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Cédric Ware

► **To cite this version:**

Cédric Ware. On optical functionalities and high-capacity communication networks. Networking and Internet Architecture [cs.NI]. Telecom ParisTech, 2013. tel-00983948

HAL Id: tel-00983948

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Habilitation à diriger des recherches
Université Pierre et Marie Curie

On optical functionalities and high-capacity communication networks

Présentée par

Cédric Ware

Maître de conférences à Télécom ParisTech

Soutenue le 26 novembre 2013 devant le jury composé de :

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Piet Demeester	Professeur, Université de Gand	Rapporteurs
Dimitra Simeonidou	Professeure, Université de Bristol	
Jean-Claude Simon	Professeur, ENSSAT	
Aziz Benlarbi-Delai	Professeur, Université Pierre et Marie Curie	Examineurs
Dominique Chiaroni	Ingénieur de recherche, Alcatel-Lucent Bell Labs	
Philippe Gallion	Professeur, Télécom ParisTech	

Acknowledgments

The Habilitation degree is an interesting exercise, whose aim is to show a consistent and independent research vision, and an ability to direct students to successful Ph. D. theses. In its form, it is similar to defending one's Ph. D. all over again; however, by the very nature of the test, one can't rely on having one's work vetted by a trusted and familiar advisor first.

Experience, both as a researcher and a lecturer, helps make it less scary the second time round. Still, confident as I am of the vision I believe in, I admit to having felt most vulnerable when I sent this document, summing up over a decade's worth of research activities, to world-class experts for their evaluation.

They seem to have liked it. I am honored by the very positive feedback from the referees, Profs. Piet Demeester, Dimitra Simeonidou and Jean-Claude Simon; for doing the reviews, I wish to express my heartfelt thanks to them, and to the other members of the jury, Profs. Guy Millot, Aziz Benlarbi-Delai, Philippe Gallion, and Dr. Dominique Chiaroni, for the lively debate that followed my presentation.

This work would not have been possible without the help and support of countless peers, colleagues and collaborators, all of whom I cannot name here. If any are to be singled out, it should be Prof. Didier Erasme, my former Ph. D. advisor and head of Télécom ParisTech's Optical Telecommunications research group; our valued exchanges and friendship most assuredly didn't end on the completion of my thesis.

In addition, I am especially grateful to Prof. Keren Bergman, who kindly hosted my recent sabbatical in Columbia University's Lightwave Research Laboratory, and thus helped shape the directions my research is now taking.

But the people who are to be genuinely thanked for their contributions to this work are the Ph. D. students I helped supervise: Hassan Teimoori, Fausto Gómez Agis, Steevy Cordette, Guilhem de Valicourt, Pierre Delesques, and Wiem Samoud; although I do assume responsibility for all the mistakes we made, *you* truly deserve the credit.

Thank you.

Abstract

The global communications network has become a pervasive and critical item of everyday life, spawning and enabling countless worldwide services that went from nonexistent to must-have in less than a decade. Its implementation makes considerable use of optical transmission systems, which are the physical medium of choice for most non-wireless links, being capable of high data rates over long distances. However, the potential of optics is still underexploited, and can help a smarter network meet the simultaneous challenges of ever-higher data rates, network switching, and the “last-mile” access network.

Very high data rates were achieved in optical transmissions in the late 1990s especially through wavelength-division multiplexing (WDM) over the C and later the L spectral bands. For some time, the way to increase data rates was forecast to be higher symbol rates per wavelength, for which optical-to-electronic (O-E) conversions are a speed bottleneck. This required all-optical functionalities, especially to process optical time-domain multiplexed signals. In that line, I contributed to **ultrafast clock recovery** using opto-electronic phase-locked loops.

However, the recent comeback of coherent optical communications points to easier ways to increase the data rate by pushing towards higher spectral efficiencies, **closer to the optical channel’s Shannon capacity** in the presence of certain physical impairments. Notably, a recent study that I contributed to suggests that polarization-dependent loss can be handled close to the limit thanks to a combination of space-time codes and more conventional error-correcting codes.

Switching is another bottleneck: the Internet’s great versatility results in part from its packet-switching paradigm, but current optical networks are essentially circuit-switched using wavelength granularity. Packet-switching functionality is implemented purely in electronics, incurring numerous energy-inefficient O-E conversions and ballooning energy costs.

My work on all-optical functionalities included an **all-optical label-processing scheme** for switching nodes, though this approach would be subject to scaling problems in practice. More recently, my concern has shifted to **hybrid switching nodes** using electronic buffers to supplement an optical switching matrix. My current studies show great improvements of their sustainable load compared to all-optical switches at a given packet-loss probability.

Access network is the last stronghold where optical transmissions are not quite dominant yet. The focus there is on cost effectiveness and resource sharing, especially in passive optical networks (PONs). In order to bring WDM to PONs, I contributed to a **pulsed continuum optical source** that could have provided optical channels to multiple users simultaneously. More recently, I also oversaw work on **reflective semiconductor optical amplifiers** designed for colorless optical network units.

Finally, the challenge goes on for a better match between network functionalities and the untapped potential of optics. My focus is currently shifting towards **cross-layer optical networking**, requiring novel network architectures to break free from the electronic-centric layered-network model, and finally meeting the energy consumption problem square-on.

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Introduction

The story of the digital revolution has taken the world largely by surprise. Indeed, unlike space travel, biological manipulations, and videoconferencing, only a small handful of works by futurists and science-fiction authors even began to take the true measure, before it was already upon us, of what global communication networks have done for society in just the past two decades.

Only in 1968 did a seminal paper [69] predict that “In a few years, men will be able to communicate more effectively through a machine than face to face” and go on to describe the modern Internet, from the packet switching paradigm to collaborative document sharing through network applications.

This vision could not have come true without the advent of high-data-rate transmission systems, which is becoming synonymous with optical fiber communications. From its roots in long-range communications, this technology is growing to embrace even the shortest links in data centers, and shaping up as a serious candidate for intra-CPU transmissions.

The only exceptions to this trend to date are applications requiring mobility, or information processing such as routing and switching. Even then, numerous optical functionalities have been and are being developed to fulfill these needs while keeping signals in the optical domain wherever possible and avoid unnecessary optical-to-electronic (O-E) conversions.

Thus, in this generation, broadband data networks have become ubiquitous and critical, including to their non-technically-oriented users, who enjoy a plethora of services, with new applications appearing at a steady rhythm.

The challenge is that *the show must go on*.

Until now, the network has performed an admirable job coping with an exponential traffic growth even faster than Moore’s law for computing power, all the while keeping with the same paradigm of everything-over-IP-packets that leverages the Internet’s flexibility and pervasiveness.

However, this growth may prove unsustainable. The ever-increasing need for ultra-high bit rates drives fiber transmission systems to the limits of their capacity as predicted by information theory. Then, bringing this data all the way to the end-users economically implies deploying solutions as good as yesterday’s core-network technologies for a fraction of the cost. Finally, indiscriminate packet switching splits traffic into such numbers of packets as to require massively-parallel electronic routers that incur heavy costs by their energy consumption alone.

This memoir describes my contribution to the field: developing optical functionalities to help the global network keep improving their performance and meet the popular demand.

Ultra-high bit rates

Data rates in excess of a terabit per second have been available over optical fibers almost ever since wavelength-division multiplexing (WDM) became commonplace in the late 1990s and early 2000s. However, increasing the bit rate per wavelength channel has not been as easy as multiplying the number of channels; for the past two decades, even

though some exotic materials and devices have operated at THz frequencies, integrated electronic circuits have been limited by a bandwidth ceiling of a few tens of GHz.

Until the mid-2000s, the focus was on increasing the symbol rate per channel, while keeping with simple mostly-intensity modulations at 1 bit per symbol. Notably, optical time-division multiplexing (OTDM) was very successful in the lab to push per-channel bit rates beyond 100 Gbit/s. Of course, transmissions using this technique required all-optical or opto-electronic functionalities for any processing needs, especially synchronization and demultiplexing at the receiver.

My contribution to this topic has been an often-overlooked functionality required for synchronization: clock recovery. First over the course of my Ph. D. thesis, then that of one of my students', I pursued opto-electronic phase-locked loops at ultrahigh bit rates, which is the topic of section 1.1.

However, OTDM has never matured enough for deployment outside research labs, all the more so that most research on high-bit-rate communications has moved in another direction since the mid-to-late-2000s: intradyne coherent optical communication. This technique, which requires high-speed signal processing, was made practical through advances in electronics (especially analog-to-digital converters). It allows ultra-high bit rates with moderate symbol rates, manageable without all-optical demultiplexing, through the use of higher-order phase and amplitude modulations which also have a higher spectral efficiency.

Moreover, once high-speed signal processing comes into the picture, digital communications techniques, well-known in radio, become usable with optics; most linear impairments—that is, forms of dispersion—can be completely compensated for, in theory at least. The advent of this technique also marks a shift towards designing optical links according to information theory limits, not just empirical constraints.

To this end, the capacity of optical fibers, including its nonlinear response at high powers, is being studied. My work in this vein, described in section 1.2, revolves around such capacity analysis in certain nonobvious situations.

Access network

All the traffic carried by the core network must ultimately reach the end users, through an access network that has now outgrown every technical trick devised to extend the life of historical twisted-pair copper wires. Successive generations of optical transmission technologies are now percolating into users' premises. Given the size of this market, though, the focus must be on cost efficiency rather than raw performance.

Therefore, techniques developed for core networks must be scaled down or adapted to share their cost among many customers. The most significant one, WDM, has been used until recently not as a capacity booster, but a way to separate traffic types: upstream and downstream; analog TV and digital data.

Still, the use of multiple wavelengths for data will soon be needed to upgrade the current generation of optical networks. However, deploying wavelength-specific equipment to users' premises would rapidly turn into a logistical nightmare; thus, the challenge is to design "colorless" equipments, compatible with any wavelength, which sounds simple technically speaking but is harder to manage economically.

Through the Ph. D. theses of two students, I have made two main contributions in this area: on the one hand, on the topic of optical CDMA and spectral slicing, a broadband optical source designed to be shared among many users was demonstrated in

an all-optical CDMA transmission, as shown in section 2.1.

On the other hand, section 2.2 summarizes a very successful work on designing reflective semiconductor optical amplifiers whose performance set the state of the art in modulation speed, low chirp and linearity. These devices, which can be mass-produced to lower their prices, were demonstrated as colorless remote modulators in conventional transmission experiments, as well as radio-over-fiber systems.

Switching capacity

For all their success, high-capacity optical communications have been and largely remain point-to-point transmissions, or point-to-multipoint in lower-capacity access networks. Reconfigurable optical add-drop multiplexers (ROADMs) have been changing this somewhat since the mid-2000s, by enabling circuit-mode wavelength switching transparently. However, in practice, the resulting optical lightpaths remain essentially static, and provisioning wavelength channels is performed manually, thus remaining a slow and costly operation.

In contrast, virtually all traffic nowadays is packet-switched; more specifically, it takes the form of IP packets, which are routed in electronic routers. These amount to dedicated computers that must convert all incoming traffic into electronic form, read and process each packet's header information, and re-send it optically. The current traffic being way beyond any individual computer's processing, core-network-scale routers are massively parallel, which is helped by the path-independence designed into the Internet.

This conventional approach has the advantages of great flexibility and reliance on mature technologies, and has been very successful ever since the inception of the Internet. However, it is unsustainable in the long run, for it causes a large energy footprint, which increases exponentially with the traffic while the energy cost per bit switched is not decreasing fast enough.

The logical alternative is to delegate some switching or routing functions to optics which, owing to its large capacity, has a low cost per bit transmitted; furthermore, keeping the signal in optical form would save on O-E conversions.

My students and I have contributed to this aim threefold. First, as mentioned in section 3.1, by demonstrating all-optical label recognition of data packets; this would have been an important part of a complete all-optical switch, although history has proven that this kind of mimicking electronic architectures is ultimately a losing proposition.

Second, aiming for a better dispatch of functionalities among optics and electronics, through a performance analysis of a hybrid switching node architecture, detailed in section 3.2, which uses an optical switching matrix coupled with an electronic buffer to alleviate the well-known issue of contention in optical switches.

Finally, section 3.3 sums up my thoughts on cross-layer optical networking. I have come to believe that the relative lack of success of optical functionalities outside the laboratory largely comes from designing them without enough consideration for the network in its globality. Instead of trying to ape conventional layered architectures modeled on the capabilities of electronics, a clean-slate approach, optimized across network layers, is required to break the energy barrier. Only such an incentive will be substantial enough to overcome the inertia of legacy solutions and let optical technologies come to their full potential.

Chapter 1

Ultra-high bit rates

It is a rare year without some transmission record being announced in major conferences' postdeadline sessions.

From the advent of erbium-doped fiber amplifiers (EDFAs), the way to high data rates lay obviously through wavelength-division multiplexing, using separate optical carriers as independent channels, which could be amplified simultaneously without the need to demultiplex and regenerate each channel electronically. Optical communication networks, especially the long-reach paths, are now built around multi-span EDFA-amplified WDM systems, each fiber's total capacity having been boosted over the years by filling up the 4-to-8-THz (C+L bands) erbium gain bandwidth with 40, 80, then 160 wavelengths along the ITU grid. Even denser WDM schemes were proposed, using e.g. offset filtering [8].

In parallel with this densification of the spectrum occupancy, each channel's individual data rate increased: optical dispersion compensation enabled 2.5 Gbit/s, and forward error correction (FEC) made 10 Gbit/s practical in the classical modulation format of non-return-to-zero on-off keying (NRZ-OOK). Commercial systems pushed that limit to 40 Gbit/s. Even that, however, only amounted to spectral efficiencies less than a fraction of bit/s/Hz.

Then, higher per-channel bit rates have had a decade-plus-long history [50, 73, 75] of laboratory demonstrations but no commercial successes, being too sensitive to dispersion, especially higher-order chromatic dispersion (CD) and polarization-mode dispersion (PMD). Also, as long as modulation formats were to remain in the OOK family, bit rates above 100 Gbit/s required OTDM and basically all-optical functionalities for multiplexing and demultiplexing. The ultrashort pulses that made up RZ-OOK signals were vulnerable to chromatic dispersion and optical nonlinearities. It appeared, then, that more advanced modulation formats such as phase-shift keying (PSK) were required if data rates were to continue their progression.

The main obstacle to PSK modulations is the difficulty of detecting the phase of optical signals; despite having the very same physical nature as radio-frequency (RF) signals, albeit with a higher photon energy, optical signals are detected through photodetectors, which are sensitive to optical power, not phase, let alone polarization. However, interferometers allow access to the optical phase, at the cost of receiver complexity and the need to maintain optical coherence. So-called coherent receivers were explored in the 1980s and early 1990s to fight fiber attenuation in long-distance systems, but were deemed impractical, and were put on the back-burner when EDFAs solved that problem. Only differential PSK (DPSK) schemes could be implemented using a simple enough ininterferometric receiver, and were somewhat less sensitive to nonlinearities and had a better spectral efficiency.

Truly spectrally-efficient systems, however, need full-fledged coherent receivers, which mix the incoming signal with a local oscillator. The main problem used to be locking that oscillator's frequency to that of the signal's optical carrier. This requirement

was relaxed with intradyne coherent systems, where the frequency detuning is tracked and compensated for using digital signal processing (DSP). That which was deemed impractical in the 1990s was thus made possible thanks to 21st-century DSP hardware. The first commercial 100-Gbit/s systems, using polarization-multiplexed quadrature-PSK (PolMux-QPSK) modulation, were deployed in late 2009 [4].

Moreover, the combination of coherent receiver and DSP enables the use of a whole arsenal of digital communications techniques, which can theoretically deal with any linear impairment; former stumbling blocks such as CD and PMD turn into non-issues if a matched linear filter can be applied in software.

Coherent optical communications have thus become the leading technique for ultra-high-bit-rate transmissions, relying on higher-order modulation formats instead of prohibitively high symbol rates, delivering much better spectral efficiencies, and pushing closer to the theoretical capacity of the optical channel.

My notable contributions In this context of optical functionalities for ultra-high-bit-rate systems, my main research axis used to be opto-electronic clock recovery. As detailed in section 1.1 below, phase-locked loops (PLLs) using nonlinear optical devices as phase comparators were successfully used to synchronize and demultiplex OTDM RZ-OOK data streams up to 640 Gbit/s, and OTDM RZ-D8PSK up to 870 Gbit/s.

After these results, my interests have turned towards coherent systems, notably their capacities in the presence of nonlinear or linear-but-nonunitary impairments. My contributions in this vein so far are the subject of section 1.2.

1.1 Clock recovery for optical time-domain multiplexing

Publications:
[28, 36–47, 77–79, 82–84, 113, 119–126, 128]

The creed of all-optical functionality research, throughout the 1990s and 2000s, was that electronics were limited to a few tens of GHz and were a bottleneck to increasing symbol rates. Even today, coherent optical systems operate at symbol rates not much higher than 50 GHz.

A vast research effort was therefore directed at opto-electronic or even all-optical signal processing. All sorts of functionalities were designed: wavelength conversion [26, 71]; regeneration [95]; logic gates [97, 98]; dispersion management [52]; and many others.

The ultra-high-symbol-rate signals toward which these functionalities were geared had to be generated using OTDM, whose principle is simply to interleave multiple low-duty-cycle RZ-OOK-modulated signals, that is, OOK-modulated picosecond pulse trains. The devil, as always, is in the details: fine-tuning the optical delays for interleaving, precise dispersion management to prevent or compensate for pulse broadening, and of course demultiplexing. The latter requires some sort of optical gating or sampling, which typically needs an optical clock synchronized to a sub-multiple of the OTDM clock frequency.

Hence the often-overlooked need for clock recovery and sub-clock extraction of ultra-high-speed optical signals, one of my major research axes until about 2010.

1.1.1 Overview of optical clock recovery techniques

The classical method of clock and frequency recovery is the phase-locked loop (PLL), which was originally developed in the 1930s for synchronous-demodulation radio re-

ceivers [14]. This technique is now in widespread use for all kinds of frequency or phase synchronization applications, including clock recovery of high-bit-rate data streams in electrical form, e.g. after a photoreceiver, up to several tens of GS/s [6].

As we shall see in section 1.1.2, the part of the PLL that receives the signal—the phase comparator—can be implemented optically, which allows clock recovery of optical signals without having to convert them. Such an opto-electronic PLL (OEPLL) is especially suited to OTDM signals, whose clock frequency may be beyond photoreceiver bandwidths. Also, OTDM demultiplexing requires extracting a sub-multiple of the clock frequency in order to isolate a single channel from the OTDM stream; OEPLLs are capable of sub-clock recovery.

My research focused on OEPLLs, but other optical clock recovery techniques have been developed in the past. They typically amount to filtering the spectral line at the clock frequency in the optical signal—either passively, using Fabry-Perot (FP) filters, or regeneratively, as with injection-locking of self-pulsating lasers or other oscillating devices.

The main advantage of OEPLLs is sub-clock recovery capability for OTDM demultiplexing. Classical PLLs can do sub-clock recovery as well, but need O-E conversion, which is too slow for OTDM signals. Also, sub-clock recovery has been demonstrated for injection-locking of self-pulsating lasers, although a feedback stage is needed.

On the other hand, filtering techniques shine in lock-in speed: the response time is the propagation time in the filter, typically nanoseconds, whereas PLLs require a rather longer time (tens or hundreds of nanoseconds [67, 74]), precluding their use in asynchronous packet links where the clock must be recovered after a few symbols. Conversely, filters are much less robust to long sequences of 0 (in OOK systems). However, an approach coupling an FP filter with an all-optical regenerator has demonstrated packet-timescale clock recovery and good resistance to 0 sequences [62].

Finally, all these techniques implicitly require that the input signal have a spectral line at its clock frequency. It is the case for OTDM signals, which must be RZ; however, NRZ signals may not include such a line, which must be re-created through some kind of nonlinear device. Classical PLLs are often coupled with an edge detector to this effect. Optical clock recovery schemes that include nonlinear optical devices may also work [126].

1.1.2 Opto-electronic phase-locked loops

PLLs are feedback systems whose principle is illustrated in figure 1.1. The recovered clock is generated by an oscillator whose frequency can be controlled, e.g. a voltage-controlled oscillator (VCO). It is driven by an error signal that stems from the phase difference between the input signal and the recovered clock, measured by a phase comparator and filtered through a loop filter.

When the PLL is locked, the error signal is constant, ensuring that this phase difference is kept constant (or even null, if the loop filter includes an integrator); this is equivalent to having a recovered clock frequency equal to that of the input signal, effecting clock recovery. For sub-clock recovery, frequency multipliers or dividers may be placed at the appropriate inputs of the phase comparator.

In this scheme, the signal is received by the phase comparator; if one is to dispense with the O-E conversion and handle ultrafast optical signals, then the phase comparator should be implemented optically.

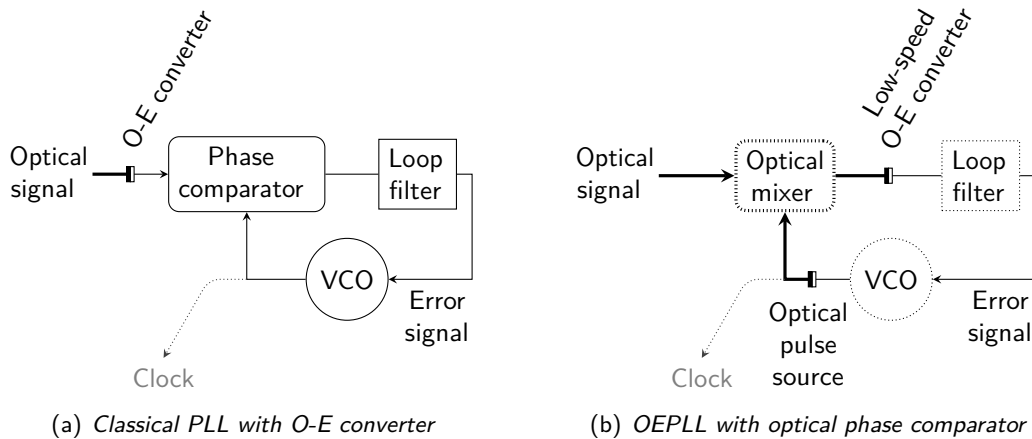


Figure 1.1: Principle of PLL and OEPLL: a phase comparator measures the phase difference between the input signal's modulated envelope and a local oscillator generated by a VCO, itself driven by the (filtered) output of the phase comparator. In the case of the classical PLL, an optical signal must be converted to an electrical one. In an OEPLL, the phase comparator is a mixer operating directly in the optical domain; only its low-speed output requires O-E conversion.

The simplest implementation of the phase difference operation is a low-pass-filtered mixer, which multiplies its inputs. As will be explained in section 1.1.3, this multiplication can be done optically by a nonlinear device; its output is then detected by a low-speed photoreceiver, which simultaneously takes care of the low-pass filtering and the conversion back into the electrical domain.

Such an OEPLL may also be capable of sub-clock recovery as-is, depending on how the clock is generated in the optical domain. If it is a short-pulse source, as in figure 1.1(b), it naturally contains higher-order harmonics of the VCO frequency, acting as a natural frequency multiplier; this results in the VCO frequency being a sub-multiple of the input clock frequency.

The PLL's stability and locking dynamics basically depend on the mathematical transfer function between the phase difference and the VCO output frequency. This transfer function can usually be separated into:

- A steady-state loop gain, which is basically the ratio of VCO frequency shift against phase difference (in units of Hz/rad, or simply Hz): the higher the loop gain, the larger the lock-in range, but the less stable the PLL; an intermediate value optimizes lock-in time.
- A loop propagation time: the shorter this time, the more stable the PLL.
- A normalized filter transfer function: depending on the order of the filter, PLL operation can be simulated or even predicted analytically.

One of my contributions was to adapt this analysis to OEPLLs. The details can be found in [47, 119].

1.1.3 Nonlinear optical devices for OEPLL mixers

Optical nonlinearity is the response of a material to light that is not simply proportional (in a tensor-product sense) to the incoming electrical field. Typically occurring at high power, its most visible results are sum- and difference-frequency generation—in general terms, having interactions occur between different spectral components. This is a major impairment in optical communications, as optical fiber presents nonlinearities—weak, but whose effects accumulate over long-distance propagation. In particular, the third-order nonlinearity known as the Kerr effect results in signal distortion and cross-talk between WDM channels, through self- and cross-phase modulation (SPM and XPM) as well as four-wave mixing (FWM).

Yet nonlinearity is the very kind of process that many all-optical functionalities require, and has been sought or enhanced in various devices:

- Semiconductor optical amplifiers (SOAs) have a strong nonlinear response due to their sub-nanosecond carrier dynamics, which result in a strong dependence of their amplification gain to the input signal's power and temporal evolution, which can be modeled as third-order nonlinearities.
- Highly-nonlinear and photonic-crystal optical fibers (HNLFs and PCFs) rely on doping the fiber glass with nonlinear dopants, or reducing the propagation mode's effective area to increase the optical intensity for a given power in the fiber, enhancing the Kerr effect.
- Periodically-poled lithium niobate (PPLN) leverages a second-order nonlinearity, the Pockels effect, which requires non-centrosymmetrical materials such as lithium niobate. Second-order nonlinearities generally ought to be stronger than third-order effects, but involve widely-separated optical frequencies, which propagate with different refractive indices in the nonlinear material, leading to impractical phase matching constraints. PPLN alleviates these constraints by having crystalline axes periodically reversed along the direction of optical propagation.

How this nonlinearity can perform the phase comparator function is best shown using the example of wave mixing. Figure 1.2 illustrates sum-frequency generation by three-wave mixing (TWM) of two pulse trains with different clock frequencies. The process results in a TWM signal modulated at the frequency difference of the desired harmonics. Other linear combinations are also generated, but are typically outside the bandwidth of either the nonlinear device or the photodetector that receives the TWM signal. The frequency difference is straightforwardly linked to the phase difference, meaning that this type of optical mixer can be used directly in an OEPLL.

Among the possible nonlinear devices listed above, fiber-based nonlinear devices are not well-suited to this functionality, having a long propagation time, hampering OEPLL stability. Discrete devices, such as SOAs and PPLN waveguides, have been successfully used in OEPLLs by myself and others, using FWM or XPM in an SOA, and three-wave mixing (TWM) in PPLN [47, 54, 80]

FWM and TWM are particularly suited to this application, as the generated signal, though weak, is centered at a wavelength different from those of the input signals—as opposed to e.g. XPM—and can be extracted by an optical filter with a good contrast. Even better, TWM being a second-order nonlinear effect, the generated signal is in a completely different waveband: for two input signals around 1550 nm, the result is at

Publications:
[58, 125]

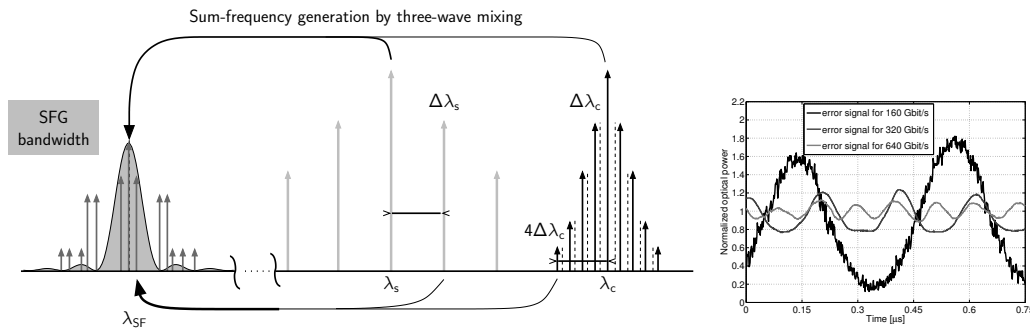


Figure 1.2: *Left: spectrum of two pulse trains S and C , of clock frequencies f_s and f_c and center wavelengths λ_s and λ_c , undergoing three-wave mixing. f_s is approximately $4 \times f_c$. Interaction between S 's first harmonics and C 's fourth harmonics results in the TWM signal at λ_{SF} being modulated at frequency $|f_s - 4f_c|$. This difference frequency is small compared to f_c or f_s , and can be filtered out by a slow photodetector, or even the nonlinear device itself, depending on its bandwidth. Right: experimental results, error signals from phase comparator based on TWM in PPLN, operating on 10-GHz reference and OTDM PRBS signals up to 640 Gbit/s. Adapted from [47, 49]*

775 nm, in the visible-light range; a silicon photodetector can isolate it from the input signals, which are outside its detection bandwidth.

The following therefore focuses on OEPLLs using phase comparators based on FWM in an SOA and TWM in PPLN.

1.1.4 Ultra-high-speed opto-electronic PLL results

Clock recovery using OEPLLs has been one of my major research axes until about 2009: first during my own Ph. D. thesis under Didier Erasme, focusing on SOA-based OEPLLs; then that of [Fausto Gómez Agis](#), centered on PPLN-based ones.

We did not originate the principle of OEPLLs, which were demonstrated in [54, 57, 89], using FWM or cross-gain modulation (XGM) in an SOA and FWM in a dispersion-shifted fiber. They were heterodyne loops, variants of the scheme described above, differing in that the optical mixer operates on the OTDM signal and an optical pulse source not at the recovered clock frequency, but at a frequency shifted by a constant intermediate frequency (IF). The error signal then has a nonzero modulation frequency even when the PLL is locked; an electronic phase comparator compares it to IF to effect clock recovery. Other teams also demonstrated setups of this type [80].

After reproducing Kamatani's setup using FWM in a SOA, we demonstrated two enhancements: first, the heterodyne loop is not necessary for clock recovery, although an optical-based phase comparator's output presents a DC offset that must be dealt with, unlike the heterodyne scheme. We thus demonstrated clock recovery using a simplified setup, doing away with the IF stage [126].

Second, we realized that an SOA-based scheme could perform clock recovery on NRZ-OOK-modulated signals. As noted in section 1.1.1, such signals do not include a spectral line at their clock frequency, which must be re-created by an edge detector or other nonlinear devices prior to clock recovery. As it happens, SOAs are nonlinear, and the error signal resulting from FWM between an NRZ-OOK-modulated input signal and a pulse-train local oscillator does indeed carry the frequency-difference spectral line that makes it a phase comparator. Therefore, the same OEPLL setup works as-is on NRZ

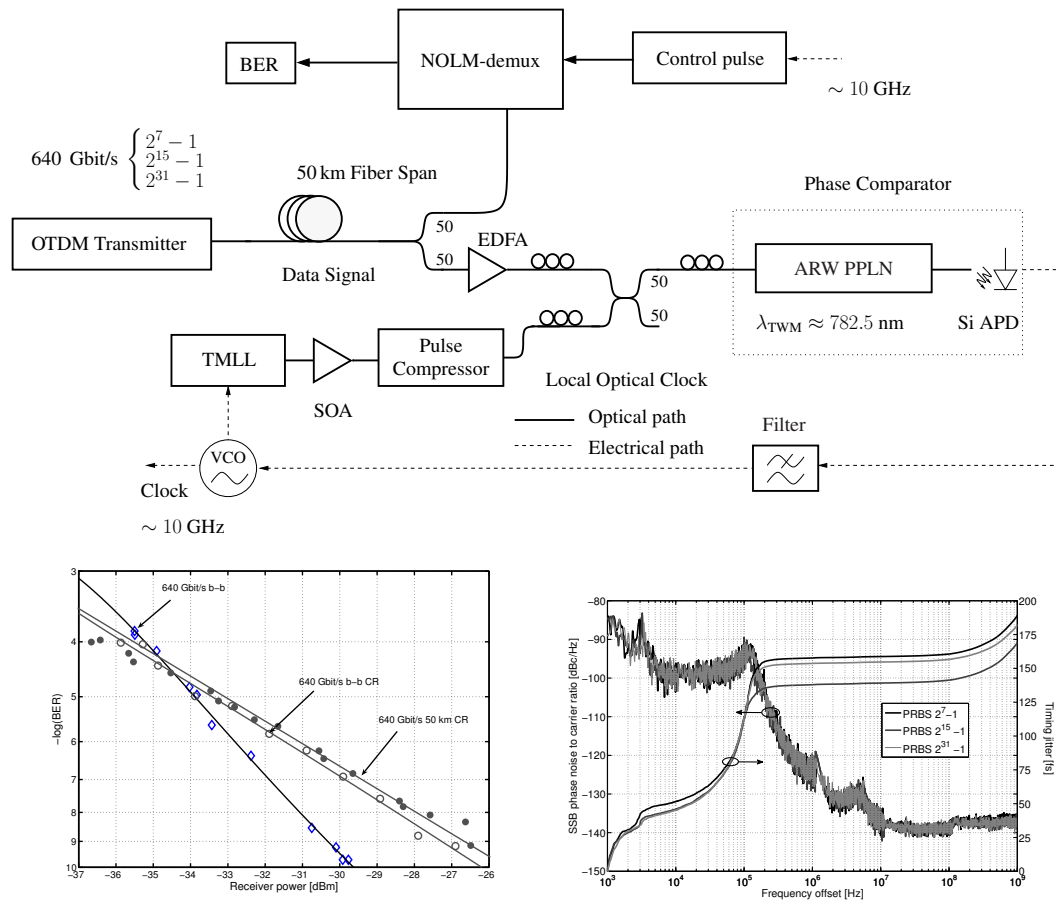


Figure 1.3: Clock recovery and OTDM demultiplexing at 640 Gbit/s. Top: experimental setup. Bottom left: BER performance. Bottom right: jitter performance. Adapted from [49, 78]

signals, albeit with a reduced loop gain [119, 126].

Our experiments were successful at progressively higher clock rates: 10 Gbit/s for RZ and NRZ-OOK, 40 GHz pulse trains; then, switching to TWDM in a PPLN, a collaboration with DTU Fotonik and NIMS through NoE *e-Photon/ONE⁺*, *EURO-FOS*, allowed us to achieve 10-GHz clock extraction from an OTDM RZ-OOK signal at a record 640-Gbit/s: [77] (“Letter of the Month” award), [78] (OFC postdeadline), [79] (JLT invited paper). At the time, this was the highest single-wavelength-bit-rate OTDM transmission including clock recovery; also the highest using a PPLN, and the second-ever at that rate, on the heels of [103] (which used XPM in an SOA).

Further experiments were performed on phase-modulated signals [113, 128] in line with the community’s renewed interest in coherent optical transmissions. From the point of view of (intensity-modulated) error signal generation, the input signal’s modulation format makes little difference beyond a change in the OEPLL’s overall loop gain (e.g. a factor of 2 between OOK and xPSK).

In parallel with brute-force experimental results, we contributed an adaptation of classical PLL theory to OEPLLs [47, 119].

Projects:
e-Photon/ONE⁺,
EURO-FOS

1.1.5 Future of optical clock recovery

In recent years, the community's interest in opto-electronic clock recovery has waned for, as I see it, two major reasons: lock-in time and especially the rebirth of coherent optical transmissions.

On the former, with μs -range lock-in time, OEPLLs are not suited to optical packet or burst switching. It may not be a problem with legacy systems which are circuit-based—or packet-based but still continuously transmit filler data even while idle—but this would hamper the upcoming transition towards truly energy-efficient systems that require “burst-mode” receivers with short wake-up times.

An interesting short-wake-up clock recovery technique was proposed [61] and demonstrated [62]: using a filter coupled with a SOA-based intensity regenerator; lock-in time is only 6 bits at 40 Gbit/s.

However, coherent optical transmissions have been a great leveler on optical functionalities in general: as coherent modulations allow higher bit rates while keeping symbol rates manageable by electronics, there is little interest in ultra-high-speed clock recovery. It might still be required for coherent OTDM; however, it is far from certain that the need will arise for such a combination.

Therefore, for the time being, this research axis of mine waits on the further requirements of future optical transmission systems.

1.2 Coherent optical communications

Publications:
[19–21]

The term “coherent” generally applies to optical communication systems that make use of the phase of the optical signal to encode information. As mentioned above, accessing this phase at the receiver requires mixing the signal with a reference oscillator in an interferometer. Except in relatively simple DPSK schemes, this reference is an independent optical beam, that ideally should be tuned to precisely the same optical carrier frequency as the signal—and therein lies the problem.

This technique was developed as early as the 1980s, but with a goal different from that of current systems: the main impediment to optical transmission at the time was the attenuation of the optical fiber, and coherent receivers have a better sensitivity than bare photoreceivers, both for ideal receivers (as OOK has a 3-dB penalty in signal-to-noise ratio (SNR) compared to BPSK), and noisy receivers (thanks to the amplification inherent to the mixing process, briefly explained in section 1.2.1).

Unfortunately, the tuning requirement was difficult to satisfy. Schemes using optical PLLs or injection-locking were worked on, until EDFAs sidestepped the issue of fiber loss by allowing easy in-line amplification of the transmitted signals.

Further research on coherent transmission was thus essentially postponed until the mid-2000s. The need was then beginning to be felt for higher spectral efficiencies, which PSK modulations could provide, but there still was no practical way to provide a coherent local oscillator at the receiver.

The solution, proposed in 2004, was a paradigm shift [104]: intradyne coherent detection uses an unsynchronized local oscillator, combined with DSP algorithms to track the phase offset between reference and signal. This ingenious technique does away with the tuning requirement and finally enables higher-order PSK modulations, as well as greatly facilitating polarization multiplexing—provided that fast enough DSP hardware is available for real-time signal processing, which it became for 100-Gbit/s systems at

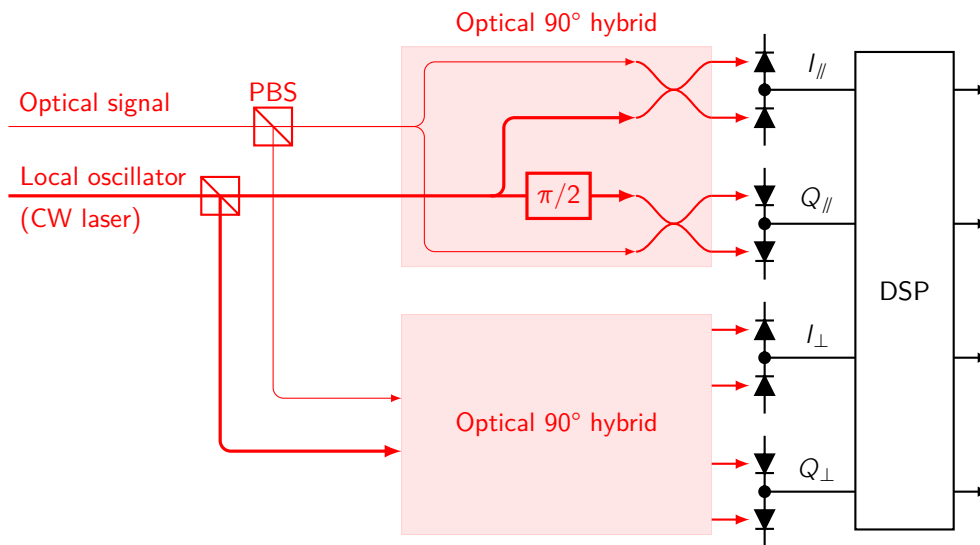


Figure 1.4: *Coherent optical receiver: the incoming optical signal is split into separate polarizations, and each polarization is mixed, through a 90° optical hybrid coupler, with a local oscillator (a continuous-wave laser) whose frequency matches that of the signal’s optical carrier within a few hundred MHz. Each hybrid’s four outputs feed two balanced photodetectors, which yield the in-phase and in-quadrature components of the signal’s complex envelope. DSP then interprets these components to recover the correct phase and polarizations, and thus extract the originally-encoded symbols.*

the very end of the 2000s [4].

Commercial solutions started deployment in late 2009, with the reference modulation format of PolMux-QPSK at 100 Gbit/s (25 GS/s) well adapted to upgrading existing systems: its spectral occupation is comparable to that of NRZ-OOK at 10 Gbit/s, allowing it to fit currently-installed WDM filters and demultiplexers, so as to upgrade WDM systems one channel at a time independently.

1.2.1 Overview of coherent optical communications

Most of the complexity of coherent optical communications is in the receiver, whose principle is shown in figure 1.4. The incoming signal is split along two polarizations; each polarization is made to beat with a local oscillator whose optical frequency is close to that of the signal (within a few hundred MHz), using a 90° optical hybrid coupler; each hybrid’s four outputs yield the intensity-coded in-phase and in-quadrature components (relative to the local oscillator) of the incoming signal, and are detected by balanced photodetectors. The resulting signals, being cross-products of input signal’s and local oscillator’s electrical fields, also feature a built-in amplification in proportion to the local oscillator’s amplitude.

Thus, all information originally present in the signal is recovered. However, it is not encoded straightforwardly at the photodetector outputs, because—unlike the kind of solutions sought in the 1980s—the receiver’s polarization axes and the local oscillator’s frequency are not identical to that of the emitter. The original information symbols are extracted via DSP, depending on the modulation scheme.

In principle, any modulation scheme is possible using this setup. PolMux-QPSK is one

of the most basic: it makes use of the two orthogonal channels that optical polarization constitutes; and on each polarization, data is QPSK-modulated, and it is known in the digital-communications world that QPSK (as well as BPSK) has the best BER-vs-SNR performance on the classical Gaussian channel.

Another interesting modulation “format” is orthogonal frequency-division multiplexing (OFDM). In principle, it is akin to spreading information on multiple frequency channels, narrowly-spaced, with a frequency interval equal to the inverse of the symbol duration, which ensures orthogonality. It can be implemented either directly by modulating the spectral lines of a frequency comb [135] (which relaxes constraints on device speeds but requires many modulators) or by generating an inverse discrete Fourier transform of the data symbols to be transmitted [93] (requiring only a single, albeit fast, modulator).

This powerful technique is the focus of a major research effort in the optical transmission community, as dispersion-type impairments (CD and PMD) materialize as simple phase shifts between channels, easily handled via a linear equalizer in DSP. (An alternate explanation is that, for a given bit rate, spreading information over multiple channels enables the use of longer-duration symbols, which suffer less from dispersion-induced broadening.)

Furthermore, from the moment DSP comes into play, a whole battery of digital communications techniques become available against remaining impairments: not just FEC, but channel equalization, multiple-input-multiple-output (MIMO) using the two polarizations (or even modes in a multimode fiber), and space-time coding.

The two main remaining impairments are, on the one hand, fiber nonlinearity, mostly in the form of Kerr effect; and polarization-dependent loss (PDL) which affects systems that comprise multiple amplified spans, where slight polarization dependencies accumulate at random. These impairments not being common in RF systems, no ready-made digital communications techniques are at hand against them.

This situation fosters a rich research field in digital and optical communications both: for the former, a new type of channel with specific problems, with processing techniques limited by computing power at high symbol and bit rates; for the latter, a new way of designing systems, more mindful of fundamental limits rather than empirical ones, with criteria such as back-to-back performance at a given optical SNR (OSNR) to be replaced by the Shannon mutual-information capacity at a given SNR expressed in energy per bit and quantum noise.

1.2.2 Capacity of the coherent optical channel

As mentioned above, the yardstick against which transmission performance is measured is the Shannon capacity. It can be expressed equivalently in terms of mutual information between emitter or receiver, or maximal data rate that can be transmitted without error, or at a given error probability.

While the conventional optical channel with a plain photoreceiver has a capacity somewhat difficult to calculate, the ideal, linear coherent optical channel is well-modeled by the classical additive-white-Gaussian-noise (AWGN) channel. Dispersive effects (CD and PMD) are non-issues with respect to the capacity, as in theory they can be exactly compensated for via a matched filter.

Unfortunately, this rosy picture is marred by two major physical impairments: optical nonlinearities in fibers, notably the Kerr effect; and PDL in multi-span systems, which is

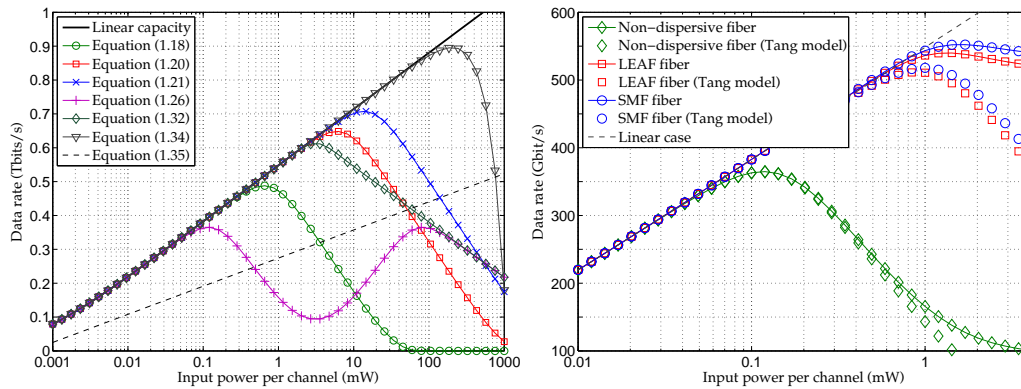


Figure 1.5: Capacity of a nonlinear optical fiber according to several models. Left: capacity per 50-GHz channel over 80 km propagation, according to models described in the literature (equation numbers from [25]: 1.18 [72]; 1.20 [53]; 1.21 [86]; 1.26 [101]; 1.32 [102]; 1.34 [76]; 1.35 [116]). Right: same with corrections to [102].

a linear effect but is not unitary, thus affects the capacity.

1.2.3 Impact of nonlinear effects

While section 1.1.3 showed that nonlinear effects can be exploited to perform interesting functions, they remain very much of a nuisance in optical transmission systems, especially at high optical powers over long distances: although increasing power improves SNR, nonlinear distortion and crosstalk also increase, leading to an optimum optical power beyond which system performance degrades. Worse, both numerical estimations [29] and theoretical or phenomenological models [53, 72, 76, 86, 101, 102] suggest that the capacity itself decreases above a certain power level, as shown in figure 1.5 (left); this is doubtful, however, and probably reflects particularities of transmission technologies rather than a true information-theoretical limitation. Indeed, [116] proposes a lower bound on capacity (dashed line in figure 1.5) that does increase with power and contradict the results of most models—although this typically occurs at such high powers that the models used of nonlinear effects would break down, if not the fiber itself, anyway.

Using the model in [102], which best seemed to take into account the relevant nonlinear phenomena, my Ph. D. student [Pierre Delesques](#) studied the capacity of a WDM transmission system, specifically to determine the influence of guard bands between channels; spacing out the channels has to be a waste of spectral bandwidth, but reduces the impact of nonlinearities on individual channels' performance.

First, we found out that [102] had omitted a term in the calculation, which led, in practice, to slightly underestimating the capacity and optimal power, as shown in figure 1.5 (right). A corrected result is given in [19, 25].

This was used to answer the question: from a capacity standpoint, overall, a guard band is no help. As shown in figure 1.6, the reduction in nonlinear effects does result in a per-channel capacity increase, but no more than a few percent, even in the case of nondispersive fiber where nonlinearities have the strongest impact. This does not compensate for the loss of spectral efficiency that wasted spectrum entails.

Ph. D. thesis:
[Pierre Delesques](#)

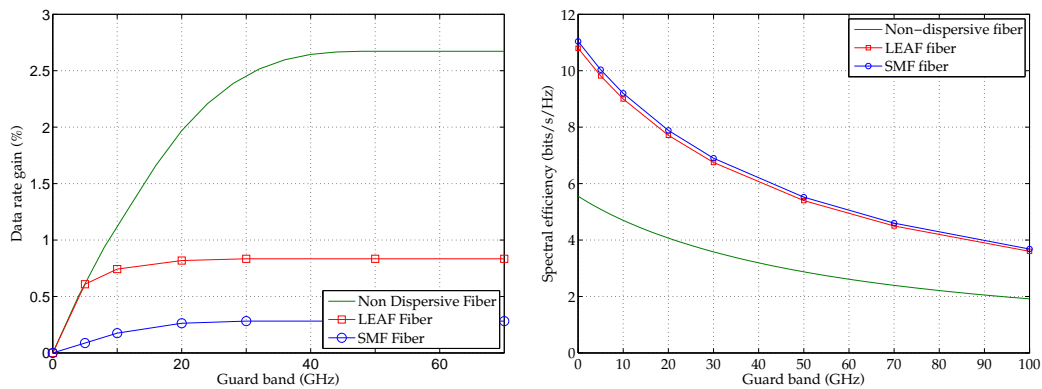


Figure 1.6: Influence of the guard band between WDM channels. Left: per-channel capacity gain. Right: overall spectral efficiency. Adapted from [19, 25].

1.2.4 Impact of polarization-dependent loss

The other major physical impairment apart from nonlinearities is PDL. It arises from the accumulation of small polarization dependencies of various elements in an optical transmission system: amplifiers, connectors, etc. In addition to the birefringence of each element, which leads to PMD, the attenuation also depends slightly on polarization.

If polarization were maintained along the transmission, PDL would simply result in different attenuations on the principal polarization axes of the system, which could then be used as two separate channels albeit with different SNRs at the receiver. Of course, polarization is not controlled in most optical transmission systems. PDL is thus subject to random variations, and must be modeled statistically.

The tool of choice to explore the fundamental limits of such a system, where the capacity varies randomly, is the *outage probability*, defined as the probability that the instantaneous capacity is below a given transmission rate—meaning the probability that the system cannot sustain this rate for one realization of the PDL [114]. By construction, the outage probability is a lower bound of the BER.

The second part of [Pierre Delesques](#)' Ph. D. studies this issue. Closed-form expressions of the outage probability were calculated for several statistical PDL models used in the literature, and compared to a carefully-set-up numerical phenomenological model. This allowed us to confirm that the most realistic statistical model is the “ Γ -Maxwellian” one, where the *logarithmic* value of the PDL (expressed in dB) follows a Maxwellian distribution.

In the course of this study, we also determined an interesting property of PDL-limited systems: the SNR penalty, for a given outage probability, between the presence and absence of PDL, has a simple upper bound whose value: $\frac{1}{2} \frac{2^R - 1}{\sqrt{2^R - 1}}$, surprisingly depends only on the spectral efficiency R in bit/s/Hz, for any PDL and outage probability values. It could serve as a useful criterion for systems designers.

Then, using this outage probability as a reference, we studied numerically the performance of an OFDM transmission system using powerful FEC: a concatenation of a low-density parity-check (LDPC) code with soft decoding, which in the case of the AWGN channel offers performance very close to the Shannon capacity; and polarization-time (PT) codes, adapted from space-time codes in the RF world, which interleave symbols

Ph. D. thesis:
[Pierre Delesques](#)

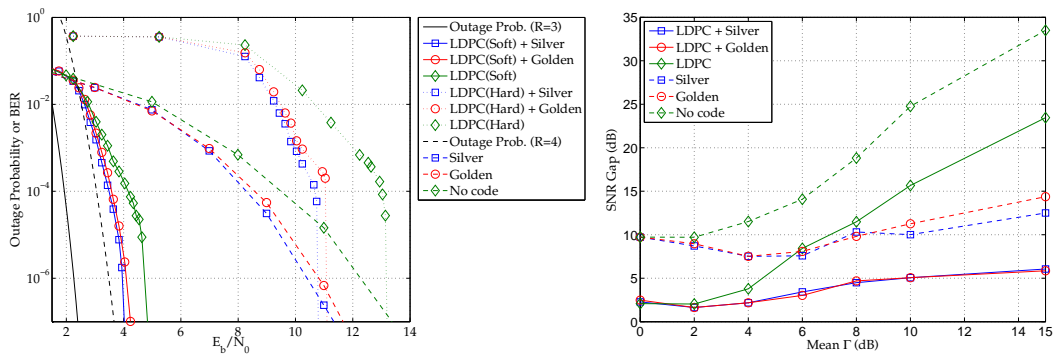


Figure 1.7: Simulated system performance against outage probability in the presence of PDL. Left: BER with $\Gamma = 3$ dB of PDL. Right: SNR gap at $P_{\text{outage}} = \text{BER} = 10^{-7}$ between fundamental limit and Monte-Carlo simulated transmissions, as a function of PDL value Γ . Adapted from [25].

over both polarizations and time slots.

We found that this simulated transmission system performs within less than 2 dB of the fundamental limit given by the outage probability in the presence of reasonable PDL values, around 2–3 dB; and remains within 5 dB up to a high PDL value of 10 dB, as shown in figure 1.7 (adapted from [25]). Interestingly, although at low PDL values PT codes bring little improvement, the LDPC code alone breaks down when PDL worsens; there, at high PDL values, PT codes work very well with the LDPC.

1.2.5 Further research on high-capacity systems

The results above on transmissions with PDL seem to indicate that linear impairments are basically solved problems: DSP can compensate for CD and PMD, and there is only a few-dB improvement to be gained to reach the fundamental limits imposed by PDL. The latter, however, requires high-cost LDPC FEC; some work could still be done on improving PT codes, so that the same performances might be reached with less computationally-intensive codes.

The remaining major impairment for coherent optical transmissions is the Kerr effect. Since it is specific to optics, and nonlinearities are rare in the RF world, no pre-existing compensation technique can be lifted from earlier work. It may even be impossible, if the Shannon capacity indeed peaks as several aforementioned studies indicate; however, all the existing models do not agree about this, and must thus be reconciled through a fuller analysis. Perhaps, considering that sine waves are not eigenmodes of nonlinear propagation, reasoning on something other than the spectrum could yield significant insights.

In the meantime, the world of research on high-speed transmissions is abuzz with space-division multiplexing (SDM): multicore and/or multimode optical fibers, using multiple-input-multiple-output (MIMO) DSP techniques to handle crosstalk, are a way to increase the capacity per fiber equivalently to multiple fibers in parallel.

Multicore fibers are becoming practical [99], especially now that multicore EDFAs have been developed. However, I do not believe that they have significant advantages over simply running parallel fibers; the exception could be in situations where space is cramped: data centers, and possibly submarine cables.

Conversely, a return to multimode optical fiber probably would help reduce the

impact of nonlinearities at a given power by having larger mode areas. Alas, the optical engineering technology to inject into and separate out different propagation modes is a much more challenging proposition. Nevertheless, few-mode transmissions are being demonstrated [51, 96]; in the end, it may prove easier than nonlinearity mitigation.

Future works

As shown above, the future of ultrahigh-bit-rate systems seems to lie in coherent optical transmissions, and the effort is now on fighting nonlinearity to increase the capacity: either through nonlinearity mitigation if information theory allows it, or thanks to SDM if not.

The same coherent transmission techniques have largely reduced the perceived need for optical functionalities that were aimed at enabling higher symbol rates, which are no longer required. The OEPLL I worked on already works with phase-modulated signals [113]; some work continues on other functionalities, against the possibility of a future interest in coherent-with-OTDM systems [59, 136], to make them at least phase-preserving [118]—or, better, phase-processing.

In the latter vein, considerable interest has come from phase-sensitive amplification enabling PSK regeneration [12, 27, 81]. Current implementations, however, require to tap some of the signal to inject-lock an optical pump, which must entail some SNR degradation. I believe that the actual overall benefit should be evaluated from a noise-factor point of view on quantum-noise-limited signals.

Nevertheless, even before the rebirth of coherent transmissions, optical functionalities in general had had little success in being deployed in real-world conditions, and no new reason has come up why this should change. I have come to believe that there is a fundamental mismatch between optical functionalities and the current network paradigm. More thoughts on the subject are given in section 3.3; basically, for its full potential to be exploited, optics must fulfil needs beyond the physical layer, which is exceedingly hard in a conventionally-layered network.

In the meanwhile, optics can still break through in specific areas. One of them is access networks, and my work on this topic is outlined in the next chapter.

Chapter 2

Optical access networks

While the previous chapter focused on driving data through a single optical link, the part of the network that actually reaches the end-users—the *access network*—has specific requirements; the numerous users in a global network are typically parceled out in few-user groups covering a small area localized around a central office (CO). The throughput and distance requirements are thus proportionately lower, the focus shifting towards low cost.

In this context, the technology is driven by the needs of two different actors: the end-users and the carriers. The carriers seek to exploit the longer range of fiber-optic systems to widen the areas covered by COs, thus reduce their numbers and the associated costs. The end-users, on the other hand, wish to use bandwidth-hungry services (notably video streaming and cloud storage, which may not fit a poor DSL line) in an increasingly mobile context.

This results in the deployment of optical systems in two ways: fiber-to-the-*{home, premises, curb...}* (FTTx) to bring them closer to the end-users; and radio over fiber (RoF) to improve cost and throughput of large-scale wireless data networks.

For FTTx, two approaches are being deployed: point-to-point (one fiber per user, flexible but requiring many fibers and especially many data ports on network equipments and passive optical networks (PONs), which share up to 40 Gbit/s on a single fiber reaching different users through passive power dividers. The main problem with PONs is the loss of optical power due to the high splitting ratio needed to reach many users.

The technology used naturally benefits from advances in core and metropolitan networks, but the focus on cost changes its typical use. For instance, until recently, PONs used different wavelengths to separate different functions rather than maximizing data rate as in WDM transmission systems.

Nevertheless, several upgrade paths have been or are being envisioned for currently-deployed PONs: WDM, Code-division multiple access (CDMA), and coherent optical transmissions.

WDM is quick to come to mind to increase PONs' available bandwidth, in the same way as point-to-point fiber transmissions in the 1990s. However, sharing multiple wavelengths among different users is not a simple problem, especially if equipment installed at the users' premises is wavelength-dependent. This hardware should ideally be "colorless" (able to work at any required wavelength) but this may entail too high a cost.

CDMA has been studied as an alternate way to share bandwidth, much as it is done in certain cell-phone RF networks, among more users than WDM alone [31]. It was envisioned especially as this multiple access technique is asynchronous; encoding and decoding could be performed all-optically, hence the name of Optical CDMA (OCDMA); and it provides some measure of security against eavesdroppers, though not as much as conventional cryptography [92].

OCDMA does have a cost in spectral efficiency. Also, many coding schemes require

broadband sources, either coherent (short-pulsed lasers) or incoherent (based on amplified spontaneous emission (ASE)), coherent having better performance [55] but a higher cost. Additional weaknesses include vulnerability to chromatic dispersion, which follows from the broader spectrum; and higher complexity, especially the difficulty of pairing all-optical encoders and decoders.

Finally, the rise of coherent optical transmissions in core networks may percolate into optical access. Of most notable interest are its easy handling of chromatic dispersion; as well as the use of the multiple subcarriers in OFDM for easy aggregation of low-bit-rate data streams. However, the much higher cost of coherent detection still keeps it out of range of realistic access networks. Solutions are being studied to reap some of the benefits of coherent modulation formats while staying compatible with direct intensity detection, such as DD-OFDM.

My notable contributions I made two separate contributions to optical access network research. First, I demonstrated a continuum wide-band optical source that can be shared among users in a WDM-OCDMA setup; the OCDMA was performed all-optically via fiber Bragg gratings, with an eye on using phase-modulated codes, which promised a much better performance than conventional intensity-modulated codes.

Second, I supervised work on reflective semiconductor optical amplifiers (RSOAs) designed for use as optical modulators. These devices set the state of the art in modulation bandwidth (enabling high bit rates), low chirp (enabling extended uncompensated-transmission range), and linearity (enabling RoF applications).

2.1 Spectral slicing for OCDMA

Along with my [SUPERCODE](#) project partners and my Ph. D. student [Steevy Cordette](#), I explored the idea of sharing, among users of an access network, a centralized optical source with a broad enough spectrum that could fulfill the needs of WDM and certain families of OCDMA.

Figure 2.1 illustrates the envisioned network architecture: a pulsed supercontinuum (SC) optical source is hosted in the CO. It is split into multiple spectral bands, then further subdivided into as many pulse trains as users. Each pulse train is OOK-modulated with a user's data, then the remaining pulses are OCDMA-encoded as per section 2.1.1. All these signals are then recombined and sent, undifferentiated, to all users' optical network units (ONUs), where a decoder yields only this user's signal.

This only covers the downlink direction, though light coming from the CO could then be remodulated (see section 2.2).

2.1.1 CDMA and optical CDMA

The basic principle of CDMA is allowing the use of a single communication channel by multiple data streams, using multiple variants of a modulation scheme depending on "codes", each separate stream using a different code among a code family. Ideally, at the receiver, each stream can be isolated from the others without penalty, that is, is orthogonal to the other streams.

For instance, Walsh-Hadamard (WH) codes can be obtained by multiplying each symbol timeslot of an NRZ signal by a line of an Hadamard matrix, as shown in figure 2.2.

Project:
[SUPERCODE](#)
Ph. D. thesis:
[Steevy Cordette](#)
Publications:
[10, 11, 32–
35, 127, 129]

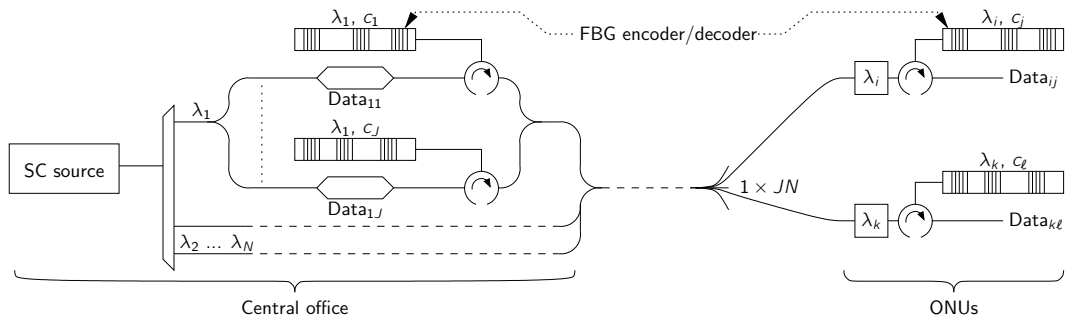


Figure 2.1: Proposed architecture for WDM/OCDMA transmission system (downlink) using a centrally-shared, spectrally-sliced SC light source. Each slice is further split by passive couplers, modulated with a user's data, and encoded. The OCDMA encoders (resp. decoders) are S-FBGs, which split or scramble (resp. recombine) each SC pulse into a coded signal.

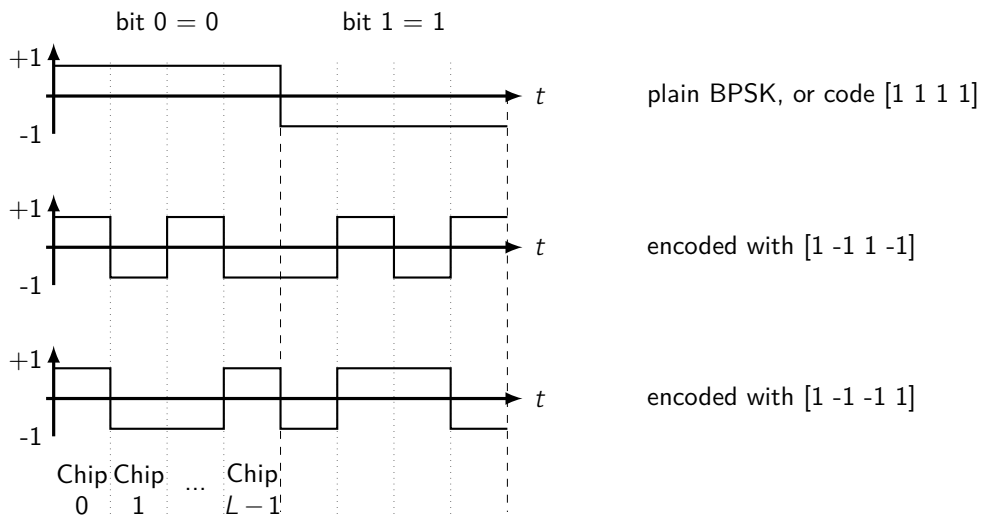


Figure 2.2: Principle of CDMA encoding in the time domain with 4-chip-long Walsh-Hadamard codes: a 2-bit sequence $[0\ 1]$ is shown encoded in plain BPSK (with 0 coded as +1, and 1 coded as -1); with a WH sequence $[1\ -1\ 1\ -1]$ (line 2 of matrix WH_4); and with a WH sequence $[1\ -1\ -1\ 1]$ (line 4 of matrix WH_4). These 3 signals are orthogonal.

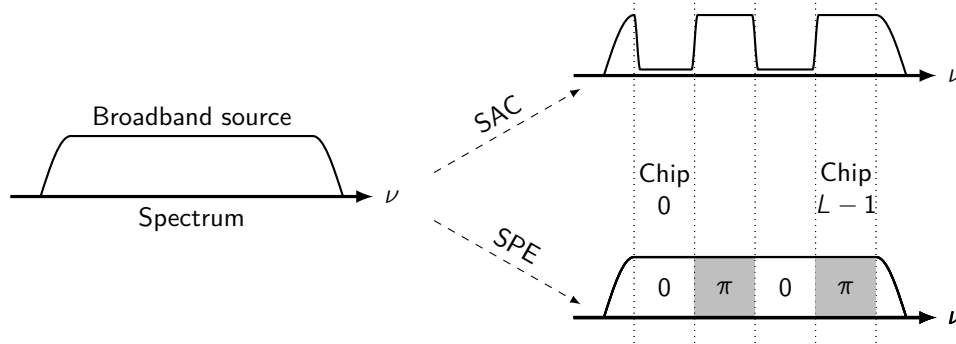


Figure 2.3: Principle of CDMA encoding in the spectral domain: a broadband signal is encoded by altering selected slices of its spectrum, in amplitude for SAC, in phase for SPE.

At the receiver, the same code is applied, re-creating the original signal, which is integrated over each timeslot before effecting a threshold decision to extract the bits. If additional signals encoded with another code are received at the same time, the multiplication by ± 1 yields a signal whose average over the timeslot is 0, eliminating these additional signals' influence over the decision.

Thus, signals encoded with different WH codes are orthogonal to each other—as long as bit timeslots are synchronous between users. Other codes also ensure orthogonality or quasi-orthogonality for asynchronous users. Encoding can also be performed in the spectral domain, as shown in figure 2.3. In spectral amplitude or phase coding (SAC [56] or SPE [90, 91]), chips are materialized by slices of the signal spectrum, which are altered according to the code: SAC carves out the power in some slices, SPE phase-shifts them. 2D coding combines both time and frequency domain, greatly improving possible throughput [30, 90].

Adapting this RF technique to optical transmissions runs into the usual problem: detecting the phase of an optical wave is difficult and, for the time being, prohibitively expensive in an access network context. Worse, the beat noise resulting from quadratic detection is exacerbated by the presence of multiple users [31], making OCDMA especially vulnerable to multiple-access interference (MAI). Additionally, transmitting many chips per bit proportionally increases the required bandwidth for a given bit rate, driving up system costs, lowering spectral efficiency, and increasing the impact of chromatic dispersion.

OCDMA coding thus has two options: first, forgo the phase altogether, working with the intensity only. Codes then couldn't be truly orthogonal, but quasi-orthogonal codes have been developed so as to minimize auto- and inter-correlation between different codes of a family. For example, prime codes (PC) or (extended-)quadratic-congruent codes (EQC) have mostly 0 chips and a few 1s, and different codes have different intervals between 1s so as to minimize intercorrelations. The bandwidth problem may be solved by generating chips all-optically: for instance, starting from a low-duty-cycle RZ-OOK modulation (a modulated pulse train), it is easy in principle to create a pulse sequence for each bit using passive splitters or fiber Bragg gratings (FBGs). Such coding formats are called “direct-sequence” optical CDMA (DS-OCDMA), and can be compatible with direct intensity detection if the pulse sequence is unipolar.

Second, it is easier to manipulate the signal's spectrum all-optically, including in phase, using optical filters, gratings, or again FBGs. Notably, specially-designed super-

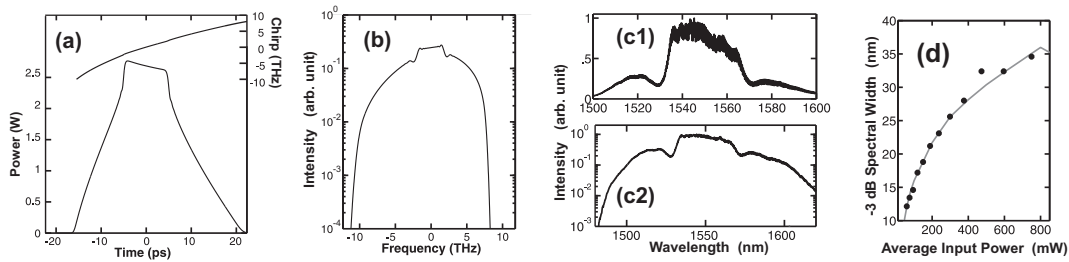


Figure 2.4: Simulated and experimental SC pulses at the output of the HNLF. (a) Simulated power and chirp in the time domain. (b) Simulated spectrum. (c) Experimental spectrum, linear and log scale. (d) Spectral width evolution, simulated (solid line) and measured (dots). Adapted from [127].

structured FBGs (SSFBGs) with a chirped index modulation can stretch short, broad-spectrum pulses and inject a controlled phase offset on each spectral slice, stretching and distorting the pulse. Two such encodings with different phase shifts are much closer to orthogonal than with DS-OCDMA: the pulse will be reconstructed only with the right phase shifts, especially in terms of peak power.

Thus **SUPERCODE** made the choice to explore OCDMA using FBG encoders and decoders, with DS and SPE codes.

Project:
SUPERCODE

2.1.2 Continuum generation

The applications we were aiming for, spectral slicing and SPE-OCDMA encoding, require a fairly broadband source; we aimed to cover the C band. Additionally, given the performance advantage and in order to enable SPE codes, we required a coherent signal, precluding the use of an ASE source.

Broadband signals can be generated by spectral broadening resulting from nonlinear effects such as those described in section 1.1.3, in our case mostly SPM in an HNLF; FWM and Raman effects would come into play for multiple-100-nm-wide supercontinua.

In order to be suitable for WDM channel carving, the source should have a flat spectrum over the desired spectral band; in addition, the resulting pulses should have a low amplitude noise, both within each pulse and for relative variations from pulse to pulse [5].

2.1.3 Demonstration results

Figure 2.4 shows the characteristics of the continuum obtained by propagating a 10-GHz, 30-dBm-average-power, 1-picosecond pulse train through a 500-m long HNLF. There is a good agreement between our partners' simulations and our joint measurements, both in the shape of the spectrum and the evolution of its width as a function of the average power at the input of the HNLF. The generated continuum's power spectral density is fairly flat over the C band (less than 3 dB of fluctuation), making it well-suited to carving out WDM channels, as shown in figure 2.6.

We tested transmission of 3 DS-OCDMA channels sharing the same wavelength, using the setup described figure 2.5. Figure 2.8 shows oscilloscope traces of the decoded signal with and without interferers (low-pass-filtered to 30 GHz due to hardware limitations). Amplitude noise levels on the pulses seem acceptable, given that the single-user eye is well open. However, MAI is definitely a problem, as confirmed by BER performance

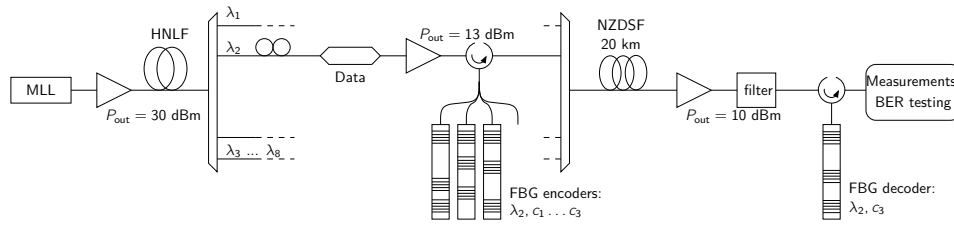


Figure 2.5: WDM/DS-OCDMA transmission setup using a sliced continuum source.

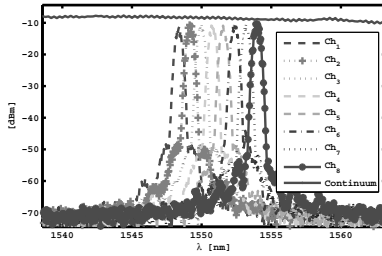


Figure 2.6: Continuum spectral slicing.

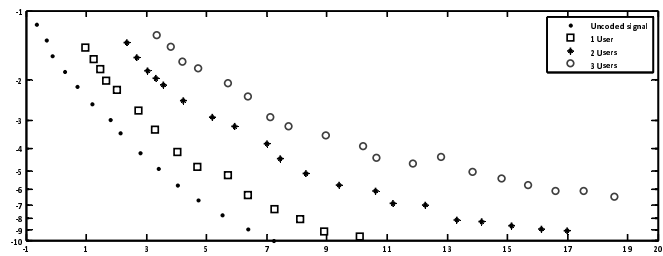


Figure 2.7: DS-OCDMA transmission: $\log_{10}(\text{BER})$ vs OSNR (dB).

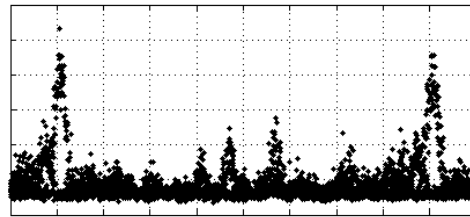
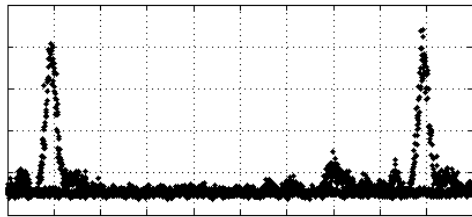


Figure 2.8: DS-OCDMA signal after decoding (X-axis: 200 ps/div; Y-axis: a.u.). (left): single user; (right): 3 users.

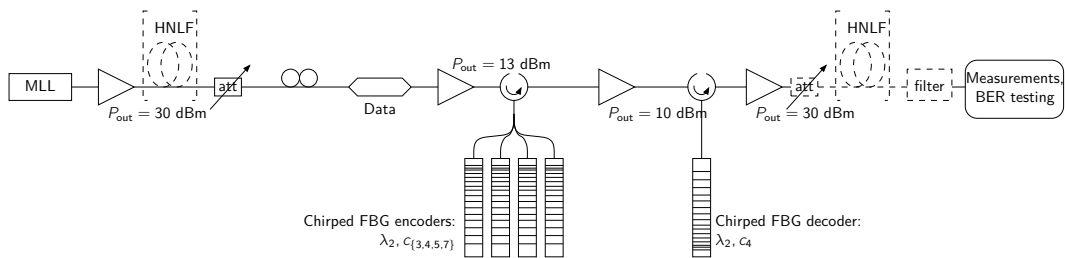


Figure 2.9: SPE-OCDMA setup: with or without continuum generation; with or without nonlinear thresholder.

shown figure 2.7: several-dB penalties for adding each user, and an error floor at about 10^{-6} with as few as 3 users. This is not particularly surprising, with a fairly short-length unipolar code; thus, we had better hopes in SPE-OCDMA.

Using the setup shown in figure 2.9, we tested transmission of 4 SPE-OCDMA channels sharing the same wavelength. At first glance on the oscilloscope traces on the left-hand side of figure 2.10, MAI looks worse than with DS-OCDMA. This is due to the fact that, although SPE does stretch the original pulse from less than a picosecond to several tens of picosecond (see figure 2.11), that doesn't make much of a difference to a

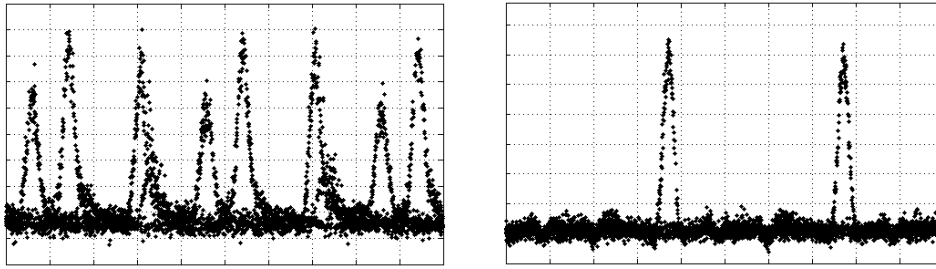


Figure 2.10: *SPE-OCDMA signal. (X-axis: 200 ps/div; Y-axis: a.u.). (left): decoding only; (right): with thresholder*

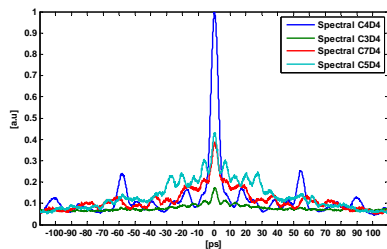


Figure 2.11: *Autocorrelation after matched (C4D4) and mismatched decoding.*

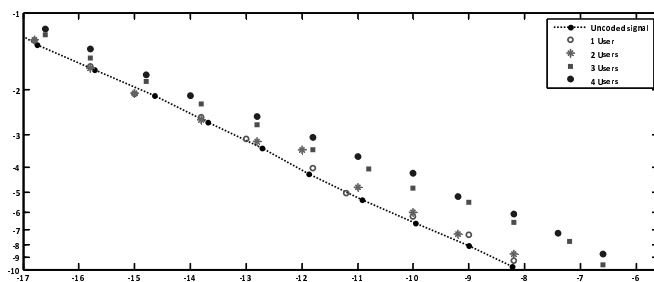


Figure 2.12: *SPE-OCDMA transmission: $\log_{10}(\text{BER})$ vs OSNR (dB).*

photoreceiver whose bandwidth is necessarily limited to a few tens of GHz at most.

Therefore, MAI must be eliminated directly in the optical domain, which can be performed using a Mamyshev-type all-optical threshold detector [70]. The right-hand side of figure 2.10 shows virtual elimination of MAI, and the BER performance shown in figure 2.12 are quite decent, with less than 2 dB penalty over the uncoded signal.

However, this system requires a high peak power at the receiver, which means keeping the pulse very short over transmission. It is thus extremely vulnerable to chromatic dispersion. We did not succeed in transmitting over a significant length of fiber, which would require a significant redesign of the experiment.

2.1.4 Future of optical CDMA

Our SPE-OCDMA demonstration was successful in that we realized data transmission of multiple users over the same channel, using a source that could potentially serve the entire C band. However, this setup remains highly vulnerable to chromatic dispersion, and the requirement of all-optical thresholding also contributes to make it rather impractical.

Since then, the asynchronousness advantage did not retain the market's interest; current and near-term PON solutions are resolutely TDM or TDM-WDM. Given the complexity of OCDMA and its yet-unsolved drawbacks, research in access networks has chosen other directions, notably OFDM [13]; OCDMA contributions to major conferences has sharply declined after 2011 or so.

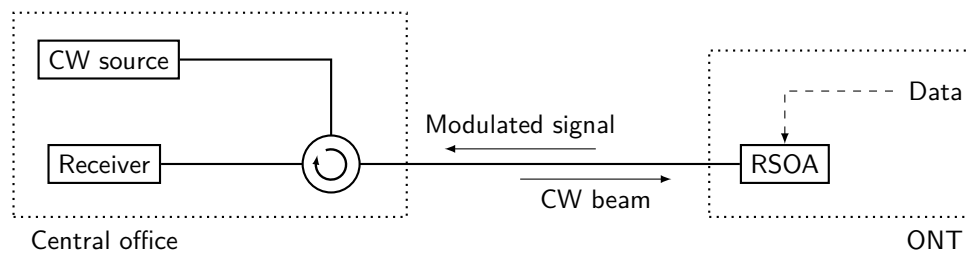


Figure 2.13: Principle of an RSOA-based colorless link.

2.2 Semiconductor optical amplifiers for access networks

Being interested in SOAs and seeking new applications and fields, I served as the academic advisor for [Guilhem de Valicourt](#)'s Ph. D. thesis, on the use of RSOAs specifically for access networks. This highly successful work, which mostly took place within III-V Lab under Romain Brenot, set the state of the art for RSOAs in optical communication systems. Guilhem de Valicourt won the Paul Baran Young Scholars Award from the prestigious Marconi Society.

Ph. D. thesis:
[Guilhem de Valicourt](#)

Publications:
[\[16, 17\]](#)

Although SOAs are well-known devices with a long history of being used for novel optical functionalities, access networks are not a traditional field for such nonconventional approaches, due to their focus on low costs. However, SOAs can help next-generation PONs fulfill one specific need: that of operating at multiple wavelengths.

Indeed, as mentioned at the beginning of this chapter, the more attractive WDM becomes as a solution to increase capacity, the more acute the need for colorless equipment. Specifically, optical network terminals (ONTs) require an optical source to emit signals; if they are to operate in a WDM network, said source must be able to generate a signal at the individual wavelength assigned to the ONT's user, without having to worry about providing specific ONT models to specific users.

The best-performing devices for this job would be tunable lasers, but they don't satisfy the low-cost, mass-production requirement. Other techniques revolve around having the optical wave generated at the CO and sent to and somehow reused or remodulated by the ONT.

RSOAs are promising devices for this application: as shown in figure 2.13, they can receive and reamplify the continuous-wave beam from the CO, and simultaneously modulate it using variations of their bias current. Compared to other candidates, RSOAs seem to be good compromises, with a large optical bandwidth (much wider than the C band), a high gain (unlike reflective electroabsorption modulators) and a low polarization dependency (unlike injection-locked lasers).

Conversely, their weak points were a limited electrical bandwidth (on the order of 1 GHz); a tendency to generate chirped signals (incurring a vulnerability to chromatic dispersion); and a poor linearity (which SOAs were sought for in the context of optical functionalities). The work thus focused on designing and fabricating RSOAs with improved performances on those points.

Notable results

On all three objectives, a variety of new RSOA devices enabled significant advances using different design choices, especially in terms of device length, number of sections,

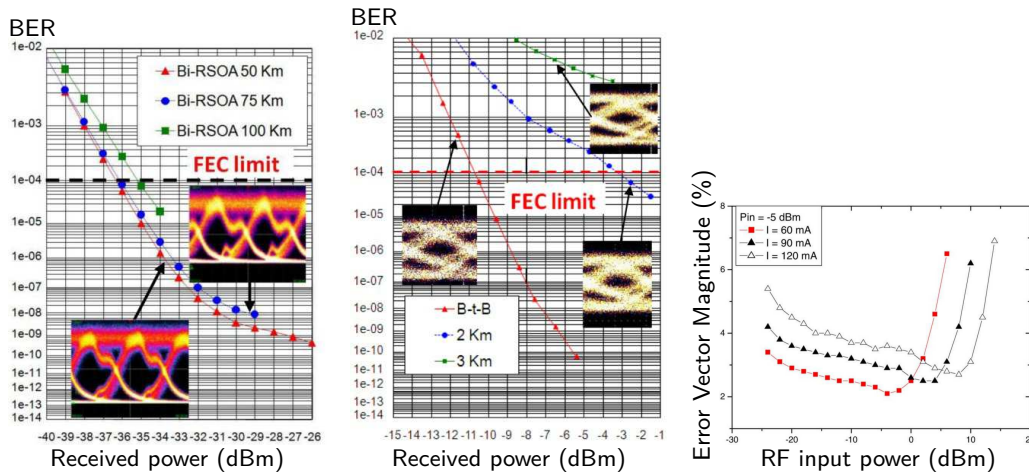


Figure 2.14: Sample transmission results obtained with modulated RSOAs. Left: BER and eye diagrams at 2.5 Gbit/s after 50, 75 and 100 km using a bi-electrode, 500- μm -long RSOA (published in [15]). Center: BER and eye diagrams at 10 Gbit/s in back-to-back and few-km configurations using a single-electrode, 850- μm -long RSOA (published in [18]). Right: linearity measurement transmitting a 54 Mbit/s Wi-Fi RF signal over a 20-km fiber using a single-electrode, 700- μm -long RSOA (published in [16]).

confinement factor, and facet tilt.

Optical transmissions were demonstrated at 2.5 Gbit/s over 100 km [15], and at 10 Gbit/s over a few km [18], both a factor of 2 over the previous state of the art in distance and bit rate. Additionally, RSOAs were tested in RoF configuration, with minimal impact on the RF signal transmitted [16], denoting a good linearity in the chosen regimes.

This generation of RSOAs has had a significant impact on PON research. It hasn't yet made a dent on the market of access networks, which has only just standardized the use of WDM to boost the data rate, and requires rock-bottom component costs—which RSOAs won't satisfy until they become mass-produced, a classic chicken-and-egg problem. Nevertheless, the solution and know-how remain available until such time, probably short, as the increasing capacity demand pushes colorless ONTs into the mainstream.

Future works

RSOAs in access networks are taking an interesting direction: colorless self-seeded sources for WDM-PONs [132]. There, assuming that different groups of users are served by different wavelengths separated by a WDM demultiplexer between the CO and ONTs, said ONTs can generate optical signals at the right wavelength without needing any external laser: by placing a Faraday rotating mirror [87] on the CO side of the WDM demultiplexer, a several-km-long optical cavity is established between each active ONT and the demultiplexer, at a wavelength selected by the demultiplexer port.

A thorough experimental investigation of this technique is given in [133], including observation of a recurrent redshift of the resulting wavelength when using flat-top WDM filters in the demultiplexer. This is an interesting phenomenon, for a solution that receives strong interest from the industry, and could perhaps benefit from more in-depth

theoretical analysis of those very-long-cavity lasers.

On a broader scope, access networks also suffer from the energy consumption problem endemic to data networks, mentioned in section 3.3. I have participated in initiatives such as the CIAN project [1] aimed at, among others, rethinking access and aggregation networks to make them more transparent, leading to drastic energy savings.

However, I am still hedging my bets on this point: the aggregation network seems like a good place to keep using electronics for what electronics does best: queuing and routing, and especially format conversion. Indeed, it seems unlikely that access network ONTs will work with the same high-performance, high-spectral efficiency modulation formats suited in ultra-long-haul optical links; the cost and performance requirements are literally worlds apart. And as long as O-E conversions are used there, a smart network architecture could concentrate the most complex switching functions at these points of the global network, in moderate-capacity electronic switches.

Still, there may come a time when all-optical format conversion and regeneration functionalities become practical, probably under the control of some SDN paradigm, enabling truly all-optical integration between core and access networks.

Chapter 3

Optical switching

Although optics and optical fiber have become the main physical medium for ultra-high-bit-rate transmission, mere point-to-point transmission does not a network make: traffic must be conveyed all the way to its specific destination among many network nodes. Moreover, virtually all traffic since these past few years has been transported as data packets, mostly over the Internet Protocol (IP). Each IP packet has its own destination address and must be routed independently.

While this allows an excellent flexibility of the network, the routing function cannot currently be performed in the optical domain. All traffic, over a great many channels per fiber, must be demultiplexed, converted to electrical data, and processed separately by electronic routers before being re-converted to optical signals along the next hop in their path. IP is of course adapted to this massively-parallel processing; but this multiplication of hardware and optical-electrical-optical (O-E-O) conversions is proving costly, especially energy-wise.

Until recently, energy considerations were not a major concern in communications networks, except for mobile devices with a limited battery life. Over the years, however, the exponential traffic growth has resulted in power consumption becoming one of the largest budget items for carriers, which may prove unsustainable.

Optics happen to have a generally lower energy cost per bit transmitted. Thus, they can be seen as a potential solution to the power consumption problem. This is of course far from certain [115], especially when trying to replicate the exact same functionalities as electronics with optics.

Yet the potential of optics does seem under-utilized; the only role it plays at this time is to provide separate channels within each fiber through WDM. Optical add-drop multiplexers (OADMs) allow convenient channel allocation in a meshed fiber network and their reconfigurable variants (ROADMs) promise fast wavelength switching; still, this only amounts to circuit switching, not packet switching, and wavelength allocation is in fact quasi-static at this time.

At the other end of the spectrum, all-optical packet switching is more ambitious, aiming at keeping the traffic in optical form and still perform the required routing and switching functionalities. Such an approach would retain the flexibility of packet switching and do away with O-E-O conversions. Unfortunately, this puzzle misses one critical piece: all-optical memories are not mature enough to store packets in a practical way; without them, switches are extremely vulnerable to contention, leading to notable packet loss rates even at unrealistically low loads [88].

As in many things, a middle road could be the best compromise: hybrid switches which use optics for simple, ultrafast processing; and electronics for more complex operations, such as buffering. For instance, packets can be buffered in the access or aggregation network, where data arrives at low bit rates and in electrical form anyway, before they are emitted in optical form into the metro and core networks. However, this isn't applicable to core-network switches, with high volumes of optical ingress and egress

traffic.

There, another type of hybrid switch has been recently proposed and demonstrated [9, 100]: an optical switching matrix routes packets optically if possible, or stores them into an electronic buffer if not. It doesn't do away with all O-E-O conversions, but limits them to the cases where contention would have resulted in packet loss. This interesting approach could bring the best of both worlds together. Whether it actually results in energy savings remains to be seen.

My notable contributions In this context of optical and hybrid switching, I have contributed work on all-optical label recognition, on the base of which a full all-optical packet switching node was proposed, as shown in section 3.1.

However, rather than all-optical switches, I now trust more in hybrid ones; as detailed in section 3.2, I have worked on optical switching and failure recovery of wavelength-spread packets, as well as an ongoing performance analysis of a buffer-assisted switch.

Finally, I have come to believe that such functions cannot be successful unless envisioned in a global network-level framework, whose optimization may require breaking away with the traditional layered-network model. My vision for this cross-layer networking is the subject of section 3.3.

3.1 High-speed label recognition

Optical packet switching has been envisioned in multiple forms since the late 1990s [134]. One question was whether to encode each packet's header (its control information, especially its destination) and payload (the actual data to be transmitted) together (in-band) or separately (out of band).

Since the amount of data in each header ought to be negligible compared to the payload, some schemes used in-band header transmission but at a lower modulation rate to help with header processing: at the time, as mentioned in section 1.1, it was accepted that symbol rates would eventually grow beyond the capabilities of electronics; a slower header would allow electronic header processing without imposing that bottleneck on the data.

However, this seemed like avoidable complexity, breaking with the time-honored tradition of encoding headers in the first few bits of the packet. Couldn't they be processed in the optical domain, either to bring them to a lower speed and let electronics do its job, or even to perform switching functions optically? Both options were explored in Hassan Teimoori's Ph. D. thesis.

Publications:
[105–112]

Ph. D. thesis:

Hassan Teimoori

3.1.1 Time-to-wavelength converter

To bring header bits to a lower speed, we demonstrated a serial-to-parallel converter based on an all-optical AND gate operating on the four-bit header and a time-delayed four-wavelength source, shown in figure 3.1.

The arrival of each packet would let a pulse be sent from the source; the different wavelengths would be shifted in time by propagating through a dispersive medium (in practice, a dispersion-compensating fiber, DCF), resulting in a sequence of four pulses of different wavelengths. These pulses would then act as pumps for nonlinear effects in an SOA, where the header bits themselves would be inserted at the required time, so

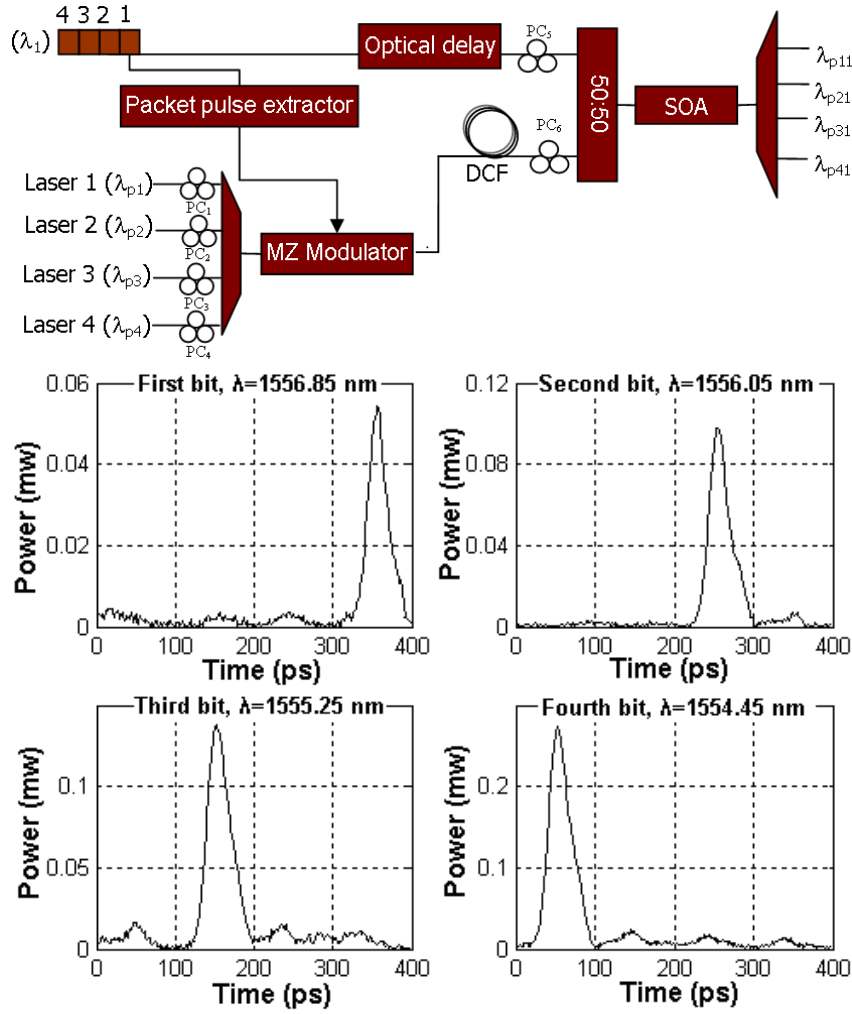


Figure 3.1: All-optical serial-to-parallel converter for label extraction based on FWM in an SOA. Top: equivalent scheme. Bottom: oscilloscope traces for extracted header bits. Adapted from [24, 111].

that each bit interact with only one pump pulse. Having thus been copied to different wavelengths, the header bits could then be separated out by a WDM demultiplexer.

We demonstrated this setup using two different nonlinear effects: FWM and cross-polarization modulation (XPolM). Figure 3.1 shows the FWM configuration and its results.

3.1.2 All-optical switching node

Going one step further, throwing enough all-optical logic gates at the problem, we proposed an all-optical packet switch based on the time-to-wavelength converter discussed in section 3.1.1 above, in conjunction with other all-optical subsystems, notably an all-optical decoder that we demonstrated.

Figure 3.2 shows the logic-gate equivalent setup of a 3×8 decoder, and three configurations of ultrafast nonlinear interferometer (UNI) gates based on XPolM in SOAs. The full decoder would require eight UNI gates in parallel, which would implement the truth

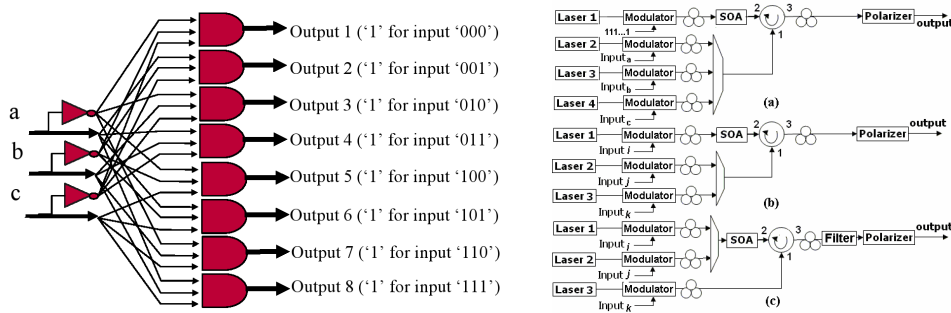


Figure 3.2: All-optical 3×8 decoder. Left: logic-gate equivalent setup. Right: 3-input UNI gate configurations required (3 out of 8): (a) NOR; (b) AND-NOT; (c) AND-NOR. Adapted from [24, 110].

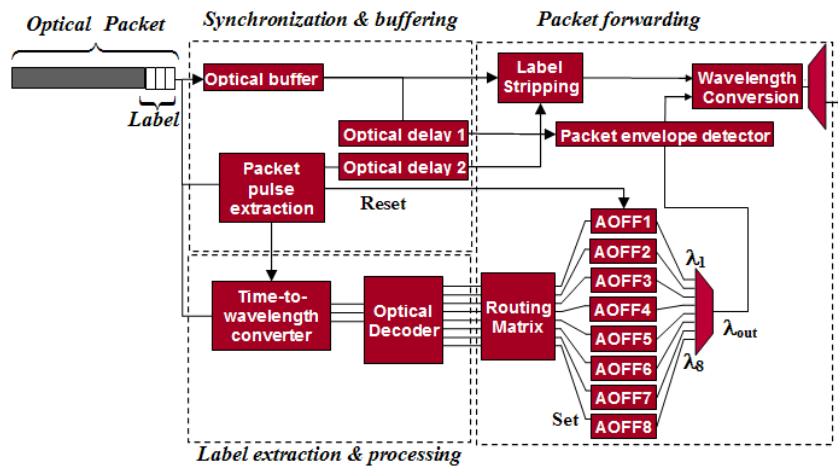


Figure 3.3: Proposed all-optical packet switch. Adapted from [24, 111].

table for each output bit.

All the required all-optical subsystems have been demonstrated by our group or others [111]; so, in theory, the full all-optical packet switch could be implemented. Unfortunately, an experimental demonstration would be exceedingly difficult, especially working with discrete components. Moreover, the proposed setup does not scale well, requiring over twice as many SOAs as the number of possible addresses. Finally, the switch attempts to replicate the very same function as electronics; history has shown that unless a clear advantage can be shown, in this case, electronics usually win.

3.2 Hybrid opto-electronic switching

Instead of competing head-to-head with electronics, a smarter approach is to assign roles according to ability: perform complex processing electronically, using fast, simple optics to make problems manageable at the speed of electronics, and keeping signals in the optical domain wherever possible.

For instance, during my sabbatical in Columbia University's Lightwave Research Laboratory, I worked on their wavelength-spread packet-switching architecture, which processes headers using low-speed electronics, enabling network-level functionalities

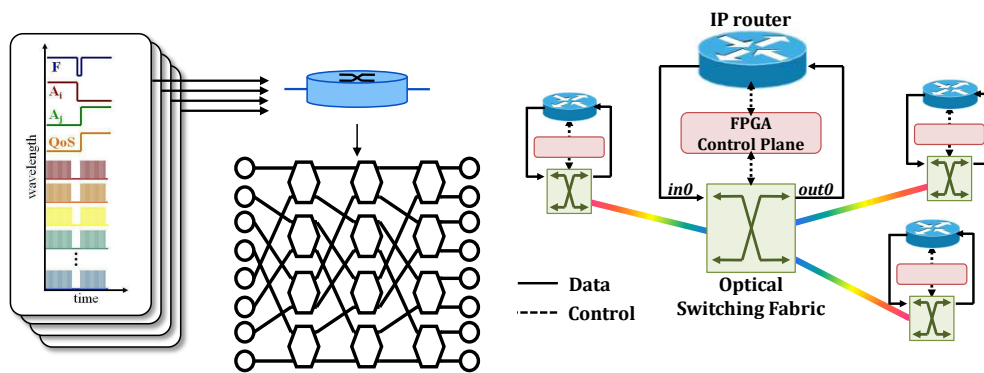


Figure 3.4: Wavelength-striped packet architecture, switched by a SOA-based optical switching matrix. Adapted from [64, 130].

Figure 3.5: Proposed hybrid network node. Packets are switched optically whenever possible, and an IP router works as a fallback. Adapted from [130].

such as Quality of Service (QoS)-aware switching or failure recovery. I later moved towards performance analysis of such hybrid switches.

3.2.1 Wavelength-spread optical packet switching

The principle of wavelength-spread packets is to use WDM to encode each packet's header out of band, as illustrated in figure 3.4. Several payload-assigned wavelengths are modulated with the data, and a few header-assigned wavelengths are OOK-modulated *at the packet rate*, not the bit rate. In other words, the optical intensity at these header wavelengths remains constant over the duration of each packet.

This greatly relaxes constraints on processing speeds, so that low-speed electronics can be used for label recognition and switching. The data is kept in the optical domain and is switched using an SOA-based switching matrix: SOAs are used as on-off switches in a broadcast-and-select configuration. This architecture's flexibility allowed the demonstration of further network functionalities, such as optical buffering and QoS-aware switching [66, 68].

Its main drawback is that allocating several wavelengths to slow-modulated headers is wasteful in terms of spectral efficiency. It is also vulnerable to chromatic dispersion, since all the wavelengths making up each packet will drift in time over long propagation lengths, and would require complex dispersion compensation in a long-haul network, or at least guard intervals between packets to allow for dispersion-induced temporal broadening. This technique would therefore seem better suited to data-center networks than metro or core networks.

3.2.2 Proposed hybrid switching architecture

The wavelength-spread architecture described above still suffers from the contention vulnerability common to optical switching matrices. We thus proposed a more complete switching node built around this SOA-based switching matrix, as in figure 3.5, adding an electronic router and a performance monitoring system.

Such a node retains all the functionality of electronic switching, supplemented by a high-capacity optical switch—the idea being to keep the signal in optics wherever

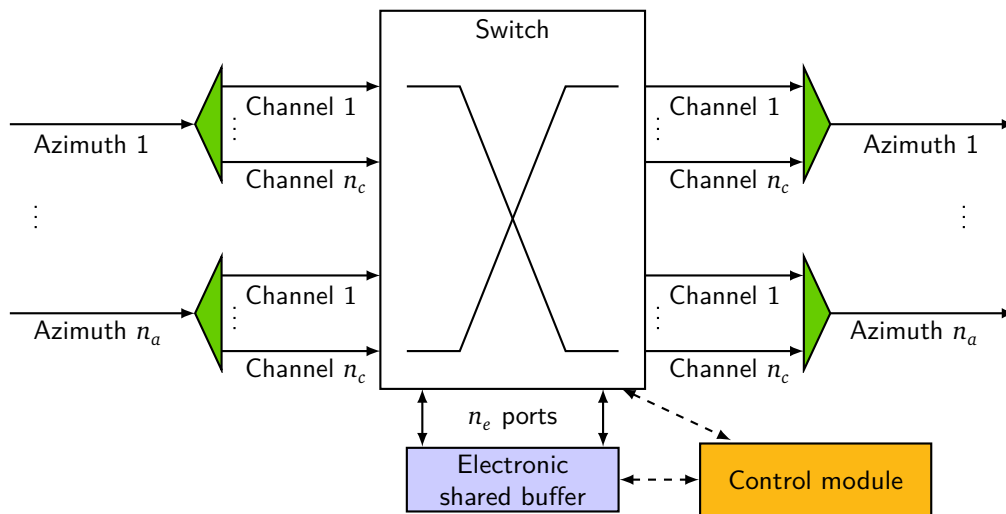


Figure 3.6: General architecture of the hybrid switch considered.

possible, and send it into the electronic router when a complex functionality is required, e.g. regeneration, label swapping, and especially buffering in case of contention.

Additionally, performance monitoring allows not only failure detection, but also to send link performance to a centralized control plane, which could then be used to optimize the overall network in terms of maximum optical path length, hence regenerator placement.

We are still far from a fully-fledged network capable of this vision. However, some parts of it have been worked on.

I contributed to a demonstration of failure-recovery-capable matrix [63, 65, 130], where traffic was sent to alternate routes depending on a “failure” input on a local control plane. In a global network using this capability, local routing tables would be maintained within each node with precomputed protection paths. This would allow near-instantaneous local network reconfiguration at the node where the failure is detected.

Another aspect is the coupling of the optical switching matrix not with a router, but with a shared electronic buffer, to alleviate contention. This was proposed and demonstrated in [9, 100]. However, no performance analysis was done.

Over part of [Pierre Delesques](#)’ Ph. D. thesis, I studied the performance, in terms of packet loss rate, of a generic shared-buffer hybrid switch (see figure 3.6). The key factors are the number of channels per destination and the number of electronic input/output ports to the buffer. With an all-optical switch (no electronic ports), the loss rate is high even at low loads [88].

With even a few electronic ports, as shown in figure 3.7, preliminary calculations indicate dramatic improvement to the loss rate, especially with few channels per link. An analytical model and numerical simulations both show that the sustainable load at a reasonable loss rate (e.g. 10^{-7}) can be brought up to a practical value (e.g. 0.6) with as few as 20 electronic ports for a 100×100 switch (10 azimuths, 10 interchangeable channels per azimuth).

These results are rather encouraging, and a more complex electronic router, as envisioned above, could possibly improve further on the performance of a simple buffer. However, care ought to be taken to compare the performance not only to that of an

Ph. D. thesis:
[Pierre Delesques](#)

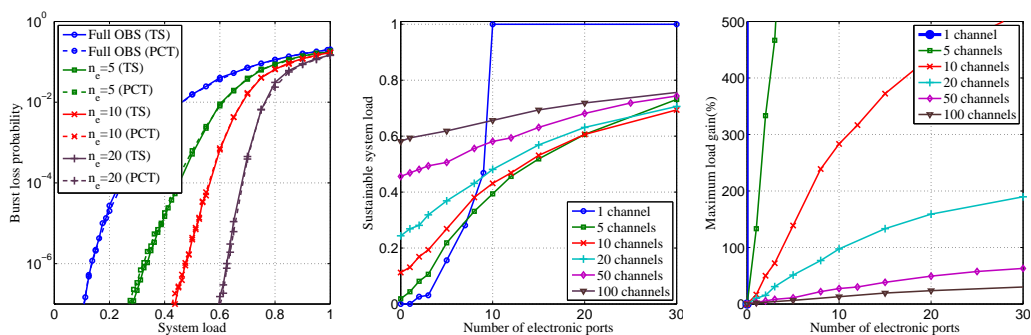


Figure 3.7: Hybrid switch simulated performance. Left: loss probability vs system load ($n_a = 10$, $n_c = 10$). Center: sustainable system load vs number of electronic ports ($n_a = 10$, loss probability $= 10^{-7}$). Right: gain in system load vs number of electronic ports ($n_a = 10$, loss probability $= 10^{-7}$). Adapted from [23].

all-optical switch, but also to an all-electronic one. In certain cases, the number of electronic ports needed to achieve a reasonably good performance is on the order of the overall number of ports in the switch; in which case the hybrid switch has no advantage over the all-electronic one. Further studies are underway to better quantify the “sweet spot” where the hybrid switch can be a viable solution.

3.3 Vision: cross-layer optical networking

3.3.1 Optical functionalities, layered networks, energy consumption: the false problem and the real problem

The astute reader who read this memoir from the beginning through here may have noticed a pattern, of optical functionalities researched, demonstrated, but remaining with little success outside the laboratory: OTDM, optical packet switching, OCDMA. Only in very specific cases does optical technology take off, when it fits existing paradigms and is compatible with legacy systems: conceptually, WDM can be thought of as multiple channels in parallel; coherent transmissions, particularly the PolMux-QPSK being deployed, fit the existing wavelength grid and work over existing fibers; and especially, neither impinges on network layers above the physical.

The conventional layered-network paradigm has been extremely successful in the past decades, for it allows expertise to be focused onto circumscribed areas, without having to consider the network in its globality. It is a simplification, which is a great help, for no human mind can simultaneously hold every aspect from the back-and-forth traffic of a Web application to the specific signal processing taking place to enable this connection.

Thus, in this light, one is tempted to conclude that “smart” optical functionalities, going beyond the physical layer, are simply not wanted—at least, as long as they can’t provide enough features to seamlessly act as another layer; this almost certainly requires competing with electronics on their own turf (e.g., for the transport layer, optical buffers and contention management), which has not been a good bet historically.

Yet this paradigm may be reaching its limits due to another factor: energy consumption, which is now a major operational expense for carriers and whose global carbon

footprint represents 1–2 % of the worldwide total [60]. Most of it is currently in access network, but with a fairly stable trend, whereas consumption due to switching is growing much faster, and could surpass access by 2018. Given the continual increase of global traffic, it would require significant technological improvements for it to remain stable. This does not mean that merely using more optical technologies would make the problem go away [2]; voices are now calling for a clean-slate redesign of the network [85] and moving towards new network and service architectures [3, 117].

This concept, of multilayer or cross-layer optimization, would call for more awareness of physical constraints in network dimensioning and operation. Already, impairment-aware routing and wavelength assignment (RWA) algorithms exist, though aimed more at long-term network planning and provisioning than quick-reaction resource allocation; dynamic wavelength switching remains to be deployed. Also, the existing algorithms may need to be rethought for coherent transmissions.

3.3.2 Past proposals, self-criticism, enlightenment?

In a dynamic, optimized network, impairment information could be used to handle failure recovery or graceful degradation. My colleagues and I proposed or demonstrated several ideas in this vein in [65, 130]: network nodes, based on hybrid opto-electronic packet switching, whose monitoring equipment could report a change in quality of transmission on one of the optical links, or an outright link failure. The node could then, on the one hand, reconfigure itself to bypass the failed link instantly, redirecting packets using deflection routing and preprogrammed alternate paths; on the other hand, network messages could be generated to instruct applications to reduce their requirements, such as a video streaming server changing its encoding quality.

Then again, these proposals still were not thought out realistically enough: not only would it be cumbersome to modify the huge number of existing applications, but monitoring information in a core switching node hardly relates to end-users' equipment. Yet it must make sense, intuitively, to propagate network information to make use of it. But one can't expect consumer products to handle so many different network environments and situations.

I now realize that the answer lies in *abstraction*: expressing different specific situations as variants of more general concepts, making them simpler to manipulate. The best example is probably modern software development, applications being written in high-level programming languages and frameworks, interfacing to computer hardware through operating systems and standard libraries, instead of attempting to handle myriads of different computers manually. Layered networks are another successful abstraction, built into the current global network and most network-capable operating systems. However, if it proves unable to express energy-efficient networks, then a better abstraction may be needed.

3.3.3 A possible future: software-defined networking and optical functionalities revisited

This abstraction could take the form of software-defined networking (SDN). SDN's goal is to simplify the design of complex network functionalities by providing a high-level framework to express them in, while specific low-level functionalities of the underlying

network hardware are abstracted. SDN for optical networks has recently become an active research field, especially based on extensions to the OpenFlow protocol [7, 48, 94].

With such a tool at our disposal, I believe it would be quite interesting to design SDN “drivers” for various optical functionalities, especially those related to switching, and see what ideas the process would generate, perhaps in implementing routing protocols. This could even be a test of the desirability of a specific function: if it can’t be expressed in an SDN framework, or if it doesn’t bring any added features compared to conventional hardware, then perhaps that function doesn’t make sense in a global context.

This may be an opportunity for optical functionalities to make a comeback, provided that they be designed with the global network in mind—that is, that they actually provide practically useful functionality for an actually reduced global power consumption—; and vice versa, meaning that the specific optical functionality is expressed in the SDN framework—just as specific computer hardware must provide device drivers to be exploited—, which could greatly help acceptance of nonconventional functionalities by network architects and engineers.

Future directions

The considerations above drive me towards two main paths. First and most immediate, a thorough energy-consumption analysis of the hybrid switch should pinpoint the specific use cases where such a solution is of interest. Further analytical investigation of its blocking probability would follow, targeted on the chosen operating conditions.

Second, optical functionalities should be revisited in an SDN-aware context, particularly in the switching, monitoring and impairment mitigation area. SDN, perhaps with yet-to-be-determined extensions, could help identify how best to put them to use.

In parallel to the latter, the moment seems ripe to redesign the global network by starting over from users’ needs and using the best available tools to fulfill them, including smarter optical functionalities. This top-down approach has a good chance to prove more efficient than the result of an anarchic “network of networks” that the Internet was designed to be.

A sine qua non condition, however, to the viability of such a radical movement, is to preserve the ease of operation, flexibility and interoperability that made the Internet’s success. This requires a strong effort on interoperability with legacy equipment and applications, as well as between different vendors, carriers, and network domains.

All this promises to be an arduous task, but I believe it is the key to the continued advancement of a global networked society.

Conclusion and Perspectives

The domain of optical communications remains just as challenging as it was over a decade and a half ago when I entered the field. Considerable work has been done in that time, from the fantasy of photonic computers, through select all-optical functionalities, and now a whole paradigm shift towards coherent that put many proposed techniques on their heads.

In all that time, the most successful use of optics has been and still is raw transmission. The bit rate per fiber core has increased by two orders of magnitude since the mid-1990s, and even more using SDM. In this vein, the very fact that SDM generates so much interest, despite breaking compatibility with standard fibers and amplifiers, indicates that fundamental, information-theoretical, limits may have been reached for data rate per core. This assessment may be overly pessimistic, as mentioned in section 1.2.3, but it has spawned a beneficial trend towards more efficient system dimensioning.

Smarter optical functionalities, however, have been largely spurned by the industry. Apart from quasi-static circuit-mode wavelength switching, the promises of all-optical regenerators and switches have not materialized in actual deployment. There has been some scramble these past few years towards updating optical functionalities that were not already compatible with phase modulations (OEPLLs were), notably using phase-sensitive amplification, but there is no indication that they will meet with more practical success as-is.

Meanwhile, a new problem has appeared: energy efficiency, especially in switching, whose power consumption is increasing uncontrolledly. Optical switching may be able to help, but is much more vulnerable to contention than electronics, and does not fit very well in the layered-network model. Given the possibility that conventional networks may not be able to overcome this energy barrier, voices are now calling for a clean-slate redesign of the network, into novel architectures, economical by design.

This may be an opportunity for optical functionalities to express their full potential. However, there is still little research activity with a global network vision, including all of energy issues, specificities of optical systems, and smarter optical functionalities.

In this context, the axes I intend to focus on in the next few years are:

Cross-layer optical networking. By starting from the users' needs and selecting the best-suited tools in our toolbox, novel network architectures can be designed from the start for efficiency. In a top-down redesign, it is likely that "smart" optics can play a much larger role than in current networks, by specifying roles that make their use practical.

Of course, the energy efficiency of any novel architecture must be thoroughly analyzed, and testbeds built, to be certain of the actual benefits and sustainability.

Another sine qua non condition is interoperability: not only should these architecture transport IP packets seamlessly and interface with legacy equipments; it must also integrate well with more conventional ideas of the future network, meaning basically SDN.

Finally, to gain mindshare, such a novel network concept must come with almost-turn-key solutions: network planning tools, progressive upgrade paths, standard libraries. Only that way does a nonconventional idea have a chance to get accepted by the pure-

network community, who can then take the ball and run with it.

Coherent optical communications. This other axis is not as novel as the preceding one, not anymore, but the articulation is needed: in an optics-centric, translucent network, where should traffic with advanced modulation formats be transparently switched, where should it be regenerated?

In a shorter-term view, I still have not gotten over the idea that coherent modulations allow for much more powerful ways of mitigating or compensating for physical impairments, especially linear ones. The idea is now well-established in core networks; however, could the access network not benefit from it as well? Obviously, this would require simplification to avoid the need to build a coherent receiver in every ONT; perhaps something can be done in the vein of direct-detection OFDM.

Finally, nonlinear impairments can probably be mitigated somewhat. In other words, as long as we don't have a better capacity model of the optical channel, as long as there may be more potential to be squeezed out of optical fibers, let us push back communication systems' ultimate limits.

Appendix A

Cédric Ware: Curriculum Vitæ

Date of birth: January 24, 1977
Marital status: single
Citizenships: French, Swiss
Contact information: Télécom ParisTech, Communications & Electronics dept
46 rue Barrault, 75634 Paris CEDEX 13, France
cedric.ware@telecom-paristech.fr / +33 1 45 81 74 85
CV dated: April 25, 2013

Professional Experience

- 2007–
- **Associate Professor** (“Maître de Conférences”), **Optical Telecommunications**
Télécom ParisTech
(*One of France’s top engineering schools specialized in Telecommunications*)
- October 2010–
July 2011
- Visiting Research Scientist, Lightwave Research Laboratory
Columbia University
- 1998–2007
- Assistant Professor (“Chargé d’Enseignement et de Recherche”¹)
Télécom ParisTech (formerly ENST)
- 1996–
- **Civil servant: “Corps des Mines”** (formerly “Corps des Télécommunications”)
(*Highly-selective, elite engineering and management civil-service corps*)
→ Rank: Senior Engineer (“Ingénieur en chef”) since 2007

Education

- 2003
- **Ph. D.** in Electronics & Communications; magna cum laude (“mention très honorable”²)
“Clock recovery using a phase-locked loop based on four-wave mixing in a semiconductor optical amplifier” [119]
Advisor: Prof Didier Erasme, Télécom ParisTech
- 1996–1998
- **Télécom ParisTech**
(*One of France’s top engineering schools, specialized in Telecommunications.*)
- 1998
- Engineer’s diploma (M. Sc. level) in Telecommunications

¹“CER” is a title specific to Télécom ParisTech for research professors hired before defending a Ph. D. Further titles are the same as French universities: “Maître de Conférences” (Associate Professor) and “Professeur” (Full Professor).

²Although “mention très honorable” is technically an honor, it is almost systematically awarded; current academic policy gives no higher honor, and only poor works get lower ones.

- **École Normale Supérieure** 1993–1996
(France's top institution of higher learning for researchers and professors.)
 - Magistère Interuniversitaire de Physique (ENS' special 3-year Physics degree)^{3,4}; cum laude 1998
 - DEA (M. Sc. level, Ph. D. track) in lasers, plasma, optoelectronics; cum laude 1996
 - Licence (B. Sc.) in Computer Science 1996
 - Successfully passed “Agrégation de physique” (French nationwide competitive exam for qualification of Physics professors) 1995
 - Maîtrise (B. Sc./M. Sc.) in Physics; cum laude 1994
 - Licence (B. Sc.) in Physics; cum laude 1994

Research

Optical functionalities for communication networks aim at bringing faster and more efficient techniques to bear on the perpetual problem of traffic growth and uncontrolled energy consumption. **Ultrafast bit rates** are enabled by performing simple signal processing directly in the optical domain, which can be leveraged by **novel cross-layer network architectures**.

Research Topics

- **Ultrafast clock recovery:** using an opto-electronic phase-locked loop with a nonlinear optical device as a phase comparator; collaboration with DTU Fotonik (Denmark) and NIMS (Japan), culminating in a full OTDM transmission at a record **640 Gbit/s** [78, 79].
- **Cross-layer optical networking:** novel network architectures to leverage optical switching in a practical way, compatible with existing IP networks, with a realistic assessment of energy consumption.
- **Coherent optical transmissions:** using advanced modulation formats and digital signal processing, to increase spectral efficiency instead of symbol rates, while doing away with classical physical impairments and pushing closer to the ultimate capacity limits.

Projects and Collaborations

European cooperative programmes (Networks of Excellence, COST actions):

- EURO-FOS (PI: Prof Hercules Avramopoulos, NTUA) 2008–2012

³My choice of preparing the “Agrégation” contest in 1995 instead of the standard 6-month internship abroad, led to my MIP degree being awarded only in 1998. However, the required exams had been validated by 1996.

⁴ENS used not to deliver specific degrees at the time, but worked through agreements with other universities. My Physics and Computer Science degrees are respectively from Université Paris VI and VII, two of the most renowned in France.

- **Leader** of “joint experimental activity” on clock recovery for OTDM.
Other active partners: DTU, Denmark; HHI, Germany; SSSUP, Italy.
- 2006–2008 • e-Photon/ONe⁺ (PI: Prof Fabio Neri, Politecnico di Torino)
 - **Leader** of “joint activity” on optoelectronic clock recovery.
Other active partners: DTU, Denmark; NIMS, Japan (outside e-Photon/ONe⁺).
Led to **640 Gbit/s** OTDM transmission with **opto-electronic clock recovery** using three-wave mixing in periodically-poled lithium niobate. [78, 79]
- 2004–2008 • COST 291: “Towards digital optical networks” (PI: Prof Ioannis Tomkos, AIT)
- 2003–2008 • COST 288: “Nanoscale and ultrafast photonics” (PI: Prof Judy Rorison, University of Bristol)
 - **National delegate** (starting in 2005, when France entered consortium)
 - **Vice-chairman** of work package 3 (ultrafast devices and systems)

French National Agency for Research (ANR) projects:

- 2006–2009 • ANR SUPERCODE: Supercontinuum generated by photonic crystal fiber for code-division multiple access
 - **Responsible** for Télécom ParisTech’s scientific contribution
 - **Leader** of work package on systems integration

Sabbatical and international exchange visits:

- 2010–2011, 10 months • Columbia University (New York, USA): cross-layer networking research; demonstration of failure recovery in optical packet switch; participated in CIAN Engineering Research Center project. (Contact: Prof Keren Bergman)
- 2009, 1 week • SSSUP (Pisa, Italy): characterized all-optical clock for use in optoelectronic phase-locked loop. (Contacts: Prof Antonella Bogoni, Dr Claudio Porzi)
- 2006, 1 week • Sup’COM (Tunis, Tunisia): modeling of four-wave mixing in semiconductor optical amplifiers. (Contact: Prof Mourad Menif)
- 1999, 2 wks • CICESE (Ensenada, Mexico): polarization rotation and four-wave mixing in semiconductor optical amplifiers. (Contact: Dr Horacio Soto Ortiz)
- 1997, 2 wks

Other collaborations:

- NIMS (Japan): optoelectronic clock recovery using three-wave mixing in periodically-poled lithium niobate (Contact: Prof Sunao Kurimura; see e-Photon/ONe⁺ above)

Supervision of Ph. D. and jury participation

Advisor (graduated Ph. D. students):

- 2012 • Dr Pierre Delesques, “*New modulation types for fiber optics communication networks*” (advisorship shared with Prof Philippe Ciblat, Télécom ParisTech and Dr Gwillerm Froc, Mitsubishi Electric R&D Centre Europe)

- Dr Guilhem de Valicourt, “*Design, realization and evaluation of remote modulators for optical access networks and radio over fiber*” (advisorship shared with Dr Romain Brenot, III-V Lab); **recipient “Paul Baran Young Scholar” award of the Marconi Society** (2012) 2011
- Dr Steevy Cordette, “*Optical frequency continuum for OCDMA application*” (advisorship shared with Prof Catherine Lepers, Télécom SudParis) 2010
- Dr Fausto Gómez Agis, “*Clock recovery of ultra-high speed OTDM signals by phase-locked loop based on PPLN*” (advisorship shared with Prof Didier Erasme, Télécom ParisTech) 2008
- Dr Hassan Teimoori, “*Optical-logic-gate aided packet-switching in transparent optical networks*” (advisorship shared with Prof Didier Erasme, Télécom ParisTech) 2007

Other jury participation:

- Invited jury member, Dr Annalisa Morea, “*Contribution to study of translucent optical networks: technical feasibility and economic interest evaluation*” (Advisor: Prof Maurice Gagnaire, Télécom ParisTech) 2006

Publications

Over 40 publications and communications to date, in high-profile journals (J. Lightwave Technology, Photonics Technology Letters, Optics Express...), international and national conferences (Optical Fiber Conference, European Conference on Optical Communications...) Includes:

- Articles: [16, 17, 35, 41, 47, 63, 65, 77, 79, 107, 109–111, 128], including **1 Invited JLT paper** [79] and 1 Electronics Letters “**Letter of the month**” award [77].
- International conferences: [19–21, 23, 33, 34, 36, 39, 42, 43, 45, 58, 64, 78, 82–84, 106, 112, 113, 124, 126, 127, 129, 130], including **1 OFC postdeadline paper** [78] and invited conferences [42, 64, 127, 129, 130].
- National conferences: [10, 11, 22, 32, 38, 44, 46, 105, 108, 122, 125, 131].
- Book chapter: [28].
- Ph. D. thesis: [119].
- Miscellaneous workshops: [37, 40, 120, 121, 123].

Teaching Experience

Participating in Télécom ParisTech engineering curriculum **since 1998**: creating and giving lectures, practicals, and exams; proposing, supervising and evaluating student projects; and course coordination and management.

Students: undergraduate, graduate, lifelong learning.

- 1998–
 - 1st-year Micro- & Nano-Physics course (**responsible** since 2011): basics of Quantum Mechanics and Statistical Physics applied to simple semiconductor devices (30 h, French language)
- 2006–
 - **Responsible** for optical communications course (ATHENS programme: European universities **exchange students** for 1 week each session)
Practical-oriented course, hands-on approach to optical communications systems and devices used therein (30 h, English language)

Individual lectures:

- Digital optical communications (3 h): specificities of optical channels
 - Guest lecture **US Engineering Research Center CIAN**: super-course (2011);
 - Included in **European Network of Excellence e-Photon/ONe⁺**: summer school (2007, shortened 2-hour version); e-Photon/ONe⁺ master curriculum
- Optical amplification for telecommunications (1.5 h)
 - Guest lecture **US Engineering Research Center project CIAN**: super-course (2011);
- Optical functionalities for signal processing (1.5 h)
- Laser basics (1.5 h)
- Semiconductor physics for optical communications devices (1.5 h)
- Various small-group lectures: semiconductor lasers, optical modulators...
- Various practicals: diffraction, holography...

Other teaching-related experience:

- Created L^AT_EX online course templates for lectures and presentations
- Member of reform committee for 1st-year Physics course (2010)
- Attended training for objectives-based course / curriculum design
- Mentor for off-profile first-year students

Other Experience

- 2004
 - **Organization of JNOG 2004 national conference:**
 - Automated compilation of proceedings from article database
 - Created proceedings templates (2012 templates still related to those)
 - Created Web site for online submission, reviewing, registration, payment (static version now at: <http://confs.comelec.enst.fr/jnog2004/>)
- 1996–2005
 - **Systems and network administration:**
 - Managed up to 200 workstations, servers & network in my research department (Windows, Linux, Solaris, HP-UX, MacOS)
 - Automated install & maintenance of 60 GNU/Linux workstations

- Unix and Web tools development (shell, C, Make, Perl...)
- **Member, Optical Society of America; Société Française d’Optique**

General Skills

Languages:

- French: mother tongue
- **English: fluent**
- German: basic

Computer / information technology:

- Typesetting: \LaTeX (advanced); Word, OpenOffice (basic to average)
 - articles, templates and classes
- Presentations: \LaTeX +Beamer
 - conferences, lectures, “Libres Savoirs” online courses templates
- Development:
 - **C, Perl, Python** (good);
 - PHP, SQL, Matlab/Octave (fair);
 - Java, C++, OCaml (basic)
- Systems:
 - Linux (good)
 - Unix: FreeBSD, Solaris, Darwin/MacOS X (fair)
 - Windows (average)

Annexe B

Résumé en français

Cédric Ware travaille dans le domaine des fonctions de traitement du signal optique pour les réseaux de télécommunications. Cette thématique vise à répondre aux défis que présente le continuel renouvellement des réseaux de données, nécessaire à assouvir les besoins insatiables d'utilisateurs toujours plus connectés et plus exigeants quant à l'infrastructure critique qu'est devenu Internet, sur lequel reposent de nombreux services en perpétuelle évolution.

Le premier de ces défis est le haut débit d'informations, condition sine qua non pour tout nouveau déploiement. Jusqu'au milieu des années 2000, cela était perçu comme nécessitant un haut débit symbole, au-delà des capacités de l'électronique, faisant donc appel à des fonctions optiques. Le multiplexage temporel optique (OTDM) a été développé en ce sens ; ma contribution majeure à ce thème a été une technique de récupération d'horloge à base de boucle à verrouillage de phase opto-électronique, démontrée expérimentalement jusqu'à 640 Gbit/s en modulation OOK (section [B.1.1](#)).

Toutefois, depuis le milieu des années 2000, les transmissions optiques cohérentes connaissent un fort regain d'intérêt grâce à l'avènement de la détection cohérente intradyne ; en rendant praticable l'utilisation de modulations à haute efficacité spectrale, elle a non seulement réduit le besoin en débits symboles élevés, mais aussi permis la résolution par traitement numérique de nombreux problèmes liés à la propagation sur fibre optique. Les systèmes approchent désormais de la limite ultime qu'est la capacité de Shannon ; mon intérêt s'est tourné dans cette direction, et j'ai contribué à l'étude de la capacité des systèmes optiques en présence de dégradations linéaires et non-linéaires (section [B.1.2](#)).

Tout ce trafic à haut débit doit parvenir jusqu'à l'utilisateur final, via un réseau d'accès qui nécessite et profite des technologies optiques, mais où l'accent se porte sur le coût plutôt que la performance brute. Témoin, le multiplexage en longueurs d'ondes (WDM), technologie phare des systèmes à hauts débits dans les réseaux cœurs, n'est pour l'instant utilisé dans les réseaux d'accès que pour séparer les catégories de trafic et non dans une optique de démultiplier le débit par fibre. Inexorablement, l'heure viendra de son utilisation dans ce second but ; un problème reste néanmoins à résoudre : d'un point de vue logistique, il est difficile de déployer chez les utilisateurs des équipements spécifiques à une certaine longueur d'onde. On cherche donc à réaliser des équipements « incolores », compatibles avec toute longueur d'onde, tout en restant bon marché.

J'ai effectué, via la thèse de doctorat de deux étudiants, deux principales contributions dans ce domaine : d'une part, la démonstration d'une source optique à spectre large destinée à être partagée entre de nombreux utilisateurs via un découpage spectral et un accès multiple à répartition par codes (CDMA), décrite section [B.2.1](#).

D'autre part, la section [B.2.2](#) résume un travail très fructueux sur la conception d'amplificateurs à semi-conducteurs réfléchissants (RSOA) dont les performances ont fait l'état de l'art en termes de vitesse de modulation, de faible chirp, et de linéarité. Ces dispositifs, qui peuvent être produits en série à bas coût, ont été démontrés comme

modulateurs déportés incolores dans des expériences de transmissions conventionnelles ainsi que de systèmes radio-sur-fibre.

Les communications optiques ont ainsi obtenu un succès considérable dans les réseaux de communications ; toutefois, elles restent cantonnées à des transmissions point-à-point, voire point-à-multipoint dans les réseaux d'accès à capacité plus faible. Un réseau doit faire en sorte que le trafic le traversant soit acheminé à bon port, ce qui est actuellement assuré par des routeurs IP tout au long du parcours. Hélas, cette approche purement électronique ne pourra être soutenue dans la durée : les conversions optique-électrique étant limitées à quelques dizaines de gigasymboles par seconde, le traitement est nécessairement massivement parallèle, ce qui mène à une multiplication des composants et une telle augmentation de la consommation énergétique que le coût en devient prépondérant. Cette tendance doit impérativement être endiguée pour ne pas faire obstacle à l'amélioration des performances, sans même parler de développement durable.

L'introduction de fonctions optiques dans les réseaux vise à répondre à ces défis : effectuer une partie du traitement directement dans le domaine optique réduit le besoin en conversions optique-électrique, évitant la limite afférente de bande passante ainsi que, potentiellement, la consommation.

Mes doctorants et moi-même avons contribué à ce but de façon triple. Premièrement, comme le mentionne la section B.3.1, par la démonstration de reconnaissance tout-optique d'en-têtes ; ce concept aurait été une partie importante d'un commutateur tout-optique complet, quoique l'histoire montre que mimer de la sorte des architectures électroniques finit généralement à l'avantage de ces dernières.

Deuxièmement, visant à mieux répartir les tâches entre optique et électronique, via une analyse de performance d'une architecture de commutateur hybride optique-électronique détaillée section B.3.2, qui utilise une matrice de commutation optique couplée à une mémoire électronique afin de pallier le problème de la contention bien connu dans les commutateurs optiques.

Enfin, la section B.3.3 résume l'état de mes réflexions sur les réseaux optiques « cross-layer ». J'estime que le relatif manque de succès des fonctions optiques hors du laboratoire résulte en large part d'une conception qui ne tient pas suffisamment compte du réseau dans sa globalité. Seule une approche nouvelle, faisant si nécessaire table rase des architectures conventionnelles de réseaux en couches, permettra de dépasser la barrière de la consommation énergétique via la réalisation du plein potentiel de l'optique.

B.1 Communications optiques à ultra-haut débit

B.1.1 Récupération d'horloge pour le multiplexage temporel optique

La récupération d'horloge est une fonction critique de tout système de communications numérique, nécessaire au niveau du récepteur ou de régénérateurs pour fixer l'instant de décision du symbole d'information. En outre, les systèmes à multiplexage temporel requièrent un sous-multiple de l'horloge pour séparer les différents flux de données.

Traditionnellement, cette fonction est assurée par une boucle à verrouillage de phase (PLL) dans le domaine électrique. Cela présuppose une conversion optique-électrique, ce qui est possible à des débits symbole de quelques gigabauds. Au-delà, on a recours à des systèmes de multiplexage optique (OTDM) qui ne peuvent plus se contenter de la

technique traditionnelle.

Plusieurs méthodes tout-optiques de récupération d'horloge ont été développées, notamment à base de filtres Fabry-Perot ou de lasers autopulsants. Toutefois, la PLL se prête mieux à l'extraction de sous-horloge, pour peu qu'elle soit utilisable dans le domaine optique. À cette fin, on remplace le comparateur de phase, cœur de la PLL, par un dispositif optique non linéaire ; le reste de la PLL peut être réalisé via de l'électronique à relativement basse fréquence, ne nécessitant pas le concours de l'optique.

Un tel schéma de PLL opto-électronique a été démontré dès 1993 [57, 89], utilisant un schéma hétérodyne (où l'optique travaille à une fréquence légèrement décalée par rapport à l'horloge récupérée). Au cours de ma thèse de doctorat, j'ai reproduit ce schéma et l'ai étendu à une PLL homodyne qui présente l'avantage de récupérer une horloge simultanément sous forme électrique et optique. Ainsi, l'utilisation en est possible aussi bien dans un récepteur classique qu'un régénérateur 3R tout-optique.

L'effet optique non-linéaire utilisé est d'une part le mélange à quatre ondes (FWM) dans un amplificateur optique à semi-conducteurs (SOA) ; puis, notamment au cours de la thèse de Fausto Gómez Agis, le mélange à trois ondes (TWM) dans le niobate de lithium périodiquement orienté (PPLN), ce qui était une première. Bien que tout effet non-linéaire puisse a priori réaliser ainsi un comparateur de phase, ces deux choix partagent l'avantage d'un dispositif de courte longueur, critique pour la stabilité de la PLL ; et d'un bon contraste, car FWM comme TWM créent un signal à une longueur d'onde différente des signaux d'entrée. En outre, dans le cas du TWM, cette longueur d'onde créée correspond à une somme de fréquence, l'amenant si loin des signaux d'entrée (760 nm pour un mélange 1500+1550 nm) que le photodétecteur lui-même l'en isole, évitant d'avoir recours à un filtre optique supplémentaire.

Il en résulte des PLL opto-électroniques d'excellente performance, qui ont été démontrées jusqu'à 640 Gbit/s en collaboration avec DTU Fotonik (Danemark) et le National Institute for Materials Science (Japon), dans le cadre du réseau d'excellence e-Photon/ONe⁺ et des actions COST 288 et 291.

Ce résultat était le plus haut débit jamais utilisé avec un PPLN, et seulement la deuxième démonstration au monde d'une transmission OTDM à ce débit avec récupération d'horloge. Il a été publié, entre autres, dans une communication postdeadline à la plus grande conférence du domaine *Optical Fiber Conference* [78] et d'un article invité dans le prestigieux *Journal of Lightwave Technology* [79]. Un résultat intermédiaire a reçu le prix de la « Letter of the Month » à *Electronics Letters*. [77]

La suite de ce travail a visé à démontrer le fonctionnement de cette PLL opto-électronique avec des signaux à modulations cohérentes, lesquelles sont actuellement privilégiées pour l'ultra-haut débit à grande efficacité spectrale, seules ou en combinaison avec l'OTDM. [113]

Une autre amélioration qui mériterait d'y être apportée serait la réduction du temps d'accrochage relativement long de la PLL : de l'ordre de la dizaine de microsecondes, à comparer avec les nanosecondes voire moins des filtres Fabry-Perot, plus adaptés aux paquets de données.

J'ai mené deux « Joint Experimental Activity » sur ce thème au sein du réseau d'excellence EURO-FOS, qui en plus de Télécom ParisTech ont rassemblé l'Athens Information Technology center (Grèce), DTU Fotonik (Danemark), le Heinrich-Hertz Institut (Allemagne), la Scuola Superiore Sant'Anna (Italie), et l'Université d'Essex (Royaume-Uni).

B.1.2 Communications optiques cohérentes

Jusque récemment, la fibre optique a été considérée comme ayant une bande passante virtuellement illimitée, ne nécessitant pas une course à l'efficacité spectrale ou à la consommation énergétique telle qu'en radio.

Deux facteurs viennent changer la donne : la nécessité de faire évoluer un réseau cœur dont la limite de bande passante n'est pas simplement celle de la fibre, mais celle des EDFA, voire des canaux des démultiplexeurs WDM déjà installés. Le souhait des opérateurs est de faire passer 100 Gbit/s dans la même bande qu'un traditionnel canal à 10 Gbit/s. D'autre part, l'augmentation de la puissance de calcul des processeurs électroniques a rendu possible la réalisation de récepteurs optiques cohérents intradyne, qui ne nécessitent pas la synchronisation d'un laser local à la porteuse optique du signal.

L'utilisation d'une modulation de phase et d'un multiplexage en polarisation offre d'immenses possibilités en termes d'efficacité non seulement spectrale mais aussi énergétique, en adaptant les techniques de communications numériques déjà développées pour les systèmes radio pour redimensionner les systèmes optiques. La limite ultime des performances du canal optique est alors donnée par la théorie de l'information. Les deux effets limitants majeurs sont les effets non-linéaires (notamment Kerr) peu présents en radio, et les pertes dépendant de la polarisation du champ optique (PDL).

Via le co-encadrement de la thèse Cifre de Pierre Delesques, j'ai contribué à l'étude de ces deux effets et leur influence sur la capacité des systèmes optiques.

Nous avons notamment étudié la pertinence d'insérer une bande de garde entre canaux WDM afin de réduire l'impact de l'effet Kerr sur la capacité. Nous avons conclu que cette réduction n'est pas suffisante pour compenser la perte de bande passante que représente le spectre inutilisé des bandes de garde ; celles-ci ne sont donc pas utiles du point de vue de la capacité du système.

D'autre part, nous avons modélisé la PDL et son impact d'un point de vue statistique, utilisant le critère de la probabilité de coupure, dérivé de la capacité. Nous avons confirmé le type le plus pertinent de distribution aléatoire pour cet effet, et trouvé une borne supérieure de la pénalité entraînée par la PDL, qui ne dépend que de l'efficacité spectrale de la modulation. Enfin, la comparaison de la probabilité de coupure à des performances système simulées a montré que l'usage de codes spatio-temporels combinés à des codes correcteurs d'erreurs LDPC permet d'approcher la limite théorique à quelques dB de pénalité sur le rapport signal à bruit.

La recherche sur les communications optiques cohérentes est maintenant portée, d'une part, sur la mitigation des effets non linéaires ; et d'autre part sur l'utilisation de fibres multimodes ou multicœurs. La première est probablement possible malgré la présence d'un maximum sur les courbes de capacité en fonction de la puissance optique — ce qui est contre-intuitif, et probablement un artefact plus qu'une limitation fondamentale. Les fibres multicœurs sont souvent citées comme une solution possible pour dépasser ce maximum de capacité, mais c'est un effet mécanique ; la capacité par cœur ne change pas. Il est possible que les fibres multimodes représentent une réelle amélioration, si les modes de propagation s'avèrent moins sujets aux non-linéarités du fait de leur plus grande aire effective, et à condition que se résolvent les problèmes liés à l'injection sur plusieurs modes.

L'avenir dira laquelle de ces solutions permettra de repousser à nouveau les limites des systèmes optiques.

B.2 Réseaux d'accès optiques

Les réseaux d'accès optiques actuellement en cours de déploiement sont dimensionnés pour des débits de l'ordre du gigabit par seconde jusqu'à des distances de 20 km, soit en point-à-point, soit via un réseau optique passif (PON) où quelques dizaines d'utilisateurs partagent la bande passante. Ils relèvent avant tout d'une problématique de faible coût, mais doivent être en mesure de répondre à l'exigence des services toujours plus gourmands en débit.

J'ai contribué au développement de systèmes optiques à accès multiple par répartition de codes (CDMA) utilisant une source continuum unique ; et au développement de SOA, notamment réfléchissants, pour le réseau d'accès.

B.2.1 Découpage spectral pour l'OCDMA

Parmi les voies possibles d'augmentation du débit des réseaux d'accès, on trouve le WDM et le CDMA. Le premier a fait ses preuves dans les réseaux cœur et métropolitain, il serait logique d'en bénéficier également pour l'accès. Toutefois, l'utilisation d'une source laser par longueur d'onde, et l'attribution d'une longueur d'onde à chaque utilisateur, posent des problèmes logistiques à grande échelle.

Dans le cas du CDMA, on exploite une technique utilisée en radio permettant une grande flexibilité dans le partage de la bande passante : plutôt qu'attribuer aux utilisateurs des fréquences ou des longueurs d'ondes, ou des intervalles temporels nécessitant une synchronisation, on leur fixe un code qui permet à leurs transmissions d'être décodées indépendamment des autres utilisateurs, même lorsque tous ceux-ci émettent en même temps dans la même bande.

Nous avons démontré des systèmes WDM et CDMA utilisant le découpage spectral d'une source large bande, à base de génération de continuum optique dans une fibre hautement non-linéaire. [127, 129] Le codage et décodage CDMA est réalisé de façon tout-optique par des codeurs à réseau de Bragg, qui permettent en outre d'effectuer le codage en phase, se rapprochant ainsi du cas idéal où le décodage élimine complètement le bruit créé par le trafic non désiré provenant d'autres utilisateurs.

Ce travail a été effectué dans le cadre de la thèse de Steevy Cordette et du projet ANR SUPERCODE, pour lesquels j'étais respectivement directeur de thèse et responsable scientifique pour Télécom ParisTech. Le projet SUPERCODE rassemblait d'autre part l'Institut Carnot de Bourgogne (porteur du projet) et les laboratoires Xlim et PhLAM. Notre contribution repose essentiellement sur la modélisation et l'intégration du système global.

B.2.2 Amplificateurs optiques à semi-conducteurs pour les réseaux d'accès

Les SOA ont actuellement développés pour deux rôles dans le réseau d'accès : d'une part, l'extension de portée, qui nécessite une amplification, surtout dans le cas des PON, dont le budget de puissance optique est limité du fait du partage d'une fibre entre de nombreux utilisateurs au moyen de coupleurs passifs. Or, pour des raisons historiques, et contrairement au cas des transmissions longue distance, les PON n'utilisent pas la bande C (1530-1560 nm) et ne peuvent donc exploiter la technologie maîtrisée des

amplificateurs à fibre dopée à l'erbium (EDFA). Ce sont donc les SOA qui sont pressentis pour réaliser des « extender-box » permettant d'éloigner le central du client.

D'autre part, les SOA réfléchissants (RSOA), notamment utilisés comme modulateurs d'une source optique déportée, pourraient éliminer les problèmes logistiques liés à l'attribution d'une source à chaque utilisateur. Ils sont adaptés aux terminaux de clients, ainsi qu'aux stations de base pour la radio sur fibre.

La thèse Cifre de Guilhem de Valicourt, que j'ai encadrée côté académique en collaboration avec III-V Lab, a permis de réaliser des RSOA d'une bande passante largement supérieure à l'état de l'art, avec démonstration de transmission jusqu'à 20 km. [16]

B.3 Commutation optique

Bien que les réseaux haut débit actuels soient fondés sur des transmissions optiques, force est de constater que toute la commutation se fait dans le domaine électrique. En effet, les traitements que permet l'électronique sont beaucoup plus complexes et mieux maîtrisés ; d'autre part, chaque conversion optique-électrique (O-E), bien qu'étant un goulet d'étranglement quant aux performances, présente l'avantage de régénérer le signal transmis ; enfin, le routage indépendant des paquets de données est un modèle qui a fait ses preuves via le protocole Internet (IP). La tendance naturelle est donc à des nœuds de commutation où tout le trafic est ramené dans le domaine électrique et acheminé par des routeurs IP, dont on fait évoluer la capacité en ayant recours à des traitements massivement parallèles.

Cette tendance touche peut-être à son terme, principalement du fait que cette approche donne lieu à une consommation énergétique incontrôlée. [60] Cette consommation, ainsi que la dissipation de la chaleur produite, sont désormais les principaux problèmes de mise en œuvre d'équipements réseau à grande échelle, avec les coûts associés.

Il n'est pas impossible que la solution vienne à nouveau du tout-électronique [115], qui après tout a été vainqueur de la plupart des confrontations avec l'optique jusqu'à présent. Néanmoins, une alternative à la prolifération des convertisseurs O-E serait grandement appréciée ; la recherche de techniques permettant de déléguer à l'optique tout ou partie de l'intelligence du réseau demeure très active.

J'ai contribué d'une part, via la thèse de Hassan Teimoori, à la reconnaissance tout-optique d'en-têtes dans une logique de commutation de paquets optiques. D'autre part, suite à mon séjour d'études à Columbia University, je me suis intéressé à la commutation hybride optique-électronique, notamment comme point de départ à une remise à plat des architectures de réseaux dans le but de surmonter la barrière de la consommation énergétique.

B.3.1 Reconnaissance d'en-têtes haut débit

La reconnaissance d'en-têtes à haut débit cible des en-têtes véhiculés par les premiers bits du paquet qu'ils étiquettent, solution conventionnelle mais impliquant un en-tête transmis au même débit que la charge utile, donc rapide. On peut soit effectuer un prétraitement optique pour se ramener au débit paquet, gérable par l'électronique ; soit avoir recours à des portes logiques tout-optiques. Ces deux possibilités ont été explorées au cours de la thèse de Hassan Teimoori, co-encadrée par moi-même.

D'une part, nous avons eu recours à un convertisseur série-parallèle à base de FWM entre les bits d'en-tête et une impulsion à spectre large, chirpée par une fibre dispersive. [109, 111] Ce dispositif recopie les bits d'en-tête successifs à des longueurs d'ondes différentes, aisément séparables. Ils peuvent alors être traités par de la logique soit conventionnelle, soit si nécessaire tout-optique. Nous avons étudié et démontré plusieurs types de portes logiques tout-optiques, notamment à base de rotation de polarisation dans les SOA, et d'interféromètres non-linéaires ultrarapides (UNI). [107, 110] Ces dispositifs restent toutefois d'utilisation délicate tant qu'ils utilisent des composants discrets. Une implémentation en optique intégrée aiderait énormément à leur utilisation pratique.

B.3.2 Commutation hybride opto-électronique

Une approche plus pragmatique, au lieu de poser l'optique en concurrence directe à l'électronique, répartit les rôles entre ces deux technologies. Par exemple, l'architecture développée à Columbia University, où j'ai effectué 10 mois de séjour d'études en 2010–2011, utilise des paquets optiques multi-longueurs d'ondes : chaque paquet comporte une charge utile (typiquement à 100 Gbps répartis sur 10 longueurs d'ondes), et plusieurs longueurs d'ondes de contrôle qui encodent l'adresse de destination à bas débit, permettant à des portes logiques de configurer une matrice de commutation 4×4 (4 blocs 2×2) à base de SOA, afin d'amener le paquet au port souhaité.

Notre vision propose d'utiliser une telle matrice optique en combinaison avec un routeur IP conventionnel (relié à deux ports de la matrice via des convertisseurs O-E) et des dispositifs de surveillance de la qualité de transmission interfacés à un plan de contrôle local. L'ensemble ainsi constitué possède ainsi à la fois une capacité de routage conventionnel, supplémentée par la matrice optique pour le trafic ne nécessitant pas la puissance d'IP (par exemple des flux de données établis au préalable), et une capacité de récupération immédiate après défaillance d'un lien ou du routeur IP lui-même en reconfigurant la matrice de commutation suivant une configuration dégradée précalculée qui aiguille le trafic vers d'autres nœuds (le calcul d'une meilleure configuration étant laissé aux soins du plan de contrôle global en temps utile). Nous avons démontré expérimentalement la méthode proposée de récupération après défaillance du routeur. [130]

J'ai par la suite, via la thèse de Pierre Delesques, contribué à l'analyse de performances d'un tel nœud hybride. Le principal problème est la contention sur la matrice de commutation optique, du fait qu'aucune fonction de mémoire n'est praticable de façon optique ; des paquets de même destination arrivant simultanément sont donc perdus, ce qui entraîne une piètre performance des commutateurs tout-optiques en termes de probabilité de perte de paquets en fonction de la charge du nœud.

Dans l'architecture hybride décrite, le routeur IP peut agir comme une mémoire permettant de stocker les paquets qui auraient été perdus, ce qui améliore grandement la probabilité de perte. Notre modèle indique que cette amélioration dépend fortement du nombre de ports du commutateur affectés à la mémoire électronique, ainsi que du degré du nœud dans le réseau et du nombre de canaux disponibles pour chaque lien optique [23].

L'étude se poursuit afin de quantifier plus précisément la gamme de paramètres où ce commutateur hybride est une solution intéressante par rapport au tout-optique et au tout-électronique.

B.3.3 Vision : réseaux optiques « cross-layer »

Les deux approches évoquées ci-dessus pour le routage optique nécessitent, pour être utilisables en pratique, une gestion évoluée du réseau, que ce soit pour l'allocation des en-têtes, ou du fait que se passer de conversions O-E renonce au bénéfice d'une régénération implicite du signal.

Le fait est que peu de fonctions optiques ont réellement été pensées pour le réseau dans sa globalité, ce qui explique leur succès limité hors du laboratoire. La conception en couches des réseaux conventionnels exacerbe ce problème, dans la mesure où l'optique reste cantonnée à la couche physique ; pour essayer vers les couches supérieures, elle nécessiterait l'implémentation de fonctionnalités très spécifiques à l'état de l'art de l'électronique.

Toutefois, la barrière de la consommation énergétique est une opportunité à saisir pour un renouveau des fonctions optiques, dans la mesure où l'architecture conventionnelle est un obstacle à dépasser cette barrière. Des architectures de réseaux « cross-layer » entièrement nouvelles, faisant table rase des couches conventionnelles, semblent indiquées [85].

Afin de rendre possible cette vision, le paradigme des couches ne peut être simplement abandonné, car le problème de la conception de réseau deviendrait intraitable. Il doit donc être remplacé par un nouveau cadre permettant l'abstraction des différents éléments des réseaux.

Les réseaux logiciels (SDN) optiques, notamment sur la base du protocole OpenFlow et ses extensions [7, 48, 94], suscitent actuellement un intérêt grandissant. Il serait extrêmement intéressant d'évaluer leur aptitude à former un tel cadre, qui permettrait aux fonctions optiques d'exprimer tout leur potentiel.

Perspectives

Mes activités de recherche des prochaines années s'orientent selon deux axes : les réseaux optiques « cross-layer » et les communications optiques cohérentes.

L'optimisation des réseaux optiques au-delà du modèle en couches répond au besoin de surmonter la barrière de la consommation énergétique. Une nouvelle conception des réseaux, partant des besoins des utilisateurs et faisant appel aux meilleurs outils possibles, laissera certainement une bien plus grande place aux fonctions optiques que dans les réseaux actuels. Traiter ce problème se fera dans un cadre tel que SDN, qui permettra d'exprimer plus simplement la complexité d'une telle approche.

Les communications optiques cohérentes, quant à elles, sont un sujet de recherche moins novateur, mais il est nécessaire d'évaluer la place qu'elles devront tenir dans un réseau centré sur les fonctions optiques. De plus, elles n'ont pas dit leur dernier mot sur la mitigation des effets non-linéaires, ce qui permettra de repousser à nouveau les limites ultimes des systèmes de communications.

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List of...

Ph. D. theses

- Fausto Gómez Agis
“Clock recovery of ultra-high speed OTDM signals by phase-locked loop based on PPLN” 2008
(advisorship shared with Prof Didier Erasme, Télécom ParisTech) [10](#)
- Guilhem de Valicourt
“Design, realization and evaluation of remote modulators for optical access networks and radio over fiber” (advisorship shared with Dr Romain Brenot, III-V Lab); 2011
recipient “Paul Baran Young Scholar” award of the Marconi Society (2012)
[26](#)
- Hassan Teimoori
“Optical-logic-gate aided packet-switching in transparent optical networks” (advisorship shared with Prof Didier Erasme, Télécom ParisTech) 2007
[30](#)
- Pierre Delesques
“New modulation types for fiber optics communication networks” (advisorship shared with Prof Philippe Ciblat, Télécom ParisTech and Dr Gwillerm Froc, Mitsubishi Electric R&D Centre Europe) 2012
[15](#), [16](#), [34](#)
- Steevy Cordette
“Optical frequency continuum for OCDMA application” (advisorship shared with Prof Catherine Lepers, Télécom SudParis) 2010
[20](#)

Projects

- e-Photon/ONe⁺
“Optical Networks: Towards Bandwidth Manageability and Cost Efficiency”. 2006–2008
European FP6 Network of Excellence. Partners: PoliTo (leader), 40 academic and industrial institutions, from 17 pan-European countries.
My role: leader, Joint Action on ultrafast clock recovery. [11](#)
- COST 288
“Nanoscale and Ultrafast Photonics”. 2003–2008
European COST action. Partners: 20 pan-European countries.
My role: National Delegate for France (2005–2008); Vice-Chairman of work package on ultrafast devices and systems.
- COST 291
“Towards digital optical networks”. 2003–2008
European COST action. Partners: 21 pan-European countries.

- EURO-FOS
“Pan-European Photonics Task Force”.
European FP7 Network of Excellence. Partners: NTUA (leader), 17 academic institutions.

2008–2012

My role: leader, Joint Experimental Activity on ultrafast clock recovery. [11](#)

- SUPERCODE
“Supercontinuum source for code-division multiple access”.
French ANR “blanc” project. Partners: ICB (leader), XLIM, LTCI, PhLAM.
This project aimed at designing and demonstrating an OCDMA setup using a broad-spectrum optical source that can be shared among users on different wavelengths and different optical codes, and all-optical OCDMA encoders and decoders based on fiber Bragg gratings for spectral phase encoding.

2006–2009

My role: scientific responsible for partner LTCI; responsible for workpackage on system integration. [20](#), [23](#)