Evolution of the optical add/drop multiplexer in dense wavelength division multiplexing optical networks

Mnotho P. Mkhwanazi[1], Khumbulani Mpofu[1], Vusumuzi Malele[2]
[1]Department of Industrial Engineering, Tshwane University of Technology, Pretoria West, South Africa
[2]North-West University, Unit for Data Science and Computing, Vanderbijlpark, South Africa

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ABSTRACT

Mobile network operators are facing ever-increasing traffic demands because of the numerous data-hungry applications used by subscribers nowadays. As a result, technologies that support high bandwidth and network availability have become essential. One such technology is dense wavelength division multiplexing (DWDM). This study investigated the evolution of an optical add/drop multiplexer (OADM), which is one of the key components of DWDM technology. The goal of this research was to investigate how the evolution of an OADM has contributed to network survivability and bandwidth enhancement in DWDM optical networks. A thorough search of the literature on an OADM was undertaken using data sources like Google Scholar, Elsevier, ResearchGate, ScienceDirect, Springer, and DWDM vendor manuals. The study found that in order to address present and future DWDM optical network demands, a reconfigurable optical add/drop multiplexer (ROADM) deployed over flex-grid spectrum is essential. The most advanced iteration of a ROADM supports colorless, directionless, contentionless, and flex-grid functionalities, resulting in the most robust, flexible, and future-proof DWDM optical network. The study further found that flex-grid technology supports uplinks with high line rates and has superior spectral efficiency.

Corresponding Author:

Mnotho P. Mkhwanazi
Department of Industrial Engineering, Tshwane University of Technology
Staatsartillirie, Pretoria West, South Africa
Emails: mnotho.mkhwanazi@gmail.com

1. INTRODUCTION

The increasing use of data-driven applications in business, social media, and entertainment has resulted in a surge in data traffic for mobile network operators. Optical communication addresses this data traffic increase adequately due to its ability to cope with high data volumes [1]. The growing demand for bandwidth propels the rapid advancement of optical fibre communication technology [2], one such technology being dense wavelength division multiplexing (DWDM). DWDM technology is used to increase transmission capacity in optical networks. This technology increases the bandwidth of an existing fibre network by combining and transmitting multiple signals simultaneously at different wavelengths on the same fibre [3]. Each input is produced by a distinct optical source with a specific wavelength. DWDM technology is the most advanced multiplexing technique available today [4]. Prior research on DWDM technology has explored its ability to meet present and future bandwidth demands, without going into great detail on the specific components that make up a DWDM system. As DWDM technology evolved, so did its fundamental components. An optical add/drop multiplexer (OADM) is one such component. The OADM is responsible for three main functions within the DWDM network: optical add, drop, and express switching of the optical wavelength. The OADM ensures better usage of current optical fiber infrastructure while also expanding network coverage [5]. A reconfigurable optical add/drop multiplexer (ROADM) is an enhanced OADM that is more commonly used nowadays due to its ability to support remote configuration and automatic wavelength routing. Because of the exponential rise of internet data traffic, a ROADM has evolved to become even more flexible. The flexibility in DWDM optical networks allows remote configuration and automatic wavelength routing, both of which are critical to network survivability. Network survivability is the ability of a network to self-heal and continue functioning correctly when a link or node fails [6].

2. METHOD

This study employs a desk research strategy. This is a research approach that entails collecting, reviewing, and processing secondary information from official sources [7]. The systematic literature review approach was used to conduct a thorough search of the literature on the OADM deployed in DWDM optical networks. A systematic literature review approach includes identifying data sources for the research, keywords to use when searching the literature, and the inclusion criteria [8]. Secondary data for this desk research was obtained from a variety of academic research databases, the internet, and data sheets from several DWDM vendors. Among the academic research databases used were Google Scholar, Springer, ResearchGate, Open Access Journals, IEEE, and Science Direct.

The study deployed a keyword search strategy to find literature on DWDM technology and its components. The keyword search method ensures that only the literature relevant to the study is considered [8]. The keywords in this study have been listed under the keywords section. The search was guided by the Boolean operators AND and OR. Inclusion criteria included:

– All publications had to be written in English.
– The publication period was between 2017 and 2023.
– Publication`s relevance to the subject matter.
– Publication`s availability to fellow academics.

2.1. DWDM technology

DWDM technology represents a significant advancement in optical communication since it allows several optical wavelengths to share a single fiber strand. DWDM systems can operate in both the conventional band (C-band) and the long band (L-band) of the spectrum. The C-band is preferred over the L-band because of its lower attenuation during data transmission [9]. The C-Band operates from 1,530 nm to 1,565 nm and is based on the ITU-T G.694.1 standard. Figure 1 shows the multiplexing of numerous wavelengths into a single composite signal and its transmission through a single optical fiber. The composite signal is demultiplexed at the receiving end, and the various wavelengths are terminated to their corresponding optical receivers [10].

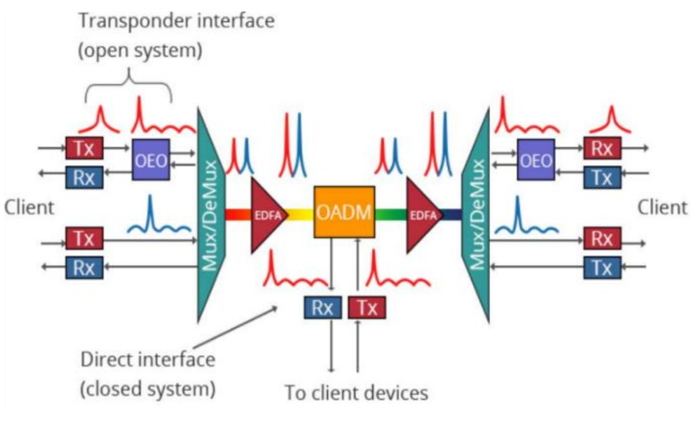

Figure 1. Multiplexing and demultiplexing of optical signals [10]

A DWDM system consists of four main components which include a transponder, multiplexer/demultiplexer, OADM, and erbium-doped fiber amplifier (EDFA) as depicted in Figure 1. Transponders are responsible for transmitting and terminating wavelengths at both ends of the DWDM system. A multiplexer combines several wavelengths and transmits them as a single composite signal over an optic fibre. A demultiplexer accomplishes the opposite of what a multiplexer does; at the receiver end, it isolates the individual wavelengths before they are terminated to their respective transponders. An EDFA is used to amplify a degraded optical signal. Depending on their placement in the DWDM system, an EDFA can function as a booster, in-line amplifier, or pre-amplifier [9]. This study focused on the OADM, its primary functions, and its evolution.

2.2. Optical add/drop multiplexer

Optical communication is an important form of data transmission in addressing the ever-increasing bandwidth demand generated by internet users. DWDM technology has enabled optical communication to reach capacities of up to 1 Tbit/s and beyond [11]. With the scarcity of fibre optic infrastructure in metropolitan locations, an OADM is deployed to make better use of existing optical fibre facilities and expand the network's coverage area [5]. An OADM is an essential component of DWDM networks because it allows carriers to create a versatile, agile, and readily controllable optical transport layer [12]. The OADM is responsible for adding and removing wavelengths from the numerous wavelengths contained by a composite signal in a fibre [13]. Figure 2 illustrates the functionality of an OADM where a composite signal consists of four wavelengths (red, orange, green, and blue). The OADM drops the red wavelength while allowing the other three wavelengths to pass through because they are not intended for this particular DWDM node. The dropped red wavelength is forwarded to a corresponding transponder module. Figure 2 also shows the OADM adding a new red wavelength, which is multiplexed into a new composite signal before being transmitted further along in the DWDM optical network.

Having established the significance of an OADM in DWDM technology, it is necessary to examine how it has evolved as the technology has matured over time. OADMs are classified into two categories, fixed optical add/drop multiplexer (FOADM) and reconfigurable optical add-drop multiplexer (ROADM). A FOADM is a conventional OADM that can only input or output one wavelength via the fixed port. A FOADM has pre-assigned wavelength channels in static nodes. It allows for the removal and reuse of one wavelength locally, as well as the addition of the same wavelength to be transported in the opposite direction. The FOADM allows for static wavelength allocation, whereas the ROADM allows for dynamic allocation [14].

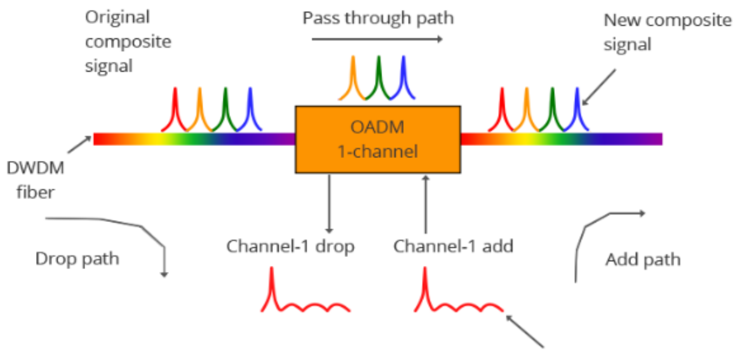

Figure 2. OADM add/drop and pass-through functionalities [13]

3. RESULTS AND DISCUSSION

The purpose of this study was to establish how the OADM has evolved as DWDM optical networks have advanced, as well as how it has contributed to network survivability and bandwidth enhancement. DWDM optical networks transmit massive volumes of essential data. As a result, mobile network operators should prioritize network survivability and bandwidth availability to avoid service disruption to subscribers.

3.1. Reconfigurable optical add/drop multiplexer

Given the massive amounts of data transported by DWDM networks and the importance of the services they provide, network survivability must be prioritized. As traffic demands became increasingly dynamic, a ROADM system capable of changing a designated wavelength route was developed. A ROADM has two main structures, the ROADM architecture, and the add/drop stage. The ROADM architecture is responsible for routing optical signals, while the add/drop stage is responsible for adding and dropping signals in the optical network [15]. A ROADM enables the removal and reintroduction of wavelengths at different nodes of the network at the command of the centralized control center [16]. Furthermore, a ROADM provides flexible wavelength management, which is used to make optical networks transparent, flexible, and scalable [17]. The wavelength selective switch (WSS) is the primary component in a ROADM. WSS modules are responsible for dynamically routing, blocking, and attenuating all wavelengths within a DWDM node. The WSS enables a ROADM to switch traffic on the optical layer remotely [12]. Figure 3 illustrates the ROADM functionality of a two-degree DWDM system where "R" stands for receive, for dropped wavelengths. "T" stands for transmit, for added wavelength. C-Band wavelengths can either terminate on the add/drop block of the node or bypass in the direction of the next DWDM system. WSS module ensures that any wavelength can be routed to any output fibre or direction available to that specific DWDM node [18]. Table 1 highlights the significant differences between a FOADM and a ROADM in terms of installation, commissioning, and maintenance activities.

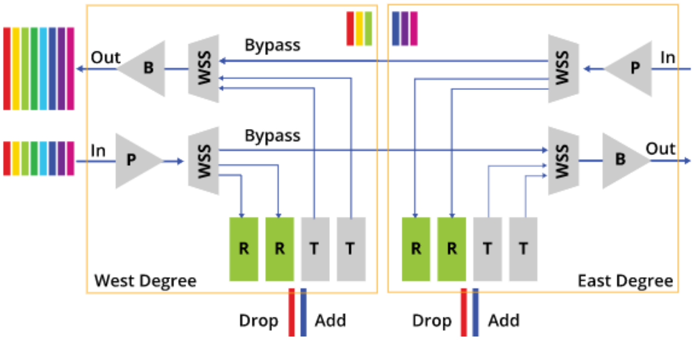

Figure 3. ROADM functional diagram [12]

Table 1. FOADM vs ROADM [19]

Installation and commissioning	FOADM	ROADM
First installation/power up	Manual/manual	Manual/automated
Cabling	Manual	Manual
Configuration/routing	Manual/manual	Automated
Power balancing	Manual	Automated
Testing	Manual	Automated
Maintenance/re-configurations		
New circuit changes/provisioning	Manual	Automated
Network re-configuration	Manual	Automated
Re-engineering and re-optimization	Manual	Automated
Training of network staff	Medium to high	Low

The automation of activities in a ROADM is important in enabling smoother network rollouts and improved maintenance features. A ROADM minimizes the number of labor hours associated with the manual provisioning needed when dealing with a FOADM [12]. The elimination of all manual tasks means that the DWDM optical network is dynamic, with various types of rerouting supported, whether at the service or wavelength level. Because of its flexibility, simpler operations, and greater efficiency, a ROADM has gained widespread industry acceptance [20]. Table 2 lists all the RAODM architectures with varying degrees of flexibility. The most elementary ROADM architecture employs fixed filters for the add/drop function. Other ROADM systems offer (i) flexibility in wavelength assignment, (ii) flexibility in add/drop direction, (iii) the ability to route wavelengths in any direction without wavelength collision/channel blocking, (iv) finally, a flexible grid WSS that supports flex-grid technology [1]. The mobile network operators select one of the ROADM architectures indicated in Table 2 based on the level of flexibility required as well as affordability. More flexibility implies more costs [21].

Table 2. ROADM architectures with differing degrees of flexibility [21]

ROADM type	Colorless	Directionless	Contentionless	Flex-grid
Colored-directional (or fixed)	x	x	x	x
Colorless-directional	✓	x	x	✓
Colored-directionless	x	✓	x	✓
Colorless-directionless (CD)	✓	✓	x	✓
Colorless-directionless-contentionless (CDC)	✓	✓	✓	✓

3.1.1. Colorless

This functionality allows the assignment of any C-Band wavelength to any port within the DWDM node. For any wavelength dropped at the local node, the corresponding added wavelength can go to any output port, regardless of which input port it comes from [22]. To get the most out of a colorless-ROADM, network operators should equip their networks with tunable transponders. It allows end hosts to connect to remote hosts with greater flexibility [23]. This is a significant advancement because it allows the same transponder to be configured to a different wavelength without the need for manual intervention on-site. Figure 4 illustrates the functionality of a colorless ROADM, where any of the C-Band wavelengths can be dropped on any port.

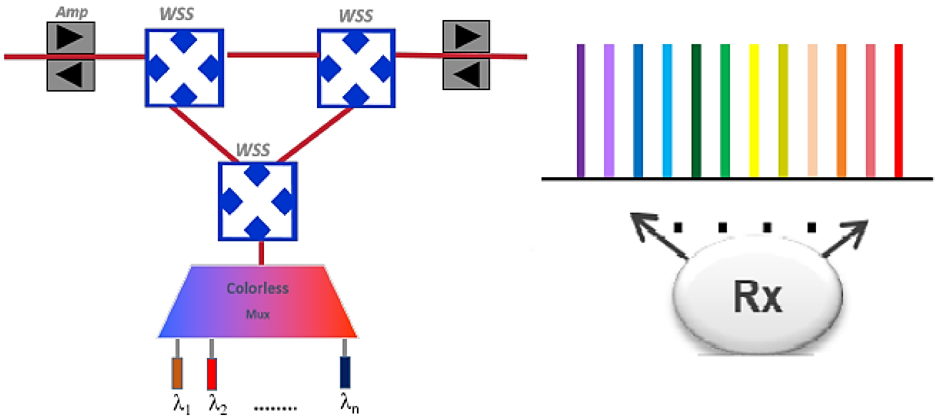

Figure 4. Colorless add/drop [22]

3.1.2. Directionless

The directionless functionality enables a DWDM system to reroute a lambda across any fibre route available in that node in the event of a failure on the nominal route. This lambda reroute occurs regardless of which add/drop block the wavelength is connected to. The directionless functionality also enables automatic reconfiguration of a wavelength direction after it has been added or dropped, increasing the flexibility of route design and implementation even further [24]. Figure 5 highlights the directionless concept where λ1 is connected to the add/drop block on "Fibre Route 1" yet it is still able to transit the DWDM node via "Fibre Route 2". This flexibility ensures improved lambda restoration, resulting in increased network survivability.

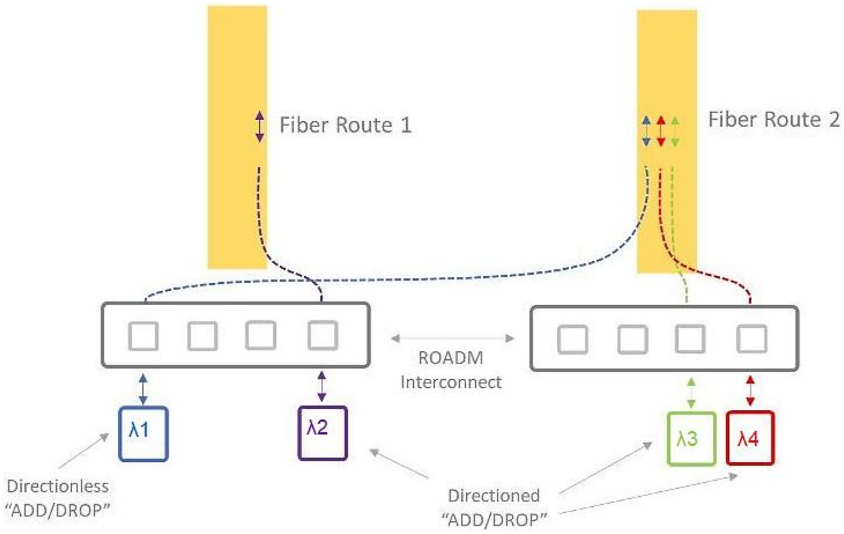

Figure 5. Directionless add/drop [24]

3.1.3. Contentionless

The breakthrough benefit of CDC ROADM is its ability to add and drop any wavelength on any port. Significantly, a CDC ROADM addresses the problem of deploying the same wavelength many times on the same path, by eliminating wavelength blocking. Two or more wavelengths with the same frequency can be connected to the same add/drop in this setup. Furthermore, the contentionless functionality enables the DWDM node to recolor wavelengths to a different frequency channel. Recoloring is the process by which the ROADM assigns an alternate frequency to an incoming wavelength that has a frequency that is already used in the add/drop block during restoration. This feat substantially improves network availability by lowering the difficulty of fault recovery [5]. Figure 6 shows three λ1s (green) added on the same add/drop without wavelength blocking. This is a significant step in improving DWDM optical network survivability.

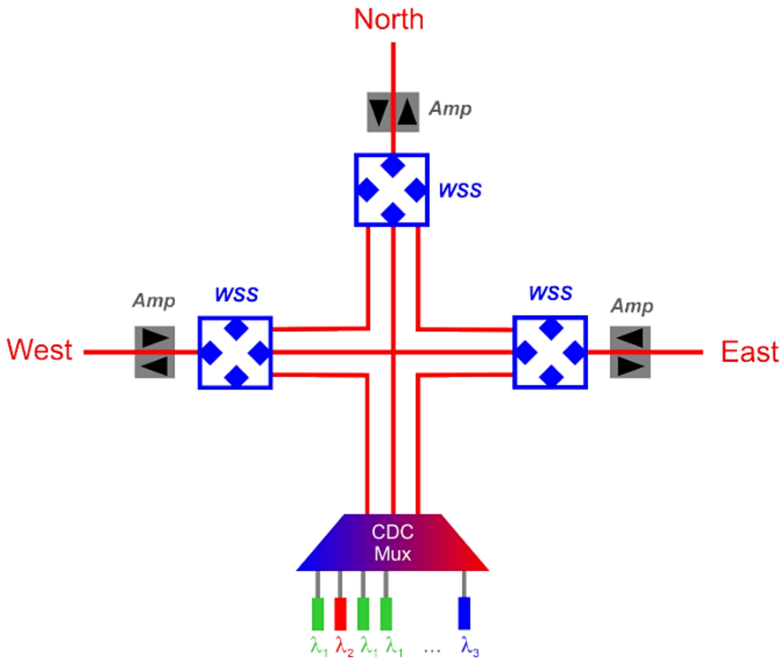

Figure 6. Contentionless add/drop [22]

3.1.4. Flex-grid technology

Flex-grid technology is replacing regular WDM channel spacing because of its greater flexibility in utilizing C-Band spectrum resources. This technology offers high line rate transmission by combining several adjacent flexible sub-channels to form a super-channel [25]. Flex grid technology, defined in ITU-T recommendation G.694.1, is based on a 12.5 GHz spectral channel spacing [26]. A CDC-ROADM that supports flex-grid technology is referred to as a CDC-F ROADM. The CDC-F ROADM presents the flexibility necessary to better utilize fibre spectral resources. To transmit high data rates, the implementation of flex-grid technology necessitates a change in the modulation scheme in the DWDM network. Higher order modulation schemes such as 16-QAM, 64-QAM, and 256-QAM are used to achieve high line rate per wavelength transmission. Similarly, high optical signal-to-noise ratio and low phase noise are just as important [27]. It is vital to note that a guard band is necessary between each channel when employing flex-grid technology to prevent interference or cross-talk [28]. Flex-grid enabled DWDM optical networks are also called EONs, short for elastic optical networks [1]. Figure 7 compares the channel spacing as well as the spectral efficiency of fixed-grid and flex-grid deployments. In the fixed-grid spectrum, channel spacing is fixed at 50 GHz, and the highest possible uplink is 100 Gbit/s per wavelength. Flex-grid technology divides the spectrum into 6.25 GHz channel spacing. The 6.25 GHz channel spacing allows flex-grid technology to make better use of the spectrum because there are fewer wasted spectrum resources. Flex-grid technology enables the configuration of uplinks or lambdas with line rates exceeding 100 Gbit/s. This technology supports line rates ranging from 100 to 1 Tbit/s and beyond. Flex-grid technology allows for more data to be packed onto a single wavelength, which is critical in meeting both current and future bandwidth needs [28]. A CDC-F ROADM is the most versatile ROADM to date [29]. This type of ROADM supports enhanced capabilities such as multi-degree, add/drop structures, colorless, directionless, contentionless, and flex-grid [30]. It is essential that optical networks transition from a fixed-grid to a flexible grid to meet present and future bandwidth demands in DWDM optical networks [31]. To avoid significant disruption in the existing fixed-grid network, a gradual transition where nodes with flex-grid capabilities coexist with fixed-grid nodes is recommended before a complete migration [32].

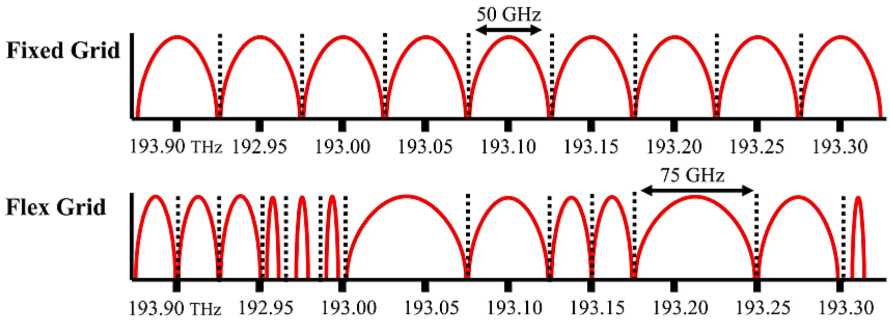

Figure 7. Fixed grid vs. flex-grid [1]

3.2. DWDM network survivability

Several attempts have been made to improve optical network survivability against single and multiple link or node failures through protection and restoration [33]. Protection is a proactive strategy in which resources are pre-allocated to ensure connectivity in the event of a failure. Restoration is when the optical system searches for resources dynamically after the failure has occurred [34]. The approach of deploying protection and restoration together is called protection and restoration combined (PRC). PRC is the fault-handling method used by an automatically switched optical network [35]. A flowchart outlining the various processes involved in the PRC approach using a CDC-F ROADM is shown in Figure 8. When a fibre cut is detected, the DWDM system establishes if it affects the nominal or protection route. If the optic fibre cable break affects the protection route, the failure is nonservice affecting. While this situation does not disrupt services, sufficient attention must be given to resolving the issue because the next failure may be service-affecting. If the fibre cut is on the nominal route, the services are switched to the protection route; the transition is heatless for the client since the switching time is sub 50 ms, this is a typical protection switching time [36]. The only obvious difference may be a change in latency depending on the length of the protection route. The lambda (s) on the failed route whether nominal or protection route, initiates the restoration process via GMPLS/ASON engine depending on the DWDM equipment deployed. Amongst other considerations, successful optical restoration is subject to whether restoration fibre routes are available at the time the failure occurs. If the failed lambda cannot be restored because network resources are unavailable, it is dropped and remains down until the failed fibre route is repaired. This relates to the significance of restoring all failed fibre routes in the network as quickly as feasible, even if they are not affecting services at the time of failure. When the next fibre route disruption occurs, a failed fibre route that is left unattended could be the one offering a restoration path to other lambdas in the network. Where network resources are available, a failed lambda is restored using a new temporal fibre route. What is more crucial in this circumstance is that a recovered lambda provides an entirely new temporal SNC-P path for the service, increasing network survivability even more. During the configuration process, both a service and a lambda can be configured to use revertive or non-revertive switching modes. In revertive switching, the service is switched back to the normal route when it has recovered from a failure. A switch to the protection route remains in place in non-revertive switching even after the nominal route has recovered from a failure [37]. Once the nominal route has been repaired and lambdas/services have reverted to their normal route, the PRC process is complete. The type of ROADM used contributes to the effectiveness of the PRC technique. The CDC-F ROADM ensures that the wavelength channel utilized by the lambda can no longer be a hindrance to the restoration process because wavelength can be recolored thanks to the contentionless feature. This feat substantially improves network availability by lowering the difficulty of fault recovery [5]. The authors reviewed agree that restoration is critical for enhancing network availability. However, it is not guaranteed because it is dependent on the available resources at the time of failure. To guarantee that restoration routes are always available, it is vital to reduce the mean-time-to-repair (MTTR) as much as possible where fibre cuts are detected.

The CDC-F ROADM also supports flex-grid technology, hence the letter "F". This technology enables the allocation of the optical spectrum at a finer granularity of 12.5 GHz, thereby enabling dynamic spectrum management [38]. According to the research reviewed in this study, improving bandwidth availability is crucial to DWDM optical networks in meeting current and future capacity demands. Flex-grid technology allows for a lot more optical channels, which means that the optical power pumped into the amplifiers of existing fixed-grid infrastructure increases, causing some amplifiers to shut down completely. Given that, flex-grid technology is being introduced over the existing fixed-grid network, skilled and experienced resources are required to manage the complexity. Furthermore, transponders with 400 Gbit/s, 1 Tbit/s, and higher capacities that use high-order spectrally efficient modulation schemes are expensive [39]. Ultimately, the decision for network operators to transition to flexible-grid technology will be influenced by the trade-off between benefit and hardware/software cost, backward compatibility with previously deployed technologies, and network management complexity [40]. Overall, a CDC-F ROADM is the most versatile ROADM to date [29].

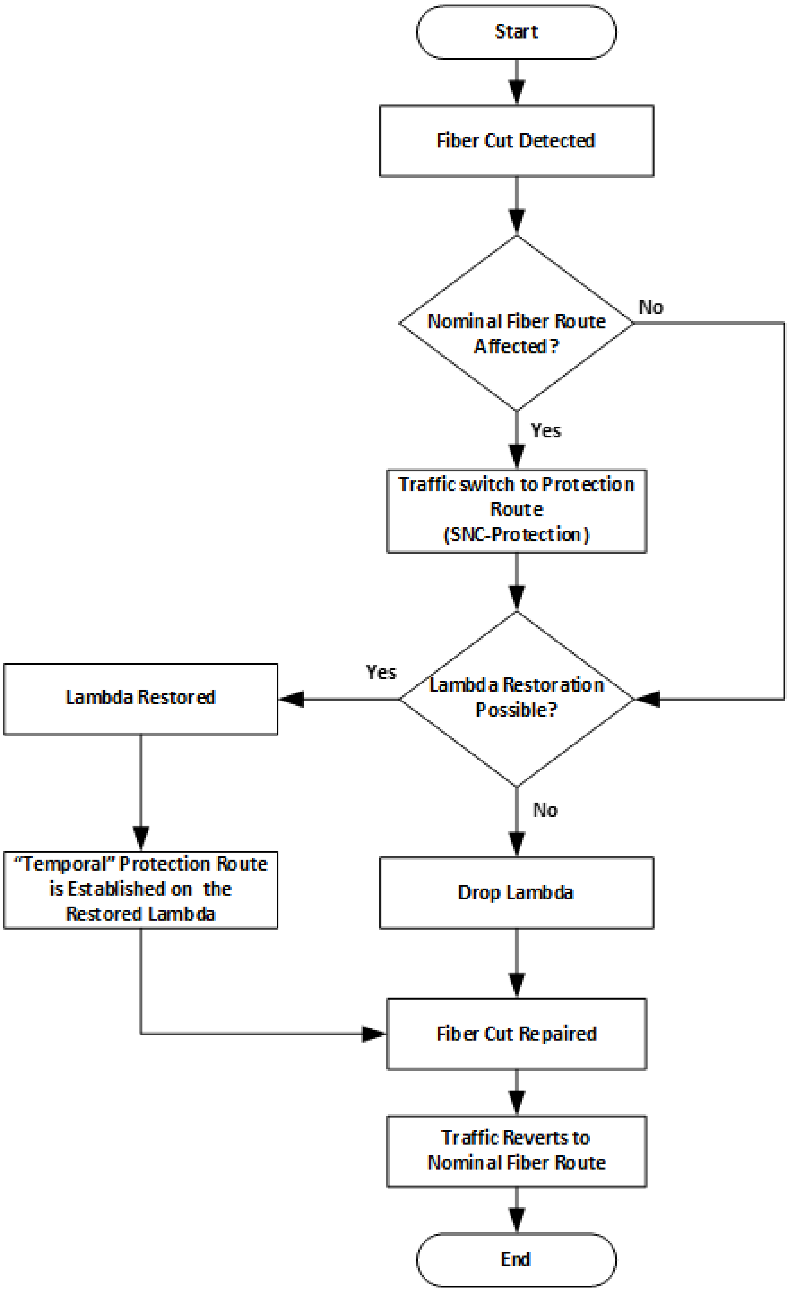

Figure 8. Flow chart of PRC process for protected services

4. CONCLUSION

This study investigated the evolution of an OADM in DWDM optical networks, from FOADM to ROADM and, more recently, to CDC-F ROADM. According to the material reviewed, CDC-F ROADM is the most recent iteration of OADM development. The CDC-F ROADM architecture addresses present and future DWDM optical network needs as it offers improved network survivability which promotes network availability. Furthermore, the literature indicates that flex-grid technology is a solution to address high bandwidth demand. This is due to the technology`s ability to transmit line rates up to 1 Tbit/s and higher while maintaining superior spectral efficiency when compared to the conventional fixed-grid. The study also found that eliminating manual provisioning and other manual processes in a ROADM, contributes to OPEX savings by reducing labor hours invested. This study suggests more research into the deployment of a CDC-F ROADM in the L-Band spectrum. The proposed study will help to determine the long-term viability of using the L-Band in DWDM optical networks.

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AUTHOR CONTRIBUTION STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Mnotho P. Mkhwanazi	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Khumbulani Mpofu		✓			✓	✓	✓	✓			✓	✓		
Vusumuzi Malele		✓		✓	✓		✓				✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

DATA AVAILABILITY STATEMENT

As this is a desk research approach, the study depended on secondary data. This secondary data was gathered from a variety of articles and trustworthy websites.

CONFLICT OF INTERESTS

The authors declare no conflicts of interest.

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BIOGRAPHIES OF AUTHORS

Mnotho P. Mkhwanazi received a Master of Engineering: Engineering Management and a Baccalaureus Technologies, Engineering: Electrical from Tshwane University of Technology (TUT). He is currently a technologist with over 16 years experience in the telecommunication industry specializing in transmission networks. He has work worked with synchronous digital hierarchy (SDH) and DWDM equipment from vendors like Nokia, ECI, Infinera, Siemens, Huawei, and ADVA. He can be contacted at email: mnotho.mkhwanazi@gmail.com.

Khumbulani Mpofu received a B.Eng. degree in industrial and manufacturing engineering, from National University of Science and Technology (ZW), M.Eng. in manufacturing systems and operations management, from University of Zimbabwe, and a D.Tech. degree in mechanical engineering from TUT. He is currently a professor of industrial engineering and the Gibela research chair in manufacturing and skills development with the TUT, South Africa. He is an NRF-rated researcher with an unbridled passion for industrial engineering. A distinguished scholar with more than 25 years experience in the field. He can be contacted at email: mpofuk@tut.ac.za.

Vusumuzi Malele received a Bachelor of Science (B.Sc.) degree in statistics and physics from Vista University South Africa, a Postgraduate Diploma (PDE) in engineering and a master of engineering science from Stellenbosch University and Doctor of Technology (D.Tech.) industrial engineering from TUT. He is currently an associate professor of computing and systems engineering a distinguished scholar with more than 25 years experience in the field. He can be contacted at email: vusi.malele@nwu.ac.za.