Optical Networking in Smart City and Wireless Future Networks Platforms

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Abstract *Innovation in optical networks is essential to delivering advanced performance for future smart city and wireless networks. Incorporating optical systems research in real-world platforms presents a number of challenges, which are addressed through recent advances in the use of software defined networking and emulation.*

Introduction

Numerous communities have developed smart city testbeds for experimenting with and testing smart city technologies and applications. Often these testbeds include a research component associated with academic and industry partners. While these testbeds commonly focus on applications, a number of examples have been developed to study the communication and computing technologies that support the applications. Bristol is Open pioneered many of the key elements of a network focused smart city testbed[1]. In the US, the platforms for advanced wireless research (PAWR) emphasize research on the wireless networks[2]. Such network research platforms allow for exploration of advanced applications that depend on the performance of the underlying networks with the potential to foster innovation of new applications.

Optical networks can be a dimension of the research testbeds for smart cities and advanced wireless networks. Optical research systems can provide ultra-reliable low latency connections and capacity far beyond what is available commercially for metro networks. In such platforms, optical systems can be integrated into the advanced wireless technologies such as massive MIMO arrays. Analog radio over fiber has performance advantages over commercial digital radio over fiber and experimentation in these testbeds can help to develop commercial solutions. Coherent PON techniques and other low cost high speed technologies promise affordable capacity solutions.

It's important to consider that many of these optical and wireless hardware technologies can be effectively studied in a research lab without resorting to a smart city testbed environment. Most research on optical transmission systems has been carried out using recirculating loop lab experiments. Transmission physics do not depend on the application environment in which the systems are deployed. However, there are effects such as polarization dynamics and wavelength switch filtering effects that can be dependent on the field environment.

Lab based optical system experiments in fact rely on hardware emulation. A recirculating loop itself is a system made up of a few fiber spans in order to emulate a much larger system of dozens or even hundreds of spans. Polarization dynamics likewise can be emulated by introducing a polarization scrambler into the loop and filtering penalties can be emulated by placing a wavelength selective switch into the loop. Recirculating loops are in fact sophisticated emulation platforms for large scale systems and it is the effectiveness of translating the emulated system performance to large scale system behavior that has made this approach effective.

Optical networking experiments by comparison have suffered from the fact that they are generally incompatible with recirculating loops. On top of this, the control dynamics of optical networks are difficult to emulate on small scales and often involve interactions with a wide range of different networking technologies. While attempts have been made to enable an element of control experimentation in recirculating loops, they have not found widespread use and suffer from a number of limitations[3]. Many aspects of control today involve multi-layer software defined networking (SDN) functionality that may require coordination with network elements outside of the optical systems through a north bound interface.

In recent years, much attention has been focused on machine learning based optical system controls such as Quality of Transmission (QoT) estimation[4]. Here again scale has become a central issue along with the control system implementation. Many QoT estimators were trained on simulators, which is effective for capturing the main transmission physics but misses the application and location specific performance issues of a deployed system.

Limitations of optical networking lab experiments motivate the use of city scale testbeds as platforms for optical networking research, particularly in a control context. They provide a means to achieve both scale and multi-

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layer control complexity. They overcome the cost barriers associated with such environments through the use of shared infrastructure. Additionally, digital twins and sandboxes can provide experimental flexibility that can approach that of an in house lab environment.

Optical Network Emulation & Simulation

The early development of optical transmission systems involved a race to increase capacity and transmission reach in a series of record setting experiments. These experiments quickly became costly and complex as the number of transceivers and optical amplifiers increased. The field underwent a dramatic transformation, however, when hardware emulation techniques were introduced. Two key innovations were the recirculating loop mentioned above and the modulation of multiple laser lines in a single modulator—eliminating the need for a full transceiver on every wavelength. In fact, numerous such emulation methods were developed in order to ensure that the recirculating loop lab experiments correctly replicated the long distance transmission phenomena.

Optical switches (i.e. reconfigurable optical add drop multiplexers, ROADMs) and mesh network topologies introduced new levels of complexity. However, recirculating loops still found application by emulating a longest path scenario through a mesh network. The impact of channels added and dropped along a path could be studied with a modified loop that effectively combined 8 loops in one[5]. Fig. 1 shows the setup in which the channel groups are selected by wavelength selective switches. Each of these groups then used a separate loop loading switch so that they can be configured to travel a different number of round trips. In this way different patterns of channels with different propagation histories could be combined and studied.

Another practice that emerged with the ROADM mesh networks is the development of digital twins to model system behavior. A digital twin simulation was developed for the LambdaXtreme system which was the first ROADM system deployed on a continental scale. This digital twin was used to develop and test algorithms for controlling optical power dynamics including transients due to fiber cuts[6].

Quality of Transmission (QoT)

QoT metrics are commonly used to predict channel performance prior to provisioning in order to spectrum assign and route signals. Historically QoT algorithms run offline prior to provisioning and involve heuristic models built from a combination of transmission physics and extensive lab system (and simulation/digital twin) tests. Today there is much interest in enabling online, real time, automated provisioning. Toward this end, many groups have explored the use of machine learning. In fact, machine learning is being studied for many different control, management, and operation functions for optical systems. A key challenge for such methods is a lack of available data for developing such algorithms and systems on which to test the algorithms and benchmark them against reference methods.

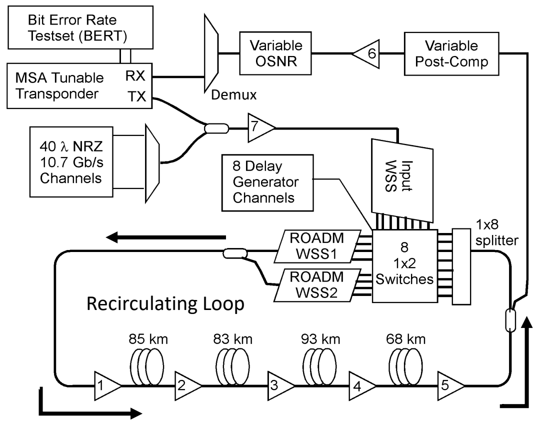

Fig. 1: Mesh network recirculating loop experiment[5].

A New Generation of System Experiments

New transmission experimental methods are needed in order to study the new generation of control methods under consideration. One such new experimental method is the use of large scale networking testbeds for smart city research. We refer to these as mesh networking platforms. These platforms do not use recirculating loops, but might use a combination of lab and field deployed fiber. These systems are necessarily deployed 'at-scale' because they physically connect radio and computing systems. While the size of such deployed networks might be limited by access to fiber or physical assets, they can be extended in labs with spooled fiber.

Recirculating loop experiments are focused on understanding transmission physics to achieve maximum reach and capacity. For a mesh networking platform the goal is to study control functionality and transmission dynamics. Control functionality includes automation methods involving data collection, analysis, and actuation cycles that must be tested over a range of conditions. Control dynamics can include optical power dynamics, alarm and feedback signal management, and switch scheduling.

Scale remains a critical feature of such testbeds that needs to be addressed and emulation methods remain important. However, the focus on the emulation is different. In a mesh transmission platform a large number of network nodes and transmission spans are required—this cannot be avoided through emulation. This is one of the key reasons that the city scale testbeds are attractive since they allow for sharing of large infrastructure investments. In addtion, there are ways in which emulation can be used to facilitate sharing and reuse of the hardware to make it more cost effective. Key emulation and mesh networking platform methods include:

1. Space switching for topology reconfiguration.

Rather than setting up a single fixed topology which then limits the range of experiments that are possible, a space switching fabric can be used to interconnect the testbed links for full flexibility in the topology configuration. First introduced as an 'architecture as a service' capability[7], this approach is well suited for testbed use. By connecting all fiber spools, outside plant fibers, amplifiers, ROADMs and PON elements, a wide variation in network architectures can be automatically configured, including both bidirectional and uni-directional systems (Fig. 2).

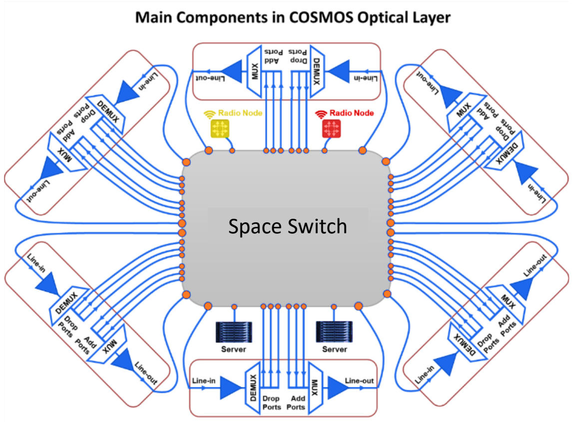

Fig. 2: ROADM mesh networking platform.

2. Comb sources/shaped ASE channel loading.

At any given time only a few channels may need to carry traffic or be of interest from a transmission performance perspective. Often the control operations only use the optical channel power and are not dependent on the modulated data. In addition, practice of using a few neighboring channels as interferers can be used as well as selectively replacing shaped ASE with active channels for channel performance measurements. Comb sources can also be split for adding at a large number of nodes in a system for little additional cost.

3. Digital twins.

Digital twins are an important tool for prototyping and debugging experiments prior to deploying them in the full scale testbed. This can be particularly effective if the digital twin accepts the same control commands and APIs as the experimental testbed. In addition to a simulation element, digital twins for a mesh networking platform should include control plane emulation and incorporate datasets collected from the hardware system (Fig. 3).

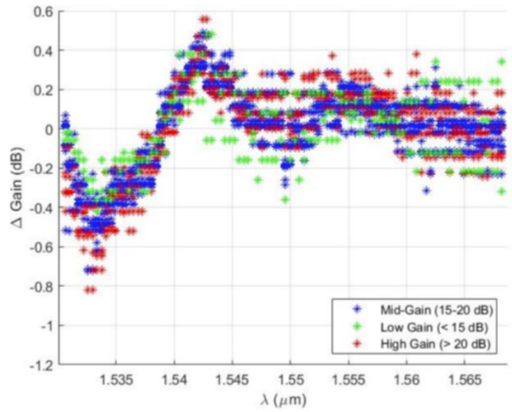

Fig. 3: Fully loaded gain ripple of six ROADM amplifiers.

4. Dual use SDN controllers.

This controller strategy allows for testbed experiment configuration and data acquisition while also supporting control system experimentation[8]. SDN supports hierarchical controllers and allows for customized functions and extensions. For experiments that do not involve custom controls, a testbed supplied controller can be used as the user interface for configuring the testbed and running experiments, including preset function for common operations. The same controller can also include hooks that allow experimenters to introduce new algorithms or contol functions under investigation.

Each of these elements have been under development within the COSMOS testbed. By combining these elements its possible to construct emulated networks in both hardware and software and study their control[9].

Conclusions

Advanced control algorithms including machine learning methods call for a new mesh networking platform approach, which is well suited for smart city networks.

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