STUDY OF POWER DYNAMICS WITH INTELLIGENT CONTROL OF COMMUNICATION NETWORKS AND POWER GRIDS FOR DISASTER RESPONSE

By

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ABSTRACT

Disaster events such as hurricanes, earthquakes, or tsunamis can have far reaching impacts across a huge geographic region, causing severe damage to infrastructure. This damage can be both to the electrical grids and the communication networks. The electrical grid can experience outages lasting for weeks. This loss involves much efforts to restore these damages both physically and with the data which was lost during these sudden events.

Within a disaster area renewable energy sources such as solar power can provide power in localized areas in emergency situations. By incorporating some intelligence in the power controls by having advanced algorithms and electronic switches to give maximum possible power output and by adding a degree of flexibility in adding/dropping channels on the fly we can make the whole system act much more efficiently than they would act independently by themselves.

Here in this study, we have demonstrated a collaborative and an efficient way, a system can be run with a network dependency between the power grids in the form of "microgrids" and dynamic optical networks provided with a degree of re-configurability. We have also investigated the power dynamics happening in the physical layer when the control plane makes decisions dynamically. This is the first time to the best of our knowledge we are investigating power dynamics due to dependencies on the power grid control. This study would be a useful tool in further investigating solutions to this problems in the area of routing and wavelength assignment in such a way we can overcome these effects or in a way to cancel out these effects which can in turn ensure reliable data transmission over many hops with dynamic abilities. Exploiting the intelligence that can be incorporated in the

power grids, calling it a smart grid and having a control plane over the optical networks to add intelligence will give us improved reliability on the whole system. We have studied the optical power dynamics such as excursions which occurs when the signals cross a number of nodes/hops, few spans of fiber and a series of Erbium Doped Fiber Amplifiers (EDFAs).

CHAPTER 1: INTRODUCTION

Dynamic Networking has been the buzz word in the Optical Networking Arena. People discuss a lot on the concept of opening up doors to dynamic optical networks, where connections are established on the fly, resources are allocated as per the need, switching to different paths when need be dynamically. This has opened up lots of challenging research areas.

Reconfigurable optical networks with distributed/centralized control have been shown for a dynamic (and rapidly) optical network [1]. This has shown potential significance reducing the operating costs and providing efficient bandwidth utilization in terms of energy and available resources. This dynamic capability along with recently introduced coherent communication which was made possible by fast signal processing from the world of electronics has given even more flexibility and strength to the agile features that can prove much more efficient. Also the flex-grid networking and OFDM/Nyquist WDM with dynamic sub carrier on/off capability has opened up lot of challenges in the area of optical communication.

1.1 Optical Access Networks

"The vision of CIAN is to create transformative technologies for optical access networks where virtually any application requiring any resource can be seamlessly and efficiently aggregated and interfaced with existing and future core networks in a cost-effective manner" [2]. Analogous to electronics world, the opto-electronic integration has taken a long leap forward in the development of optical networks with affordable and flexible access services delivering rates up to 100Gb/s in the recent times.

1.2 Dynamic Optical Networking

Over the last 25 years, dramatic increase in the capacity of commercial optical networks has pushed revolutions in network services through research [3]. Initially this capacity increase was made possible by increase in the fiber optic capacity. Since 1983, transmission system capacity has grown by more than four orders of magnitude, which is much slower than the technology growth. More recently, we have seen the commercial deployment of optical network elements that can set up and reconfigure wavelengths under intelligent software control.

1.3 Network Service Evolution

It is interesting to see the way optical networks have evolved over the last 25 years. While the present day traffic mostly consists of data and video with less voice data, the opposite was true in the mid-1980s. Back then, networks were built to carry voice traffic, and not so many data services were available and the legacy were more optimized for voice based infrastructure. In the computer world people started developing their own custom made applications or protocols. Later, open networking systems enabled standards for all personal communications such as e-mail, voice services, data services and so on.

On the other side, digital technology over fiber optics was giving out greatly simplified protocols which can be easily exploited with highly error free communication. Frame Relay/ATM service exploited these innovations and was highly successful in the commercial world. There was a giant leap in networking technologies, with protocols such as internet protocol (IP), and other standards. While data networking capabilities of that era were primitive, and the infrastructure was all for voice data, many visionaries in the networking community saw a lot more advances in future such as traffic growth in terms of integrated voices, data, video and other applications which can be delivered with fiber optics with high orders of magnitude efficiencies. This vision has led to great strides towards fulfillment of such as scalable, dynamic and efficient networks.

CHAPTER 2: SMART POWER GRIDS AND DYNAMIC OPTICAL NETWORKS

Distributed generation of power encompasses a wide range technologies, such as internal combustion (IC) engines, biogas, gas turbines, micro turbines, photovoltaic, fuel cells, hydroelectric power and wind-power. Lot of these technologies are still in the development stages, due to their expensive initial investments followed by proper maintenances. However many of these methods of power generation are being welcomed in underdeveloped areas where generation of power has left no legacy yet.

Massive failures of the power grids have demonstrated that large-scale and/or long-term failures will have devastating effects on almost every aspect in modern life, as well as on interdependent networks [4]. In particular, we care more about the optical networks because most of the devices in Telecom are dependent on power networks. Natural disasters, such as earthquakes, floods and hurricanes as well as physical attacks, such as an electromagnetic pulse (EMP) attacks can cause severe damage to optical/telecom networks and since there are a lot of people directly associated with the application of the networks, they will be more affected. Such real world events happen in specific geographical locations which are more prone to failures. There are lot of such cases pointed out. One such example is the effects showing lack of redundancy in sub-transmission lines in Fig 1.

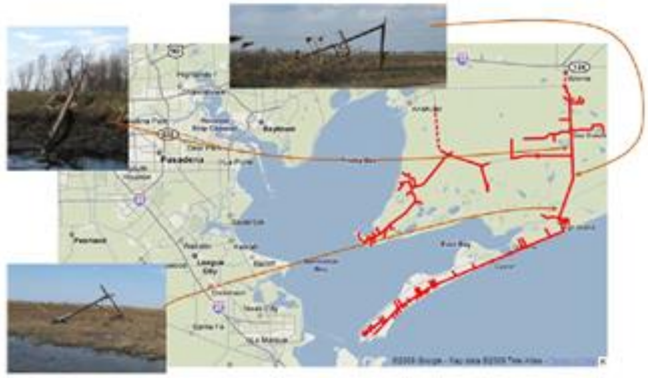


Fig 1 Example of lack of redundancy in sub-transmission lines. Grid data obtained from [4].

In Fig 3 we see clearly that in case of tsunami attack in Japan, the elevated areas are less affected when compared to lowlands. This can be thought of as a fine example of stronger points based on geographical areas at the time of natural disasters. This creates an opportunity to route the power and communication through such islands.

Fig. 2. Onagawa, Japan. While all buildings and infrastructure in the foreground were demolished by the tsunami, there is little damage in the background area higher on the hills where the tsunami did not reach [4].

Fig. 3 Broken and tilted poles caused by Hurricane Ike in the only line serving the Bolivar Peninsula area [4].

2.1 Renewable Power and Micro Grid Islands

The concept of Renewable Power has long been seeming to be a promising solution to the growing power demands on one end and from the fossil fuels which are rapidly depleting. There are different schemes in utilizing the present available power grids in a much more efficient way such as in the concept of microgrid islands.

2.1.1 Micro Grid Islands

At times of sudden disasters, the microgrids has become smart enough over years in the sense that it can look for priorities and can rise to emergencies and provide enough power to those areas while limiting power to other areas thereby balancing the load on its own. This has given us a better and efficient system over time from constant research. The smaller size of the system combined with its smartness has given us ways even to utilize the excess heat dissipated back into the same system. These type of systems can easily double the efficiencies. We can have micro grid islands based on geographic locations, need based, optimized points for the distribution of load. A general schematic of a micro grid is as shown in Fig. 4 [6].

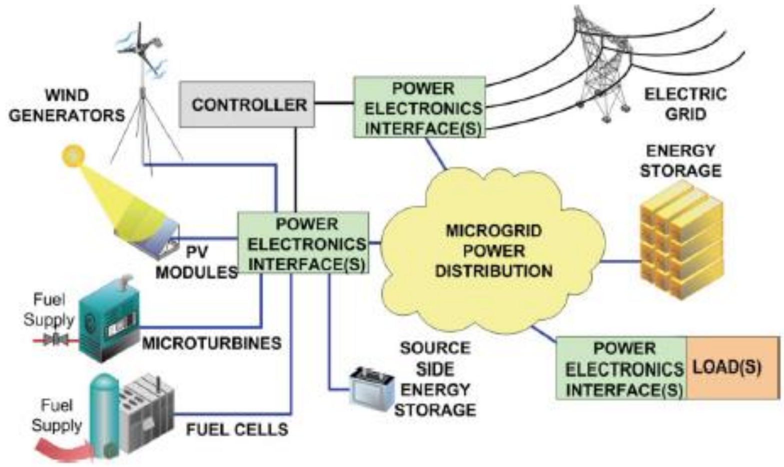


Fig. 4 A general schematic of a micro grid [6].

Centralized and Distributed power systems has always been debated for better efficiency. Both have their own merits and de-merits. Micro Grids has been a novel way of optimized and much more efficient power distribution by separating the connected loads into islands. This type of island generation and the distribution of power to loads have much more reliability and efficiency in energy. In this type of system model, heat is a major factor to account for. So it’s always better to segregate the loads between the micro grid islands thereby dissipating less heat.

Recent trends have moved more towards smaller distributed power generation as opposed to large centralized systems for power generation. Across US these type of power generation schemes has not yet reached significant levels.

2.2 Power Dynamics

We [7] begin to talk about efficiency in spectrum as the data usage demand grows exponentially. As [8] population literacy grows, more and more people become aware of internet and make their best use. On the other side to support the demand of the networks researchers invest lot of their time and interest towards finding better ways to feed the hunger of people towards internet. Majority of issues arise not in finding a better technique to support more users in a network, but a technology which is scalable as well. And with [9] lot of power hungry devices installed to grow demanding infrastructure, energy efficiency becomes another major issue which has to be dealt with as a priority. Because energy can, in common phrases contribute to global warming indirectly and the fossil fuels are fast getting depleted. Rising energy concerns has triggered in a lot of research towards better utilization of spectrum to cope with the demands of growing traffic.

Agility is how quick a system can respond to changing events. In Telecom, agility is a term frequently used to denote a response of a wavelength switch, laser response, channel established on the fly and configuring the network and so on.

The vision here is to have a dynamic, agile and an energy efficient optical networks as opposed to current static networks. Lots of redundancies in equipment installations are done, to mitigate the effects in case of disasters or emergencies.

Agile methods of switching channels/establishing connections in the physical layer have been proposed and has shown good results through research which can be incorporated by industries in future. Though these methodologies are complex and involves a lot of modifications from the current legacy optical network systems, this technology has been seen as a major breakthrough both in the research side and amidst the industries. Bringing in what are called reconfigurable optical add drop multiplexing (ROADM) nodes which are Colorless and directionless are available today and provide a potentially high level of dynamic capability. These ROADMs give better network flexibility and more dimension in a larger network [9]. Though this has seen as solution to a large number of problems, this in turn has thrown out large number of challenges. This can truly be an end to all the redundancies in installations and over provisioning.

In these type of Agile and dynamic networks, stability has been a major question which is still to be answered. Cross layer complexities has been another big issue with this type of networks. One such problem which has been given out is the transient problem. Current EDFAs are all designed for static networks. Once we start doing switching in the networks, the gain spectrum starts to give out all funny results with the wavelength dependencies of the gain, tilts, ripples, excursions and what not.

2.2.1 The Transient Problem

Transparent networks are optical networks with no or little signal regeneration within the network [10]. A ROADM provides us with a add and drop capability passively through a network. ROADM architectures become handy in the sense that they provide us with more flexibility like adding/dropping a channel at a node. It also gives us features to reduce wavelength blocking thereby virtually supporting more channels at a time.

Fig. 5 shows an illustration of an optically transparent network [10]. As indicated by the figure, these networks have been used for applications such as core Internet backbones, wireless backhaul, metropolitan networks. More often these WDM transparent networks are said to feed the edge networks through an opaque interface [11, 12]. More than just connecting the EDFAs, nodes and links, we now have a routing problem which comes with another degree of complexity. So we will have to deal with dynamic routing in an agile network. Routing and assignment problems have become much more complex involving linear programming [12] and advanced optimizations. When these algorithms are poorly designed the channels can end up in a loop thereby causing a recirculating loop. Now the signal gets trapped and gets amplified to reach high power levels damaging certain devices. These type of malfunctions has to be carefully taken care of. Such effects has been thoroughly studied [13, 14]. Adding another dimension to this problem is the transient problem.

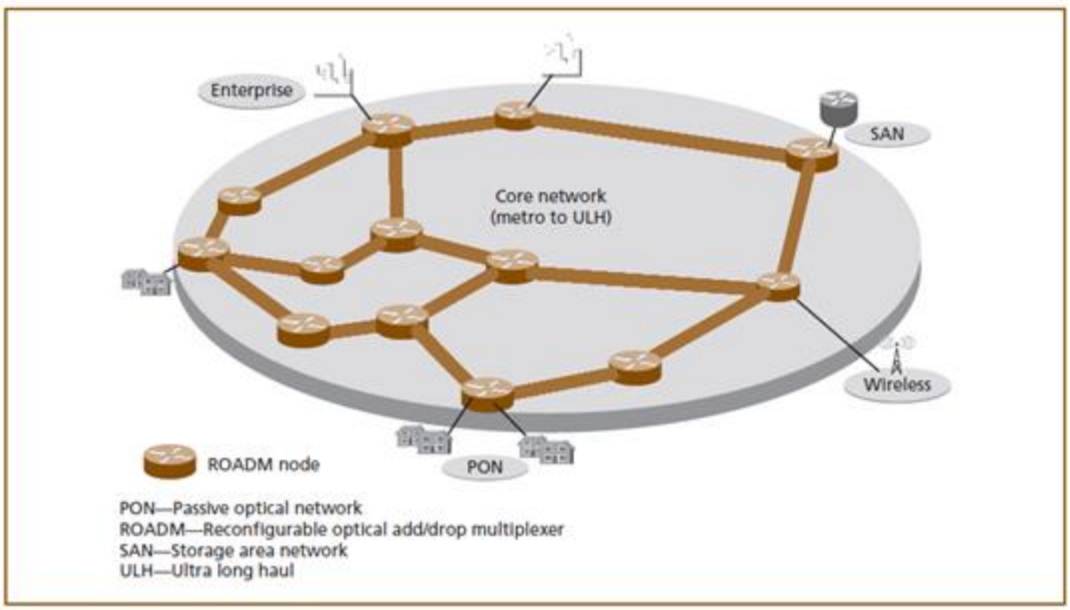


Fig. 5 Optical Transmission Network

In this case, let us say due to a failure in a component or a damage in the fiber the power of a channel goes up suddenly. A transient power excursion is generated on the other channels until a controller tries to control or settles it down such that each of the other channels are back to their target powers.

"Thus, the transient is a divergence of channel power from target levels that is created by the response of the system to a perturbation"[7]. This transient problem can exist with a nonlinear system with nonlinear devices. This can also occur due to interaction with other channels in a WDM system. In a nonlinear system, this problem can take shape and can vary with distance as a varying parameter whereas in a WDM system, It can always propagate and get coupled with interaction over time. Both are primarily due to optical amplifiers. Both these effects comes as a major challenge in a dynamic environment arising as a result of the behavior of erbium ions in the optical amplifiers.

When we add or drop channels which in turn are passing through the EDFAs in a network, there are power excursions due to tilted gain spectrum and the slower gain control response of the EDFAs. Because of this, initially a substantial increase in the power of other channels will occur. To avoid this, modern amplifiers come with feedback or feedforward control loops in order to restore the channel powers to the target power for each channels. The duration of this restoration can be a critical performance evaluating parameter. Usually these controls work well at certain gains, what we call nominal gains, where the response is at its fastest.

This basic transient scenario has been extensively studied and numerous techniques to mitigate theses effects have been proposed [16–18]. Models have been developed to study accurately during these events [19-21]. Recently, coupling effects has been recently studied in transparent networks with a network having more nodes and degrees[15]. This problem is complicated by the wide array of potential network configurations.

Especially these type of power fluctuations/power coupling effects through a chain of amplifiers or ROADMs give a better idea of propagation of such effects over hops or distance. This will be the first step in the study of power coupling effects in a metro network where the signal passes through a chain of EDFAs and then with ROADMs along the path which can also vary the tilt slightly depending upon the reliability of the WSS and their design. .

2.3 Wavelength dependent gain dynamics

Reconfiguration is a new dimension added to the present static networks to add flexibility in order to achieve dynamic bandwidth allocation, channel establishment on the fly and sometimes restoration in case of disasters. [22]. ROADMs for the main component in such as dynamic system [23]; however, the software acts as another strong layer on top of the hardware. Given all the flexibility with the software the legacy networks has a lot of EDFAs in the optical network. These cause power excursions when the amplifiers are operated in constant gain mode and due to the wavelength dependence of gain.

Mainly in WDM systems, since the EDFAs are operated in saturation to have a linear performance in gain, these power excursions give out high coupling effects when it travels long distances or many hops. This excursions can vary depending upon the design of the amplifiers, its control loops, and for worst case the transients can vary from milliseconds to few seconds in DWDM systems. In case of failure of few channels these excursions are huge and these may cause even damage of the equipments which can lead to a high BER which in turns decreases the quality of the signal. The control and ill effects of such gain transients have been extensively studied [24]–[26]. In networks, sometimes it's possible to maintain constant power as opposed to constant gain to mitigate some of the effects. But still we will have wavelength dependent transient and variations in gain in the existing channels. On the other hand GFF (Gain Flattening filters) can give up to a certain level of flatness, much more specifically at some optimum gain only [27]. Spectral hole burning can add more errors or quality degradation to these excursions particularly in the shorter wavelength region. This effect when carefully designed and exploited can be a useful trait which can be incorporated to mitigate some of the other transients [28].

In this study we look at the power excursions when we add channels at the worst case, which means adding channels at the gain peaks and this effect is studied in a link having a bunch of nodes and EDFAs which can be considered a part of a larger network.

A bunch of wavelengths travelling through a chain of EDFAs will experience additive gain ripple but this can be tolerated up to say 1dB before we see degradation in OSNR due to cross talk and other penalties suffered by low power channels [29]. If there are more channels going through a chain of EDFAs and then through a long span of fiber, this implies that high power is launched through the fiber span. Here comes penalties from non-linearities and now the penalties due to these effects such as SRS can strongly affect channels on the lower side of the spectrum. Through a chain of EDFAs these effects can be additive and can lead to a large power divergence between channels [29]. These effects, though can be small in a very small network can become additive, in case of ripple effects and it accumulates, in case of coupling effects. So these reconfiguration issues in a physical layer perspective has to be thoroughly studied in a scaled network.

While there are capacity limits and non-linearities adds a threshold tag to scaling optical networks, heat issues act as a major constraint in expanding electronics following Moore's law [30]. Thus, in future these reconfigurable ROADMs with high dynamic capability and flexibility with add and drop channels actively can be high beneficial and welcomed by the industry as a key solution to growing energy and capacity demands.

Dynamic provisioning of future services can be in the order of time scales as fast as 50 ms [31]. Reconfiguration switching when done at nodes in case of a disaster can affect the active channels when they are closely packed in case of a WDM systems. Recent simulation results showed that power coupling between channels can also be produced in the event of end-to-end link restoration [22]. Thus, to mitigate these effects the controllers have to be fasters and smart in their response such that the response of the feedback/feedforward control is faster than the response of the amplifier itself. The stabilizing time after restoration or switching depends highly on the number of channels affected during the restoration or switching. If there are more channels disturbed when this action is performed in general the controller has to go through many loops acting accordingly with a power flattening algorithm. This settling time is expected to scale along the length of the fiber span and the nodes the channel has travelled for. This cumulative effect may be a hard hit to the quality of the signal.

Present WDM systems are static with a lot of redundant provisioning to be free from disasters [32]. Though these software controls on top of the amplifiers can be fast enough, it cannot cope with the fast growing complexity of the networks and the future dynamic networks can consist of more flexibility and features [33].
And things can even become worse with a larger network and it can go out of control [34]. Stimulated Raman scattering and other nonlinear effects when many number of channels travelling through the fiber span which may clearly add another lay of complexity [35, 36]. Nonlinear processes and other wavelength-dependent effects such as spectral hole burning are fully developed within microseconds [37,38] and

can be considered essentially static. The impact grows larger and larger with increasing amplifiers and number of nodes it crosses with the hops.

These effects are not true with the static networks. Particularly response time is not considered a major parameter for theses WDM design networks since they can take enough time to wait till the transients settles down and then launch the channels or establishes the link.

Novel routing and wavelength assignment (RWA) strategies [40] and transport architectures [31] are developed taking into consideration all the amplifier transients and the network control systems are influenced largely by the physical layer dynamics [41].

For individual amplifiers with better transient control, the controller is designed to act quickly before the amplifier even sees the change by quenching the transients. By WSSs we can have the channels flattened by adjusting the variable optical attenuators (VOAs) for the individual channel. We can also adjust port specific attenuation. So we can have algorithms running as a local controller at each node, adjusting the VOAs of each channel whenever a channel is added or dropped. This might be a better solution for a smaller network. But in a huge network, this becomes a never ending loop because of the cross channel interactions, it's hard to get all the channels flat through the whole network. So people have always had techniques to divide the roles of a local controller and a centralized controller. In this case a centralized controller will have a much wider field of view over the network. The main issue here is the time required to achieve this in a reasonably scalable environment.

The dependency with gain for different channels can be another problem with different vendors designing amplifiers [42] with varying amounts of doping depending upon the requirement of their design. [43]. This uneven characteristic of different amplifiers should be accounted when considering a larger network. This can add another degree of complexity. Nonlinear effects can cause different [44] tilts depending upon the input to an amplifier and the gain and also depending on the fiber glass composition [45]. This EDFA tilt in the spectrum, if carefully designed it can be compensated by Raman tilt [46]; thereby analogous to having a DCM module to compensate the dispersion over a length of the fiber.

Modern vendors are fast realizing the importance of software over the physical layer to gain flexibility in networks and are deploying in the field since it is very attractive to meet their customer needs and to run ahead of their competitors [47]. There is always a tradeoff between control time in case of a centralized or unified control plane and a distributed control plane. To realize these capabilities and reduce energy consumption [48], the channel setup time should decrease drastically from days to hours to minutes to seconds. One challenge to enable networks with a dynamic physical layer is the impact on the transmission performance, which [48], is examined with respect to the optical channel power. The per channel power needs to be maintained to a reference level say 0 to -2dBm even throughout the network configuration. This forms the biggest challenge considering all the ripple, coupling effects, tilt, and nonlinear behavior and in turn has to be scalable as well. This impact can be solved in a smaller network but for bigger network the transients accumulates[49,50].

CHAPTER 3: Intelligent Control of Communication Networks and Power Grids for Disaster Response

Fig. 6. Hurricane Sandy takes data centers offline with flooding, power outages (http://arstechnica.com/information-technology/2012/10/hurricane-sandy-takes-data-centers-offline-with-flooding-power-outages/)

Electrical grids have become smarter over time in order to recover faster in case of disasters. Fig1 shows a disaster event of hurricane “sandy” where the data centers had to be offline due to power outage. Either a prediction has to be done in case of a disaster and the network has to be reconfigured in such a way that the network doesn’t get affected or post disaster steps are to be taken to restore network traffic by reconfiguring the network. This saves resources and cost required to install redundant equipment to overcome disaster situations. So, in such cases, an alarm will be started and a person manually has to go to the place of fiber break or disaster to change configurations in present day static networks. In case of future networks, they might be designed such that power shutdown in some areas or to some devices will initiate reconfiguration such that the network is still live. During the recovery process, renewable energy sources such as solar power can be used to keep the communication links or the network status up, particularly in areas more prone to natural disasters, but in this case the extra cost here is installing feedback or alarm systems to trigger the use of other energy resources to power up the networks. On the other hand, solar panels are becoming intelligent and smarter so as to adapt their operation to the changing load and still output maximum power to the load by switching to different loads based upon priority or some other constraint.

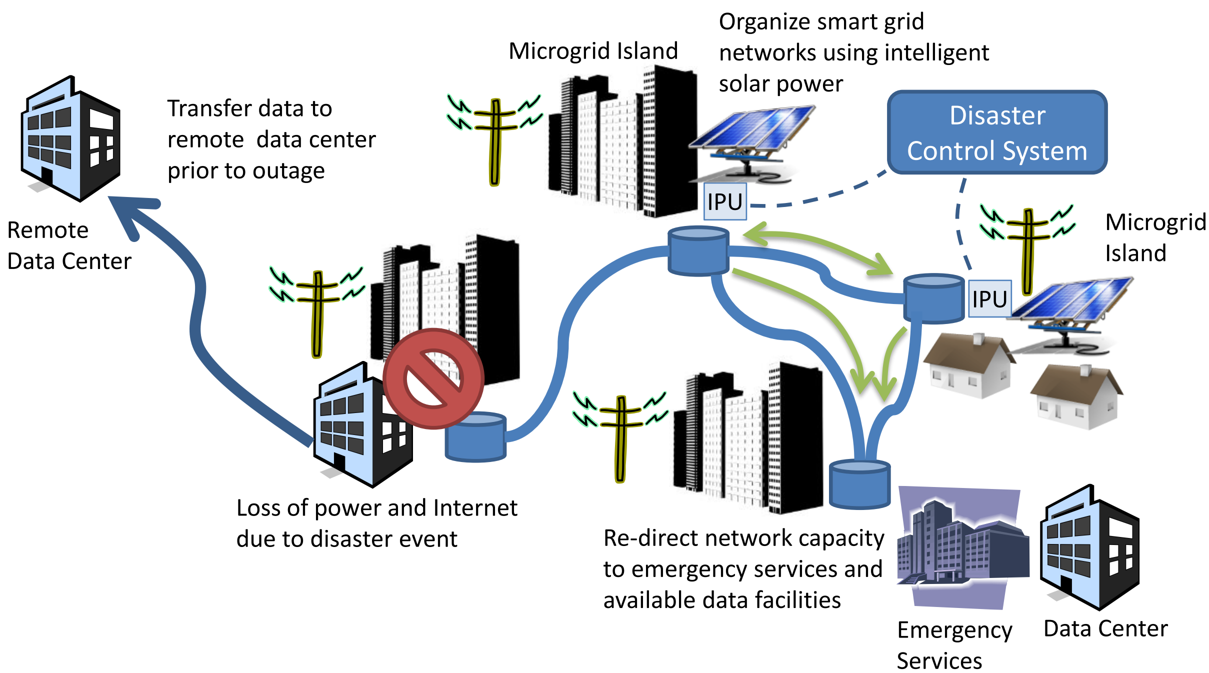


Fig. 7 Intelligent photovoltaic panels with integrated power units

Fig. 7 shows an intelligent photovoltaic panels with integrated power units (IPU) utilize a disaster control system to form microgrids, dynamic communication networks reorganize to increase connectivity for microgrids, emergency services and available data facilities, data is transferred to remote centers prior to outages.

3.1 Smart Solar Panel Arrays

Let's say we completely switch power generated from fossil fuels to renewable energy resources such as solar energy to power up the optical networks. Now any damage to a solar panel in a series of array, or varying load between different panels in an array, or in case of a cloudy weather can cause power fluctuations. A control panel is needed either to control the high current generated by one panel in a sunny afternoon and when we have low current from the panels, the control has to be smart enough to combine with other solar arrays or with other grids to give maximum output possible. QESST is an ERC involved majorly in research developing new smart solar systems that can reconfigure intelligently to give maximum output in spite of the input load variations due to environmental conditions. By using electronic devices such as DPDT (Double-Pole Double-Throw) switches to switch to different loads with the help of a controller can considerably reduce the cost of energy in a power grid perspective.

3.1.1 Basic Idea and Impact

Within a metropolitan area relatively smaller grids can be formed to power up smaller islands of networks called the Microgrids [52]. In this project, we have solar panels forming the microgrid structure. These microgrids can by itself act as standalone systems incorporated with smart controls and backup generators. These structures can have major advantages with such distributed controls within the microgrids. These systems can be highly energy efficient given the controls and smartness to the power grids. Given the reconfiguration capability and the smart controls and optimization algorithms in the power network we can come at a point where there is a tradeoff between power grid reconfiguration based on the load and the optical network reconfiguration based on the number of active channels established which indirectly corresponds to the power requirement. Thus in a system where we have dependencies between a power grid network and the optical network can be efficient given the amount of smartness in both the power and the optical networks[53]. There can also be battery backups connected to the optical networks just in case the maximum output decreases under extreme environmental circumstances such as rainy days. Thus the communication and power networks can work together to collaborate and maximize their efficiencies and recovery times.

3.1.2 Implementation

Solar panels are equipped with an integrated power unit (IPU) that includes a maximum power point tracking system, sensors, and a communication transceiver. The IPU monitors electrical properties such as current and voltage of the panel, monitors environmental conditions such as temperature, humidity etc., and optimizes the power output of the individual solar panel to deliver maximum peak power possible at any point in time. The communication link between the transceivers and the solar panels can exchange data between them. Alarms can be initiated on both sides, in case of power grids if there are not enough power available or in case of optical networks if more power is required. And the controllers are programmed to act accordingly.

Furthermore, in case of multiple controllers distributed over a region it can communicate with regional controllers that coordinate both the power and communication response. The local controllers switch to no load or varying loads opening and closing the electrical interconnections to maximize the output given the state of solar panels at any point of time. We also study the power dynamics caused due to this interdependency. Algorithms for the control of solar panels and adaptation in a larger smart grid network has been studied through experiments and simulations at Arizona State University. Intelligent PV panels developed by QESST was implemented with the IPU and disaster recovery algorithms. Different disaster related failure scenarios were demonstrated where those smart panels sit on rooftop connected with the optical network setup at The University of Arizona. Once we shade the panels mimicking a cloudy morning our controller drops channels which are of least priority thereby reconfiguring the network depending upon the power availability. Thus demonstrating a one way dependency.

3.2 DISASTER MITIGATION AND RECOVERY USING DYNAMIC OPTICAL NETWORKS

3.2.1 BASIC IDEA AND IMPACT

The current communication infrastructure is static and rigid and can be re-organized by spending enough time at that location manually [54]. Both the communication networks and data repositories are configured for best operation during normal conditions. In the event of a disaster, the data channels has to be switched to a path which does not go through that portion of the network which has been hit by a natural disaster are prone abnormal events such as impairments or fiber cut in case of emergency services.

Furthermore, because the network is so rigid even for a small change or a small hit, we had to switch to the backup resources before the actual resources are manually fixed [55]. Although these facilities can have large backups with batteries to overcome times of disasters, they can still suffer from such events. By creating a communication network that can act smart during times of disaster, then it’s easier to manage data resources through the failure and then once that channel is maneuvered to a different path on the fly, then it can be optimized to give maximum capacity and this can be repeated as and when there is failure. Keeping the communication networks alive in this way further enables the potential to use smart grid techniques to manage the changing electrical power grid.

New fiber optic switching technologies also enable wavelength reuse by allocating spectrum in a timely manner or different wavelengths to different links. Typically this reuse takes a lot of time and we have to keep track of all the wavelengths used and this can bring in problems of blocking in a link. But this can improve the efficient utilization many folds. Generally an operator takes care of this operations with the help of a NMS (Network Management System) [56].

In a disaster situation, these tunings could be relaxed depending on the criticality of the communication lines. A disaster recovery mode can be automated and the switching can be done relatively faster based on the feedback from the controller which can make things faster when compared to manual network recovery modes. Some performance degradation might be encountered during the connection arrivals and departures which may stop the network from getting fully optimized, but allowing for this capability would allow for communication that otherwise would not be possible.

A key challenge would be to study the impact of add/drop channels given at various amplifier gain curves. Rules for automatic switching would need to be established to ensure that unstable operating points are not reached. In some cases the behavior of the signal can be abnormal , for example increased signal amplification can add more ASE noise which can degrade the quality of the signal and vary the EDFA characteristics by increasing the average input power to the amplifier. This can sometimes saturate the input power to the amplifier, which can cause the EDFA to behave differently.

Within this experiments with QESST and CIAN, we have demonstrated a disaster management using intelligent solar panels and agile capabilities. Intelligent photovoltaic panels in the QESST testbed has been demonstrated to adapt to varying environmental and load conditions in response to disaster scenarios. Disaster response dynamic optical network with 4 nodes, showcasing a smaller part of the larger network and the reconfiguration in this testbed was CIAN’s TOAN testbed. Within the testbed, wavelength routing is done based on random connection arrivals and departures at each nodes based on the requests to the controller. We have done experiments and associated analyses to study the power dynamics in this type of power/optical network interdependency.

CHAPTER 4: EXPERIMENTAL SETUP IN TOAN (TESTBED FOR OPTICAL AGGREGATION NETWORKS)

Here in our study we have two important things to explain. One is the demonstration of interdependency between a power grid network and an optical network. Next the study of power dynamics during the reconfiguration of the optical networks.

4.1.1 Optical Network Setup in UA:

We setup a 4 node Optical Network in TOAN (Testbed for Optical Aggregation Networks) at the University of Arizona. Each of these nodes consists of a Wavelength selective switch (WSS) and an EDFA to compensate the losses. There are add channels in each node, where different channels are added randomly at each add port. The drop ports comprise of one arm from the passive splitters. So if we would like to look at the available channels on each link, we can either control the WSS where all the drop ports comes in or we can just plug the drop fiber into an OSA.

For the initial setup, the Transmitter consists of 10 channels from the laser bank muxed together and modulated with a 10G modulator. So we now have ten 10G channels arriving and departing at each of the add/drop ports.

This random adding/dropping is done by a centralized control plane, wherein each of the WSS is controlled by a PC via RS232 and a software written in Python 2.7.7. Gain in each EDFA is set at an optimum value and in such a way that the power dynamics can be observed and also the output power is not saturated. The setup block diagram is as shown in the Fig. 8.

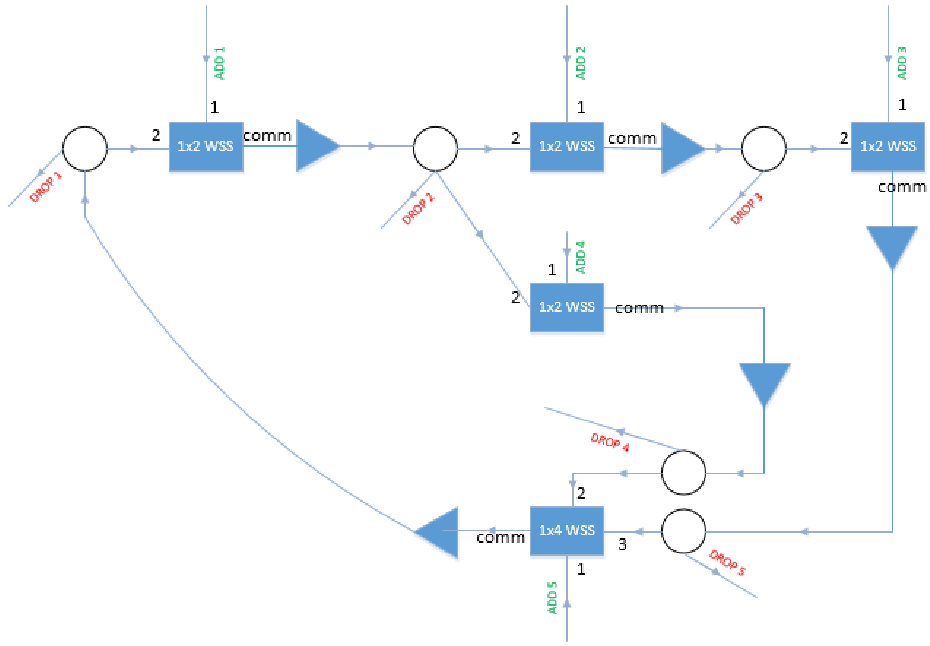


Fig. 8 Block Diagram of the Demonstration Setup

The figure below shows how these four nodes are aggregated, to be associated with two micro grid islands. This can be used when one centralized power grid supporting the communication networks is not active, for example in a disaster/emergency scenario. Here in this figure, a DE (Distance Emulator) consists of a Wavelength Selective Switch (WSS), an Erbium Doped Fiber Amplifier (EDFA) and a 5km fiber spool.

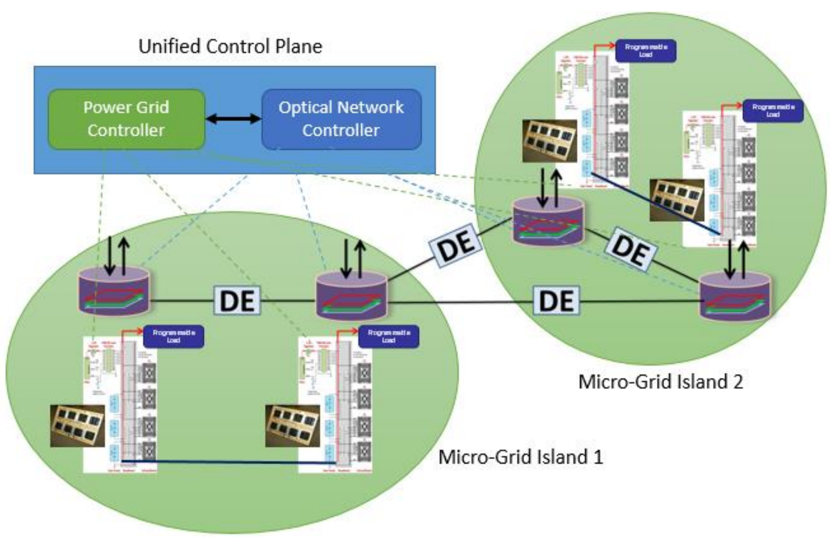


Fig. 9 Four Optical Nodes associated with Two microgrid islands

4.1.2 Communication of power information:

The setup in Arizona together with the setup in ASU are used to emulate a coupled microgrid and communication network. This requires signaling between the labs so that loads at ASU representing the communication elements can be set based on the active communication equipment and the communication equipment at Arizona is shut off when the power drops too low. The communication between the power grid controller and the communication network controller is as explained in the block diagram below. Let's say we request a power Pmax depending upon the number of channels which are to be supported at an instance of time. There will be a request placed to the power node P_R through XMPP and if the controller responds positive we would go ahead and support further requests. If there is not enough power available, say on a cloudy afternoon then we would drop some channels which are of less priority to tackle this situation. Thus we have shown a one way dependency between the power network and the communication network.

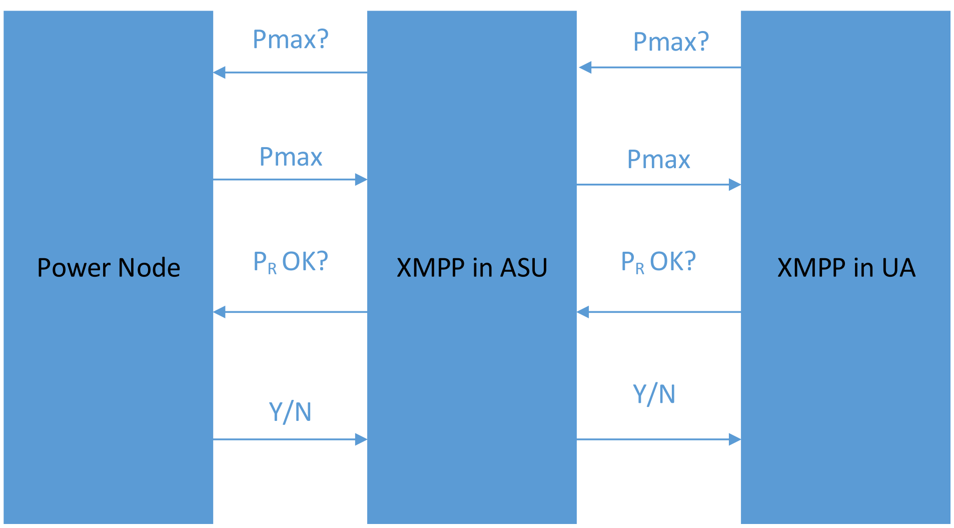


Fig. 10 Power communication steps for one node. The communication protocol between power node and 'XMPP in ASU' is serial. XMPP protocol is used for remote connection between ASU and UA

4.1.3 Solar Panel Setup at ASU:

On their side, they have solar panels on a roof top. The system comprises of 3 solar panels of 5V, 1A each. These are small few cell panels whose behavior can be scaled to correspond to much larger panels. Connected to each panel is a current sensor, relay and 2 loads. The loads are named local and utility load respectively. The solar panel connects to the loads via a SPDT relay. Load open and close corresponds to utility and local load respectively. The output of the sensor is fed into the ADC of MSP430 microcontroller. The microcontroller adds up power generated by each of these panels and stores it in memory.

Now when the external system places a request to the utility load. This is done via RS232 of the microcontroller. The microcontroller compares this power requested to the total power generated by the system and accordingly switches relays to provide power required by the utility load.

The Fig.11 shows a simple setup with 3 panels connected to relays through a microcontroller which stays on the rooftop. The current varies as a function of exposure to sun. But the smart power grid is configured to give maximum current by optimizing the loads.

The block diagram shown below shows the setup of the power network at ASU which was used for the demonstration.

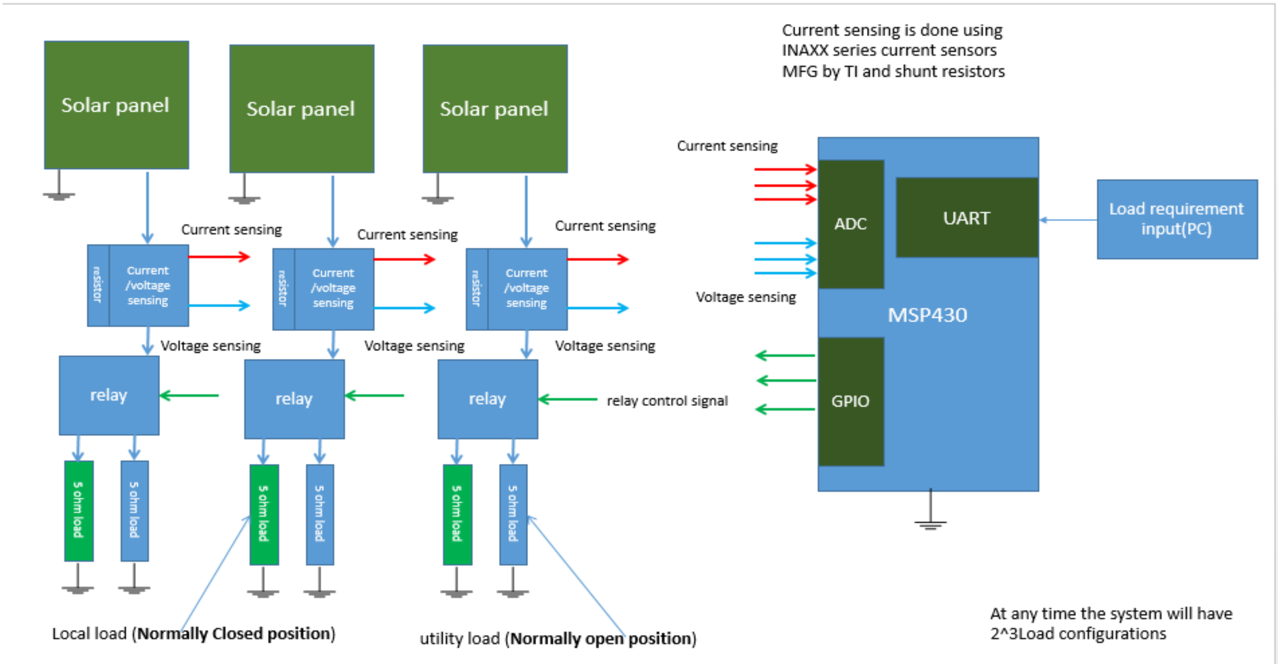


Fig. 11 Block Diagram of the Solar Panel setup with controllers at ASU

The power values are generated and associated with hexadecimal digits and associated with the microcontroller as shown in Fig. 11. The steps involved in power generation and controller response are:

- Each panel generated 1.6 W, 1W, 0.5W power respectively
- Load requirement is 2 watt
- From a lookup table we can get the all possible power combinations
- Out of these we select the next best power combination which is highlighted
- Depending on this combination we switch the relay positions to supply 2.1watt to utility load

- In case of shading the power generated by each panel will change ,Thus the positions of the relays will also change to maintain the power delivery to the utility above 2Watt.

Power Calculations:

We calculated power consumed by a simple network system including racks, shelves, transceivers and the cooling systems to model the power in the networking system. So, now we know what each transceiver requires to be active during an active communication between nodes. For each request, we deploy a channel from the available pool and before we deploy we send a request to the power controller to see if we have enough power to support the channel. If not we would drop some less priority channels to support only the much needed channels by switching off some transceivers.

CHAPTER 5: RESULTS

In our experiments we have setup up and demonstrated a joint system wherein the power grid and communication network are interdependent and the joint decisions are made by the controllers with the goal of making the combined system work much more efficiently and smarter than they would if they work independently.

5.1 Power Excursion Results

First and Foremost motivation for this study is to design reconfiguration rules to enable fast switching during the dynamic behavior. While in the current system, arrivals and departures are random and the power excursions can be coupled and accumulated in a larger network, we need to address this issue. Designing a set of rules based on this study will add some constraints to the wavelength assignment during requests arrivals. This study of gain and power excursions will give us insights on how to switch channels with minimum excursions possible.

From the Network setup from chapter-5 we have analyzed one long link as shown in Fig 8 to study the gain and the power excursions with more amplifiers added in each link to study the power dynamics. The figures Fig. 13.1 13.2 13.3 show the gain excursions at the output of EDFA 3, 6, 9 respectively which is plotted by subtracting the output and input at each EDFAs. These measurements show how the amplifier gain changes as the channel loading configuration changes. From this we can understand the power excursions that result on the channels. Here we can also see evidence of Spectral Hole Burning (SHB) on the shorter wavelengths.

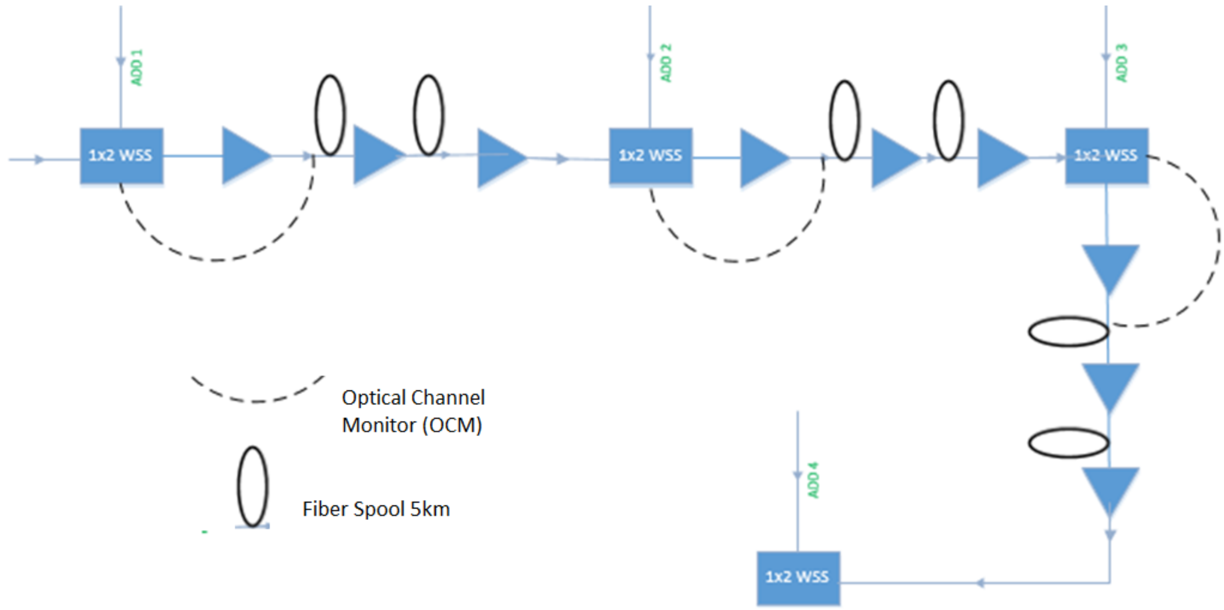


Fig. 12 One Long link from the Network setup for power excursion study

During this experiment, all the inputs and outputs of the EDFAs were kept constant with a fixed 13dB gain. The EDFAs were set to AGC mode wherein a constant gain is applied to all the wavelengths. During the transients/excursions we observe a phenomenon called the Spectral Hole Burning (SHB) [57]. It is evident by the dome or dip in a cluster of channels and can be distinguished by its channel power dependence. The fact that this sharp feature changes from a dip to a dome with the channel power is a clear marker.

This effects is mostly related to different inversions of the erbium ions [58, 59]. These ions have similar emission and absorption spectra, the difference being they are shifted in wavelength with respect to each other.

Some authors [60, 61] believe that this spectra also depends on the orientation of the erbium ions with respect to the polarization state of the propagating light.

Fig. 13 Worst case scenario adding channels at gain peaks

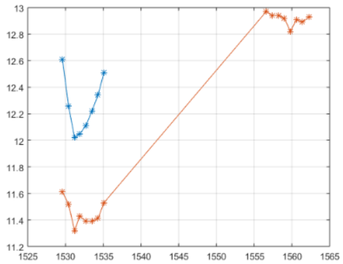


Fig. 13.1

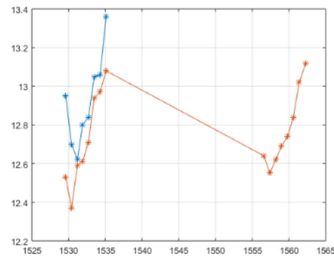


Fig. 13.2

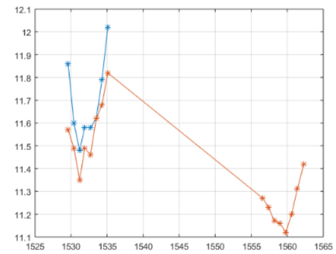


Fig. 13.3

Fig. 14 shows the worst case scenario, in which we select add channels at the peaks, from the gain characteristics of the EDFA. In this case the excursion nominally becomes worse at the output of each EDFA. However, all amplifiers are not identical therefore there is some variation. In total, we have over 5 dB excursion in the worst case.

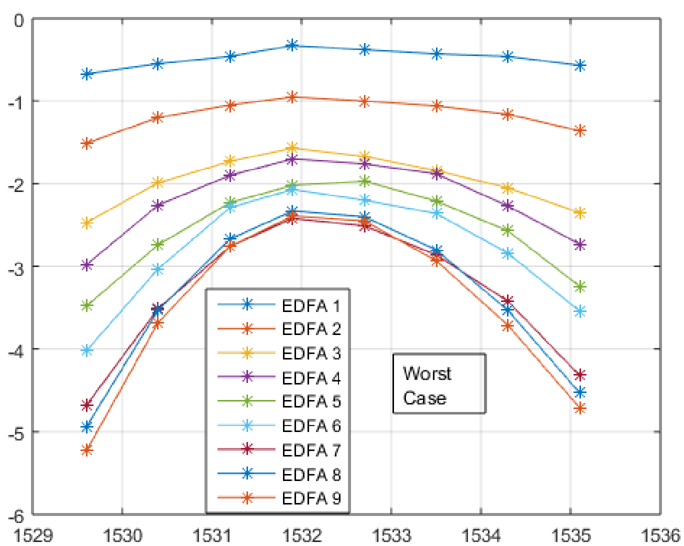
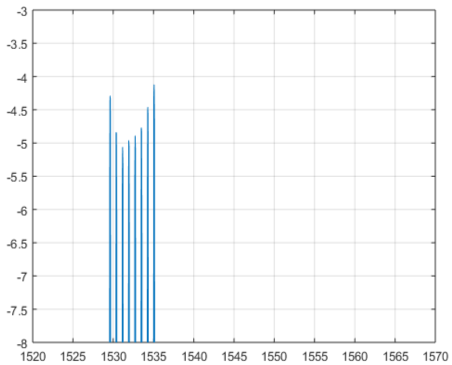


Fig. 14 Wavelength Vs Excursion for worst case

Similarly for the average and best case in which we select add channels which are spread across the C band and channels which give equal positive and negative excursion so that they cancel out. For the nearly best case we get channel excursions of about 2dB and for the average case we get excursions of about 4dB respectively. These clearly shows that channels have to be carefully selected when deploying them on the fly such that the wavelengths are selected at peaks and valleys alternatively from the knowledge of the gain spectrums in the EDFAs



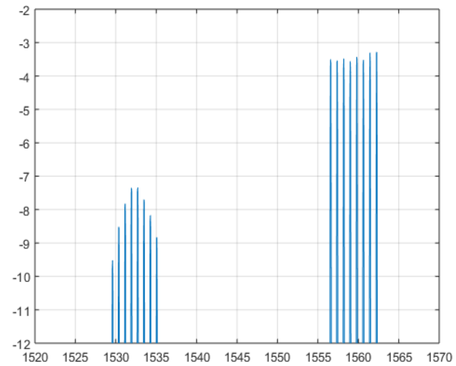


Fig. 15.1 *Fig. 15.2*

The spectrums in Fig 15.2, 15.2 are from the output of EDFA-9 and we can see the excursion on the shorter wavelengths when we add 8 more channels on the peak of the gain spectrum.

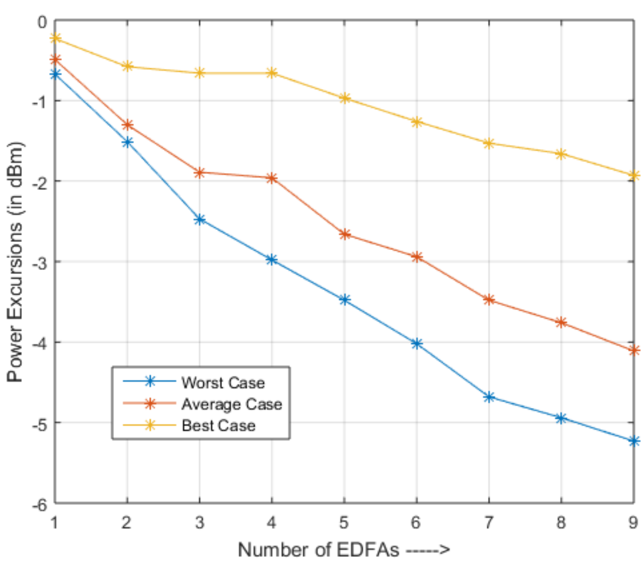


Fig. 16 shows an excursion plot for one particular wavelength Vs the number of EDFAs.

5.2 ASU and UA collaborative demonstration:

The figure below shows a live demonstration between the power grid and the optical network. Here as we get random requests and departures, channels are deployed continuously from the pool of available wavelengths. And then after a while a shading event is performed, analogous to a cloud passing. Now we can see the power drops and the number of channels are dropped based on the amount of power generated during this event. This clearly demonstrates an automatic decision controller system between a power grid network and a communication network. The spectrums also show the output at each of the drop ports and we can clearly see the channel drops at each drop ports in the nodes.

In this demonstration, a local controller runs power flattening algorithm to make sure, all the channels added are flat and has the peak reference power about 0dBm.

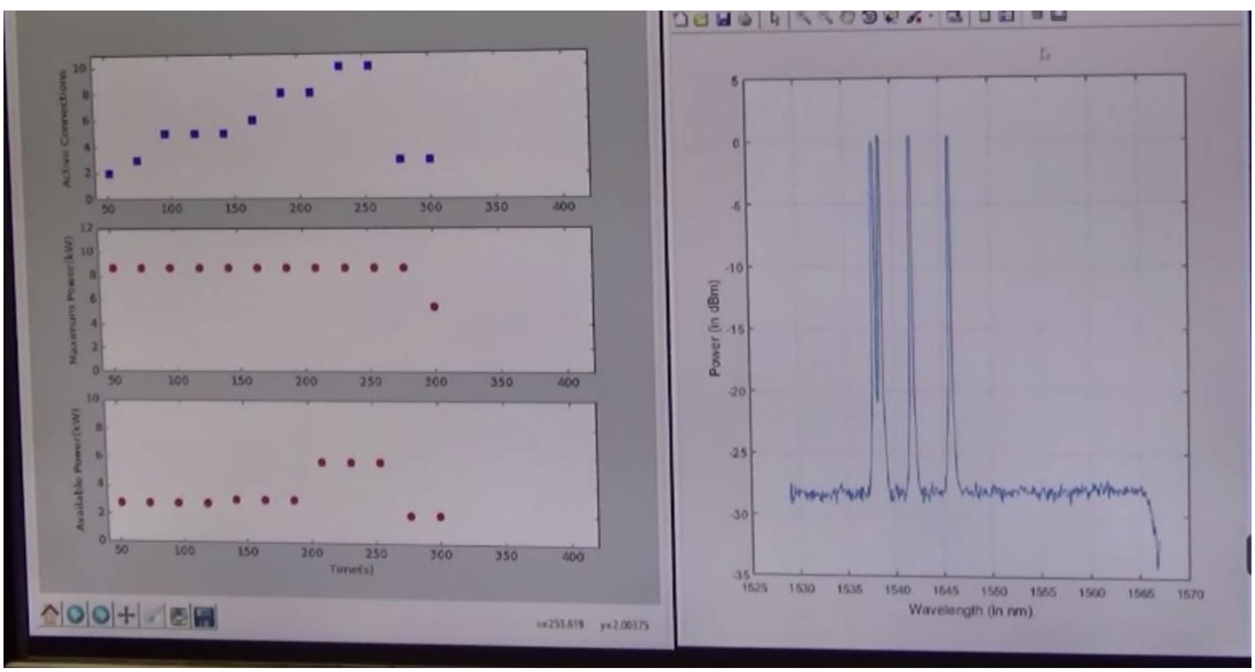


Fig. 17 LHS: Available power, Maximum power, No. of Connections Vs Time and RHS: Spectrum connected to Drop port 4

DROP 1 - BEFORE AND AFTER SHADING

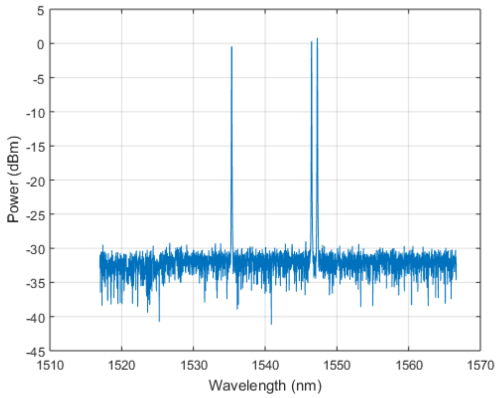


Fig. 18.1

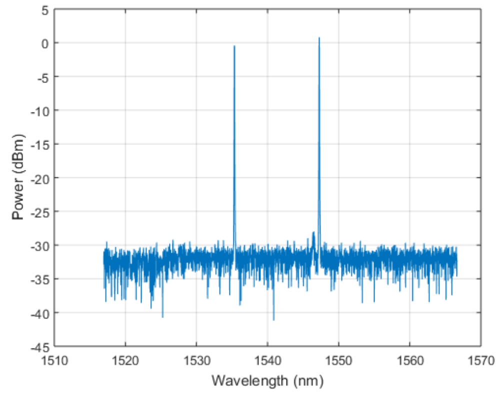


Fig. 18.2

DROP 2 - BEFORE AND AFTER SHADING

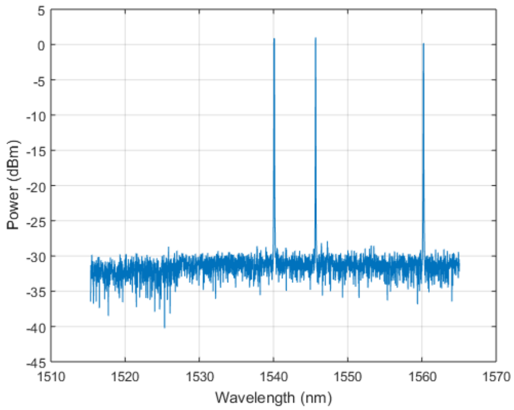


Fig. 18.3

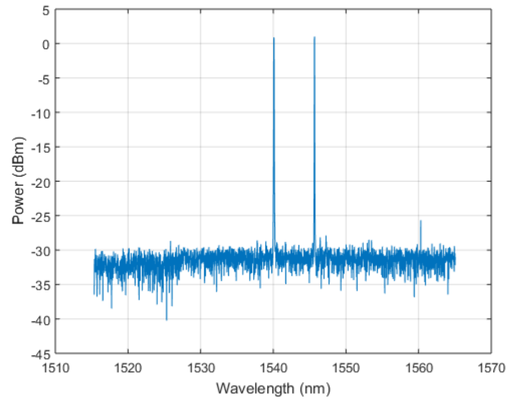


Fig. 18.4

DROP 3 - BEFORE AND AFTER SHADING

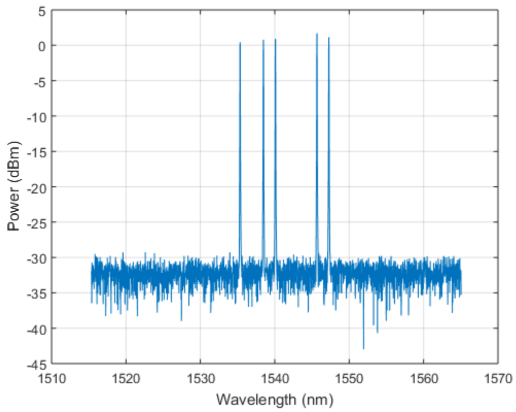


Fig. 18.5

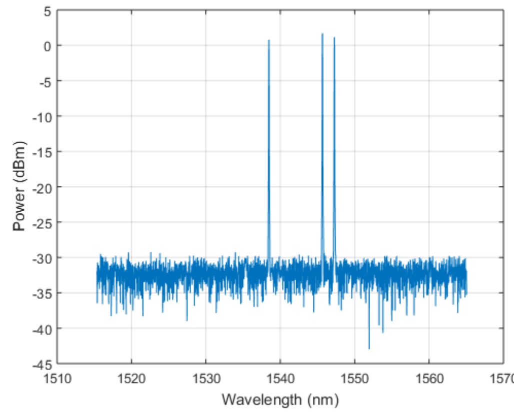


Fig. 18.6

DROP 4 - BEFORE AND AFTER SHADING

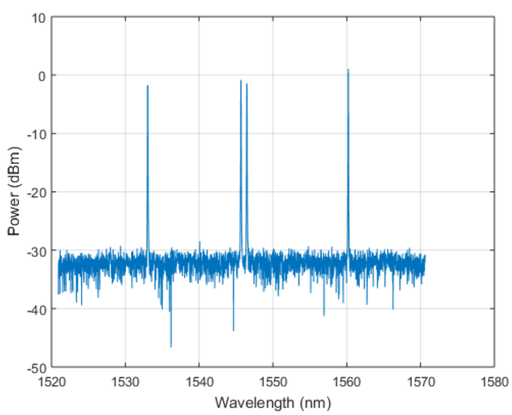


Fig. 18.7

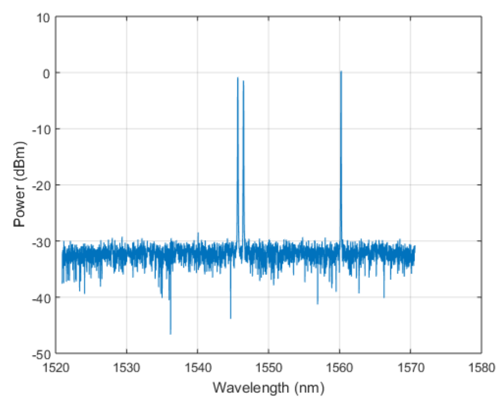


Fig. 18.8

DROP 5 - BEFORE AND AFTER SHADING

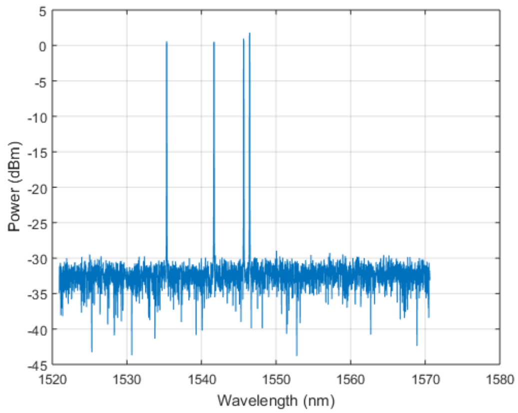


Fig. 18.9

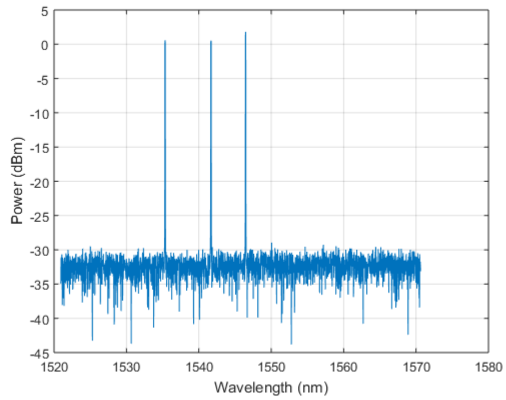


Fig. 18.10

The Fig. 19 below is more realistic, it was recorded as one of the trial runs on a cloudy day. We can see the power variations and the channels adds and drops automatic by smart decisions by the controllers.

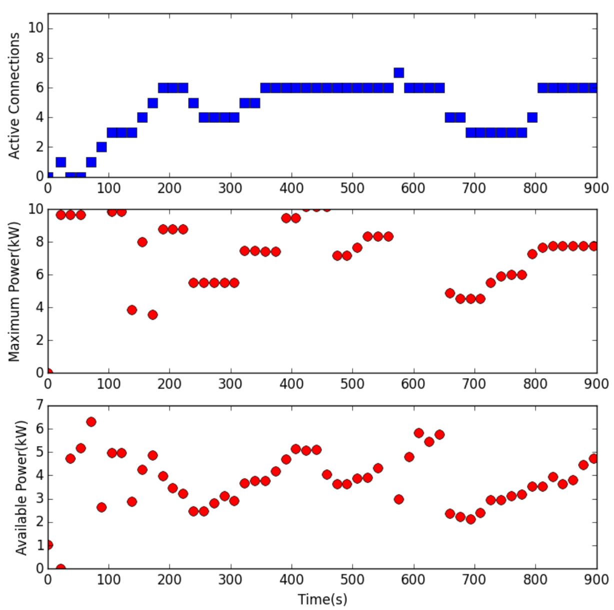


Fig. 19 *Available power, Maximum power, No. of Connections Vs Time*

CHAPTER 6: SUMMARY

Such a demonstration showing interdependency between the power grid and the communication network helps us to better understand the optimization challenges to deliver maximum power within the microgrids in case of failures/disasters and to study the power dynamics in the optical networks. These initial results discussed in chapter-6 has given us an idea of the behavior of the gain spectrums along a longer link with chain of EDFAs. The analysis of power excursion when new channels are added at the peaks and valleys gives us better understanding on choosing wavelengths from the pool of available wavelengths while adding into the system whenever there is a new request. In future work, wavelength assignment algorithms based on these studies of the power dynamics can lead to stable and reliable fast reconfiguration in the full interdependent network and power grid system.

Thus a development of a smarter integrated system can be much more efficient than just a passive power grid and communication networks with more backups/redundancies. Such smart systems can try to satisfy the growing capacity crunch, by being able to use the available resources in an intelligent way.

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