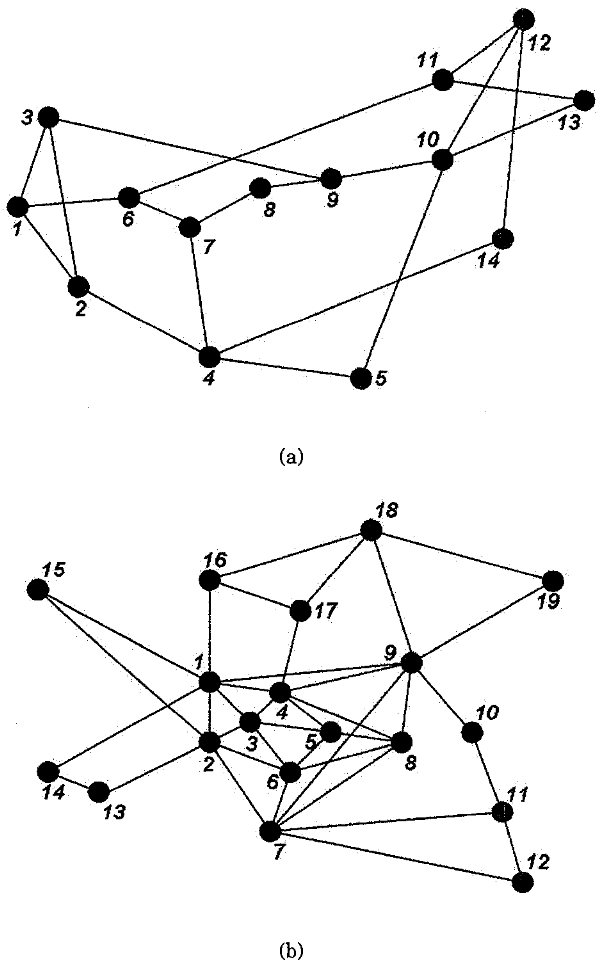


Fig. 3.3: Network topologies (a) 14-node NSFNet, (b) 19-node European Optical Network (EON).

by pre-inserting it into the link and evaluating the interactions caused by the co-propagating signals together with the candidate itself. Results are shown in Fig. 3.9 (a).

5. *FWM-aware adaptiveLambda RWA:* this scheme computes all the connection requests based on ICBR by estimating the cost function (3.2), and chooses one by one candidate wavelength to evaluate the level of FWM crosstalk, if the first computed candidate wavelength is blocked then it takes the next candidate wavelength until it finds the wavelength that satisfies the threshold permission level, if neither of the candidate wavelength satisfy the permitted threshold level then the call request will be blocked. Results are shown in Fig.3.9 (b).

3.3.2 System parameters

Each link consists of one-way fiber pairs for both directions, and each pair of nodes is connected with two links. The network prototypes were connected with Dispersion-Shifted Fiber (DSF) links of 100km length, each with 8 WDM channels with the same input signal power of 0 dBm. The frequencies used in the simulation were set to 193.1 - 193.8 THz with 100 GHz channel spacing. We neglect the effect of

Table 3.1: System Parameters used in the Simulation

Physical Parameters	Value
Fiber	Dispersion Shifted Fiber
Fiber nonlinear coefficient	2.3 /W/km
Fiber attenuation	0.22 dB/km
Channel power	0 dBm
Channel spacing	100 GHz
Threshold power	-20 dBm
Network Parameters	**Value**
Number of nodes	see network prototypes
Distance between adjacent nodes	100 km
Number of calls	500,000
Number of wavelengths	8, f_c = 193.45 THz
Signal wavelengths	1546.92 – 1552.52 nm
Model of call generation	Poisson distribution
Model of call duration	Exponential distribution

polarization states of input lights for simplification. The connection blocking probability is the metric used to measure the network performance. The weighted factors of the cost function α and β are set to 1 and 10, respectively.

Table 3.1 shows the main characteristics of the network prototypes and summarizes the transmission system parameters adopted in the simulations.

3.3.3 Blocking performance analysis

Figure 3.4 depicts the blocking probability as a function of the total offered load for the network topology of 6 nodes shown in Fig.3.2 (a), it shows the impact of using the proposed *FWA-aware FF RWA* in comparison to the *FWM-blind* and to the *FWM-partially-blind RWA*. Results depicted in Fig. 3.4, show that an algorithm RWA ignoring FWM effect gives rise to an unrealistic network performance (plot as a continuous-line with solid-circles), their system performance are considered as underestimation compared to those given by real networks. Amount the RWA with FWM-awareness, the *FWM-aware FF RWA* (shown as a continuous-line with solid-triangles) gives an improvement of blocking compared to the *FWM-partially-blind RWA* depicted as continuous-line with opened-squares.

By considering the network topologies shown in Fig.3.2 and 3.3, corresponding to 6, 9 and 19-node NSFNet networks, as well as 14-node NSFNet and 19-node EON network topologies, respectively, we applied the RWA algorithms with FWM-awareness, comparing the connection blocking probability of the *FWA-aware FF RWA* with *FWM-partially-blind RWA*. Results are depicted in Figs. 3.5, 3.6 and 3.7. *FWM-partially-blind* algorithm results are shown as a continuous-line with open-circles, and the

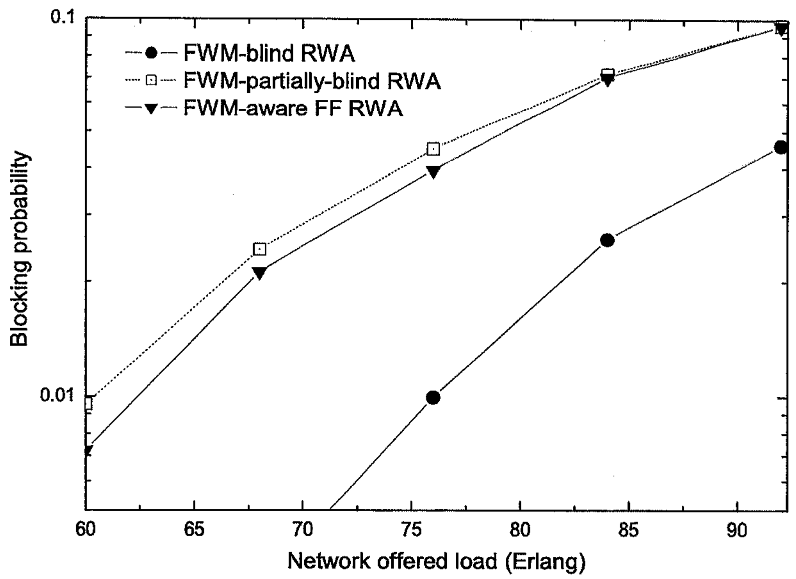


Fig. 3.4: Impact of using RWA with FWM-awareness in comparison with FWM-blind RWA.

FWA-aware FF RWA are depicted by using continuous-line with solid-triangles showing the reduction on the blocking probability. Results show an improvement of the network performance in terms of the decreasing blocking probability when the physical impairment of FWM is taken into account in both steps of the RWA problem, during the routing process added to the wavelength assignment process. This improvement becomes more evident while the number of network nodes increases, giving evidence that the physical impairment should not be avoid during the dynamic routing algorithm design.

The performance of several network topologies (including those presented in Figs. 3.2 and 3.3), are depicted in Fig. 3.8, the node degree of each network has been considered and comparison with the relation of number of links per number of nodes (L/N) are carried out. In order to set a common value of L/N in all the network prototypes, the number of links has been changed by setting some links of the networks to single fiber. It is observed that the blocking probability gives rise to a margin related with different network topologies that possess equal value of L/N. These results show that the proposed *FWA aware RWA* algorithm leads to a better characterization of the network in terms of given an average constant behavior on the blocking probability of a network topology according with a similar relation L/N under the current algorithm scenario.

Results on the simulation carried out with *FWM-aware minLambda RWA* algorithm (Fig. 3.9) show no improvement on the network performance, this is due to the stochastic process of the dynamic algorithm. A wavelength selection scheme that favors a wavelength with less FWM noise, wavelengths with equally adjacent spacings seems to be more prone to be established, increasing the blocking, since the degradation is much more severe for equally spaced channels [3], at the same time this is aggravated by accomplishing the wavelength continuity constraint along the path and attending the random

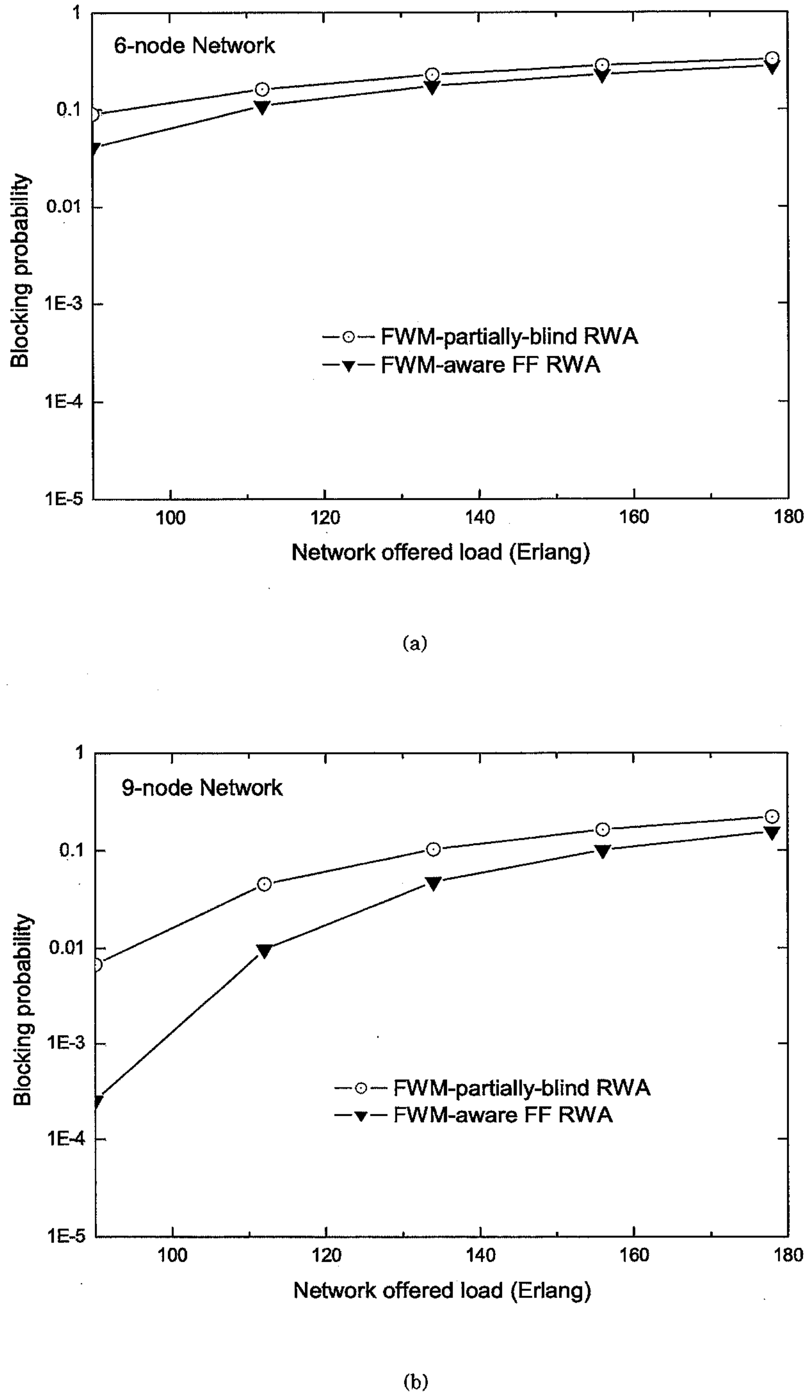


Fig. 3.5: Network performance of the proposed FWM-aware RWA in comparison with the FWM-partially blind scheme for network topology (a) 6-node network, and (b) 9-node network.

arrival and departure time of the connection requests. However, an improvement on the blocking performance is achieved with the adaptive scheme (*FWM-aware adaptiveLambda RWA*). In this case, the first candidate wavelength is inserted and the FWM crosstalk along the path is precalculated, and

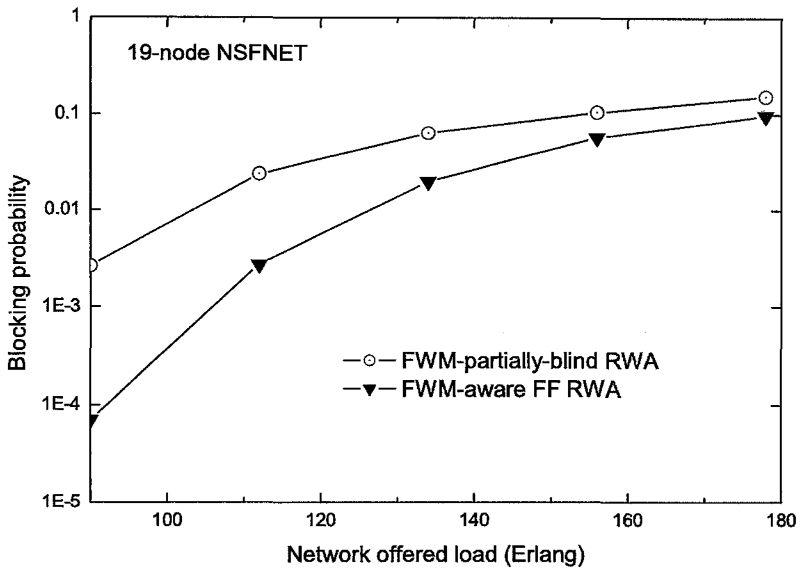


Fig. 3.6: Network performance of the proposed FWM-aware RWA in comparison with the FWM-partially blind scheme for network topology of 19-node NSFNet.

only if the lightpath could not be established then it evaluates the next candidate wavelength, but the *FWM-aware minLambda RWA* needs to compute all the possibility which causes an increasing of connection blocking. In order to reduce the lightpath establishing time a new adaptation introduced into the FWM-aware RWA is proposed in the following section.

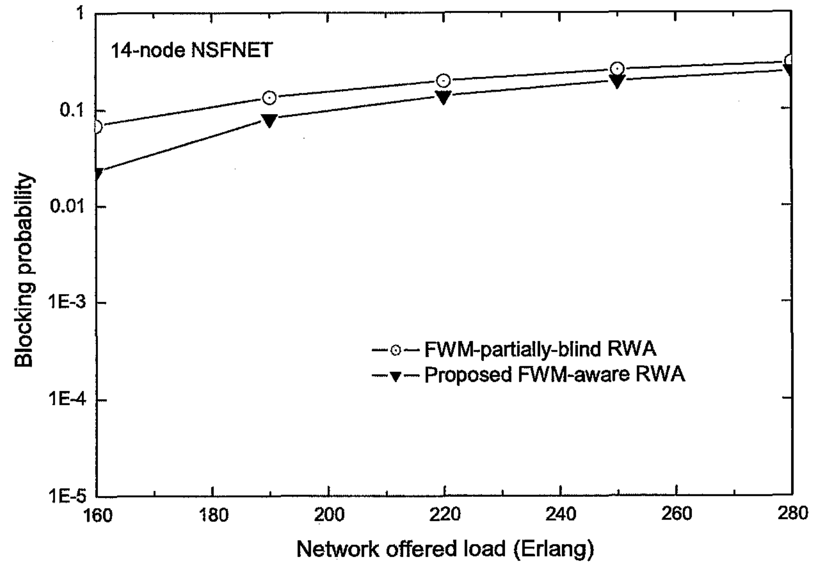
In this section we have introduced and evaluated three novel algorithms:

- *FWM-aware FF RWA*
- *FWM-aware minLambda RWA*
- *FWM-aware adaptiveLambda RWA*

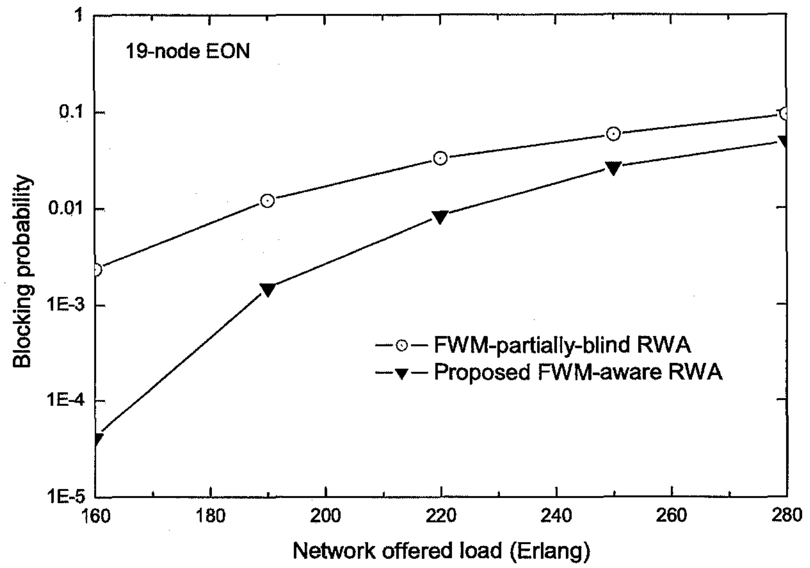
And used two algorithms for comparison purposes as:

- *FWM-blind RWA*, and
- *FWM-partially-blind RWA*

In summary, the impact of introducing FWM-induced crosstalk as a constraint of the dynamic lightpath establishing process has been evaluated by comparing the novel *FWM-aware FF RWA* with the traditional *FWM-blind RWA* and the *FWM-partially-blind RWA*. The RWAs encompassing the effect of FWM (*FWM-partially-blind RWA* and *FWM-aware FF RWA*) can guarantee QoS and give results for realistic scenarios.



(a)



(b)

Fig. 3.7: Network performance of the proposed FWM-aware RWA in comparison with the FWM-partially blind scheme for network topology (a) 14-node NSFNet, and (b) 19-node EON network.

Moreover, when the effect of FWM-induced crosstalk is evaluated into the routing scheme besides the wavelengths assignment process (*FWM-aware FF RWA*) an improvement in the network performance is registered, which become more significantly with the increase of the network size.

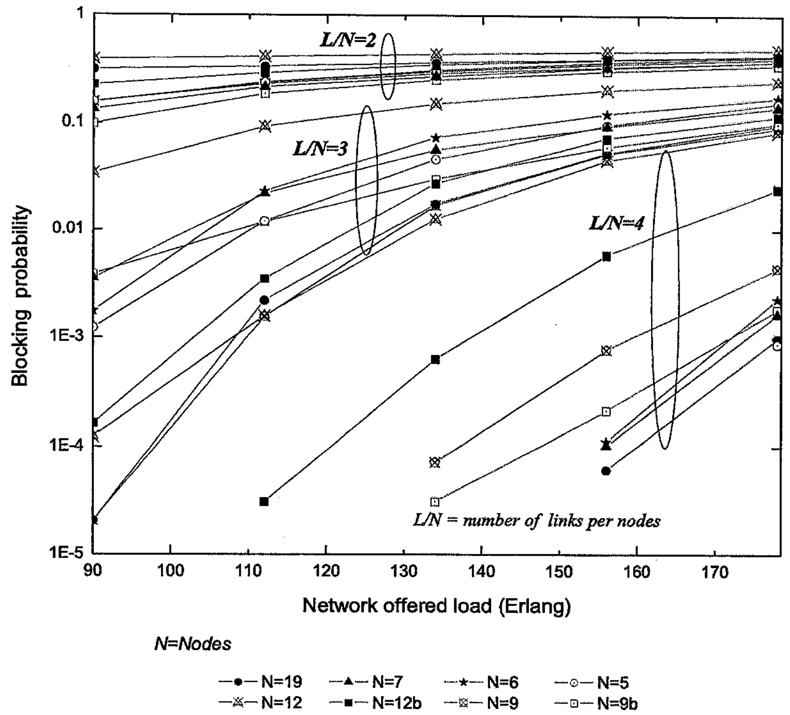


Fig. 3.8: FWA aware RWA network performance and the relation with L/N on different networks

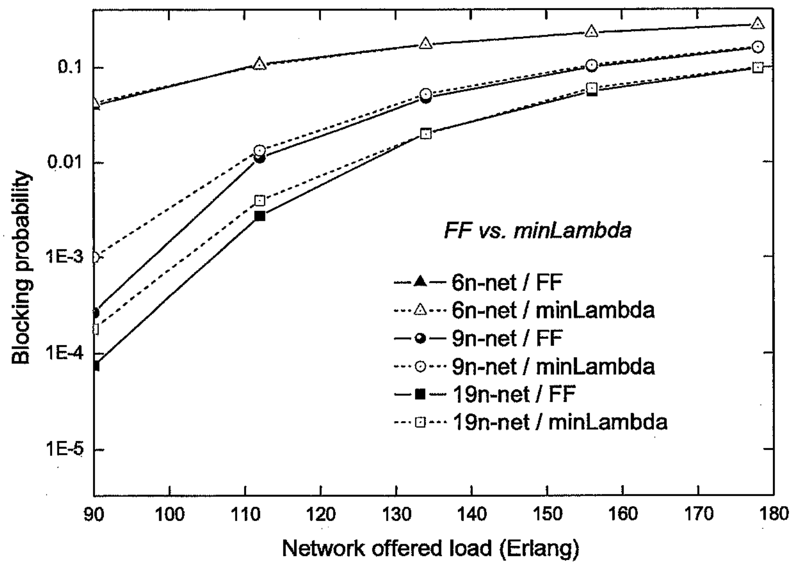
Results show that in all the networks used as a prototype the *FWM-aware FF RWA* outperforms the *FWM-partially-blind RWA*, indicating that physical impairments constraints should be taken into account in both: the routing scheme and the wavelengths assignments process. In addition, a small improvement has been obtained with the *FWM-aware adaptiveLambda RWA*.

3.4 Reduction of lightpath establishing time approach

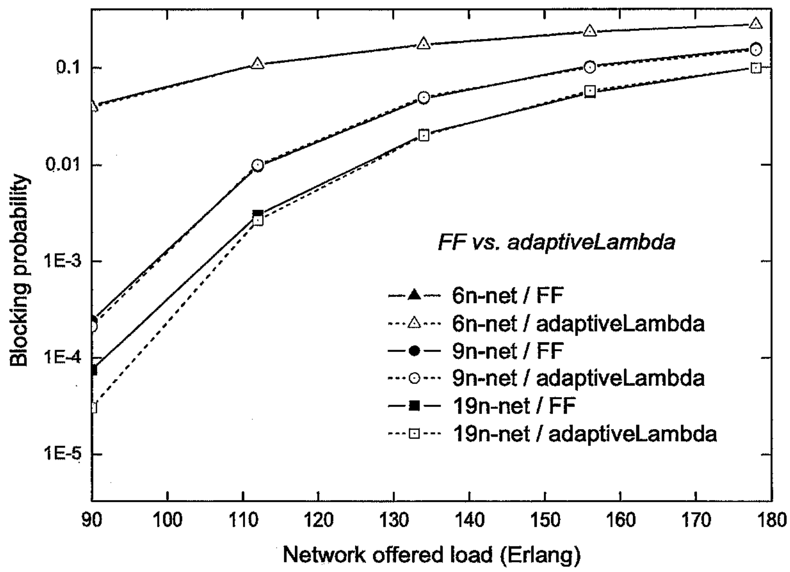
A hybrid scheme using the advantage of offline precalculation and the online implementation to capture the network state is introduced accomplishing the effect of FWM calculation during the lightpath establishing process and faster set up the lightpath.

In order to setup a lightpath it is required to exchange various control information among the nodes. A timely manner of dynamic provisioning is an important issue, here a distributed adaptive routing is proposed to fast provisioning lightpaths.

One of the challenges involved in designing wavelength-routed optical networks with dynamic traffic demands is to develop efficient algorithms and protocols for establishing lightpaths. It is believed that dynamic or on-demand lightpath establishment, will enable service providers to respond quickly and economically to customer demands. Therefore, connection setup time and blocking rate are two important parameters for any optical data communication network [59–64]. Additionally, in a transparent



(a)



(b)

Fig. 3.9: Different wavelength assignment schemes, Adaptive and Minimum FWM power.

and managed long-reach networks, the optical signal quality degrades during its transmission due to physical impairment accumulation. Hence, Impairment Constraint Based Routing (ICBR) has been proposed as a solution [19, 54].

As it has been shown through the previous chapters, our study primary focuses on the accumulation of Four-Wave Mixing (FWM) crosstalk which causes a fatal degradation in wavelength-routed optical network performance; it is considered as a major source of nonlinear crosstalk for WDM lightpath systems [3, 8]. Particularly, this section focuses on a faster process to setup a lightpath based on the FWM-aware RWA already described in the previous sections of this chapter. Since to solve a Routing and Wavelengths Assignment (RWA) problem is well-known to be NP-complete, heuristics must be used to address this problem to reduce the computational complexity.

We propose distributed adaptive routing where each node in the network must maintain the complete network state information. Whenever there is a connection request it will try to find a route in a distributed manner [5, 65, 66]. The establishment or removal of any lightpath must update the state information of all nodes in the network. When lightpaths are being established or removed at a higher rate, it requires a significant control overhead to broadcast the update messages to all nodes. To setup a lightpath, it is required to exchange various control information among the nodes. The signaling protocols are closely related to the different types of RWA protocols. Signaling protocols for setting up lightpaths must effectively manage the distribution of control messages and network state information in order to establish a connection in a timely manner [59]. It may reserve the resources in parallel, on a hop-by-hop basis along the forward path or along the reverse path. Although our main subject of research lies on dynamic routing, our improved algorithm gives advantages to the next connection or release task of the signaling protocol by reducing connection setup time and the amount of data per link that should be edited to maintain the network state information updated. Additionally, given the wide range of services envisioned for future IP networks, network survivability is a crucial concern, and by making use of the WDM channel efficient routing capabilities, a variety of lightpath protection schemes can be designed.

In a dynamic process of lightpath provisioning, the active wavelengths in a link causes FWM-induced crosstalk products to be generated [3], differing in number and levels of products that depend on the presence of neighbor wavelengths, on their relative spectral position and the presence of the wavelength candidate itself.

We introduce another algorithm which cope with reducing the lightpath establishing time based on the FWM-aware RWA. The new algorithm is called mxFWM-aware RWA, described and validated through simulations shown in the rest of this chapter.

3.4.1 FWM matrix elements, computation and accessibility

The FWM-induced crosstalk products are calculated offline for all possible combinations of coexistent active lightpaths in a link. In a discrete time event simulation, for the online full FWM-aware RWA scheme [56], online calculation of FWM crosstalk has been required during the evaluation of the signal quality of the candidate lightpath, in order to capture and update the network state. With the precomputed matrix scheme, the FWM components are stored into a matrix, called FWM-Mx, creating the database of crosstalk elements to have access during the signal quality evaluation of the online lightpath establishment process using our updated version mxFWM-aware RWA. The goal of using a

Table 3.2: Possible groups of active wavelengths for $W = 8$ and their corresponding wavelength as placed by FWM-induced crosstalk. Active wavelengths = 1, Idle wavelengths = 0 and FWM-induced product that fall within the channel spectrum = x.

No.	λ_8	λ_7	λ_6	λ_5	λ_4	λ_3	λ_2	λ_1
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	1
2	0	0	0	0	0	0	1	0
3	0	0	0	0	0	0	1	1
4	0	0	0	0	0	1	0	0
5	0	0	0	0	0	1	0	1
6	0	0	0	0	0	1	1	0
7	0	0	0	0	0	1	1	1
8	0	0	0	0	1	0	0	0
9	0	0	0	0	1	0	0	1
10	0	0	0	0	1	0	1	0
...	.	.	.	.	.	.	.	.
...	.	.	.	.	.	.	.	.
254	1	1	1	1	1	1	1	0
255	1	1	1	1	1	1	1	1

precomputed matrix is to minimize the time of establishing a lightpath dynamically by eliminating the processing time of calculating the FWM products online, and therefore to decrease the network blocking probability.

For a defined number of WDM channel systems of N wavelengths or channels, the process of creating FWM-Mx uses the concept of an initial base-matrix with dimension [2^NxN] where 2^N corresponds to the number of rows of the matrix and constitutes all possible combinations of simultaneously coexisting lightpaths in a link, creating in one row one group of active lightpaths ($1Set/actWs$) that can match with the network state in one discrete unit of time during the online mxFWM-aware RWA algorithm, and N represents the number of columns or number of WDM channels.

For each group of active wavelengths, all the FWM products are calculated and only those products that fall within the channel spectrum are stored into the rows of FWM-Mx. The predefined FWM-Mx has a dimension of [2^NxN] with 2^N corresponding to the FWM-Mx rows that capture the amount of FWM-induced crosstalk. Each row of the FWM-Mx corresponds to the same row of the base-matrix.

For illustration, Table 3.2 gives the structure of FWM-Mx. For one network with $N = 8$, the matrix has a dimension of $[256, 8]$, set from $0 - 255$ with eight wavelengths. Each row shows one set of active wavelengths ($1Set/actWs$), and the circles represent the wavelengths that will be affected by FWM crosstalk and their stored position within the matrix.

For illustration, one set called $1\ Set/actWs$ of row 7, equal to [0 0 0 0 0 1 1 1], can be seen in

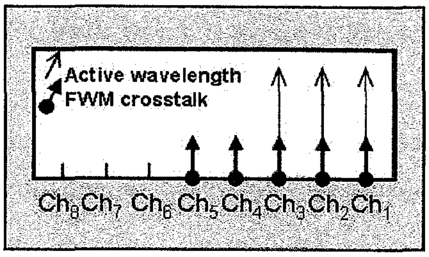


Fig. 3.10: FWM products illustration inside a system spectral window.

Fig.3.10, meaning that $\lambda_4, \lambda_5, \lambda_6, \lambda_7, \lambda_8$ are idle wavelengths (set as 0) and $\lambda_1, \lambda_2, \lambda_3$ are active (set as 1) in a link under evaluation and their interactions will cause generation of FWM noise (marked by circling the state of the wavelength). As can be seen some products will fall into the occupied frequencies of λ_1, λ_2, λ_3 and into some of the idles as λ_4, λ_5 affecting their power levels. Considering the case, when eight wavelengths are active or occupied, 392 total FWM products will be generated, products that fall onto the same frequency their values will be added resulting that 224 different wavelengths will be added by the effect of FWM crosstalk noise, but only those related to the eight spectrum channels will be stored into the FWM-Mx.

To implement the process of creating and accessing FWM products into the mxFWM-aware RWA, a digital number has been assigned to each wavelength in a reverse numerical order (power of two), i.e., $\lambda_8 = 2^7$ and $\lambda_1 = 2^0$. By setting 1 and 0 to active/occupied and idle wavelengths, respectively, a unique binary number is create for each $1Set/actWs$, using an exclusive-or function the binary number is converted directly to a decimal value corresponding to a row of FWM-Mx and easily gives access to the precalculated/stored FWM elements of each wavelength originated by the respective $1\ Set/actWs$.

General considerations for mxFWM-aware RWA

In addition to the general assumption mentioned in Section 3.2.3 and in 3.3.2, the following characteristics have been introduced to define the functionality of the mxFWM-aware RWA algorithm:

- The algorithm has been designed for N wavelengths or WDM channels.
- For each group of coexisting lightpaths or active wavelengths ($1Set/actWs$), the FWM-induced crosstalk products have been precomputed using Eq. (2.2). The process adds all the products that fall into the same frequency.
- The generated FWM noise for all the combinations of simultaneously occupied frequencies is precomputed and stored in the FWM-Mx, given 2^N $1Set/actWs$ or rows.
- Each group of active lightpaths will correspond to one index of the FWM-Mx matrix of 2^N rows.
- Only the FWM products that fall within the channel spectra are stored into the FWM-Mx associated row.

- The elements of the FWM-Mx will be accessed during the online mxFWM-aware RWA lightpath setup.
- We intent to assign a candidate lightpath that originates the minimum level of FWM crosstalk and fulfills a threshold that guarantees the QoS, using the same criteria implemented in Section 3.2.

3.4.2 Adaptation of the FWM procedure calculation

The computation of Eq. (2.2) to find $P_{FWM} = P_{ijk}$ together with the following equation, fills all elements of matrix FWM-Mx.

$$P_{FWM_{Mx}} = \sum_{f_{kc}} \sum_{f_{jc}} \sum_{f_{ic}} P_{FWM}(f_{ic}, f_{jc}, f_{kc}), \tag{3.3}$$

The procedures involved in Eq. (3.1) have been divided in several steps as follows:

1. calculation of FWM products generated by groups of coexisting lightpath (offline),
2. summation of the crosstalk components that fall into the same channel frequency (offline),
3. summation of the crosstalk components along the lightpath (online),
4. searching FWM elements into a matrix (online).

then Eq. (3.1) can be modified as:

$$P_{DN}\ (1Set/actWs) = \sum_{c=1}^{h} P_{FWM_{Mx}}, \tag{3.4}$$

where all the combinations of frequencies i, j and k are given by $1Set/actWs$, and are obtained directly from the online algorithm. The $P_{FWM_{Mx}}$ represents the elements stored into the FWM-Mx corresponding to the row index equal to the decimal number equivalent to the binary number of $1Set/actWs$. This procedure is repeated and their values of same frequencies is summed up hop-by-hop until it reaches the destination node.

For an specific route given by the modified shortest path algorithm to establish an end-to-end connection request, the following algorithm steps are carried out as part of the ICBR technique, bringing the network state information used into the cost function:

1. For each link or hop h along the path find the number of simultaneously active wavelengths per link.
2. Compute the list of candidate/tentative wavelength of the path taking into account the principle of wavelength continuity constraint.
3. For each candidate wavelength, together with the active wavelenghts of a link find the index r_N of the FWM-Mx row.
4. To compute the FWM crosstalk noise of a ligthpath from source to destination, use Eq. (3.4).

Table 3.3: Reduction factor for different networks and number of wavelengths.

Network / Reduction factor	6-node	9-node	14-NSF	19-NSF	19-EON
REDUCTION FACTOR (w = 8)	0.08	0.09	0.13	0.18	0.33
REDUCTION FACTOR (w = 4)	0.30	0.33	0.43	0.54	0.58

5. Using the index r_N, search into FWM-Mx the FWM product of the specified candidate lightpath using the column that matches the wavelength under evaluation and store the value into an array.

6. Repeat the same procedure until it finishes evaluating the candidate wavelength through all the links along the path and by adding it to the previous value update the level of FWM crosstalk for the tentative lightpath under evaluation.

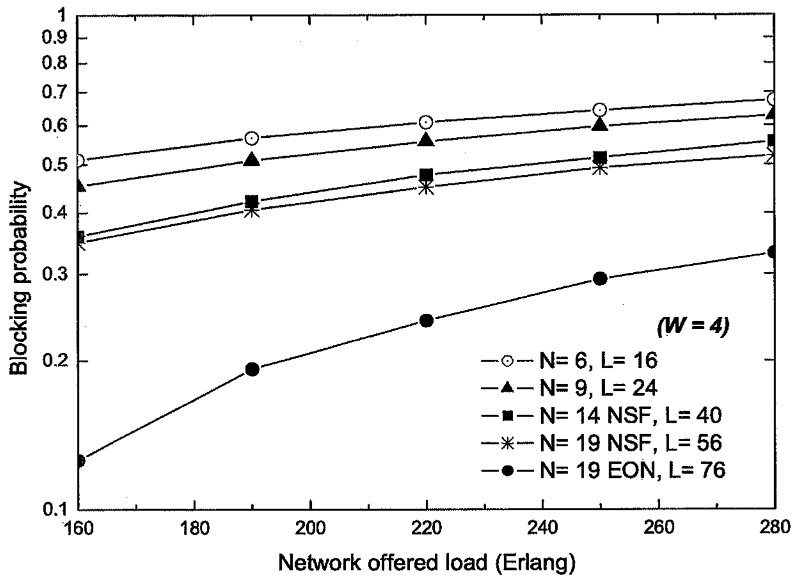
7. Compare the value of FWM noise of each candidate wavelength with a fixed threshold assuming the conventional OOK modulation format. The selection of a path will be in accordance with the effect giving by the cost function, avoiding FWM crosstalk and better use of network resources.

3.4.3 Simulation results and analysis of the mxFWM-aware RWA

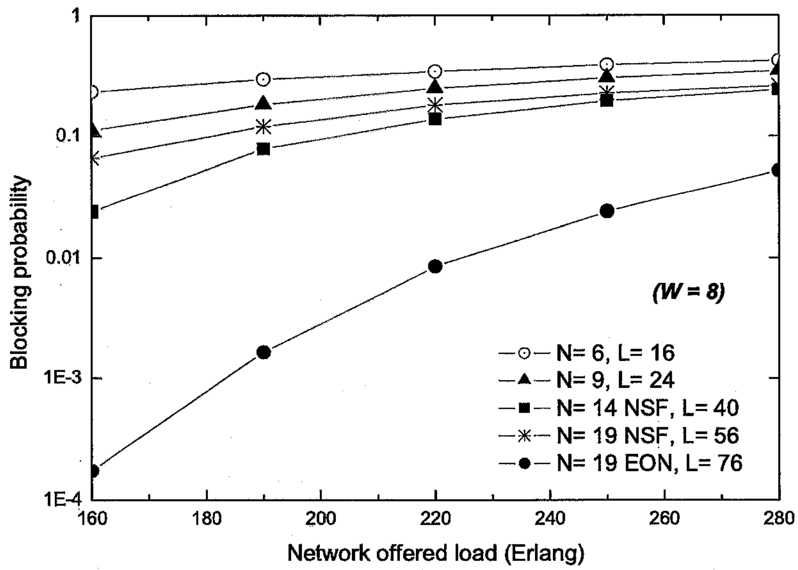
For these set of simulations, once again, the networks are assumed to have bidirectional links, each carrying the same number of wavelengths in each direction, where no wavelength conversion is available. The sources and destinations of calls are uniformly distributed over the set of nodes, and the same assumptions taken in Section 3.3.2 and 3.3.1 are assumed for this round of simulations. Under these conditions extensive simulations were carried out over different network topologies shown in Fig. 3.2 and 3.3, by measuring the network performance in terms of blocking probability.

The proposed precomputed mxFWM-aware RWA scheme were validated through simulations. The proposed *mxFWM-aware RWA* scheme were compared with the full online calculation of FWM (i.e., *FWM-aware RWA*) in order to evaluate the lightpath establishment time. The seed of the random number of both algorithms were fixed to be same in order to generate the same number of call requests during the same duration of lightpaths and evaluated the impact of the time in both algorithms.

The corresponding estimate reduction factor are summarized in Table 3.3 for eight and four number of wavelengths on each network topologies given in Figs. 3.2 and 3.3. The observed reduction factor shows that our novel algorithm can establish lightpaths faster, which contributes to decrease the blocking probability. It is shown that the algorithm can setup lightpath faster up to 20 percent when decreasing the number of wavelength by a factor of two, in most of the network topologies, when comparing it to the same topology and different number of wavelengths. However, by running the algorithm for a more complex network topology, the variation of the reduction factor in topologies with the same number of wavelengths, with higher level of network connectivity, the reduction of lightpath setting up time seems to be small, e.g., for eight wavelengths, 6-node network yields 8 percent reduc-



(a)



(b)

Fig. 3.11: Network performance of the proposed mxFWM-aware RWA with different number of wavelengths as follows (a) W = 4, and (b) W = 8.

tion factor while EON network with 19 nodes 33 percent, albeit the variation value of reduction factor between network topology complexity seems to be small, it can be a valuable change considering huge

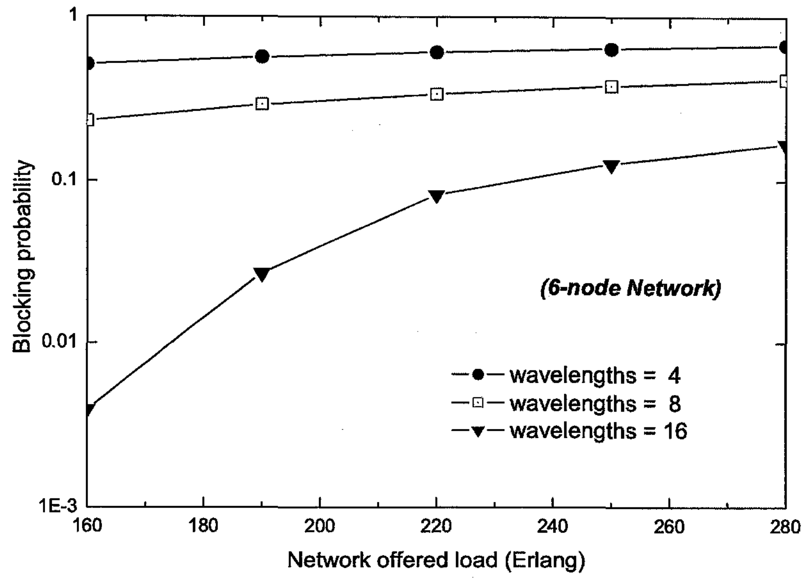


Fig. 3.12: Network performance of the proposed mxFWM-aware RWA for 6-node network and different number of wavelengths 4, 8 and 16.

traffic demand.

Results for the *mxFWM-aware RWA* scheme are plotted in Figs. 3.11(a) and 3.11 (b), for four and eight wavelengths, respectively. Results confirmed the strong correlation between the blocking probability and the network diameter and the mean inter-nodal distance, which have been recognized in the literature as some topological features that gives impact on blocking probability [67]. According to this, in Fig.3.11 (a) can be seen that the blocking probability decreases by increasing the level connectivity or number of links per nodes (L/N). However, results also show in Fig. 3.11 (b) by the increment of the number of nodes in a same topological design, that the node degree of a network yields major impact on the network performance, so the NSFNet with $N = 14$ and $L = 40$ gives better results because of its higher node degree although its relation L/N is lower in comparison to the NSFNet with $N = 19$ and $L = 56$.

Results also shows that the algorithm yields better performance by increasing the number of wavelengths in a same network as it is expected. And for simplicity, Fig. 3.12 shows results of setting the number of wavelengths to four, eight and sixteen into a 6-node network of Fig.3.2 (a), showing that the algorithm can be adaptive to N number of wavelengths.

3.5 Conclusion

A dynamic RWA algorithm that is capable of incorporating not only the network constraints, but also the physical constraint due to the FWM crosstalk has been described by introducing a novel cost function into both the wavelength assignment process and the routing scheme. An ICBR approach in a distributed scheme was proposed.

The blocking probability were calculated in wavelength routed optical networks impaired by FWM-induced crosstalk, allowing the inclusion of interchannel effects to avoid signal quality degradation.

Our approach leads to more realistic networks model design in terms of capturing the nonlinearity effect due to FWM crosstalk. The impact of using an integration of network and physical layers constraints has been evaluated, showing that the physical constraints must not be avoided into the routing process in order to guarantee the signal quality during the end-to-end dynamic lightpath setup. The introduced FWA-aware RWA can achieve good results compared with the referred algorithm found in the literature and furthermore accomplished an improvement of the network performance by using the modified version called FWM-aware adaptiveLambda RWA.

In addition, a technique to reduce the lightpath establishing time has been analyzed. This proposed hybrid model precomputed the FWM generated products according to all the possible groups of coexisting lightpaths that could be found in a network under evaluation. The algorithm reduces the setup time of a lightpath and therefore improves network performance. The FWM-Mx represents an optimal access method compared to the FWM-crosstalk products online calculation. The algorithm was validated for different number of wavelengths, and was demonstrated that more improvement can be achieved with more available wavelengths per link. Results of the proposed mxFWM-aware RWA algorithm show improvement up to 30-50 percent of faster establishing lightpath in various network topologies in comparison with an online full dynamic computation scheme.

Achieving faster lightpath establishment leads to several advantages, especially it gives a positive impact into the network, which can be studied through the metrics, namely, connection set up time, blocking probability, stabilizing time and scalability.

Chapter 4

Dynamic Lightpath Provisioning with Modulation Format Conversion Interface

Envisaged optically transparent modulation format conversion from 2-channels on-off-keying (OOK) to quadrature phase-shift-keying (QPSK) between MAN and WAN in future wavelength-routed networks, in this chapter a novel FWM-induced crosstalk-aware dynamic RWA algorithm is demonstrated to minimize the connection blocking probability.

4.1 Introduction

In a wavelength-routed optical networks in the near future, a rapid and flexible bandwidth provisioning on-demand will be required. The multi-level modulation format such as quadrature phase-shift-keying (QPSK) modulation format has been actively studied to be introduced to enhance the signal quality in long-haul DWDM transmission systems at the bit rates of 40 Gbit/s and beyond. Therefore, it is likely that at a gateway node between wide area network (WAN) and metro area network (MAN), a transparent modulation format conversion between the PSK signals and conventional cost-effective on-off-keying (OOK) becomes a key technique for maintaining optical transparency. There has been proposed and experimentally demonstrated non-return-to-zero (NRZ)-OOK/return-to-zero (RZ)-QPSK modulation format conversion using semiconductor optical amplifier (SOA) based parallel Mach-Zehnder Interferometers (MZI). We have developed an algorithm called four-wave-mixing (FWM)-aware and dynamic routing and wavelength assignment (RWA) to capture the network state encompassing the effect of FWM into the wavelength-routed network provisioning, explained in the previous chapter.

Different modulation formats may be selectively used, depending on the network size and the bit rate. Optical communication systems have been long employing primarily conventional OOK signals, which convey the information in the amplitude. In contrast, PSK formats [68] carry information in

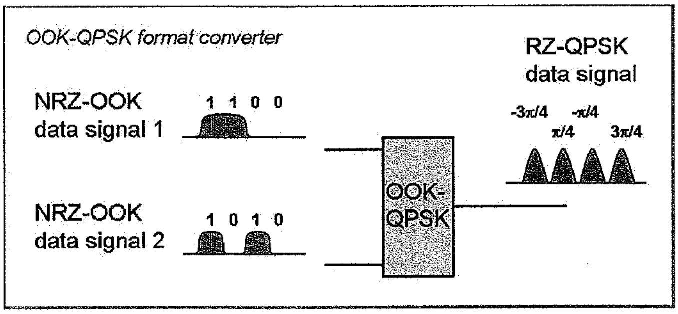


Fig. 4.1: Illustration of OOK to QPSK converter.

the phase of the optical carrier itself. Recent studies have revealed that DPSK preferably exhibits better performance than conventional OOK for long-haul transmission [22]. More advanced modulation format [69,70], differential quadrature phase-shift keying (DQPSK), appears to be promising technique in order to exploit the better receiver sensitivity and to secure the compatibility with 50 GHz channel spacing in ultra-dense wavelength division multiplexed (DWDM) transmission [70].

Our contribution presented in this chapter has been inspired from Mishina et al. research work [71] and the work presented in [22] related to the studies on optical modulation format converters. In this chapter we maintained the name of our original algorithm *FWM-aware RWA* but this time the algorithm will include a modulation format conversion interface. This scheme will improve the blocking performance by minimizing the effect of generating FWM crosstalk via modulation format. In Chapter 3 we have assumed conventional OOK modulation format. In this chapter we introduce a new module and the respective interface into our algorithm to cope with the advantages of QPSK modulation format into the network design.

4.2 FWM-aware RWA incorporating modulation format conversion

Our designed system model assumes using an all-optical modulation format conversion from NRZ-OOK to RZ-QPSK, illustrated in Fig. 4.1. The NRZ-OOK-to-RZ-QPSK format conversion scheme is based on parallel MZI OOK/binary-PSK (BPSK) converters, consisting of integrated SOAs. This scheme has been experimentally demonstrated and verified through numerical simulation by Mishina et al., additionally it uses balanced detection scheme, combination that brings the benefit of 3-dB of DPSK over OOK. An schematic diagram of the proposed modulation format conversion and the principle of operation can be found in [42,71].

The designed algorithm can be understood by following the flowchart depicted in Fig.4.3 that comparing with the flowchart presented in Fig.3.1 can be noticed one main different characteristic, a modulation format conversion module. In our initial network model that obeys the algorithm of Fig.3.1 only conventional OOK modulation format has been assumed. In this chapter we extended our work by incorporating a novel interface related to modulation format conversion from OOK to QPSK into our

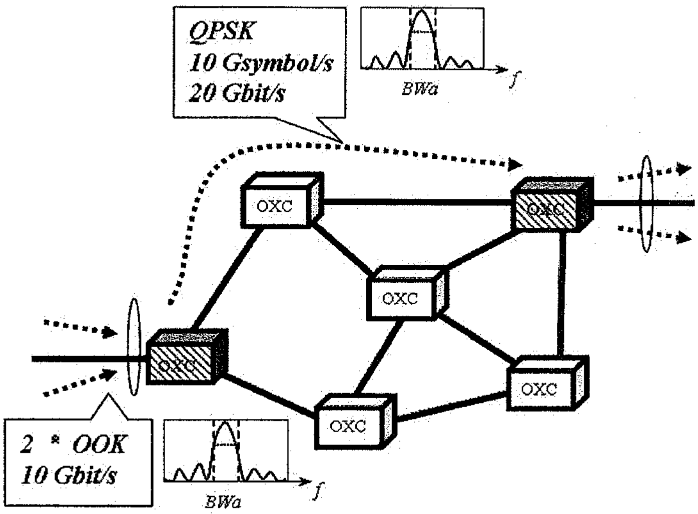


Fig. 4.2: Illustration of an all-optical modulation format conversion at the gateway node, lightpath from source to destination node with QPSK modulation format.

algorithm in order to mitigate the effect of FWM-induced crosstalk. We introduce a new module into our network design, called encapsulation, to cope with this feature.

The advantage of using modulation format converter from OOK to QPSK is that QPSK can aggregate two OOK channels keeping the same signal bandwidth, while decreasing the call blocking probability and therefore improving the network performance. Through the encapsulation functionality a double capacity of transmitted data can be sent under the same FWM affected condition of one signal if the two OOK signals have the same source-destination pair of nodes, see Fig. 4.2 for illustration, where two signals each modulated with OOK format at 10 Gbit/s are encapsulated at the source and converted to QPSK format, keeping the same bandwidth and carrying data at 20 Gbit/s to be established as one lightpath form source to destination, and then to be separated and demodulated at the destination node after the call establishing time duration has ended. The effect of this encapsulation functionality brings positive advantages on the teletraffic network performance.

4.3 Encapsulation module design

A flowchart shown in Fig. 4.4 addresses the novel encapsulation module and their functionalities. This interface is implemented at the beginning of the algorithm shown in Fig. 4.3. We assume that call requests arrive in the network with OOK modulation format. The encapsulation module consists on creating a queue of calls with an specific queue size managed by a controller. An initialization process to filling the queue begins by generating call request and storing them into the queue until it finds a pair of two calls with same source-destination (S-D) nodes. A comparison between the call requests stored in a queue is carried out to find a pair of call with the same S-D nodes. Once a pair of calls with same S-D is found, both calls are converted using NRZ-OOK-to-RZ-QPSK format conversion scheme

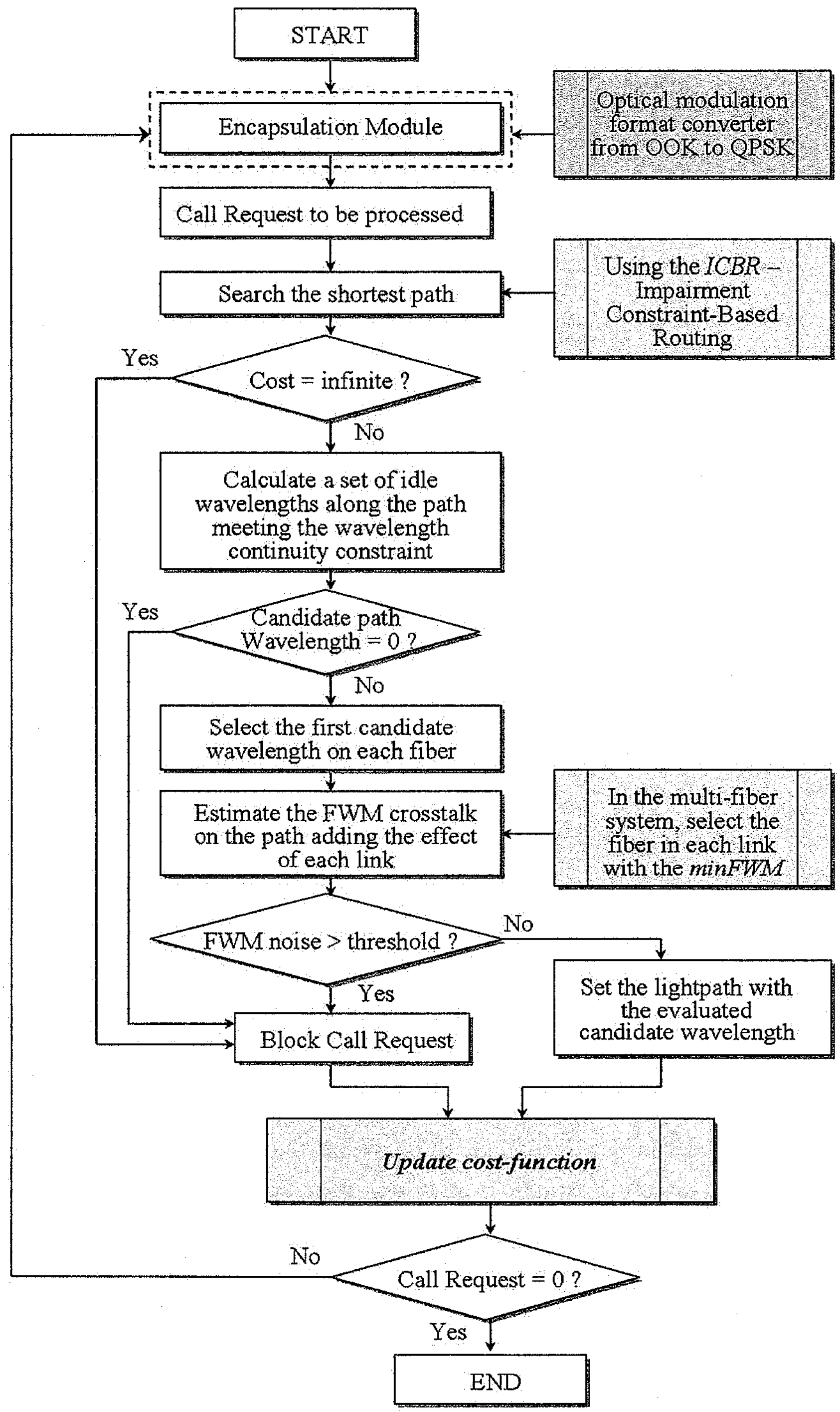


Fig. 4.3: Flow diagram of the simulation ICBR scheme incorporating the modulation format conversion interface.

and generate one encapsulate call with QPSK format. In addition, for simplification the duration time of the encapsulated call is set to the maximum duration time between the two original calls. After the encapsulated process finished, the new call is sent to be processed, and the FWM-aware RWA through the ICBR approach is performed to calculate a new lightpath with QPSK format to

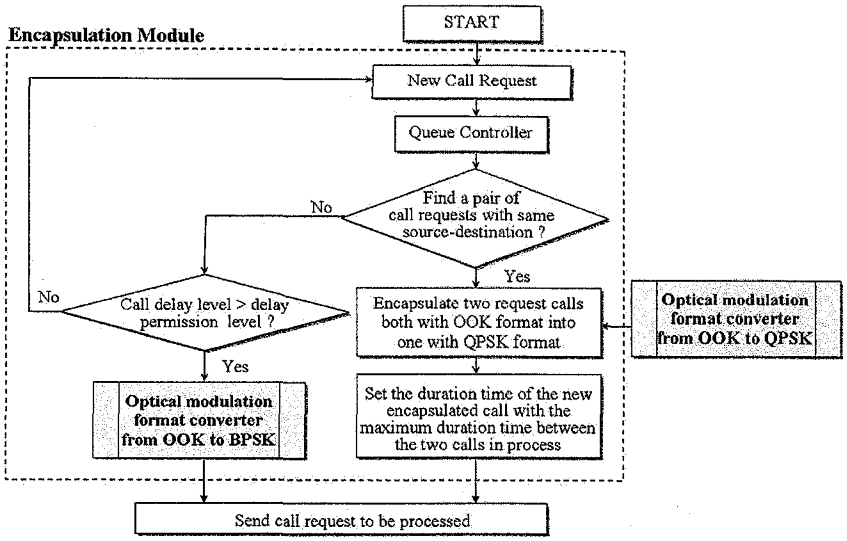


Fig. 4.4: Flow diagram of the optical modulation conversion functionality.

establish carrying two original call requests into one. After the encapsulation module functionalities are completed, another call request is generated and stored in the queue, and these processes continue until the last call of the system is processed.

A queue is created to find a pair of calls with same S-D nodes, one issue presented in this process is the probability that any call stay in a queue during a long period of time waiting to find another call request with the same S-D pair of nodes. In order to avoid this case, a delay permission level has been set inside the controller. The call delay level consists on the waiting time in the queue for a call to find another call with the same S-D pair of nodes, if this level exceeds the permission delay level, then the call will be sent to the system, carrying binary PSK format with using the format conversion.

4.4 Simulation results and analysis

Extensive simulations were carried out over the network topologies shown in Figs. 3.2 and 3.3, by measuring the network performance in terms of blocking probability versus network offered load. The threshold power is set to −20 dBm with OOK modulation format and −17 dBm when QPSK is adopted.

By incorporating the modulation format conversion interface into our designed and validated FWM-aware RWA algorithm, a new algorithm called FWM-aware RWA with OOK-QPSK modulation interface is generated, which is indicated in the plots with the name of QPSK for short. The new algorithm is introduced as follows:

- *FWM-aware RWA with OOK-QPSK modulation interface:* in addition to the characteristics of FWM-aware RWA algorithm scheme, this approach incorporated the encapsulation module where the NRZ-OOK-to-RZ-QPSK format conversion takes place giving a notorious improvement on the network performance.

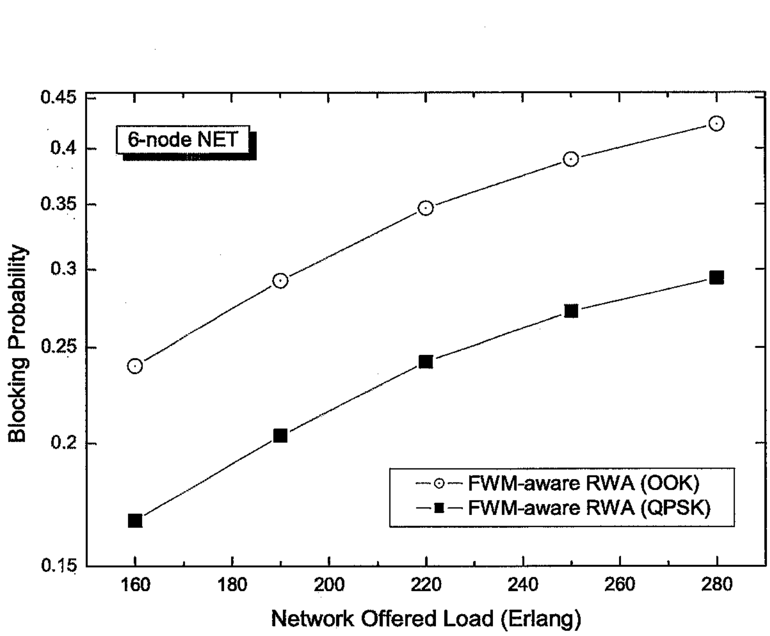


Fig. 4.5: Comparison of the performance evaluation in a 6-node network in terms of blocking performance between FWM-aware RWA (OOK) and FWM-aware RWA with OOK-QPSK modulation interface (QPSK).

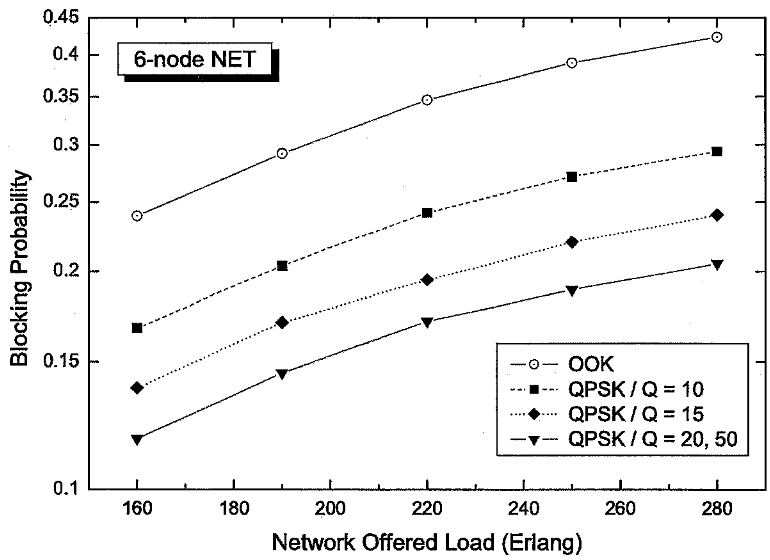


Fig. 4.6: Effect of varying queue size on the network performance of a 6-node network with QPSK.

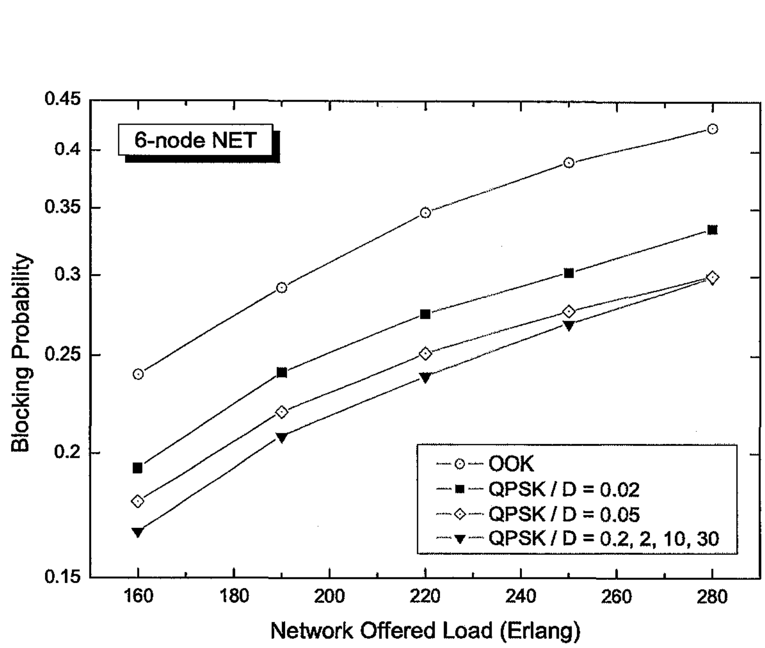


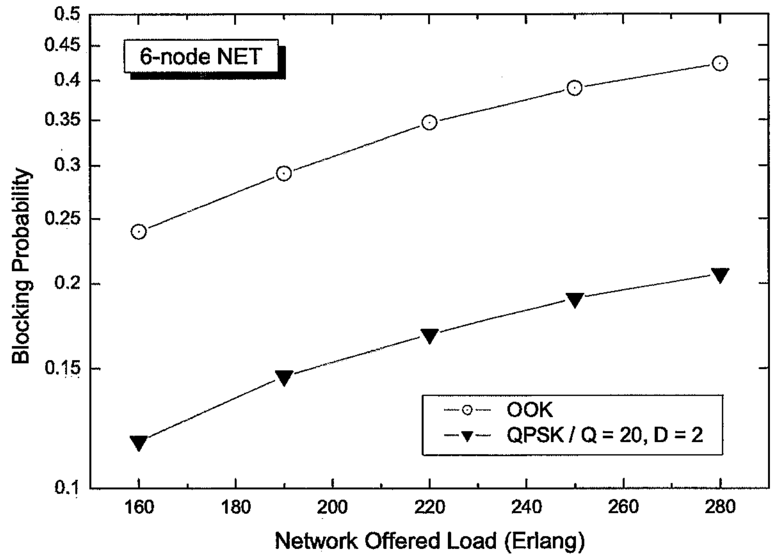
Fig. 4.7: Effect of varying the delay of a call in queue finding another call with the same source-destination pair of nodes on the network performance of a 6-node network with QPSK.

The performance of the new dynamic FWM-aware RWA algorithms with modulation format conversion interface is evaluated over different network topologies, and compared with the connection blocking probability obtained with the FWM-aware RWA that uses OOK modulation formats.

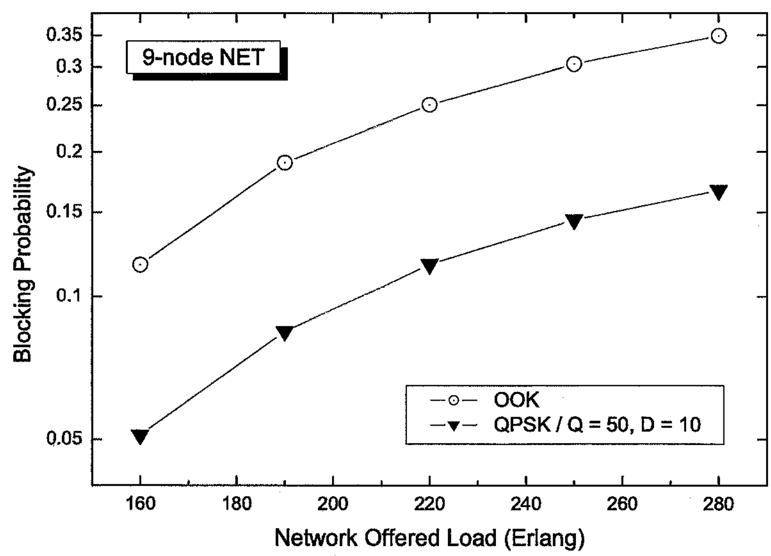
The network performances evaluation of a 6-node network topology (shown in Fig. 3.3(a)) for FWM-aware RWA (OOK) and FWM-aware RWA with OOK-QPSK modulation format conversion interface (QPSK) with queue size equal to 10 are shown in Fig.4.5. It has been demonstrated that the new algorithm FWM-aware RWA with OOK-QPSK modulation format conversion interface adds a significant improvement on the network performance in terms of decreasing the connection blocking probability.

Extensive simulations were carried out to study the effect on the blocking probability of the queue size (Q) parameter and the waiting time of a call inside a queue to find another call with the same source-destination pair (D), under different network prototypes. The queue size is measured in terms of a fixed number of connections or call requests (e.g., Q = 10 means that the queue consists of 10 connection requests), and the time of a call inside the queue were updated via a discrete event system clock simulation. The upper and lower value of parameter Q and D are found for each network under study. For simplicity we have shown for a network of 6 nodes depicted in Fig. 3.3(a), the effect of changing parameter Q which has been plotted in Fig.4.6 and the behavior of varying D shown in Fig.4.7.

Fig.4.6 shows the blocking probability versus offered load of a 6-node network for various queue size of the controller (Q = 10, 15, 20 and 50), results for QPSK consideration are presented with solid symbols and for these sets of simulations the parameter D was not taken into account. In addition, for comparison purpose the case of FWM-aware RWA assuming OOK has been incorporated and results



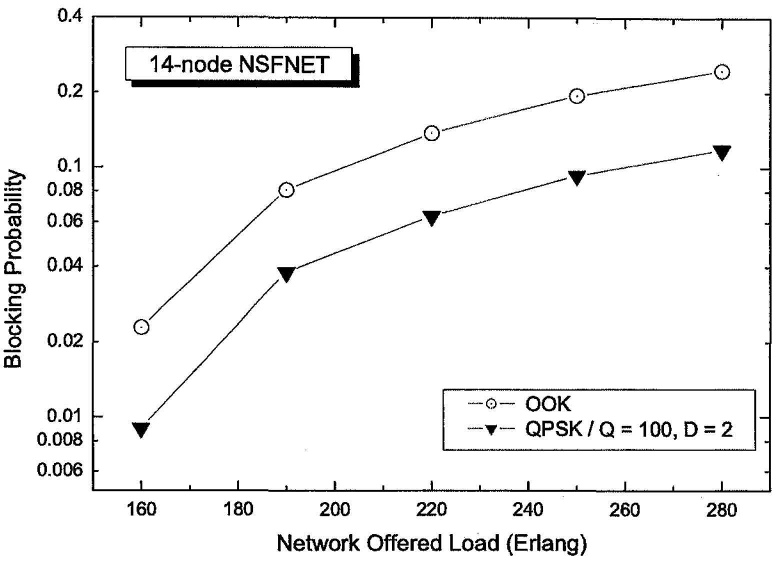
(a)



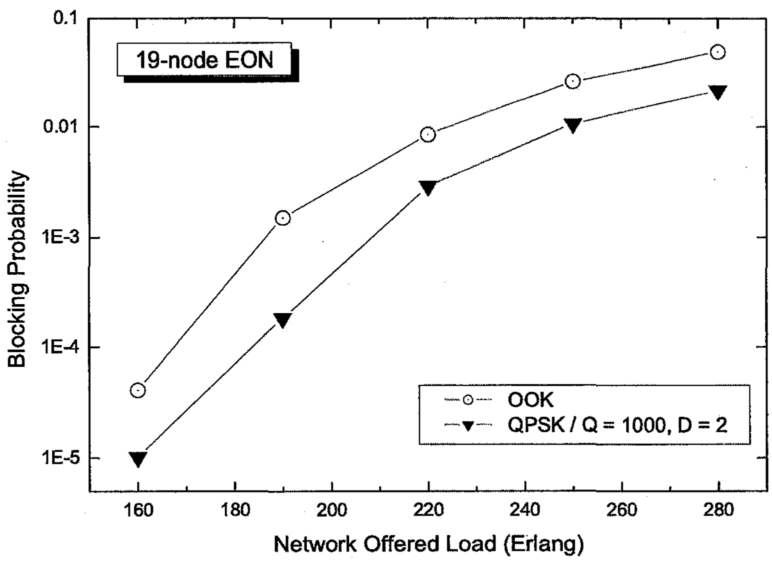
(b)

Fig. 4.8: Best network performance found with the lower bound of queue size and delay in queue parameters for the FWM-aware RWA incorporating QPSK, for networks 6, 9-node networks

are shown with solid line and open circles (indicated as OOK for short). It can be observed that by increasing the number of Q the blocking probability can be minimized, finding a lower bound with Q = 20. Similarly, by varying the parameter D in Fig. 4.7 and fixing the Q equal to 10, the lower bound has



(a)



(b)

Fig. 4.9: Best network performance found with the lower bound of queue size and delay in queue parameters for the FWM-aware RWA incorporating QPSK, for networks 14 and 19-node networks

been reached with D equal 0.2, it can also be observed that for D = 2, 10 and bigger values, results are similar to those obtained with D = 0.2. Results show that our new algorithm can significantly reduces connection blocking probability. Similar studies of parameter Q and D have also been carried out for

9-node network, 14-node NSFNet, and 19-node EON networks.

By selecting the best Q and the best D for each network which gives the lower bound of blocking probability have been feasible to find the possible best network performance according to each network topology. Results for the network topologies presented in Figs. 3.2 and 3.3 are depicted in Fig. 4.8 and 4.9. By incorporating a module with optical modulation format converter into the network model, the blocking probability can be reduced by a factor of 2, found with the lower bound of Q and D parameters, given a positive impact on the network performance.

From Figs. 4.8 and 4.9, can also be observed that the blocking probability of the FWM-aware RWA with OOK-QPSK modulation format conversion interface (QPSK) is lower than the obtained in FWM-aware RWA (OOK), and that the margin that separates the results of both algorithms within the same network topology increases while decrease the size of the network. For instance, comparing the number of blocking probability obtained for the overall traffic load equal to 250, in a 14-node NSFNET network the number of blocking probability of the FWM-aware RWA with OOK-QPSK modulation format conversion interface (QPSK) has 0,012 less blocking than the obtained in FWM-aware RWA (OOK) while for a 6-node network the blocking probability experiences a more significant lower amount of blocking comparing it to the FWM-aware RWA (OOK) an resulting in 0,22 difference giving a more positive impact to the network performance.

4.5 Conclusion

A new technique to reduce the effect of FWM-induced crosstalk by using an all-optical modulation format conversion from 2-channels OOK to QPSK had been proposed, which improves significantly the network performance by reducing the number of blocking calls. The proposed scheme is expected to realize an all-optical transparent interconnection between networks that employ diverse modulation formats. Studies of varying the queue size and the waiting time of a call inside the queue to find another call with the same source-destination pair were carried out. Lower bound of blocking probability with the best values of queue size and delay in a queue parameters were obtained giving the possible best performance according to the network topology.

From the obtained results, it is conclude that, for a same amount of total traffic and under different network prototypes, the algorithm with the modulation format conversion from 2-channels OOK to QPSK interface improves the network performance in comparison with the FWM-aware RWA assuming OOK. Results show that our scheme of establishing lightpaths and transmitting the end-to-end connection requests with QPSK modulation format give a positive impact in the network performance, bringing advantages as: transparency, higher-speed transmission, and coping with FWM-induced crosstalk.

Chapter 5

Conclusions

The rapid development and evolution of optical technologies make it possible to move beyond point-to-point WDM transmission systems to an all-optical backbone network that can take full advantage of the available bandwidth. The architecture that is widely expected to form the basis for a future all-optical infrastructure is built on the concept of wavelength routing, and the so-called wavelength-routed optical networks consist of a number of optical cross-connects (OXCs) arranged in some arbitrary topology, and its main function is to provide interconnection to a number of IP/MPLS subnetworks, supporting provisioning, protection and restoration at the optical layer. In Chapters 1 and 2 the trends and some important issues on optical networks has been addressed.

IP over WDM networks are aiming to eliminate the intermediate layers (ATM, SDH, etc.) to improve the network management efficiency and avoid task duplication. These networks aim to rely on an intelligent control plane providing flexibility and optimization of the optical layer use and reduced complexity.

This dissertation newly proposed an impairment-constraint-based routing technique, which copes with two main issues: the FWM-induced crosstalk awareness and the transparent modulation format conversion from 2-channel conventional OOK to QPSK in wavelength-routed optical networks dynamic lightpath provisioning. Results are validated via exhaustive discrete event time simulations. The main results obtained in this dissertation are summarized as follows:

In Chapter 3, since future telecommunications networks not only require very high information bandwidths but also need to support a wide range of services with different traffic statistics and good quality conditions, in order to address these characteristics, a novel FWM-aware RWA has been proposed and evaluated thorough extensive simulations under different network topologies. The FWM-aware RWA allows establishing end-to-end lightpaths on demand, by updating the network states information stored in a novel cost function. The cost function is evaluated and updated at generating a link state. It validates the computed path under the implemented constraints (network resource utilization and FWM-induced crosstalk). It is examined at the end of the calculation candidate path through the ICBR approach, following the policy that if the computed candidate on-line path satisfies a fixed permitted threshold then the candidate path is established, otherwise, it is rejected. The algorithm guarantees the QoS by avoiding setting up lightpaths that have been degradated by FWM-induced crosstalk. Qualitatively, in comparison with previous algorithms found in the literature, this approach improves the network performance while guarantees the QoS.

In Chapter 4, a transparent 2xOOK-to-QPSK modulation format conversion interface in the dynamic FWM-aware RWA has been proposed. Results show a feasibility of transparency between different modulation formats and a significant decreasing of the blocking connection request while simultaneously guarantee the QoS connections.

From all the obtained results, it is concluded that, the proposed FWM-induced crosstalk aware dynamic RWA with modulation format conversion has the feasibility to enrich the network performance, guarantee quality of services (QoS), increase scalability, and support transparency. Consequently, the proposed scheme is considered as one possible base to develop the network design framework for the future transparent optical communication networks.

Bibliography

[1] A. Bjarklev and C. Lin, "Applications of photonic crystal fibres in optical communications - what is in the future?" in *The 18th Annual Meeting of the IEEE Lasers and Electro-Optics Society (LEOS)*, Sydney, Australia, Oct. 23-27, 2005, Paper ThM1.

[2] O. Tooyama, T. Kinoshita, M. Tanaka, H. Ito, and M. Fujita, "Photonic crystal fibers(3)-application to supercontinuum light sources," *Mitsubishi Cable Industries Review*, vol. F0516A, no. 102, pp. 33–36, 2005.

[3] G. P. Agrawal, *Applications of Nonlinear Fiber Optics*, 1st ed. San Diego, CA: Academic Press, 2001, ch. 7.

[4] K. Mori, T. Moriota, and M. Saruwatari, "Wavelength-shift-free spectral inversion with an optical parametric loop mirror," *Opt. Lett.*, vol. 21, no. 2, pp. 110–112, Jan. 1996.

[5] Z. Zhang, J. Fu, D. Guo, and L. Zhang, "Lightpath routing for intelligent optical networks," *IEEE Network*, vol. 15, no. 4, pp. 28–35, July 2001.

[6] B. Ramamurthy, H. Feng, D. Datta, J. P. Heritage, and B. Mukherjee, "Transparent vs. opaque vs. translucent wavelength-routed optical networks," in *Proc. Optical Fiber Communication Conference (OFC'99)*, San Diego, CA, USA, Feb. 1999, Paper TuF2-1, pp. 59–61.

[7] B. Mukherjee, *Optical Communication Networks*, 1st ed. New York, NY: McGraw-Hill, 1997.

[8] *Impairments and other constraints on optical layer routing*, IETF RFC 4054. Informational, May 2005. [Online]. Available: ftp://ftp.rfc-editor.org/in-notes/rfc4054.txt

[9] H. Zang, J. P. Jue, and B. Mukherjee, "A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks," *SPIE Optical Networks Magazine*, vol. 1, no. 1, pp. 47–60, Jan. 2000.

[10] Y. Zang, J. P. Heritage, and B. Mukherjee, "Connection provisioning with transmission impairment consideration in optical WDM networks with high-speed channels," *IEEE / OSA J. Lightwave Technol.*, vol. 23, no. 3, pp. 982–993, Mar. 2005.

[11] I. Tomkos, D. Vogiatzis, C. Mas, I. Zacharopoulos, A. Tzanakaki, and E. Varvarigos, "Performance engineering of metropolitan area optical networks through impairment constraint routing," *IEEE Commun. Magazine*, vol. 42, no. 8, pp. s40–s47, Aug. 2004.

[12] *Architecture for the automatically switched optical network (ASON)*, ITU-T Rec. G.8080/Y.1304, Nov. 2001.

[13] *Generalized multi-protocol label switching (GMPLS) architecture*, IETF RFC 3945. Standards Track, Oct. 2004. [Online]. Available: http://www.ietf.org/rfc/rfc3945.txt?number=3945.txt

[14] *OSPF extensions in support of generalized multi-protocol label switching (GMPLS)*, IETF RFC 4203. Standards Track, Oct. 2005. [Online]. Available: http://www.ietf.org/rfc/rfc4203.txt?number=4203.txt

[15] *Generalized multi-protocol label switching (GMPLS) signaling resource reservation protocol-traffic engineering (RSVP-TE) extensions*, IETF RFC 3473. Standards Track, Jan. 2003. [Online]. Available: http://www.ietf.org/rfc/rfc3473.txt?number=3473.txt

[16] *OSPF version 2*, IETF RFC 2328. Standards Track, Apr. 1998. [Online]. Available: http://www.ietf.org/rfc/rfc2328.txt?number=2328.txt

[17] *A border gateway protocol 4 (BGP-4)*, IETF RFC 1771. Standards Track, Mar. 1995. [Online]. Available: http://www.ietf.org/rfc/rfc1771.txt?number=1771.txt

[18] D. Penninckx and C. Perret, "New physical analysis of 10-Gb/s transparent optical networks," *IEEE Photon. Technol. Lett.*, vol. 15, no. 5, pp. 778–780, May 2003.

[19] Y. Pointurier, M. Brandt-Pearce, T. Deng, and S. Subramaniam, "Fair QoS-aware adaptive routing and wavelength assignment in all-optical networks," in *Proc. IEEE International Conference on Communications (ICC 2006)*, Istanbul, Turkey, June 11-15, 2006, Paper OS-02-01.

[20] I. E. Fonseca, M. R. N. Riveiro, R. C. Almeida-Jr., and H. Waldman, "Preserving global optical QoS in FWM impaired dynamic networks," *Electron. Lett.*, vol. 40, no. 3, pp. 191–192, Feb. 2004.

[21] F. Cugini, N. Andriolli, L. Valcarenghi, and P. Castoldi, "Physical impairment aware signaling for dynamic lightpath set up," in *Proc. 31st European Conference on Optical Communication (ECOC 2005)*, vol. 4, Glasgow, Scotland, Sept.25-29, 2005, Paper Th 3.5.6, pp. 979–980.

[22] T. Mizuochi, K. Ishida, T. Kobayashi, J. Abe, K. Kinjo, K. Motoshima, and K. Kasahara, "A comparative study of DPSK and OOK WDM transmission over transoceanic distances and their performance degradations due to nonlinear phase noise," *IEEE/OSA J. Lightwave Technol.*, vol. 21, no. 9, pp. 1933–1943, Sept. 2003.

[23] T. Hoshida, O. Vassilieva, K. Yamada, S. Choudhary, R. Pecqueur, and H. Kuwahara, "Optimal 40 Gb/s modulation formats for spectrally efficient long-haul DWDM systems," *IEEE/OSA J. Lightwave Technol.*, vol. 20, no. 12, pp. 1989–1996, Dec. 2002.

[24] R. Hui, S. Zhang, B. Zhu, R. Huang, and C. Allen, "Advanced optical modulation formats and their comparison in fiber-optic system," Technical report ITTC-FY2004-TR-15666-01, Information and telecommunication technology center, University of Kansas, Jan. 2004. [Online]. Available: http://ittc.ku.edu/publications/documents/Hui2004_15666-01.pdf

[25] A. Chraplyvy, "Limitations on lightwave communications imposed by optical-fiber nonlinearities," *IEEE/OSA J. Lightwave Technol.*, vol. 8, no. 10, pp. 1548–1557, Oct. 1990.

[26] E. Goldstein and L. Eskildsen, "Scaling limitations in transparent optical networks due to low-level crosstalk," *IEEE Photon. Technol. Lett.*, vol. 7, no. 1, pp. 93–94, Jan. 1995.

[27] N. Antoniades, A. Boskovic, I. Tomkos, N. Madamopoulos, M. Lee, I. Roudas, D. Pastel, M. Sharma, and M. Yadlowsky, "Performance engineering and topological design of metro WDM optical networks using computer simulation," *IEEE J. Select. Areas Commun.*, vol. 20, no. 1, pp. 149–165, Jan. 2002.

[28] G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. San Diego, CA: Academic Press, 2001, ch. 10.

[29] R. Ramaswami and K. N. Sivarajan, *Optical Networks: A Practical Perspective*, 2nd ed. San Francisco, CA: Morgan Kaufmann, 2002.

[30] G. P. Agrawal, *Fiber-Optic Communication Systems*, 2nd ed. New York, NY: John Wiley & Sons, 1997.

[31] K. O. Hill, D. C. Johnson, B. S. Kawasaki, and R. I. MacDonald, "CW three-wave mixing in single-mode optical fibers," *J. Appl. Phys.*, vol. 49, no. 10, pp. 5098–5106, Oct. 1978.

[32] K. Inoue, H. Toba, and K. Oda, "Influence of fiber four-wave mixing on multichannel FSK direct detection transmission systems," *IEEE/OSA J. Lightwave Technol.*, vol. 10, no. 3, pp. 350–360, Mar. 1992.

[33] K. Inoue and H. Toba, "Theoretical evaluation of error rate degradation due to fiber four-wave mixing in multichannel FSK heterodyne envelope detection transmissions," *IEEE/OSA J. Lightwave Technol.*, vol. 10, no. 3, pp. 361–366, Mar. 1992.

[34] K. Inoue, "Four-wave mixing in an optical fiber in the zero-dispersion wavelength region," *IEEE/OSA J. Lightwave Technol.*, vol. 10, no. 11, pp. 1553–1561, Nov. 1992.

[35] N. Shibata, R. P. Braun, and R. G. Waarts, "Phase- mismatch dependence of efficiency of wave generation through four-wave mixing in a single-mode optical fiber," *IEEE J. Quantum Electron.*, vol. QE-23, no. 7, pp. 1205–1210, July 1987.

[36] R. A. Linke and A. H. Gnauck, "High-capacity coherent lightwave systems," *IEEE/OSA J. Lightwave Technol.*, vol. 6, no. 11, pp. 1750–1769, Nov. 1988.

[37] R. S. Vodhanel, A. F. Elrefaie, M. Z. Iqbal, R. S. Wagner, J. L. Gimlett, and S. Tsuji, "Performance of directly modulated DFB lasers in 10 Gb/s ASK, FSK, and DPSK lightwave systems," *IEEE/OSA J. Lightwave Technol.*, vol. 8, no. 9, pp. 1379–1386, Sept. 1990.

[38] J. P. Gordon and L. F. Mollenauer, "Phase noise in photonics communications systems using linear amplifier," *Opt. Lett.*, vol. 15, no. 23, pp. 1351–1355, Dec. 1990.

[39] A. H. Gnauck, G. Raybon, S. Chandrasekhar, J. Leuthold, C. Doerr, L. Stul, A. Agarwal, S. Banerjee, D. Grosz, S. Hunsche, A. Kung, A. Marhelyuk, D. Maywar, M. Movassaghi, X. Liu, C. Xu, X. Wei, and D. M. Gill, "2.5 Tb/s (64 x 42.7 Gb/s) transmission over 40 x 100 km NZDSF using RZ-DPSK format and all-Raman-amplified spans," in *Proc. Optical Fiber Communication Conference (OFC 2002)*, Anaheim, CA, USA, Mar. 17-22, 2002, Paper FC-2 (Postdeadline paper).

[40] A. H. Gnauck, "40-Gb/s RZ-differential phase shift keyed transmission," in *Proc. Optical Fiber Communication Conference (OFC 2003)*, vol. 2, Atlanta, GA, Mar. 2003, Paper ThE1 (Invited), pp. 450–451.

[41] A. H. Gnauck, G. Raybon, S. Chandrasekhar, J. Leuthold, C. Doerr, L. Stulz, and E. Burrows, "25 x 40-Gb/s copolarized DPSK transmission over 12 x 100-km NZDF with 50-GHz channel spacing," *IEEE Photon. Technol. Lett.*, vol. 15, no. 3, p. 467.469, Mar. 2003.

[42] K. Mishina, A. Maruta, S. Mitani, T. Miyahara, K. Ishida, K. Shimizu, T. Hatta, K. Motoshima, and K. Kitayama, "NRZ-OOK-to-RZ-BPSK modulation-format conversion using SOA-MZI wavelength converter," *IEEE/OSA J. Lightwave Technol.*, vol. 24, no. 10, pp. 3751–3758, Oct. 2006.

[43] C. Xu, X. Liu, and X. Wei, "Differential phase-shift keying for high spectral efficiency optical transmissions," *IEEE J. Selected Topics in Quantum Electron.*, vol. 10, no. 2, pp. 281–293, Mar. 2004.

[44] P. J. Winzer, S. Chandrasekhar, and H. Kim, "Impact of filtering on RZ-DPSK reception," *IEEE Photon. Technol. Lett.*, vol. 15, no. 6, pp. 840–842, June 2003.

[45] C. J. Xie, L. Moller, H. Haunstein, and S. Hunsche, "Comparison of system tolerance to polarization-mode dispersion between different modulation formats," *IEEE Photon. Technol. Lett.*, vol. 15, no. 8, pp. 1168–1170, Aug. 2003.

[46] C. Xu, X. Liu, L. F. Mollenauer, and X. Wei, "Comparison of return-to-zero differential phase-shift keying and on-off keying in long-haul dispersion managed transmission," *IEEE Photon. Technol. Lett.*, vol. 15, no. 4, pp. 617–619, Apr. 2003.

[47] V. Grigoryan, P. Cho, and Y. Godin, "Novel modulation techniques," in *Proc. Optical Fiber Communication Conference (OFC 2003)*, vol. 2, Atlanta, GA, USA, Mar. 2003, Paper FD1 (Invited), pp. 646–647.

[48] R. J. Essiambre, B. Mikkelsen, and G. Raybon, "Intrachannel cross phase modulation and four-wave mixing in high speed TDM systems," *Electron. Lett.*, vol. 35, no. 18, pp. 1576–1578, Sept. 1999.

[49] X. Liu, C. Xu, and X. Wei, "Nonlinear phase noise in pulse-overlapped transmission based on return-to-zero differential-phase-shift-keying," in *Proc. 28th European Conference on Optical Communication (ECOC 2002)*, vol. 4, Copenhagen, Denmark, Sept. 8-12, 2002, Paper 9.6.5.

[50] X. Wei and X. Liu, "Analysis of intrachannel four-wave mixing in differential-phase-shift-keyed transmission with large dispersion," *Opt. Lett.*, vol. 28, no. 23, pp. 2300–2302, Dec. 2003.

[51] C. Xu, X. Liu, and X. Wei, "Ultra-long haul DWDM transmission with differential phase shift keying dispersion managed soliton," in *Proc. 28th European Conference on Optical Communication (ECOC 2002)*, vol. 1, Copenhagen, Denmark, Sept. 8-12, 2002, Paper 1.1.5.

[52] B. Ramamurthy, D. Datta, H. Feng, J. P. Heritage, and B. Mukherjee, "Impact of transmission impairments on the teletraffic performance of wavelength-routed optical networks," *IEEE/OSA J. Lightwave Technol.*, vol. 17, no. 10, pp. 1713–1723, Oct. 1999.

[53] M. Ali, D. Elie-Dit-Cosaque, and L. Tancevski, "Enhancements to multi-protocol lambda switching to accommodate transmission impairments," in *Proc. IEEE Global Communications Conference (GLOBECOM 2001)*, vol. 1, S. Antonio, Texas, USA, Nov. 25-29, 2001.

[54] G. Markidis, S. Sygletos, A. Tzanakaki, and I. Tomkos, "Impairment-constraint-based routing in ultra long-haul optical networks with 2R regeneration," *IEEE Photon. Technol. Lett.*, vol. 19, no. 6, pp. 420–422, Mar. 2007.

[55] W. Zeiler, F. D. Pascuale, P. Bayvel, and J. E. Midwinter, "Modeling of four-wave mixing and gain peaking in amplified WDM optical communication systems and networks," *IEEE/OSA J. Lightwave Technol.*, vol. 14, no. 9, pp. 1933–1942, Sept. 1996.

[56] A. Marsden, A. Maruta, and K. Kitayama, "FWM-aware dynamic routing and wavelength assignment for wavelength-routed optical networks," *IEICE Trans. Commun.*, vol. E91-B, no. 7, pp. 2145–2151, July 2008.

[57] M. W. Maeda, W. B. Sessa, W. I. Way, A. Yi-Yan, L. Curtis, R. Spicer, and R. I. Laming, "The effect of four-wave mixing in fibers on optical frequency-division multiplexed systems," *IEEE/OSA J. Lightwave Technol.*, vol. 8, no. 9, pp. 1402–1408, Sept. 1990.

[58] P. V. Mieghem, *Performance Analysis of Communications Networks and Systems*, 1st ed. Cambridge, UK: Cambridge University Press, 2006.

[59] H. Zang, J. P. Jue, L. Sahasrabuddhe, R. Ramamurthy, and B. Mukherjee, "Dynamic lightpath establishment in wavelength-routed WDM networks," *IEEE Commun. Magazine*, vol. 39, no. 9, pp. 100–108, 2001.

[60] S. Shen and G. Xiao, "Evaluating the impact of the link-state update period on the blocking performance of wavelength-routed networks," in *Proc. Optical Fiber Communication Conference (OFC 2004)*, Los Angeles, CA, USA, Feb. 22-27 2004, Paper Th G.6.

[61] S. Pachnicke, J. Reichert, S. Spalter, and E. Voges, "Fast analytical assessment of the signal quality in transparent optical networks," *IEEE/OSA J. Lightwave Technol.*, vol. 24, no. 2, pp. 815–824, Feb. 2006.

[62] M. Tornatore, G. Maier, and A. Pattavina, "WDM network design by ILP models based on flow aggregation," *IEEE/ACM Trans. on Networking*, vol. 15, no. 3, pp. 709–720, June 2007.

[63] S. Sanchez-Lopez, X. Masip-Bruin, J. Sole-Pareta, and J. Domingo-Pascual, "Fast setup of end-to-end paths for bandwidth constraint applications in an IP/MPLS-ATM integrated environment," *Computer Networks*, vol. 51, no. 3, pp. 835–852, Feb. 2007.

[64] M. S. Kumar and P. S. Kumar, "Lightpath setup time optimization in wavelength routed all-optical networks," *Computer Communications*, vol. 24, no. 10, pp. 984–995, May 2001.

[65] R. Ramaswami and A. Segall, "Distributed network control for optical networks," *IEEE/ACM Trans. on Networking*, vol. 5, no. 6, pp. 936–943, Dec. 1997.

[66] R. Martinez, C. Pinart, F. Cugini, N. Andriolli, L. Valcarenghi, P. Castoldi, L. Wosinska, J. Comellas, and G. Junyent, "Challenges and requirements for introducing impairment-awareness into the management and control planes of ASON/GMPLS WDM networks," *IEEE Commun. Magazine*, vol. 44, no. 12, pp. 76–85, Dec. 2006.

[67] R. Lao and R.Killey, "Impact of wavelength-routed network physical topology on blocking probability using a dynamic traffic growth model," in *Proc. 8th Opto-Electronics and Communications Conference (OECC 2003)*, Shanghai, China, Oct. 13-16, 2003, Paper P5-17.

[68] A. H. Gnauck and P. J. Winzer, "Optical phase-shift-keyed transmission," *IEEE/OSA J. Lightwave Technol.*, vol. 23, no. 1, pp. 115–130, Jan. 2005.

[69] P. J. Winzer and R. J. Essiambre, "Advanced optical modulation formats," in *Proc. 29th European Conference on Optical Communication (ECOC 2003)*, Rimini, Italy, Sept. 21-25, 2003, Paper Th 2.6.1.

[70] R. A. Griffin, R. I. Johnstone, R. G. Walker, J. Hall, S. D. Wadsworth, K. Berry, A. C. Carter, M. J. Wale, J. Hughes, P. A. Jerram, and N. J. Parsons, "10 Gb/s optical differential quadrature phase shift key (DQPSK) transmission using GaAs/AlGaAs integration," in *Proc. Optical Fiber Communication Conference (OFC 2002)*, Anaheim, CA, USA, Mar. 17-22, 2002, Paper FD6.

[71] K. Mishina, S. M. Nissanka, A. Maruta, S. Mitani, K. Ishida, K. Shimizu, T. Hatta, and K. Kitayama, "All-optical modulation format conversion from NRZ-OOK to RZ-QPSK using parallel SOA-MZI OOK/BPSK converters," *Opt. Express*, vol. 15, no. 12, pp. 7774–7785, June 2007.

Acronyms

AC	Admission Controller
ASE	Amplified Spontaneous Emission
ASK	Amplitude-Shift Keying
ASON	Automatic Switched Optical Network
ATM	Asynchronous Transfer Mode
BPSK	Binary Phase-Shift Keying
BGP	Border Gateway Protocol
CAPEX	Capital Expenditure
CC	Connection Controller
CD	Chromatic Dispersion
CR-LDP	Constraint-Based Routing Label Distribution Protocol
CW	Continuous Wave
D	Delay of a connection request to find another call with same S-D pair
DFB	Distributed-Feedback semiconductor laser
DSF	Dispersion-Shifted Fiber
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-Doped Fiber Amplifier
EON	European Optical Network
ERM	Electro-Refraction Modulation
FEC	Forward Error Correction
FF	First-Fit
FMI	Frequency Modulation Index
FSK	Phase-Shift Keying
FWM	Four-Wave Mixing
GAN	Global Area Network
GMPLS	Generalized Multiprotocol Label Switching
ICBR	Impairment Constraint-Based Routing
IETF	Internet Engineering Task Force
IGP	Interior Gateway Protocol
IM/DD	Intensity Modulation with Direct Detection

InP	Indium Phosphide
IP	Internet Protocol
IRWA	Impairment-aware RWA
ITU	International Telecommunication Union
ITU-T	ITU's Telecommunication Standardization Sector
LRM	Link Resource Manager
LSA	Link State Advertisement
LSP	Label Switched Path
MAN	Metro Area Network
MPLS	Multiprotocol Label Switching
MQW	Multi-Quantum Well
MZDI	Mach-Zehnder Delay Interferometer
MZI	Mach-Zehnder Interferometer
NRZ	Non-Return-to-Zero
NSFNet	National Science Foundation Network
OADM	Optical Add/Drop Multiplexer
OCS	Optical Circuit-Switching
O-E-O	Optical-Electrical-Optical
OOK	On-Off Keying
OPEX	Operating Expenditure
OPG	Optical Parametric Gain
OSPF-TE	Open Shortest Path First Traffic Engineering
OTDM	Optical Time Division Multiplexing
OXC	Optical Cross-connect
PAM	Pulse Amplitude Modulation
PMD	Polarization Mode Dispersion
PSK	Phase-Shift Keying
Q	Queue size measured by a number of connection request
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-Shift-Keying
RC	Routing Controller
ROADM	Reconfigurable Optical Add/Drop Multiplexer
RSVP-TE	Resource Reservation Protocol Traffic Engineering
RWA	Routing and Wavelength Assignment
RZ	Return-to-Zero
S-D	Source-Destination
SDH	Synchronous Digital Hierarchy

SE	Spectral Efficiency
SMF	Single Mode Fiber
SOA	Semiconductor Optical Amplifier
SONET	Synchronous Optical Networking
SPM	Self Phase Modulation
SRS	Stimulated Brillouin Scattering
TE	Traffic Engineering
TED	Traffic Engineering Database
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WRN	Wavelength-Routed Network
WSS	Wavelength Selective Switch
XPM	Cross-Phase Modulation

List of Publications

I. Journals

1. Adelys Marsden, Akihiro Maruta, and Ken-ichi Kitayama, "FWM-aware Dynamic Routing and Wavelength Assignment for Wavelength-Routed Optical Networks," *IEICE Transactions on Communications*, vol. E91-B, no.7, pp. 2145-2151, July 2008.

2. Adelys Marsden, Akihiro Maruta, and Ken-ichi Kitayama, "Reducing the Lightpath Establishing Time of FWM-Aware Dynamic RWA for Wavelength-Routed Optical Networks," accepted for publication in *Photonic Network Communications (PNC)*, date of acceptance December 2, 2008.

II. International Conferences

1. Adelys Marsden, Akihiro Maruta, and Ken-ichi Kitayama, "Routing and Wavelength Assignment Encompassing FWM in WDM Lightpath Networks," in *Proc. of 12th International Conference on Optical Network Design and Modelling (ONDM 2008)*, Vilanova i la Geltru, Barcelona, Catalonia, Spain, Paper F1.1, pp. 141-146, March 2008.

2. Adelys Marsden, Akihiro Maruta, and Ken-ichi Kitayama, "Dynamic Lightpath Establishment Incorporating the Effects of FWM-Induced Crosstalk Enhancement in Wavelength-Routed Optical Networks," in *Proc. of 5th International Conference on Broadband Communications, Networks, and Systems (BROADNETS 2008)*, London, UK, Poster Session, Sept. 2008.

III. Domestic Conferences

1. Adelys Marsden, Shaowei Huang, Akihiro Maruta, and Ken-ichi Kitayama, "FWM-aware Dynamic Routing and Wavelength Assignment for All-Optical Networks," in *Proc. of IEICE General Conference*, B-12-23, Nagoya, Japan, March 2007.

2. Adelys Marsden, Akihiro Maruta, and Ken-ichi Kitayama, "Routing and Wavelength Assignment Encompassing FWM Awareness for Wavelength Routed Optical Networks," in *Proc. of IEICE Society Conference*, B-12-10, Tottori, Japan, Sept. 2007.

3. Adelys Marsden, Akihiro Maruta, and Ken-ichi Kitayama, "Dynamic Routing and Wavelength Assignment Incorporating the Effects of FWM Crosstalk Enhancement in Wavelength-Routed Optical Networks," in *Proc. of 1st Global COE Student Conference on Innovative Electronic Topics (SCIENT 2008)*, Osaka, Japan, Poster Session P-6, p. 83, Aug. 2008.

IV. Submissions under the peer-review process

1. Adelys Marsden, Akihiro Maruta, and Ken-ichi Kitayama, "Dynamic connection provisioning assessing FWM-induced crosstalk in Intelligent Optical Networks," submitted to *Optical Switching and Networking (OSN)*, waiting for initial decision.

2. Adelys Marsden, Akihiro Maruta, and Ken-ichi Kitayama, "Impact of 2xOOK-to-QPSK Format Conversion on Dynamic RWA with FWM-induced Crosstalk-Aware Wavelength-Path Networks," submitted to *Proc. of Optical Fiber Communication Conference and Exposition and National Fiber Optic Engineers Conference (OFC/NFOEC 2009)*, waiting for decision.