Excursion-Free Dynamic Wavelength Switching in Amplified Optical Networks

Atiyah S. Ahsan, Colm Browning, Michael S. Wang, Keren Bergman, Daniel C. Kilper, and Liam P. Barry

Abstract—Dynamic optical networking with rapid wavelength reconfiguration is a promising capability to support the heterogeneous, bursty traffic rapidly growing in metro-area networks. A major obstacle to realizing dynamicity in the optical layer is the channel power excursions that occur due to continuously changing input conditions into gain controlled optical amplifiers. Here we present a technique of distributing an optical signal across multiple wavelengths chosen to reduce or cancel the power dynamics so that excursion-free switching can be achieved in an optically amplified transparent network. The use of variable wavelength dwell times for excursion-free switching using arbitrary wavelength pairs is presented. Spectral efficiency loss in utilizing multiple wavelengths is recovered through time-division multiplexing two signals distributed over the same wavelengths.

Index Terms—Erbium-doped fiber amplifiers; Optical power excursion; Wavelength division multiplexing; Wavelength switching.

I. INTRODUCTION

Growing demand for speed and bandwidth, along with increasing energy consumption in today’s networks, are driving the need for intelligent next-generation networking architectures that can efficiently scale while fulfilling tightening energy and optical spectrum constraints. Current quasi-static optical networks, with peak traffic capacity provisioning of large static “big pipes,” make poor use of available resources and are ill-equipped to support emerging traffic trends [1]. Network traffic is increasing at near-exponential rates, and new sources of demand are continuously emerging [2]. With the advent of the Internet of Things, the number of data-intensive devices connected to the Internet is projected to reach 50 billion by 2020. Bulk data transfer between geographically distributed data centers over commodity Internet is on the rise due to growing big data and cloud computing applications. This inter-data-center traffic is bursty, with the amount of data transferred ranging from several terabytes to petabytes [3,4]. The rapid growth in metro-only traffic, which is expected to surpass long-haul traffic by 40% in 2017, is further contributing to the high volume of less aggregated, bursty network traffic. Dynamic optical networking capabilities, in which bandwidth is allocated in real time in the physical (optical) layer in response to changing traffic demands, become increasingly desirable to enable next-generation networks to support such unpredictable, high-bandwidth but short-lived traffic flows [5].

Fast wavelength reconfiguration is key to achieving a dynamic optical network. While there has been significant work on protocols to enable dynamic wavelength reconfiguration and studies have shown light-path setup times below 3 s [6–8], fast wavelength reconfiguration has yet to be implemented at scale in commercial networks. A key unresolved obstacle to implementation is the channel power excursions that arise and propagate throughout a network due to changing channel wavelength configurations in an automatic gain controlled (AGC) optically amplified system [9]. Recent studies on dynamic optical networks either use prereserved wavelengths or assume that the power dynamics problem will be solved—but to date, no comprehensive solution exists [5]. To realize a truly dynamic optical network, it is necessary to develop techniques that allow reconfiguration on the order of seconds or faster while maintaining stable network operation. Previous work has demonstrated that power excursions can be reduced by using a center-of-mass-based wavelength assignment approach [10]. However, this was only shown to provide a 15% improvement, while limiting the available configuration.

In this work, we propose a new approach of distributing the optical power of a single signal over multiple wavelengths such that the sum of the individual gain excursions cancels, thus mitigating the power dynamics of wavelength reconfiguration. The networking problem being addressed by this technique is discussed in detail in Section II. The proposed technique and the experimental setup are described in Sections III and IV, respectively. The use of this technique to null power excursions of 2 dB is experimentally demonstrated using 1) wavelengths that cause equal and opposite power excursions and 2) wavelengths that cause opposite excursions of different magnitudes by varying the wavelength dwell time. Time-division multiplexing (TDM) of two signals distributed over the same wavelengths is successfully implemented to avoid loss of...
spectral efficiency. These results are presented in Section V.

II. PROBLEM BACKGROUND

Channel powers in networks have to be maintained within a certain range to meet the optical signal-to-noise ratio requirements and avoid cross-talk from high-power neighboring channels (lower bound) and to avoid nonlinear transmission impairments (upper bound). Channel power excursions can be highly detrimental when they cause deviation from this required power range. These power excursions occur because AGC algorithms maintain constant gain by monitoring the total input and output optical powers, and do not take into account the wavelength-dependent gain arising from the gain tilt and ripple of the amplifier and fiber plant. Consequently, a change in input wavelength configuration into an amplifier, even for constant input power on each channel, can affect the gain of individual channels, as depicted in Fig. 1. Consider initially $\lambda_C$ as the only input channel. If $\lambda_1$, which has higher gain than $\lambda_C$, is added at the same input power, the total input power doubles, but the total monitored output power increases by more than a factor of 2. In order to maintain constant gain, the AGC decreases the gain and $\lambda_C$ undergoes a negative power excursion. The reverse process happens if $\lambda_2$ is added instead, and $\lambda_C$ undergoes a positive power excursion. The size of the excursions depends on a variety of factors such as the number of channels, the channel distribution, and the number of links. These excursions can further be impacted by spectral hole burning and mean gain-dependent gain tilt in erbium-doped fiber amplifiers (EDFAs) and stimulated Raman scattering (SRS) in the transmission fiber [11]. Excursion values as high as 7.5 dB for a 20 channel add/drop have been reported [12].

The channel power coupling effect described above grows with a cascade of amplifiers [13], and power divergences of 15 dB were observed in recirculating loop experiments with AGC EDFAs [9]. As a result, the effect of a single reconfiguration event can propagate through the network and cause persistent power excursions and network instability, and even oscillations in the worst case [14,15]. This issue is particularly acute in mesh metro-area networks, which is characterized by a large number of short amplified ROADM links with many amplifiers. In current generation quasi-static optical transmission systems, power excursions are avoided by using offline planning tools and long reconfiguration times encompassing many adjustments along an optical path [9,16]. This reconfiguration time has to be decreased to the order of seconds in order to enable promising technologies for emerging traffic patterns such as real-time wavelength switched optical bypass, physical layer protection/restoration, and energy-efficient transceiver sleep modes. Thus it is imperative to develop techniques that enable excursion-free, rapid wavelength reconfiguration.

III. PROPOSED TECHNIQUE

A. Principle of Operation

The proposed technique distributes the optical power of a single signal over multiple wavelengths such that the individual gain excursions cancel one another, so that the power dynamics of wavelength reconfiguration are reduced or eliminated. Fast-tunable lasers that can switch between wavelengths on nanosecond time scales are used to distribute the optical power. EDFAs have gain response time constants on the order of hundreds of microseconds or even milliseconds and therefore do not respond to any power fluctuations occurring at a faster time scale. For example, if the tunable laser switches over N wavelengths with equal dwell times summing to less than a microsecond, the EDFA perceives it as N static channels, each at (1/N) the total laser power. By using balanced wavelengths, which cause equal and opposite power excursions, the power fluctuations that arise when switching these signals can be negated.

Due to network constraints it may not always be possible to choose a balanced pair/set of wavelengths that cause equal and opposite excursions. However, by varying the dwell time ratio (DTR) between a pair of unbalanced switching wavelengths, their relative contributions to the resultant excursions can be skewed so that excursion-free operation is achieved. For example, two unbalanced wavelengths, $\lambda_1$ and $\lambda_2$, added at equal power, cause excursions of $+x$ and $-y$ dB, respectively, where $|x| > |y|$. Since the amount of excursion caused by a wavelength depends on its power, zero net excursion can be achieved by decreasing the power on $\lambda_1$ and increasing the power on $\lambda_2$. For the fast-switching scenario, the effective power on a wavelength, as perceived by the EDFA, is proportional to the dwell time on that wavelength, and excursion-free switching using $\lambda_1$ and $\lambda_2$ can be achieved by increasing the dwell time on $\lambda_2$.

B. Time-Division Multiplexing for Spectral Efficiency

Since the signal is switching over multiple wavelengths, it occupies only a single wavelength at any given instant in time. Thus there are times when a wavelength is not being utilized but is still reserved for the signal, resulting in spectral inefficiency. While this is not a problem in lightly
The model predicts the output system can be modeled using the dynamic power control paradigm in the network. The response of an AGC amplified techniques have to be developed in order to deploy this paradigm in the network. Once network considerations, it is not scalable for networks that have higher traffic demands. For example, if signals are distributed over two wavelength positions, then the total spectral efficiency of the system would be reduced by 1/2. In order to overcome this issue, TDM can be used. For example, initially signal 1 is distributed over \( \lambda_1 \) and \( \lambda_2 \) but occupies either the \( \lambda_1 \) or the \( \lambda_2 \) time slot at any given instant in time. When a new demand for capacity is initiated, and signal 2 is provisioned, it can be distributed over \( \lambda_1 \) and \( \lambda_2 \) as well by ensuring that it occupies the \( \lambda_1 \) slot when signal 1 is at \( \lambda_2 \) and vice versa. The effective power on each wavelength, as perceived by the EDFA, doubles in this case. This concept is illustrated in Fig. 2.

C. Network Considerations

New wavelength assignment and network control techniques have to be developed in order to deploy this paradigm in the network. The response of an AGC amplified system can be modeled using the dynamic power control equations outlined in [17]. The model predicts the output powers of WDM channels from an amplified system for different input conditions so that wavelength sets can be chosen intelligently for zero excursion. The model requires information about the accumulated gain ripple in the amplified link, and this can be measured using probe wavelength signals [18,19]. Fast-tunable lasers can also be used as short duration probes for gain spectrum measurements. In systems that use a wide variety of makes and models of amplifiers, the variation in gain ripple will limit how well the power excursions are reduced. The extent of benefit will depend on how many wavelengths the signals are distributed over and how well they sample the range of gain spectra. Synchronization techniques for the TDM operation have to be explored. Signals from the same source location may use a common low-frequency clock for synchronization. Additional TDM synchronization will be required when sources from different locations are multiplexed.

Since a signal is distributed over multiple wavelengths, the amount of dispersion will be different for the different wavelengths across the band. Electronic dispersion compensation needs to rapidly compensate for the different amount of dispersion, and this can be achieved by using preset values given that the switching is between known wavelength sets. For metro-area networks, where dynamicity will be most beneficial, differences in dispersion are not going to be considerable as the distances traversed are relatively short.

Data on the switching wavelengths can be received error-free within nanoseconds of the switching event. Previously, it was demonstrated that for \( m \)th power double differential QPSK signals, data transmission is error free 30 ns after switching [20]. For direct detection burst mode orthogonal frequency division multiplexing (OFDM) signals, error-free transmission is achieved after 8 ns [21]. Note that additional delays may be introduced due to group delay differences between channels at different wavelengths. For dispersion shifted fibers and dispersion compensated systems, this effect is likely to be negligible. For uncompensated standard single-mode fiber (SSMF) delays on the order of 1 ns/km are possible leading to 100 ns scale delays in large metro networks. This introduces some amount of overhead in the system. For example, for 200 ns dwell time on each wavelength, which is the configuration for this experiment, the overhead (neglecting fiber group delay variations) is 15% for DD-QPSK and 4% for DD-OFDM signals. The overhead can be decreased by increasing the dwell time on each wavelength. For dwell times of 10 ns (which is still significantly lower than the EDFA response time), the overhead is less than 1%. The capacity loss due to this amount of overhead is acceptable since this technique allows wavelength re provisioning on the order of seconds and faster, limited by the switching speeds and not by the optical power tuning. Wavelength re provisioning using current techniques can take up to days and results in significantly greater capacity loss. The world record for the fastest wavelength provisioning was recently reported as 19 min and 1 s [16].

D. Scope of Current Work

The main focus of this work is to investigate the ability of the proposed technique to achieve excursion-free fast wavelength reconfiguration. Power fluctuations of the channels in the system are studied as the introduction of switching channels in the network will affect existing channels through power coupling effects; consequently, power excursions on these other channels are the best indicators of both the transmission quality of the channels and the network stability. We establish the parameters (wavelength and wavelength dwell time) that can be adjusted so that any available wavelength sets can be used for excursion-free wavelength reconfiguration. We ensure that spectral
efficiency can be maintained by successfully implementing excursion-free TDM fast wavelength switching. Future work will investigate 1) the transmission performance of different modulation formats for TDM fast wavelength switching, 2) network control techniques for TDM synchronization of sources from different locations, and 3) wavelength assignment using offline models and gain spectrum probing.

IV. EXPERIMENT

The experimental setup is shown in Fig. 3. A software controlled sampled grating–distributed Bragg reflector (SG-DBR) fast-tunable laser is used to perform wavelength switching. The laser can operate in both static and fast-switching modes and can access 83 wavelengths (numbered 11–94) across the 50 GHz ITU grid in the C-band. In fast-switching mode, each wavelength can be assigned a dwell time of between 200 ns and 10 μs. Since the power coupling effect due to the wavelength switching is agnostic to the presence of data and depends solely on the wavelength configuration and power values, a comb source in conjunction with a wavelength selective switch (WSS) is used to introduce additional wavelengths across the band. This provides the flexibility to study a wide range of channel configurations, and the results for a worst-case scenario are presented in the following section. The input power of all wavelengths is maintained at −23 dBm per wavelength into the first EDFA. All EDFAs operate in constant gain mode at 9.0135 dB. Two spans of SSMF (25 and 20 km) are used, and VOAs after each span adjust the optical power to an average of −23 dBm per wavelength. A WSS is used to drop one of the static wavelengths that are detected with a 250 MHz PIN detector, followed by a 2 MSa/s data acquisition (ADC) board to measure power dynamics.

In order to study TDM operation, the transmitter block of the setup diagram in Fig. 3 is replaced with the transmitter block shown in Fig. 4. As only one SG-DBR was available, the TDM operation was synthesized by time multiplexing a pair of CW signals from the comb source using electro-optic switches. In this case the switching wavelengths are always on as the fast electro-optic switches are used to switch, alternately, between the two wavelengths. The two pairs of signals are synchronized with a common clock and combined in a 50/50 optical combiner. Note that this is also an alternative implementation to using a fast-tunable laser source: using multiple single wavelength signals and selectively activating or modulating them with a fast switch or modulator. The switch dwell time in this experiment for the TDM case was varied from microseconds to seconds, with no additional excursions on other wavelengths.

V. RESULTS AND DISCUSSION

A. Balanced Wavelength Switching: Basic Operation

Figure 5(a) shows the experimental and modeled power excursion amplitudes, caused by transmission through one EDFA, on wavelength 1547.72 nm (No. 45) when an additional wavelength is added at a wavelength corresponding to the “Channel Index” on the horizontal axis. The figure shows that the observed wavelength experiences both positive and negative excursions as channels are added at different wavelengths across the spectrum. These excursions are not symmetric as the tilt and ripple functions of the EDFA are not symmetric and the tilt varies with the gain. The figure shows that the addition of wavelength No. 11 (1561.44 nm) causes an opposite excursion to that caused by wavelength No. 73 (1536.61 nm): ±0.4 dB (referred to here as a “balanced” pair). These excursions are shown in the time domain in Fig. 5(b). This figure also shows that no excursion is caused when the laser switches quickly (dwell time = 200 ns) between these two balanced wavelengths. Since the dwell time of the two fast-switching channels is below the gain response time of the EDFA (microseconds), they have the same effect as two static channels that cause opposite excursions. Thus, by distributing the channel power over two or more wavelengths that are balanced in this way, the system no longer exhibits channel power excursions when the new signal is added or removed. Thus, persistent power excursions, which are a key limitation preventing dynamic wavelength operation, are removed.
B. Balanced Wavelength Switching: Network Scenario

It is important to show how excursion-free fast wavelength switching can work in a metro network scenario as excursions grow larger with each additional amplifier along the path [13]. To study this we examine wavelength switching of such wavelength distributed signals in a WDM system (the setup in Fig. 3) with multiple wavelengths. Figure 6 shows the output spectra of the WDM signals used to test the technique. The accumulated wavelength-dependent gain ripple through the system is 7.5 dB. Here the tilt is adjusted to be high to emulate the effect of a much larger amplified system. A single amplifier with large ripple or tilt has been shown to be equivalent to a cascade of identical amplifiers with a combined ripple and tilt of the same form, neglecting gain-dependent tilt [13]. Excursions on four wavelengths provided by the comb source (pink) are measured as the SG-DBR is repeatedly moved (on a millisecond time scale) from one balanced pair (switching on a nanosecond time scale) of wavelengths (light blue, 1538.98 and 1539.77 nm) to an unbalanced pair (black, 1529.95 and 1530.33 nm); i.e., the SG–DBR initially switches on a nanosecond time scale between two balanced wavelengths (light blue), and is quickly reconfigured to switch between two unbalanced wavelengths (black). This reconfiguration, between the balanced pair and the unbalanced pair, is continuously repeated on millisecond time scales. The same measurements are made as the laser repeatedly tunes from one balanced pair (light blue) to another balanced pair (orange, 1535.45 and 1554.95 nm).

The resultant excursions on the four static wavelengths in the system (pink channels in Fig. 6) are shown in Fig. 7, which exhibits excursions of around 2 dB on each channel, as the laser repeatedly tunes between a balanced pair and an unbalanced pair. In contrast, excursion-free operation is obtained on all wavelengths when the laser repeatedly tunes between two balanced pairs of wavelengths. We observe similar behavior in simulation. Note that the tuning back and forth between different wavelength pairs, shown in these figures, is on the scale of hundreds of microseconds, which is the typical response time of AGC EDFAs. These results show how choosing the nanosecond switching wavelength locations intelligently can provide excursion-free addition, and rerouting, of packet/burst/circuit switched data channels in a network.

C. Variable Dwell Time Ratio

The results in the previous section show the mitigation of power excursions using balanced wavelengths with...
equal dwell times. As dwell times are well below the EDFA response time, the addition of this pair of switching wavelengths is the equivalent, to the amplifier, of adding two static wavelengths at 3 dB below their actual input power; i.e., the equal allocation of sub-EDFA response dwell times translates (from the point of view of the EDFA) to distributing the instantaneous optical power equally over two wavelengths. This effect can be observed in Fig. 6 because the sweep time of the optical spectrum analyzer used is also significantly longer than the dwell time. In the figure, switching wavelength pairs are both shown to have a power of 3 dB below neighboring static wavelengths, even though all launch powers are maintained instantaneously at \(-23\) dBm. As the AGC EDFA algorithm works by monitoring the total input optical power, power excursions arising from the addition of new wavelengths depend on the input power of those wavelengths (as they appear to the EDFA) and, by extension, the ratio of the switching wavelength dwell times.

Figure 8 shows unbalanced switching wavelengths with variable DTRs used for excursion-free operation. The same static wavelengths (pink) and initial balanced switching wavelengths (blue), as outlined in Subsection V.B, are used. This time, however, the laser is reconfigured to switch between the unbalanced pair 1561.42 and 1530.33 nm [solid black, Fig. 8(a)]. A second unbalanced pair, 1549.75 and 1530.33 nm [dashed black, Fig. 8(b)], is also demonstrated. Figure 9(a) shows excursions on all static channels when the laser is reconfigured from the balanced pair (blue) to the unbalanced pair [solid black, Fig. 8(a)], for DTRs of 1:1 and 4:1. When equal dwell times are employed there is a residual excursion of about 1 dB on all wavelengths. However, with a DTR of 4:1, excursion-free operation is achieved as the effective contributions to excursion, from either wavelength, are equalized. Figure 9(b) shows the same results for the second wavelength pair used [dashed black, Fig. 8(b)]. In this case, a wavelength closer to the mean gain of the channel, 1549.75 nm, is used in conjunction with 1530.33 nm to balance the excursions. As the new wavelength causes smaller excursion than the previous one, an increased DTR of 6:1 is required to achieve excursion-free operation.

**Fig. 8.** Spectra of the network configuration with a balanced wavelength pair (blue) and balanced wavelength pairs with different dwell time ratios (black).

**Fig. 9.** Excursions on all static wavelengths for (a) wavelength switching with DTRs of 1:1 and 4:1 (solid black, Fig. 8) and (b) wavelength switching with DTRs of 1:1 and 6:1 (dashed black, Fig. 8).

**Fig. 10.** Power excursion from balanced TDM wavelength switching.
D. Time-Division Multiplexing

The effect of TDM switching signals on channel power is also studied. Figure 10 shows the excursions on the wavelengths in the system (pink in Fig. 6) when the two time multiplexed CW signals are changed, between the two balanced wavelength pairs (light blue and orange in Fig. 6) as outlined in Subsection V.B. Excursions of <0.1 dB are achieved on all measured wavelengths. In the TDM configuration, for dwell times ranging from seconds down to 125 μs, negligible excursions are observed as the multiplexed wavelengths smoothly alternate within the time slots and are well synchronized.

VI. CONCLUSION

Excursion-free wavelength switching and reconfiguration has been shown in the transmission of WDM wavelengths through multiple transient controlled EDFA's and fiber spans by using a novel technique of distributing the signals over multiple channels using a fast-tunable laser. Results presented show how varying the ratio of dwell times, between distributed signal wavelengths, can offer an additional degree of freedom when choosing wavelengths that can provide excursion-free operation. Furthermore, this excursion balancing technique has been applied to the case in which full TDM switching is employed, to preserve the spectral efficiency of the system, again exhibiting negligible power excursions. While many implementation issues remain to be studied for commercial viability, this work has investigated the basic operating principles and first (to the best of our knowledge) demonstration of the technique, which opens up an entirely new form of wavelength-division multiplexing. This technique has the potential to enable the rapid growth, or rerouting, of wavelengths in a network without causing excursions on other wavelengths, which is highly desirable in next-generation reconfigurable networks.

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REFERENCES


Atiyah Ahsan received the B.Sc. degree in electrical engineering (summa cum laude, thesis with highest honors) from Tufts University, Boston, and the M.Sc. degree from Columbia University, New York, in 2010 and 2012, respectively. From May 2012 to January 2013, she worked as a student collaborator on a project led by Dr. Daniel Kilper at Bell Labs Alcatel Lucent. She is currently a Ph.D. candidate at the Columbia University Lightwave Research Laboratory under the advisement of Dr. Keren Bergman. Her research is focused on advanced optical performance monitoring techniques and cross-layer architectures for next-generation dynamic access and metro networks.

Colm Browning graduated from Trinity College Dublin (Dublin University), Ireland, in 2009 with an honors degree in electronic engineering (B.A.I.) and an ordinary degree in mathematics (B.A.). He then received his Ph.D. from Dublin City University, Dublin, Ireland, in 2013 for his study on the use of orthogonal frequency division multiplexing in optical communications systems. In 2014 Dr. Browning was awarded a Fulbright Fellowship in order to undertake visiting research at Columbia University, New York, USA. Dr. Browning is currently working as a post-doctoral researcher in the Radio and Optical Communications Laboratory at Dublin City University.

Michael S. Wang received the B.S.E. degree from Princeton University, Princeton, New Jersey, in 2008, and the M.S. and Ph.D. degrees from Columbia University, New York, in 2010 and 2014, respectively, all in electrical engineering. His doctoral thesis focused on energy efficient, cross-layer enabled, dynamic aggregation networks for next-generation Internet.

Keren Bergman (S’87–M’93–SM’07–F’09) received her B.S. degree from Bucknell University, Lewisburg, Pennsylvania, in 1988 and her M.S. and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge, Massachusetts, in 1991 and 1994, respectively, all in electrical engineering. She is currently the Charles Batchelor Professor and Chair of Electrical Engineering, Columbia University, New York, where she directs the Lightwave Research Laboratory. Her research programs involve optical interconnection networks for advanced computing systems, photonic packet switching, and nanophotonic networks on-chip. She is a Fellow of The Optical Society (OSA) and a Fellow of the Institute of Electrical and Electronic Engineers (IEEE).

Daniel C. Kilper (SM’07) is a research professor in the College of Optical Sciences, University of Arizona, and the administrative director of the Center for Integrated Access Networks (http://www.cian-erc.org/), an NSF engineering research center. He received his Ph.D. in physics from the University of Michigan. From 2000 to 2013, he was a member of the technical staff at Bell Labs, Alcatel-Lucent. He served as the founding technical committee chair of the GreenTouch Consortium and was the Bell Labs Liaison Executive for the Center for Energy-Efficient Telecommunications at the University of Melbourne, Australia. While at Bell Labs, he received the President’s Gold Medal Award and was a member of the President’s Advisory Council on Research. He is an adjunct professor at Columbia University and a senior member of the IEEE. He serves as an editor on the green communications and computing series for IEEE Communications Magazine. Dr. Kilper has conducted research on optical performance monitoring and on architectures and control systems for energy-efficient optical networks. He has co-authored four book chapters and more than 100 peer-reviewed publications.

Liam P. Barry (SM’10) received the B.E. degree in electronic engineering and the M.Eng.Sc. degree in optical communications from University College Dublin, Ireland, in 1991 and 1993, respectively, and the Ph.D. degree from the University of Rennes, France, in 1996. From February 1993 until January 1996, he was a Research Engineer in the Optical Systems Department of France Telecoms Research Laboratories (CNET) in Lannion, France. In February 1996, he joined the Applied Optics Centre, Auckland University, Auckland, New Zealand, as a Research Fellow, and in March 1998 he took up a lecturing position in the School of Electronic Engineering, Dublin City University. In 1999, he established the Radio and Optical Communications Laboratory, which is part of the Rince Institute. He is currently a Professor in the School of Electronic Engineering and a Principal Investigator for Science Foundation Ireland, Dublin, Ireland. His research interests include all-optical signal processing, hybrid radio/fiber communication systems, and wavelength tunable lasers for reconfigurable optical networks. Dr. Barry has served as a TPC member for the Optical Fiber Communication Conference (OFC), the European Conference on Optical Communication, and the Conference on Lasers and Electro-Optics Europe, serving as a Chair of the opto-electronic device strand for OFC 2010.