Design of an OTN-based Failure/Alarm Propagation Simulator

by

Zening Li

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

This thesis presents OTN failure/alarm propagation behavior analysis and an OTN simulator based on failure/alarm propagation behavior on the optical layer of optical transport network (OTN) architecture. The simulator code is implemented by Python. The failure, alarm, and propagation behavior examples discover from the Huawei Optix OSN 8800/6800/3800 V100R009C10 reference book[3]. The simulator is used to restore the basic failure/alarm propagation behavior and generates valuable results, including alarm, alarm flow, the ground truth matrix of alarm flow, and the active alarm flow dependency graph. The results are the ground truth data for future applications such as root cause analysis and restoring hidden propagation behaviors.

Acknowledgements

Firstly, I would like to thank my supervisor, professor Pin-Han Ho, for all the support of my research.

Secondly, I would like to thank my parents for their spiritual and financial support.

Finally, I would like to thank all my colleagues who provided me with a lot of guidance and help on my research.

Dedication

This thesis is dedicated to my parents, who gave me a lot of courage to complete my research.

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Chapter 1

Introduction

1.1 Background and Motivation

Optical Transport Network(OTN) is a new efficient telecommunication protocol that provides an efficient way to multiplex different services onto optical light paths[5]. SONET and SDH are the primary technique for multiplexing, but the speed of SONET and SDH are much slower than OTN. The OTN control plane can handle light paths from source to destination and report alarms from specific network failures. A failure event may happen at more than a single board and/or fiber segments that affect numerous lightpaths. The interrupted lightpaths and alarm notifications will propagate throughout the network domain, and the alarm notifications will report on the control plane. However, the OTN control plane can only present the alarm information. It is impossible to get the failure information from the alarms. Thus, to find the root failure of each alarm, it is crucial to have an OTN failure/alarm propagation simulator based on the design of the OTN failure propagation behavior. The data generated from the simulator are the ground truth data. These data have more than root cause analysis applications such as atomic rule learning and future failures prediction.

Inside OTN, two types of vertices(nodes) involve in this simulator: the **reconfigurable optical add-drop multiplexer (ROAMD)** and the **optical line amplifier (OLA)**. ROADM is a device that can add, block, pass or redirect modulated infrared (IR) and visible light beams of various wavelengths in a fiber-optic network that employs wavelength division multiplexing[6]. OLA is the device to amplify the signal. There are two other types of vertices in OTN: optical transport module (OTM) and regenerator. This simulator simplifies the device into ROADM and OLA because the ROADM and OLA cover all the essential boards in OTM and regenerator, and the propagation behavior is similar. Moreover, this simulator focuses on the optical layer failure/alarm propagation because the optical layer has the same or even more complex propagation behaviors as the electric layer.

This thesis presents the technical detail of an OTN simulator that can handle single and multiple failures with eight representative test cases of failure/alarm propagation simulation. An abstract **time step** is involved in this simulator to solve the multiple failure problem. The simulator takes the *rule database*, *failure(s)*, the beginning *time step* of each failure, and the network *node-level subgraph* as the input. The outputs are the *alarm*, the *alarm flow*, the *ground truth of the alarm flow matrix (AF_{GT})*, and the *active alarm flow dependency graph (aAFDG)*. The technical terms' detailed information will present in the terminology section.

1.2 Terminology

A few important terms notation are listed as follows. All other terms notation are explained based on these terms.

- **Event** is the exceptional condition occurs in the OTN.
- **Failures** are the events which can trigger the boards from the OTN nodes to report alarms.
- **Alarms** are the events which triggered by failures.

Alarm flow is the most important term in this thesis, which is is defined as a pair of boards that satisfies one of the following two types of causal relationship corresponding to a predefined alarm generation atomic rule:

- **Type 1** Board B_1 detects failure $F_1 \rightarrow$ board B_2 reports alarm A_1
- **Type 2** Board B_1 reports alarm $A_1 \rightarrow$ board B_2 reports alarm A_2

Type 1 alarm flow establishes the relation between board B_1, which either detects a failure or receives an alarm, and board B_2, which reports the root alarm A_1. Note that B_1 and B_2 could be the same board, and in such a circumstance, the alarm A_1 locally

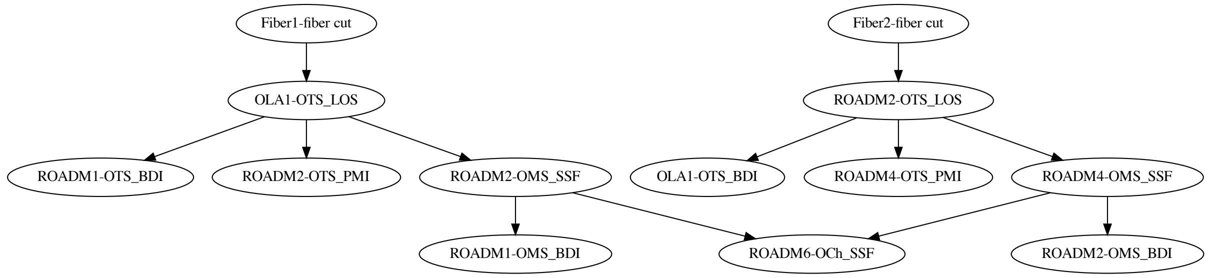


Figure 1.1: Example of aAFDG

reports on the faulty board. Type 2 alarm flow describes the root-descendant/descendant-descendant alarm relationship from the view of boards. Board B_2 will report alarm A_2 when it receives the alarm signalling sent by board B_1 that reports alarm A_1. Also, A_1 and A_2 could be the same alarm. The alarm flow presents the propagation behavior and the relationship between the two alarms. An alarm flow is a pair of alarms with corresponding locations and the time of occurrence. The alarm generation atomic rules form the **alarm generation database** in the simulator, which use to generate the alarm flow.

The **node-level subgraph** is the subset of the network topology, which contains nodes traversed by lightpaths. Since the whole network topology can be enormous, nodes not covered by the lightpaths are not necessary for future analysis in active lightpaths. Therefore, using a node-level subgraph as the input can simplify the simulator program.

An **aAFDG** provides the failure/alarm dependency, which is a tree shape graph/multigraph exemplified in Fig. 1.1 where each vertex represents an alarming board or a faulty fiber segment with the associate failure/alarm. The aAFDG is a helpful visualization to understand the propagation behavior to do the root cause analysis.

The board locations of the two alarms in alarm flows can classify into two categories: **inter-site** and **intra-site**. Inter-site means a failure/alarm propagates from one node to another. In contrast, failure/alarm propagating inside the current node define as intra-site. Resulting alarms for both inter-side and intra-site are generated based on the rule database. Although alarms reported by intra-site alarm flow are in the same node, propagation may occur in different layers.

For ROADM and OLA, multiple important boards cover in the simulator. Fig. 1.2 and Fig. 1.3 are the structure of ROADM and OLA. The **Fibre interface unit(FIU)** is the

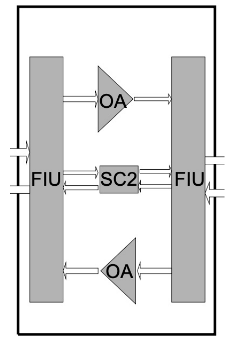


Figure 1.2: OLA Structure[3]

interface connected to fibers that can detect failures related to fibers. It is the start and endpoint of the OTS layer. The **optical amplifier(OA)** is the board to amplify signals. The **optical multiplexer(OM)** and **optical demultiplexer(OD)** are the start and end-point of OMS layer which multiplex and demultiplex signals. The **optical transponder unit(OTU)** stands for the OCh layer endpoint, which converts client-side services into standard optical signals after performing mapping, convergence, and other procedures[1]. The SC2 is the **optical service channel(OSC)** which manages the overhead information.

OTN has electrical and optical layers. Since the simulator only considers the optical layer, this thesis will not explain the electrical layer. The optical layer have three layers, which are **optical transmission section (OTS)**, **optical multiplex section (OMS)**, and **optical channel (OCh)** [7]. These layers are the monitoring section in different granularity. OTS locates between the FIU or OA boards of two sites, and OMS locates between the MUX and DEMUX boards of two sites, and OCh is a span on a single wavelength[4], which can express as a lightpath in the OTN network. Different layers have different alarm types. Failures can trigger the same layer and cross-layer alarms. The details are in the following chapters. Note that OLA does not have multiplex and demultiplex sections; therefore OMS layer ignores OLA in the OTN network.

Fig. 1.4 presents a failure propagation example. This example is a linear network containing three stations. Stations ROADM1 and ROADM3 are ROADM, and site OLA1 is OLA with optical fibers connecting all stations. Assume that there is a locally added lightpath at station ROADM1. The failure fiber cut occurs on fiber between stations ROADM1 and OLA1. The OTS layer, station OLA1 FIU board detects and reports OTS_LOS alarm from fiber cut failure. From OTS_LOS alarm, station ROADM1 FIU board detects and reports OTS_BDI alarm, and station ROADM2 FIU board detects and

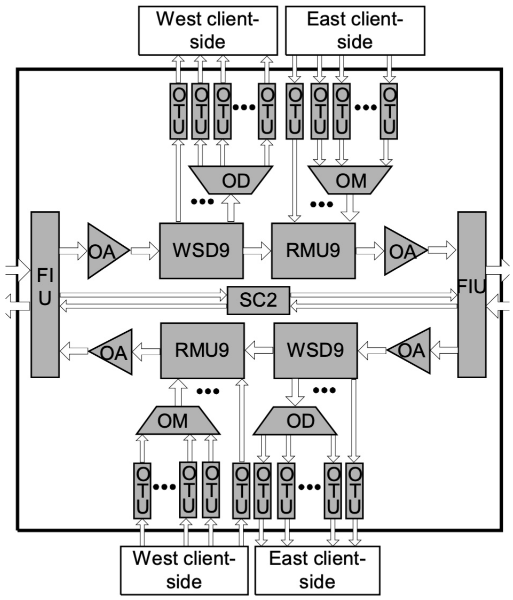


Figure 1.3: ROADM Structure[3]

reports OTS_PMI from OTS_LOS alarm in station OLA1. The OTS_LOS is the parent alarm for some cross-layer alarms. In the OMS layer, station ROADM2 OD board detects and reports OMS_SSF alarm. OMS_SSF alarm triggers an OMS_BDI alarm to station OLA1 OM board. In the OCh layer, station ROADM2 OTU board detects and reports OCh_SSF.

1.3 OTN structure

OTN is migrating from SONET technology to wavelength-division multiplexing (WDM) architectures [2]. WDM is a technology that multiplexes multiple wavelengths into a single fiber [2], which increases the network capacity and reduces the cost of single-channel network distribution. ITU-T G.709 is the OTN standard that add SONET-like performance monitoring, fault detection, communication channels, and multiplexing hierarchy to WDM wavelengths [2]. The benefits of OTN are listed as follows:

- Enhanced OAM for wavelengths [2]
- Universal container supporting any service type [2]

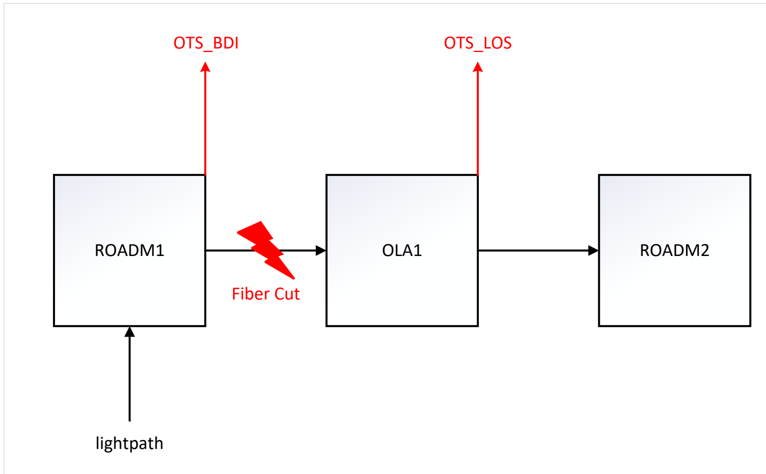


Figure 1.4: Example of Failure/alarm Propagation

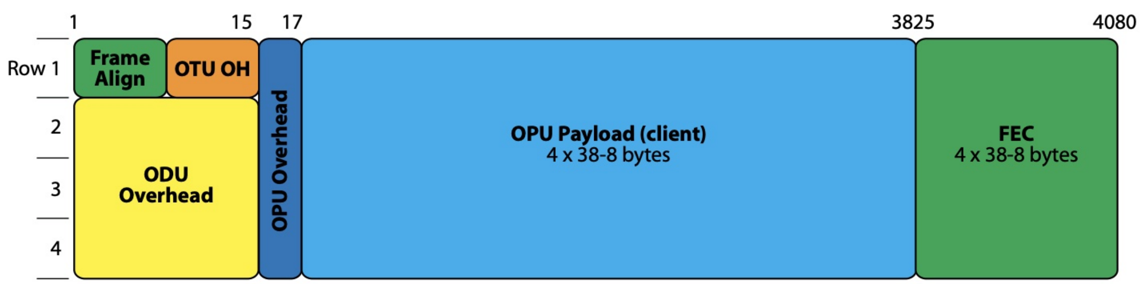


Figure 1.5: OTN Structure[2]

- Standard multiplexing hierarchy [2]
- End-to-end optical transport transparency of customer traffic [2]
- Multi-level path OAM [2]

Fig. 1.5 presents the frame structure of OTN. The payload encapsulates the overhead information in order to do operations, administration, and maintenance by the OTN standards[2]. There are three overhead areas in an OTN frame: the Optical Payload Unit (OPU) overhead, the Optical Data Unit (ODU) overhead, and the Optical Transport Unit (OTU) overhead which provides path and section performance monitoring, alarm indication, communication, and protection switching capabilities[2].

1.4 Contribution

The main contribution of this thesis are listed as follows:

- This thesis designs and summarizes failure propagation behaviors in the simulator, which helps understand the typical failure/alarm propagation pattern. Furthermore, a failure/alarm propagation simulator has been implemented based on these failure propagation behaviors.
- The simulator provides ground truth data: alarm, alarm flow, AF_{GT}, and aAFDG, which is useful for future applications such as fault localization and hidden failure/alarm propagation behavior learning.

1.5 Organization

This thesis organizes into six chapters. Chapter one is the introduction of the entire thesis. Chapter two concentrate on some useful literature review related to the simulator and the OTN structure. These critical reviews help construct the failure propagation behaviors and the simulator.

Chapter three provides proper failure propagation behaviors in the network simulator. Firstly, this chapter summarized some critical features related to failure propagation behavior. Then, this chapter presents four generic types of alarm propagation behavior in the simulator.

Chapter four presents the detailed simulator design and the important definition in the simulator. The simulator is built by using Python, and it can handle single and multi-failure scenarios. Also, this chapter provides a simple example of failure suppression in a multi-failure case. Also, this chapter introduces the time domain in the simulator. Moreover, the essential contents in the simulator purposed in this chapter, such as rule database and aAFDG.

Chapter five has eight test cases in the simulator, which tests the four generic types of alarm propagation behavior, the propagation behavior for the same failure on different locations, the affections of the OCh lightpath, different failures on the exact location, and some more complex multi-failure example. All the detailed test results are in chapter five.

Chapter six is the summary of the thesis. Also, the simulator limitations and future works are in this chapter.

Chapter 2

Literature Review

Several highly relevant references have been available in the literature and reviewed in this section.

The "Optix OSN 8800/6800/3800 V100R009C10 Alarm and Performance Events"[3] presents the relevant alarm information and some samples of optical layer alarm signal processing. The alarm information provides the detailed alarm description, parameter, impact on the system, and possible cause that are highly essential for analyzing and creating the simulator's rule database. The examples of alarm signal flow in the optical layer specify the possible failures and the corresponding procedures to solve the failures in OTN. Most of the atomic rules in the rule database refer to these examples.

The "The Key Benefits of OTN Networks"[2] presents an introduction of OTN. This article specifies the OTN frame structure and OTN client signal mapping. First, the client signal mapped into the optical payload unit(OPU) payload with the OPU overhead for information on the type of signal, then it added optical data unit(ODU) overhead for optical path-level monitoring, alarm indication signals, automatic protection switching bytes, and embedded data communications channels. Finally, optical transport unit(OTU) overhead add to the signal to provide optical section layer PM, alarm indication, and the GCC0 data communications channel. The whole picture of OTN is the basis of the OTN simulator, which helps to understand how the alarm propagates through OTN.

Chapter 3

Failure/Alarm Propagation Behavior

Each OTN device has many boards such as FIUs and optical amplifiers, and failure events can happen at one or multiple boards and/or fiber connected with boards. The failure events can affect one or multiple lightpaths. The alarm generated from the failure will propagate through the lightpaths. This chapter provides the design of useful failure propagation behaviors for the simulator design.

First of all, a number of unique features are summarized as follows:

- Firstly, it is crucial to transform OTN topology into a node-level subgraph. Each vertex represents the node or fiber in the OTN. All the vertices are connected by fiber. The combination of node-level subgraphs are the **complete subgraph (CSG)** which contains all the vertices involved in the simulator.
- An alarm flow is represented by a pair vertices in the CSG, where a failure or alarm event triggered an alarm signal and initiated notifications and/or reporting to the network management system (NMS) under a predefined atomic rule in the rule database to the corresponding vertices and boards. An alarm flow has parent and child vertices where the alarm is transmitted from the parent and received and reported by the child.
- There are three rules defined over the alarm flows: **forward notify and report (FNR)**, **backward notify and report (BNR)**, and **locally reported (LR)**. The FNR is the parent vertex that transmits the alarm signal to the child vertex, and the child vertex locates in the same direction of data flow. The BNR operates the same, but the child vertex locates in the opposite direction of data flow. For example, In

Fig. 3.1 , vertex A is the parent of B in FNR, but in BNR, vertex B is the parent. The LR means the alarm locally reports at the vertex and board. The LR is not presented in the alarm generation database, but it can operate in the simulator.

Figure 3.1: Example of Propagation Rule

Based on the previous features, there are three generic types of alarm propagation behavior presents in the simulator, which is defined as the relationship of alarms, which are listed as follows:

- **SameLayer-one2one-FNR** The parent vertex triggers an FNR alarm signal and the alarm report in the same OTN layer at the child node.
- **SameLayer-one2one-BNR** The parent vertex triggers a BNR alarm signal and the alarm report in the same OTN layer at the child node.
- **CrossLayer-one2one-FNR** The parent vertex triggers an FNR alarm signal, and the alarm signal causes an alarm reported in the different layers at the child vertex.

Chapter 4

Simulator Design

The objective of the simulator is to generate alarms, alarm flows, aAFDG and AF_{GT} in single and multi-failure cases. The inputs are alarm generation database, failure events, and node-level subgraph.

Since the simulator can solve the single and multi-failure problem, it requires the ability to handle failure suppression where the precedence of failures can suppress some alarms. For instance, the diagram of a lightpath with two failures is present in Fig. 4.1.

In this scenario, there are three vertices involved: two ROADM and one OLA. The arrow presents the direction of the lightpath. If the fiber connecting OLA1 and ROADM2 is broken before the optical amplifier (OA) board is faulty at OLA1, this fiber cut will suppress alarm OTS_LOS_P.

However, if the OA board faulty comes first, this failure suppression will not be executed. The timelines regarding the mentioned two scenarios show in Fig. 4.2.

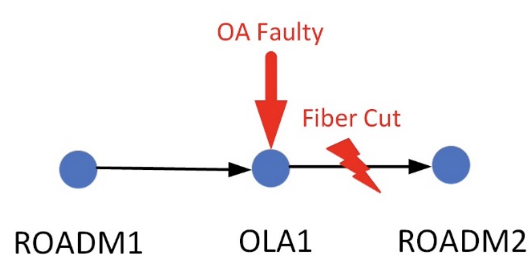


Figure 4.1: Example of Multi-Failure Example

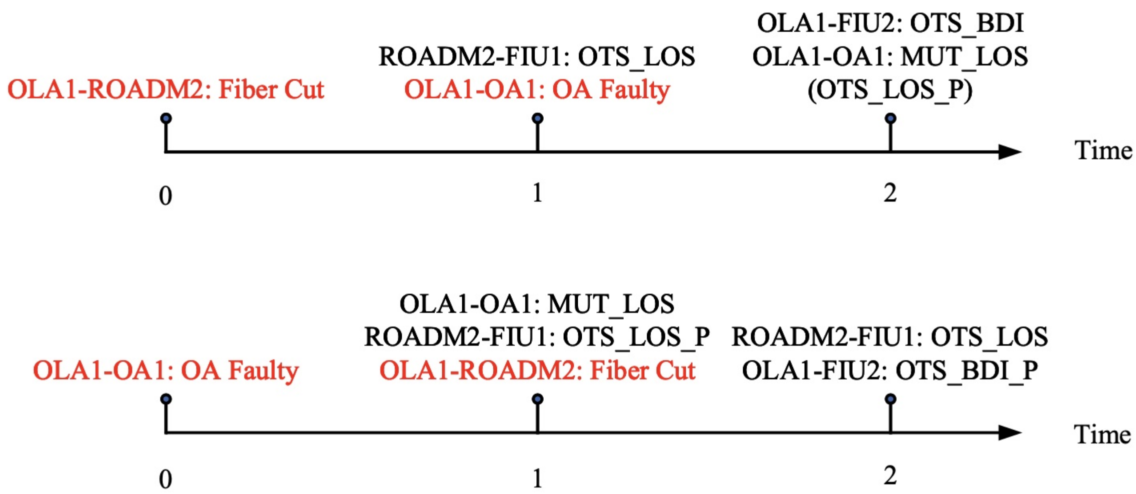


Figure 4.2: Example of Multi-Failure Timeline

The first timeline demonstrates the first case where the failure of fiber cut suppresses alarm OTS_LOS_P passing through fiber. The second timeline presents the other case where failure suppression is not triggered.

To approximate the moments associated with occurrences of failures or alarms, the abstract *time step* was introduced to record the sequential order of any events. The initial time step is set to be zero. The time step will be increased by one for each hop of alarm propagation. If the failure location interrupts the alarm propagation path, the descendent alarms cannot be produced.

The architecture of robust simulator illustrates in Fig. 4.3. Failure event(s), node-level subgraph, and the database containing all alarm generation rules take as the input to the alarm flow generator. According to the query request, the database will invoke qualified rules and return corresponding alarms and alarm flow that form the basis for producing AF_{GT} .

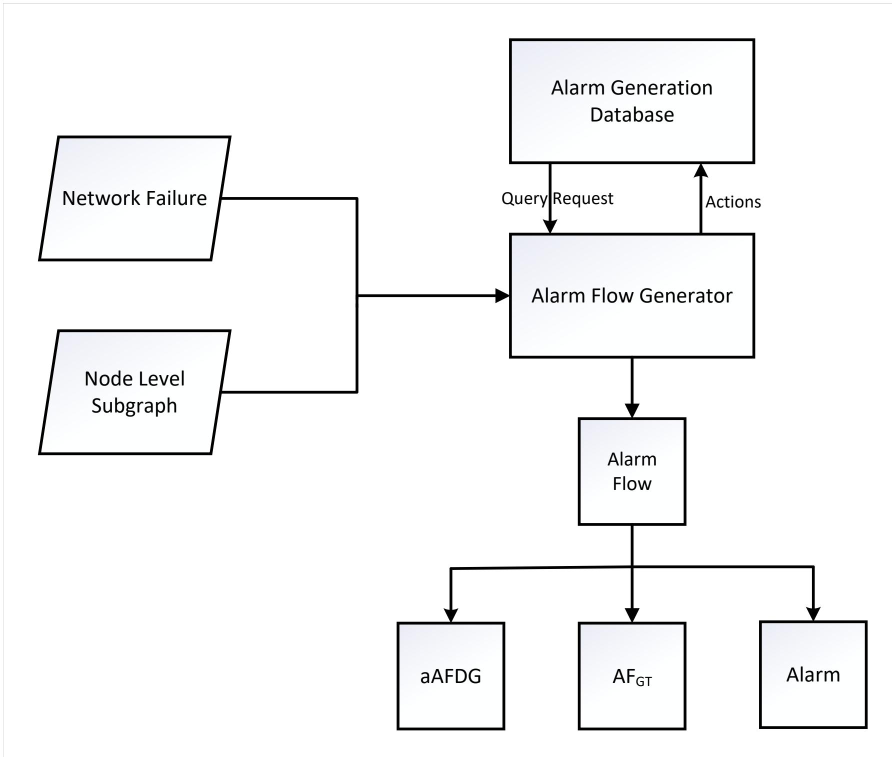


Figure 4.3: Flowchart of OTN-based Simulator

The subsequent four subsections present the design of the alarm generation database, alarm and alarm flow generator, AF_{GT} and the aAFDG. Note that the alarms signal is processed and propagated via an abstract control board by **inter-node** and **intra-node** signaling functionality. The intra-node means the alarm dependent on the occurrence of a fault or an alarm on a local node and board, whereas inter-node means alarm is reported/generated because of a fault/alarm on another node. All intra-node signaling paths always function properly subject to no failure in the simulator. Two additional assumptions are taken in this stage to simplify the simulator program. Firstly, FIU boards and fibers connected to the control board will not malfunction. Moreover, no more than one failure is allowed to happen at an arbitrary time step.

Note that inside each node, several boards with the same name exist. For example, there are four OA in ROADM. Thus, an index is added to the boards. The index organizes by left to right and top to button format. For example, in Fig. 1.3 the top left side of OA is defined as OA1, and the top right OA is defined as OA2. For OTU, there will be eight

OTU in each ROADM.

4.1 Alarm Generation Database

Fig. 4.4 presents the screenshot of the alarm generation database where entries cover all the rules of alarm generation is constructed with MySQL. Table 4.1 provides the explanation of each field in an atomic rule. "Board", "ReceiveDetectEvent" and "Parameter" are the keys to determine the query request, i.e. what kind of parametric event is received/detected at a particular board/fiber segment. Consequently, the database is responsible for returning all eligible actions to the alarm flow generator. Each entry corresponds to single/multiple actions parsed by four attributes, including "OutputParameter", "OutputType", "Output" together with "OutputBoard".

Field name	Description	Sample content
Board	Board/Fiber segment name in an OTN node	fiber1, FIU1, SC2
ReceiveDetectEvent	Received/Detected event on a board/fiber segment	fiber cut, OTS_LOS, OTM_PMI
Parameter	Parameter of the received/detected event	None
OutputParameter	Parameter regarding to the output alarms/signal insertion	None, on routing path
OutputType	Type of alarm generation behaviour	transmit downstream, transmit upstream, to board
Output	Name of output alarm/signal insertion	OTS_LOS, OTS_PMI
OutputBoard	Destination board of output alarm/signal insertion	FIU1, FIU2, SC2, OTU1

Table 4.1: Explanation of Alarm Generation Database

Board	ReceiveDetectEvent	Parameter	OutputParameter	OutputType	Output	OutputBoard
fiber	fiber cut	None	None	transmit downstream	OTS_LOS	FIU1
FIU1	OTS_LOS	None	on routing path;None;None	transmit upstream;transmit downstream;transmit downstream	OTS_BDI;OTS_PMI;OMS_SSF	FIU2;FIU1;OD1
OD1	OMS_SSF	None	on routing path;None	transmit upstream;transmit downstream	OMS_BDI;OCh_SSF	OM1;OTU1
OA	board faulty	None	report locally;None	to board;transmit downstream	MUT_LOS;OTS_LOS_P	OA;FIU1
FIU1	OTS_LOS_P	None	on routing path;None;None	transmit upstream;transmit downstream;transmit downstream	OTS_BDI_P;OTS_PMI;OMS_SSF_P	FIU2;FIU1;OD1
OD1	OMS_SSF_P	None	on routing path;None	transmit upstream;transmit downstream	OMS_BDI_P;OCh_SSF_P	OM1;OTU1
FIU1	TTI inconsistency	None	report locally	to board	OTS_TIM	FIU1
FIU1	OTS_TIM	None	on routing path;None	transmit upstream;transmit downstream	OTS_BDI;OCh_SSF	FIU2;OTU1
OA	lose input light	None	None	transmit downstream	OTS_PMI	FIU1
SC2_FIU2	SC2_FIU2 fiber cut	None	None	transmit downstream	OTS_LOS_O	FIU1
FIU1	OTS_LOS_O	None	on routing path;None;None	transmit upstream;transmit downstream;transmit downstream	OTS_BDI_O;OTS_PMI;OMS_SSF_O	FIU2;FIU1;OD1
OD1	OMS_SSF_O	None	on routing path;None	transmit upstream;transmit downstream	OMS_BDI_O;OCh_SSF_O	OM1;OTU1
OM	board faulty	None	None	transmit downstream	OMS_LOS_P	OD1
OD1	OMS_LOS_P	None	on routing path;None	transmit upstream;transmit downstream	OMS_BDI_P;OCh_SSF_P	OM1;OTU1
OTU	board faulty	None	on routing path	transmit downstream	OCh_LOS_P	OTU1
OTU	ODUk_PM_AIS	None	None;None	to board;transmit downstream	ODUk_PM_AIS;ODUk_PM_AIS	OTU;OTU1
WSD9	board faulty	None	None	transmit downstream	OTS_LOS_P	FIU1
RMU9	board faulty	None	None	transmit downstream	OTS_LOS_P	FIU1
FIU1_SC2	FIU1_SC2 fiber cut	None	None	transmit downstream	OTS_LOS_O	FIU1
OD	board faulty	None	None	transmit downstream	OMS_LOS_P	OD1
FIU1_OA1	FIU1_OA1 fiber cut	None	None	transmit downstream	OTS_PMI	FIU1
OA1_WSD91	OA1_WSD91 fiber cut	None	None	transmit downstream	OTS_LOS_P	FIU1
WSD91_RMU91	WSD91_RMU91 fiber cut	None	None	transmit downstream	OTS_LOS_P	FIU1
RMU91_OA2	RMU91_OA2 fiber cut	None	None	transmit downstream	OTS_LOS_P	FIU1
OA2_FIU2	OA2_FIU2 fiber cut	None	None	transmit downstream	OTS_LOS_P	FIU1
WSD91_OTU1	WSD91_OTU1 fiber cut	None	None	transmit downstream	OCh_LOS_P	OTU1
WSD91_OD1	WSD91_OD1 fiber cut	None	None	transmit downstream	OMS_LOS_P	OD1
OD1_OTU2	OD1_OTU2 fiber cut	None	None	transmit downstream	OCh_LOS_P	OTU1
OTU3_RMU91	OTU3_RMU91 fiber cut	None	None	transmit downstream	OCh_LOS_P	OTU1
OTU4_OM1	OTU4_OM1 fiber cut	None	None	transmit downstream	OCh_LOS_P	OTU1
OM1_RMU91	OM1_RMU91 fiber cut	None	None	transmit downstream	OMS_LOS_P	OD1

Figure 4.4: Screenshot of Alarm Generation Database

4.2 Alarm and Alarm Flow Generator

The outputs of the Alarm and Alarm Flow Generator are summarized into an alarm flow table and an alarm table as exemplified by Table 4.2 and Table 4.3.

start	destination	alarm flow	time step
Fiber2-fiber1	ROADM2-FIU1	Fiber2-fiber cut;ROADM2-OTS_LOS	1
ROADM2-FIU1	OLA1-FIU2	ROADM2-OTS_LOS;OLA1-OTS_BDI	2
ROADM2-FIU1	ROADM4-FIU1	ROADM2-OTS_LOS;ROADM4-OTS_PMI	2
ROADM2-FIU1	ROADM4-OD1	ROADM2-OTS_LOS;ROADM4-OMS_SSF	2
ROADM4-OD1	ROADM2-OM1	ROADM4-OMS_SSF;ROADM2-OMS_BDI	3
ROADM4-OD1	ROADM6-OTU1	ROADM4-OMS_SSF;ROADM6-OCh_SSF	3

Table 4.2: Example of Alarm Flow Table

node	alarm	time step
ROADM2-FIU1	OTS_LOS	1
OLA1-FIU2	OTS_BDI	2
ROADM4-FIU1	OTS_PMI	2
ROADM4-OD1	OMS_SSF	2
ROADM2-OM1	OMS_BDI	3
ROADM6-OTU1	OCh_SSF	3

Table 4.3: Example of Alarm Table

Each alarm flow records by indicating the parent vertex and board and child vertex and board, the alarm flow's name, and the time step attribute. In this example, the CSG presents in Fig. 4.5. According to the query request, suppose ROADM2-FIU1 board detects and reports "OTS_LOS" alarm, which implies the alarm flow originates from "ROADM2-FIU1" board. While the resultant three actions give rise to different alarm flows. The first one is on the OLA1-FIU2 board report "OTS_BDI" alarm, and the second is on the ROADM4-FIU1 board report "OTS_PMI" alarm, and the third one is on ROADM4-OD1 board report "OMS_SSF" alarm. The combination of "OTS_LOS" and all three alarms are three alarm flows. The time step indicates the time step that the child alarm occurs time.

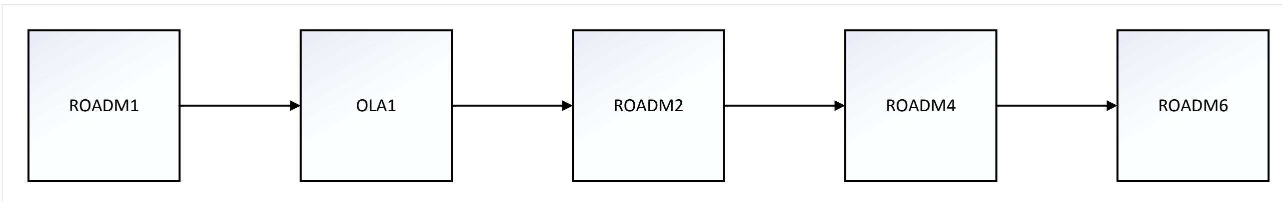


Figure 4.5: CSG for Alarm and Alarm Flow Generator Example

4.3 Ground Truth of Alarm Flow Matrix (AF_{GT})

The AF_{GT} record the amount and locations of alarm flows, which is the ground truth data for future mathematics operation on atomic rule learning and root cause analysis. In the AF_{GT}, each entry of this matrix suggests the number of alarm flows between the corresponding two boards.

Table 4.4 provides an sample of AF_{GT}. This example is the same as section 4.2.

	ROADM1-OTU1	ROAMD1-OM1	ROADM1-FIU2	ROADM1_OLA1-fiber1	OLA1-FIU1	ROADM2-FIU1	ROADM2-OD1	ROAMD6-OTU1
ROADM1-OTU1	0	0	0	0	0	0	0	0
ROADM1-OM1	0	0	0	0	0	0	0	0
ROADM1-FIU2	0	0	0	0	0	0	0	0
ROADM1_OLA1-fiber1	0	0	0	0	1	0	0	0
OLA1-FIU1	0	0	1	0	0	1	1	0
ROADM2-FIU1	0	0	0	0	0	0	0	0
ROADM2-OD1	0	1	0	0	0	0	0	1
ROADM6-OTU1	0	0	0	0	0	0	0	0

Table 4.4: Example of AF_{GT}

4.4 Active Alarm Flow Dependency Graph (aAFDG)

The aAFDG presents the failure and alarm dependency by a tree shape graph/multigraph. The simulator uses the graphviz package in Python to construct.

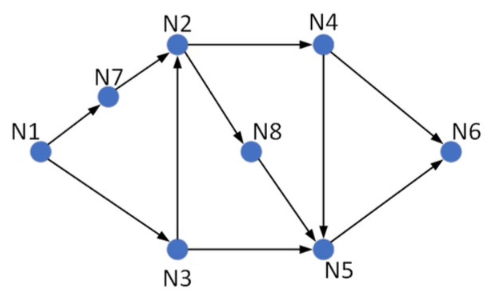
Due to the possible alarm propagation and causality, an aAFDG can divide into multiple hop levels. An alarm flow is divided into two parts, the parent failure/alarm at hop level-l and child alarm at hop level-l+1 connected by an arc. The maximum alarm propagation hops as k, and the exact failure/alarm location cannot repeatedly appear at the same level. Also, the aAFDG always starts from a failure.

Chapter 5

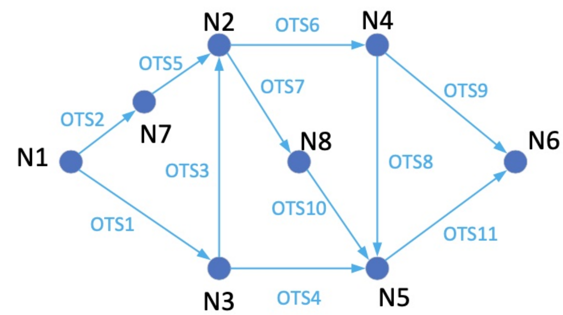
Test Cases and Simulator Results

The following paragraphs introduce eight test cases and the corresponding simulation results containing alarm table, alarm flow table, the AF_{GT}, and the aAFDG, aiming to validate the proposed failure propagation behavior and verify the correctness of the simulator we developed. Six test cases stand for single-failure scenarios, while the other two test cases are multi-failure scenarios.

The physical topology, as well as the OTS and OMS virtual topologies considered in the test cases for the simulator, are shown in Fig. 5.1. The OTS and OMS virtual topologies are static and used in all test cases. On the other hand, the virtual topology of OChs may be different from one another.



(a) Physical topology



(b) OTS Virtual Topology

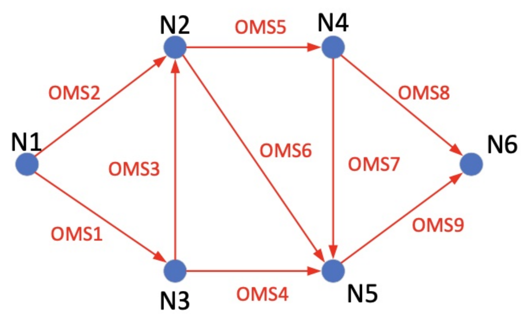


Figure 5.1: Network Topology of Simulation

Note that the simulator only considers one direction in physical topology because if the direction is bidirectional, then the number of OTS and OMS are doubled. Thus, for simplicity, the physical topology is only in one direction.

Note that there is a mapping between the node named starting with "N" and that in the alarm flow tables for the following test cases. The mapping relationships are summarized as follows: N1 → ROADM1, N2 → ROADM2, N3 → ROADM3, N4 → ROADM4, N5 → ROADM5, N6 → ROADM6, N7 → OLA1, N8 → OLA2.

5.1 Test Case 1

The physical network topology and the OTS and OMS virtual topologies of test case 1 are as shown in Fig. 5.1. The vertex in Fig. 5.1 represents the network stations, which can decompose into boards connected by fibers. The network state with the established lightpath is shown in Fig. 5.2. For all the OTN optical layers shown in the previous figure, the names of the layers are shown in the following simulator analysis and result. The locations of the layers are the same as the location in the simulator, only with a different name. For example, OMS2 means the OMS between node $N1$ and $N2$.

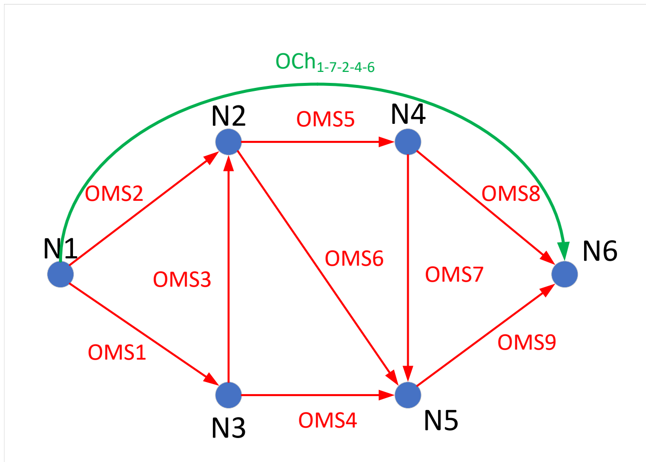


Figure 5.2: Established OCh lightpath in Test Case 1

The simulation goal, network state, and simulator result are described as follows. For all the OTN optical layers, the name in Fig. 5.1

- **Goal**: Test case 1 is designed to verify the SameLayer-one2one-FNR relationship. The cause and descendant alarms are generated in the same OTN layer, forming an FNR alarm flow.

- **Network State**

  $OCh_{1-7-2-4-6}$ is established along with the routing path $N1 \rightarrow N7 \rightarrow N2 \rightarrow N4 \rightarrow N6$. $OCh_{1-7-2-4-6}$ is originated at the OTU board of node $N1$ and then multiplexed onto $OMS2$ (between optical multiplexer (OM) board at node $N1$ and optical de-multiplexer (OD) board at node $N2$), $OMS5$(between OM board at $N2$ and OD board at $N4$), and $OMS8$(between OM board at $N4$ and OD board at $N6$). As a result, there are three concatenated segments in the server layer of $OCh_{1-7-2-4-6}$: $OMS2$, $OMS5$, and $OMS8$.

- **Analysis of Generated Alarms** In the network state of test case 1, the failure is $N1$ detects the failure OA lose input light. $N1$ then inserts an OTS_PMI signal to the child node $N7$. After the FIU1 board at $N7$ detects OTS_PMI signal, $N7$ reports OTS_PMI alarm.

The results of collected alarms can be expected according to the predefined alarm generation rules, where are summarized in Table 5.1.

Node Name	Board Name	Reported Alarm
OLA1	FIU1	OTS_PMI

Table 5.1: Collected Alarms in Test Case 1

- **Simulator Result**

  The alarm flow table given in Table 5.2 form the basis of AF_{GT} in Table 5.3 and aAFDG in Fig. 5.3.

start	destination	alarm flow	time step
ROADM1-OA	OLA1-FIU1	ROADM1-lose input light;OLA1-OTS_PMI	1

Table 5.2: Alarm Flow Table of Test Case 1

Boards	ROADM1-OA	OLA1-FIU1
ROADM1-OA	0	1
OLA1-FIU1	0	0

Table 5.3: AF_{GT} of Test Case 1

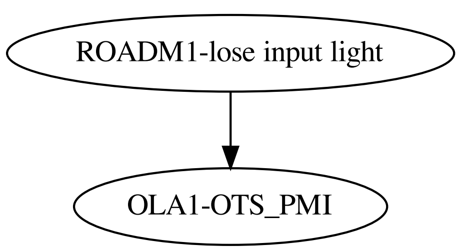


Figure 5.3: aAFDG of Test Case 1

5.2 Test Case 2

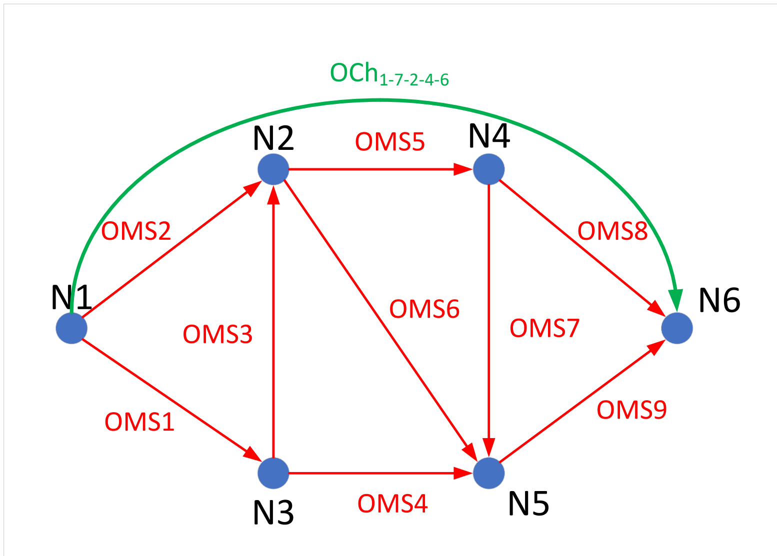


Figure 5.4: Established OCh lightpath in Test Case 2

The simulation goal, network state, and simulator result are described as follows. For all the OTN optical layers, the name in Fig. 5.1

- **Goal**: Test case 2 is designed to verify the SameLayer-one2one-BNR relationship. The cause and descendant alarms are generated in the same OTN layer, forming an BNR alarm flow.
- **Network State**

  $OCh_{1-7-2-4-6}$ is established between the OTU boards at $N1$ and $N6$ as two endpoints of a lightpath connection which is the same as test case 1.
- **Analysis of Generated Alarms**

  In this test case, the failure is fiber cut at $Fiber_{N1\to N7}$. However, this test case only uses the OTS_LOS and OTS_BDI example. Assume that the FIU1 board at $N7$ detects the OTS_LOS alarm, $N7$ will insert an OTS_BDI signal to the child node $N1$ at the FIU2 board. After the $N1$ FIU2 board detects the signal, $N1$ reports OTS_BDI alarm.

The results of collected alarms can be expected according to the predefined alarm generation rules, where are summarized in Table 5.4.

Node Name	Board Name	Reported Alarm
ROADM1	FIU2	OTS_BDI

Table 5.4: Collected Alarms in Test Case 2

- **Simulator Result**

  The alarm flow table given in Table 5.5 forms the basis for AF_{GT} in Table 5.6 and the aAFDG in Fig. 5.5. Note that the simulator can only start with failure. However, since no failure can trigger SameLayer-one2one-BNR relationship, this test case is tested by a fiber cut failure. The simulator results are part of the simulator results that have the SameLayer-one2one-BNR relationship. The failure is a fiber cut at location $N7 \rightarrow N2$. Since the aAFDG are constructed by the simulator program, the aAFDG in this test case is the complete aAFDG for fiber cut. $N7$ sends OTS_BDI signal to $N1$, and $N1$ detects and reports OTS_BDI.

start	destination	alarm flow	time step
OLA1-FIU1	ROADM1-FIU2	OLA1-OTS_LOS,ROADM1-OTS_BDI	1

Table 5.5: Alarm Flow Table of Test Case 2

Boards	OLA1-FIU1	ROAMD1-FIU2
OLA1-FIU1	0	0
ROADM1-FIU2	1	0

Table 5.6: AF_{GT} of Test Case 2

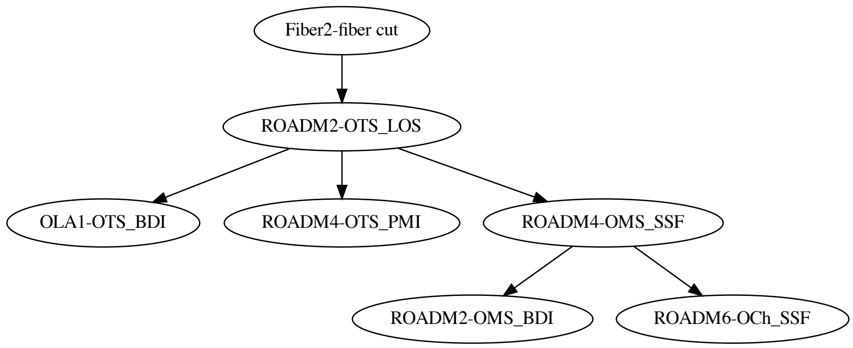


Figure 5.5: aAFDG of Test Case 2

5.3 Test Case 3

In test case 3, network physical topology, OTS, and OMS virtual topologies are as shown in Fig. 5.1. For comparison, there are three network states which are present in Fig. 5.6, Fig. 5.7, and Fig. 5.8.

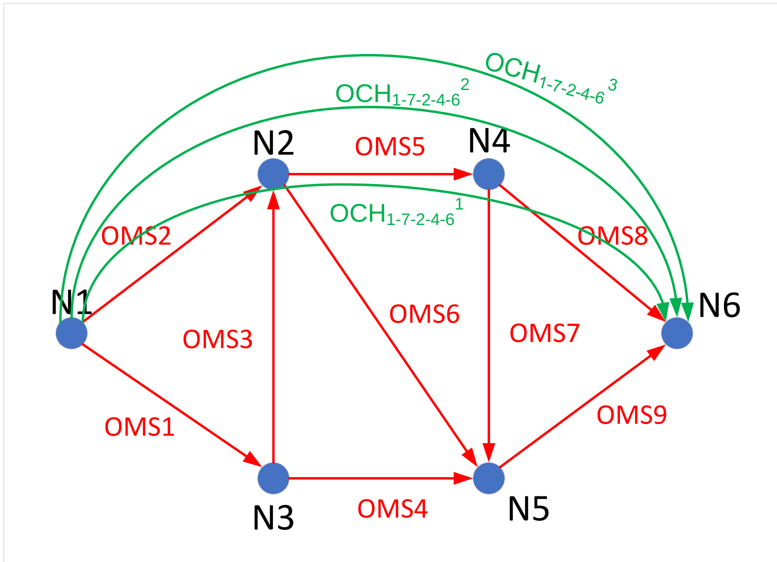


Figure 5.6: Network State 1 in Test Case 3

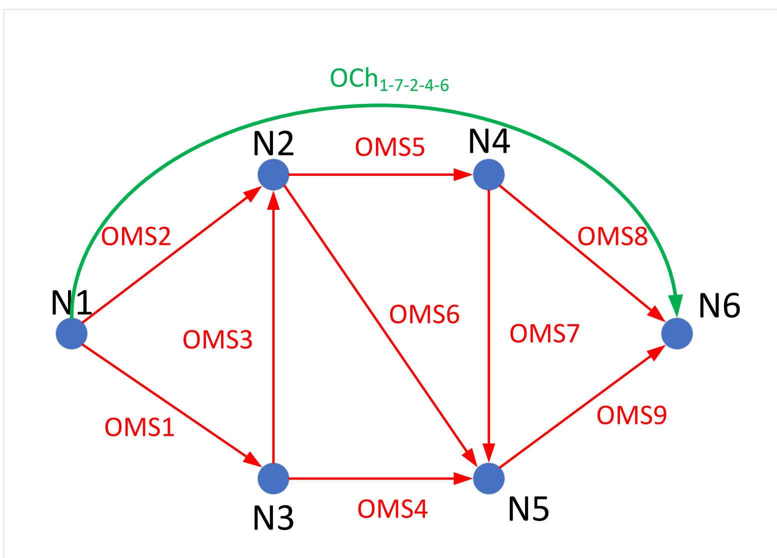


Figure 5.7: Network State 2 in Test Case 3

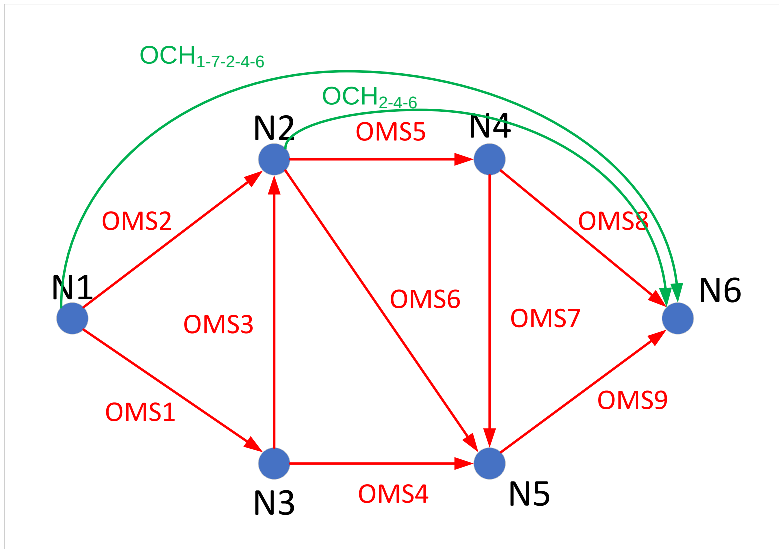


Figure 5.8: Network State 3 in Test Case 3

- **Goal** Test case 3 is designed to verify the combination of all three generic relationships. The cause alarm and descendant alarms generate in different OTN layers. This test case provides the complete procedures of a failure passed into the simulator and results.

- **Network State 1** Between node $N1$ and node $N6$ three lightpath connections are established: $OCh^1_{1-7-2-4-6}$, $OCh^2_{1-7-2-4-6}$, and $OCh^3_{1-7-2-4-6}$ along with the routing path $N1 \rightarrow N7 \rightarrow N2 \rightarrow N4 \rightarrow N6$. Hence, all the OChs are served by the same concatenated segments: $OMS2$, $OMS5$, and $OMS8$. $OCh^1_{1-7-2-4-6}$, $OCh^2_{1-7-2-4-6}$, and $OCh^3_{1-7-2-4-6}$ are configured on OTU board at $N1$, then multiplexed on the same OM board at node $N1$, and demultiplexed on the same OD board at node $N6$, bypassing the intermediate nodes $N7$, $N2$ and $N4$.

- **Network State 2** Between node $N1$ and node $N6$ one lightpath connection is established: $OCh^1_{1-7-2-4-6}$ along with the routing path $N1 \rightarrow N7 \rightarrow N2 \rightarrow N4 \rightarrow N6$. The OCh is served by $OMS2$, $OMS5$, and $OMS8$. $OCh^1_{1-7-2-4-6}$ is originated on OTU board, then multiplexed on OM board at node $N1$, and terminated on OTU board after demultiplexing process on OD board at node $N6$, bypassing the intermediate nodes $N7$, $N2$ and $N4$.

- **Network State 3** Between node $N1$ and node $N6$ a lightpath connection is established: $OCh_{1-7-2-4-6}$ along with the routing path $N1 \rightarrow N7 \rightarrow N2 \rightarrow N4 \rightarrow N6$.

$OCh_{1-7-2-4-6}$ is originated at the OTU board and then multiplexed on OM board at node $N1$. At destination station, $OCh_{1-7-2-4-6}$ is terminated at the OTU board after demultiplexing process on OD board at node $N6$. The server layer of $OCh_{1-7-2-4-6}$ composes of OMS segments $OMS2$, $OMS5$, and $OMS8$. Another lightpath connection, OCh_{2-4-6}, is configured along with the routing path $N2 \rightarrow N4 \rightarrow N6$. $OMS5$ and $OMS8$ segments work as the server layer for OCh_{2-4-6}.

- **Analysis of Generated Alarms** In this test case, the failure is fiber cut at $Fiber_{N1 \rightarrow N7}$. The alarms are involved in all three OTN optical layers. In network states 1, for the OTS layer, $N7$ will detect and report OTS_LOS, which triggers $N1$ to report OTS_BDI and $N2$ report OTS_PMI. For the OMS layer, OTS_LOS at $N7$ pass OMS_SSF signal to $N2$. OMS_SSF at $N2$ will trigger $N1$ to report OMS_BDI and send OCh_SSF signal to the OCh endpoint. Since three OCh layers end in $N6$, $N6$ will report three OCh_SSF alarms.

  In network states 2, OTS, OMS layer alarms are the same as network state 1. For the OCh layer, since there is only one OCh ending in $N6$, $N6$ will report one OCh_SSF alarm.

  In network states 3, OTS, OMS layer alarms are the same as network state 1. For the OCh layer, since OCh_{2-4-6} does not cross the failure location, $N6$ will still report one OCh_SSF alarm.

  The results of collected alarms can be expected according to the predefined alarm generation rules, where are summarized in Table 5.7 and 5.8.

Node Name	Board Name	Reported Alarm	Time Step
ROADM2	FIU1	OTS_LOS	1
OLA1	FIU2	OTS_BDI	2
ROADM4	FIU1	OTS_PMI	2
ROADM4	OD1	OMS_SSF	2
ROADM2	OM1	OMS_BDI	3
ROADM6	OTU1	OCh_SSF	3
ROADM6	OTU1	OCh_SSF	3
ROAMD6	OTU1	OCh_SSF	3

Table 5.7: Collected Alarms in Test Case 3 Network State 1

Node Name	Board Name	Reported Alarm	Time Step
ROADM2	FIU1	OTS_LOS	1
OLA1	FIU2	OTS_BDI	2
ROADM4	FIU1	OTS_PMI	2
ROADM4	OD1	OMS_SSF	2
ROADM2	OM1	OMS_BDI	3
ROADM6	OTU1	OCh_SSF	3

Table 5.8: Collected Alarms in Test Case 3 Network State 2 and 3

- **Simulator Result** The alarm flow tables listed in Table 5.9, 5.10 form the basis for AF_{GT} and aAFDG. aAFDGs are in Fig. 5.9 and Fig. 5.10, and $AF_{GT}s$ are in Table 5.11 and Table 5.12.

start	destination	alarm flow	time step
Fiber2-fiber1	ROADM2-FIU1	Fiber2-fiber cut;ROADM2-OTS_LOS	1
ROADM2-FIU1	OLA1-FIU2	ROADM2-OTS_LOS;OLA1-OTS_BDI	2
ROADM2-FIU1	ROADM4-FIU1	ROADM2-OTS_LOS;ROADM4-OTS_PMI	2
ROADM2-FIU1	ROADM4-OD1	ROADM2-OTS_LOS;ROADM4-OMS_SSF	2
ROADM4-OD1	ROADM2-OM1	ROADM4-OMS_SSF;ROADM2-OMS_BDI	3
ROADM4-OD1	ROADM6-OTU1	ROADM4-OMS_SSF;ROADM6-OCh_SSF	3
ROADM4-OD1	ROADM6-OTU1	ROADM4-OMS_SSF;ROADM6-OCh_SSF	3
ROADM4-OD1	ROADM6-OTU1	ROADM4-OMS_SSF;ROADM6-OCh_SSF	3

Table 5.9: Alarm Flow Table of Test Case 3 Network State 1

start	destination	alarm flow	time step
Fiber2-fiber1	ROADM2-FIU1	Fiber2-fiber cut;ROADM2-OTS_LOS	1
ROADM2-FIU1	OLA1-FIU2	ROADM2-OTS_LOS;OLA1-OTS_BDI	2
ROADM2-FIU1	ROADM4-FIU1	ROADM2-OTS_LOS;ROADM4-OTS_PMI	2
ROADM2-FIU1	ROADM4-OD1	ROADM2-OTS_LOS;ROADM4-OMS_SSF	2
ROADM4-OD1	ROADM2-OM1	ROADM4-OMS_SSF;ROADM2-OMS_BDI	3
ROADM4-OD1	ROADM6-OTU1	ROADM4-OMS_SSF;ROADM6-OCh_SSF	3

Table 5.10: Alarm Flow Table of Test Case 3 Network State 2 and 3

Boards	Fiber2-fiber1	ROADM2-FIU1	OLA1-FIU2	ROADM4-FIU1	ROADM4-OD1	ROADM2-OM1	ROADM6-OTU1
Fiber2-fiber1	0	1	0	0	0	0	0
ROADM2-FIU1	0	0	1	1	1	0	0
OLA1-FIU2	0	0	0	0	0	0	0
ROADM4-FIU1	0	0	0	0	0	0	0
ROADM4-OD1	0	0	0	0	0	1	3
ROADM2-OM1	0	0	0	0	0	0	0
ROADM6-OTU1	0	0	0	0	0	0	0

Table 5.11: AF_{GT} of Test Case 3 Network State 1

Boards	Fiber2-fiber1	ROADM2-FIU1	OLA1-FIU2	ROADM4-FIU1	ROADM4-OD1	ROADM2-OM1	ROADM6-OTU1
Fiber2-fiber1	0	1	0	0	0	0	0
ROADM2-FIU1	0	0	1	1	1	0	0
OLA1-FIU2	0	0	0	0	0	0	0
ROADM4-FIU1	0	0	0	0	0	0	0
ROADM4-OD1	0	0	0	0	0	1	1
ROADM2-OM1	0	0	0	0	0	0	0
ROADM6-OTU1	0	0	0	0	0	0	0

Table 5.12: AF_{GT} of Test Case 3 Network State 2 and 3

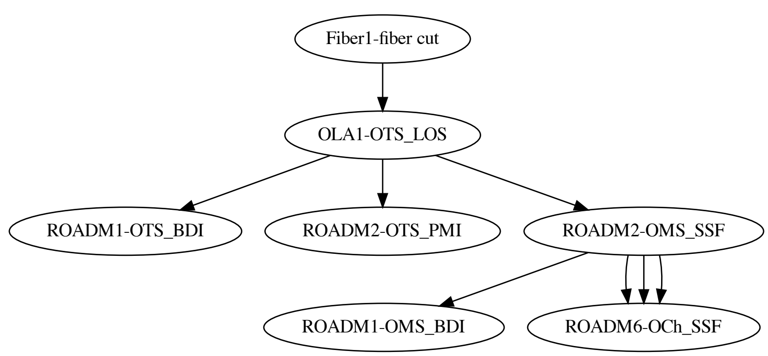


Figure 5.9: aAFDG of Test Case 3 Network State 1

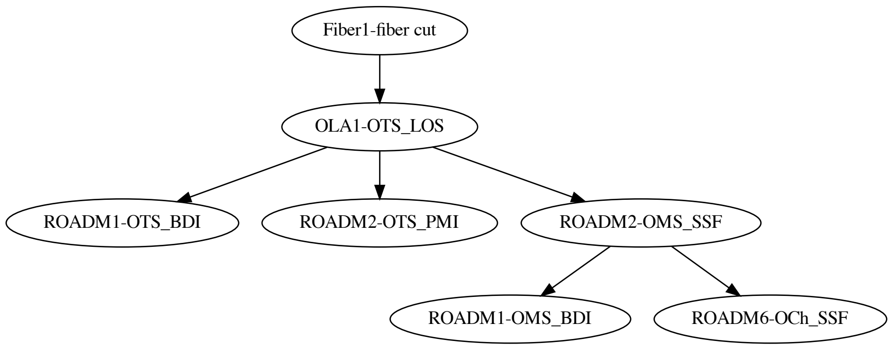


Figure 5.10: aAFDG of Test Case 3 Network State 2 and 3

5.4 Test Case 4

In test case 4, network physical topology, OTS, and OMS virtual topologies are shown in Fig. 5.1. This test case also uses the three network states as shown in Fig. 5.6, Fig. 5.7, and Fig. 5.8.

- **Goal** Test case 4 is designed to verify the failure location that will affect the generation of alarm flow.
- **Network State** All three network state are the same as in test case 3.
- **Analysis of Generated Alarms** If $Fiber_{N4 \rightarrow N6}$ is broken, Node $N6$ will detect and report OTS_LOS. Meanwhile, $N6$ inserts OTS_BDI to the child vertex $N4$. However, in this situation, since $N6$ is the last vertex in the lightpath, the OMS and OCh layer alarms are suppressed. Moreover, the OTS_PMI alarm is suppressed in this situation because there is no upcoming vertex after $N6$.

  The results of collected alarms can be expected according to the predefined alarm generation rules, where are summarized in Table 5.13

Node Name	Board Name	Reported Alarm
ROADM6	FIU	OTS_LOS
ROADM4	FIU	OTS_BDI

Table 5.13: Collected Alarms in Test Case 4 Network State 1 and 2 and 3

- **Simulator Result** The alarm flow table given in Table 5.14 forms the basis for AF_{GT} in Table 5.15 and aAFDG in Fig. 5.11.

start	destination	alarm flow	time step
Fiber4-fiber1	ROADM6-FIU1	Fiber4-fiber cut;ROADM6-OTS_LOS	1
ROADM6-FIU1	ROADM4-FIU2	ROADM6-OTS_LOS;ROADM4-OTS_BDI	2

Table 5.14: Alarm Flow Table of Test Case 4

Boards	Fiber4-fiber1	ROADM6-FIU1	ROADM4-FIU2
Fiber4-fiber1	0	1	0
ROADM6-FIU1	0	0	1
ROADM4-FIU2	0	0	0

Table 5.15: AF_{GT} of Test Case 4

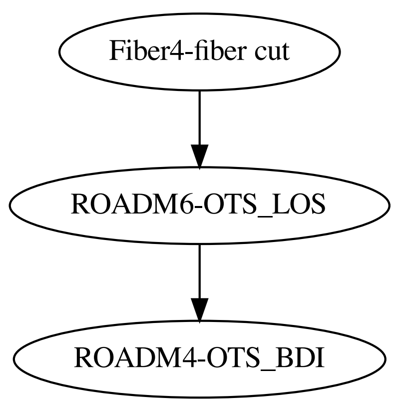


Figure 5.11: aAFDG of Test Case 4

5.5 Test Case 5

In test case 5, network physical topology, OTS, and OMS virtual topologies are shown in Fig. 5.1.

- **Goal** Test case 5 is designed to verify that the failure will affect all the OCh lightpaths that pass through the failure location, but it will not affect the OCh lightpaths that do not pass through the failure location. This test case is a more complex version of test case 3. The OCh lightpath presents in Fig. 5.12 and Fig. 5.13

- **Network State 1** Between node $N1$ and node $N6$ two lightpath connections are established: $OCh^1_{1-7-2-4-6}$ and $OCh^2_{1-7-2-5}$ along with the routing path $N1 \rightarrow N7 \rightarrow N2 \rightarrow N4 \rightarrow N6$ and $N1 \rightarrow N7 \rightarrow N2 \rightarrow N5$. $OCh^1_{1-7-2-4-6}$ uses $OMS2$, $OMS5$, and $OMS8$ whereas $OCh^2_{1-7-2-5}$ uses $OMS2$ and $OMS6$. $OCh^1_{1-7-2-4-6}$ and $OCh^2_{1-7-2-5}$ are configured on OTU board at $N1$, then multiplexed on the same OM board at node $N1$. $OCh^1_{1-7-2-4-6}$ demultiplexed on the OD board at node $N6$ bypassing the intermediate nodes $N7$, $N2$ and $N4$. $OCh^2_{1-7-2-5}$ demultiplexed on the OD board at node $N5$ bypassing the intermediate nodes $N7$ and $N2$.

- **Network State 2** Between node $N1$ and node $N6$ two lightpath connections are established: $OCh^1_{1-7-2-4-6}$ and OCh^2_{3-5-6} along with the routing path $N1 \rightarrow N7 \rightarrow N2 \rightarrow N4 \rightarrow N6$ and $N3 \rightarrow N5 \rightarrow N6$. $OCh^1_{1-7-2-4-6}$ uses $OMS2$, $OMS5$, and $OMS8$ whereas OCh^2_{3-5-6} uses $OMS4$ and $OMS9$. $OCh^1_{1-7-2-4-6}$ configured on OTU board at $N1$ and multiplexed on the OM board at node $N1$, but OCh^2_{3-5-6} configured on OTU board at $N3$ and multiplexed on the OM board at node $N3$. $OCh^1_{1-7-2-4-6}$ demultiplexed on the OD board at node $N6$ bypassing the intermediate nodes $N7$, $N2$ and $N4$. OCh^2_{3-5-6} demultiplexed on the OD board at node $N6$ bypassing the intermediate nodes $N5$.

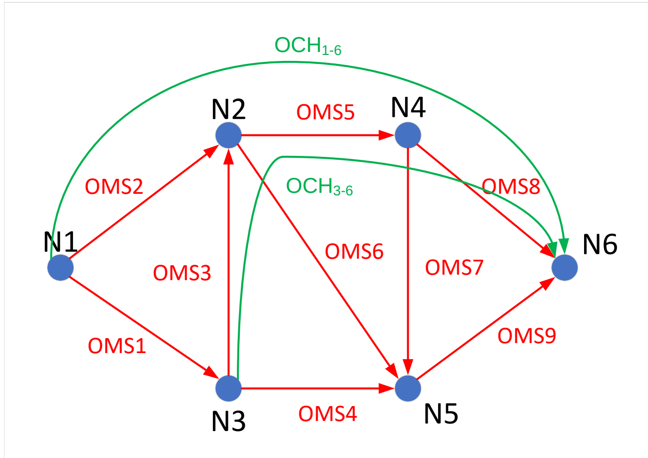


Figure 5.12: Network State 1 in Test Case 5

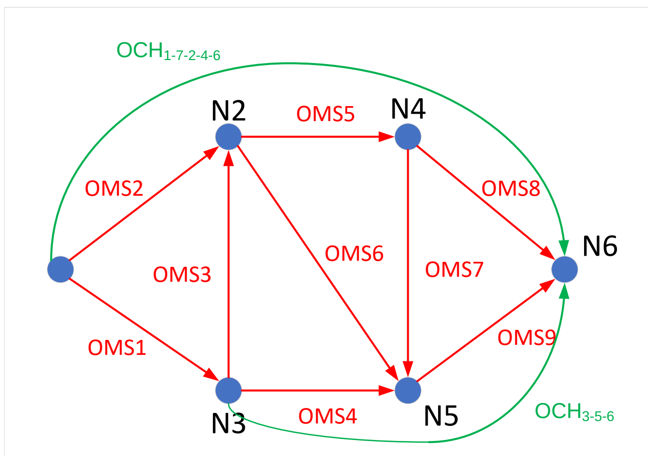


Figure 5.13: Network State 2 in Test Case 5

- **Analysis of Generated Alarms** The failure in the test case is $Fiber_{1\to7}$ is broken. In network state 1, $N7$ will firstly detect and report OTS_LOS then $N1$ will detect and report OTS_BDI. The OTS_LOS will also trigger OTS_PMI and OMS_SSF signal to $N2$. $N2$ will detect and report OTS_PMI and OMS_SSF. From OMS_SSF, N1 will detect and report OMS_BDI. For the OCh layer. $N6$ and $N5$ will both detect and report OCh_SSF because the $Fiber_{1\to7}$ is in both $OCh^1_{1-7-2-4-6}$ and $OCh^2_{1-7-2-5}$.

In network state 2, all the OTS and OMS alarm propagation behaviors are the same. However, since OCh^2_{3-5-6} does not cover $Fiber_{1\to 7}$, $N6$ will be the only node that reports OCh_SSF

The results of collected alarms can be expected according to the predefined alarm generation rules, where are summarized in Table 5.16 and Table 5.17

Node Name	Board Name	Reported Alarm
OLA1	FIU1	OTS_LOS
ROADM1	FIU2	OTS_BDI
ROADM2	FIU1	OTS_PMI
ROADM2	OD1	OMS_SSF
ROADM1	OM1	OMS_BDI
ROAMD6	OTU1	OCh_SSF
ROADM5	OTU1	OCh_SSF

Table 5.16: Collected Alarms in Test Case 5 Network State 1

Node Name	Board Name	Reported Alarm
OLA1	FIU1	OTS_LOS
ROADM1	FIU2	OTS_BDI
ROADM2	FIU1	OTS_PMI
ROADM2	OD1	OMS_SSF
ROADM1	OM1	OMS_BDI
ROADM6	OTU1	OCh_SSF

Table 5.17: Collected Alarms in Test Case 5 Network State 2

- **Simulator Result** The alarm flow table given in Table 5.18 and Table 5.19 forms the basis for AF_{GT} in Table 5.20 Table 5.21 and aAFDG in Fig. 5.14 and Fig. 5.15.

start	destination	alarm flow	time step
Fiber1-fiber1	OLA1-FIU1	Fiber1-fiber cut;OLA1-OTS_LOS	1
OLA1-FIU1	ROADM1-FIU2	OLA1-OTS_LOS;ROADM1-OTS_BDI	2
OLA1-FIU1	ROADM2-FIU1	OLA1-OTS_LOS;ROADM2-OTS_PMI	2
OLA1-FIU1	ROADM2-OD1	OLA1-OTS_LOS;ROADM2-OMS_SSF	2
ROADM2-OD1	ROADM1-OM1	ROADM2-OMS_SSF;ROADM1-OMS_BDI	3
ROADM2-OD1	ROADM6-OTU1	ROADM2-OMS_SSF;ROADM6-OCh_SSF	3
ROADM2-OD1	ROADM5-OTU1	ROADM2-OMS_SSF;ROADM5-OCh_SSF	3

Table 5.18: Alarm Flow Table of Test Case 5 Network State 1

start	destination	alarm flow	time step
Fiber1-fiber1	OLA1-FIU1	Fiber1-fiber cut;OLA1-OTS_LOS	1
OLA1-FIU1	ROADM1-FIU2	OLA1-OTS_LOS;ROADM1-OTS_BDI	2
OLA1-FIU1	ROADM2-FIU1	OLA1-OTS_LOS;ROADM2-OTS_PMI	2
OLA1-FIU1	ROADM2-OD1	OLA1-OTS_LOS;ROADM2-OMS_SSF	2
ROADM2-OD1	ROADM1-OM1	ROADM2-OMS_SSF;ROADM1-OMS_BDI	3
ROADM2-OD1	ROADM6-OTU1	ROADM2-OMS_SSF;ROADM6-OCh_SSF	3

Table 5.19: Alarm Flow Table of Test Case 5 Network State 2

Boards	Fiber1-fiber1	OLA1-FIU1	ROADM1-FIU2	ROADM2-FIU1	ROADM2-OD1	ROADM1-OM1	ROADM6-OTU1	ROADM5-OTU1
Fiber1-fiber1	0	1	0	0	0	0	0	0
OLA1-FIU1	0	0	1	1	1	0	0	0
ROADM1-FIU2	0	0	0	0	0	0	0	0
ROADM2-FIU1	0	0	0	0	0	0	0	0
ROADM2-OD1	0	0	0	0	0	1	1	1
ROADM1-OM1	0	0	0	0	0	0	0	0
ROADM6-OTU1	0	0	0	0	0	0	0	0
ROADM5-OTU1	0	0	0	0	0	0	0	0

Table 5.20: AF_{GT} of Test Case 5 Network State 1

Boards	Fiber1-fiber1	OLA1-FIU1	ROADM1-FIU2	ROADM2-FIU1	ROADM2-OD1	ROADM1-OM1	ROADM6-OTU1
Fiber1-fiber1	0	1	0	0	0	0	0
OLA1-FIU1	0	0	1	1	1	0	0
ROADM1-FIU2	0	0	0	0	0	0	0
ROADM2-FIU1	0	0	0	0	0	0	0
ROADM2-OD1	0	0	0	0	0	1	1
ROADM1-OM1	0	0	0	0	0	0	0
ROADM6-OTU1	0	0	0	0	0	0	0

Table 5.21: AF_{GT} of Test Case 5 Network State 2

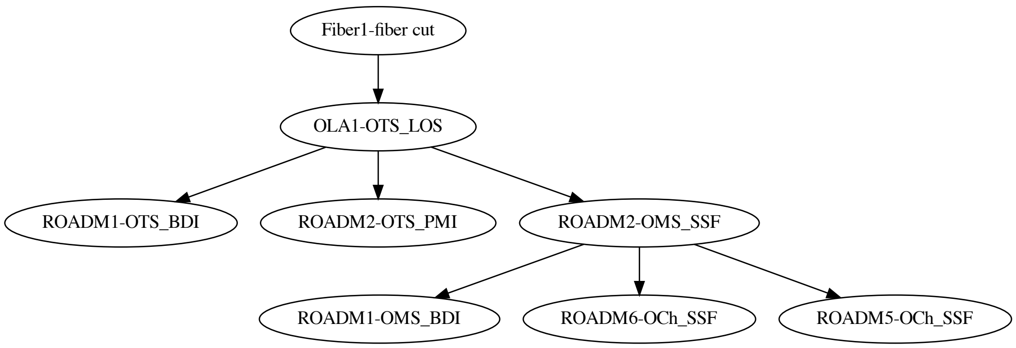


Figure 5.14: aAFDG of Test Case 5 Network State 1

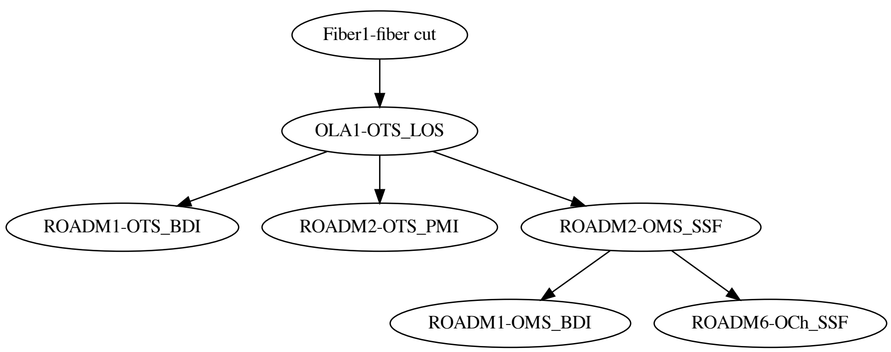


Figure 5.15: aAFDG of Test Case 5 Network State 2

5.6 Test Case 6

In test case 6, network physical topology, OTS, and OMS virtual topologies are shown in Fig. 5.1.

- **Goal** Test case 6 is designed to test some other failures that are necessary in the network.

- **Network State** The network state is the same as test case 3 network state 2.
- **Analysis of Generated Alarms** The failures are OM board faulty, OA board faulty, and OTU board faulty. The OM, OA, and OTU boards failed on $N2$. For OM board faulty, $N4$ detects and reports OMS_LOS_P from $N2$. $N4$ then send OMS_BDI_P signal to $N2$, and $N2$ reports the alarm. $N6$ detects and reports the OCh_SSF_P from $N4$. For OA board faulty, $N2$ detects and reports MUT_LOS, and $N4$ reports OTS_LOS_P from OA board faulty failure. $N6$ reports the OTS_PMI and OMS_SSF_P and sends OMS_BDI_P signal to $N4$. $N4$ then reports OMS_BDI_P. $N6$ also reports OCh_SSF_P. For OTU board faulty, only $N6$ reports OCh_LOS_P.

  The results of collected alarms can be expected according to the predefined alarm generation rules, where are summarized in Table 5.22, Table 5.23, and Table 5.24

Node Name	Board Name	Reported Alarm
ROADM4	OD1	OMS_LOS_P
ROADM2	OM1	OMS_BDI_P
ROADM6	OTU1	OCh_SSF_P

Table 5.22: Collected Alarms in Test Case 6 OM Board Faulty

Node Name	Board Name	Reported Alarm
ROADM2	OA1	MUT_LOS
ROADM4	FIU1	OTS_LOS_P
ROADM2	FIU2	OTS_BDI_P
ROADM6	FIU1	OTS_PMI
ROAMD6	OD1	OMS_SSF_P
ROADM4	OM1	OMS_BDI_P
ROADM6	OTU1	OCh_SSF_P

Table 5.23: Collected Alarms in Test Case 6 OA Board Faulty

Node Name	Board Name	Reported Alarm
ROADM6	OTU1	OCh_LOS_P

Table 5.24: Collected Alarms in Test Case 6 OTU Board Faulty

- **Simulator Result** The alarm flow table given in Table 5.25, Table 5.26, and Table 5.27 forms the basis for AF_{GT} in Table 5.28, Table 5.29, and Table 5.30 and aAFDG in Fig. 5.16, Fig. 5.17, and Fig. 5.18.

start	destination	alarm flow	time step
ROADM2-OM1	ROADM4-OD1	ROADM2-board faulty;ROADM4-OMS_LOS_P	1
ROADM4-OD1	ROADM2-OM1	ROADM4-OMS_LOS_P;ROADM2-OMS_BDI_P	2
ROADM4-OD1	ROADM6-OTU1	ROADM4-OMS_LOS_P;ROADM6-OCh_SSF_P	2

Table 5.25: Alarm Flow Table of Test Case 6 OM Board Faulty

start	destination	alarm flow	time step
ROADM2-OA1	ROADM2-OA1	ROADM2-board faulty;ROADM2-MUT_LOS	1
ROADM2-OA1	ROADM4-FIU1	ROADM2-board faulty;ROADM4-OTS_LOS_P	1
ROADM4-FIU1	ROADM2-FIU2	ROADM4-OTS_LOS_P;ROADM2-OTS_BDI_P	2
ROADM4-FIU1	ROADM6-FIU1	ROADM4-OTS_LOS_P;ROADM6-OTS_PMI	2
ROADM4-FIU1	ROADM6-OD1	ROADM4-OTS_LOS_P;ROADM6-OMS_SSF_P	2
ROADM6-OD1	ROADM4-OM1	ROADM6-OMS_SSF_P;ROADM4-OMS_BDI_P	3
ROADM6-OD1	ROADM6-OTU1	ROADM6-OMS_SSF_P;ROADM6-OCh_SSF_P	3

Table 5.26: Alarm Flow Table of Test Case 6 OA Board Faulty

start	destination	alarm flow	time step
ROADM2-OTU1	ROADM6-OTU1	ROADM2-board faulty;ROADM6-OCh_LOS_P	1

Table 5.27: Alarm Flow Table of Test Case 6 OTU Board Faulty

Boards	ROADM2-OM1	ROADM4-OD1	ROADM6-OTU1
ROADM2-OM1	0	1	0
ROADM4-OD1	1	0	1
ROADM6-OTU1	0	0	0

Table 5.28: AF_{GT} of Test Case 6 OM Board Faulty

Boards	ROADM2-OA1	ROADM4-FIU1	ROADM2-FIU2	ROADM6-FIU1	ROADM6-OD1	ROADM4-OM1	ROADM6-OTU1
ROADM2-OA1	1	1	0	0	0	0	0
ROADM4-FIU1	0	0	1	1	1	0	0
ROADM2-FIU2	0	0	0	0	0	0	0
ROADM6-FIU1	0	0	0	0	0	0	0
ROADM6-OD1	0	0	0	0	0	1	1
ROADM4-OM1	0	0	0	0	0	0	0
ROADM6-OTU1	0	0	0	0	0	0	0

Table 5.29: AF_{GT} of Test Case 6 OA Board Faulty

Boards	ROADM2-OTU1	ROADM6-OTU1
ROADM2-OTU1	0	1
ROADM6-OTU1	0	0

Table 5.30: AF_{GT} of Test Case 6 OTU Board Faulty

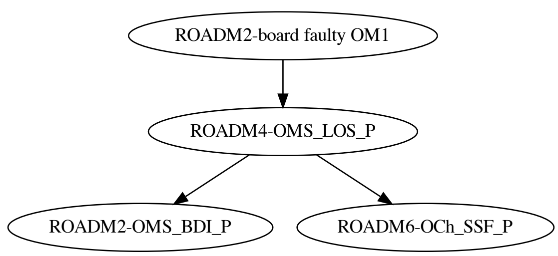


Figure 5.16: aAFDG of Test Case 6 OM Board Faulty

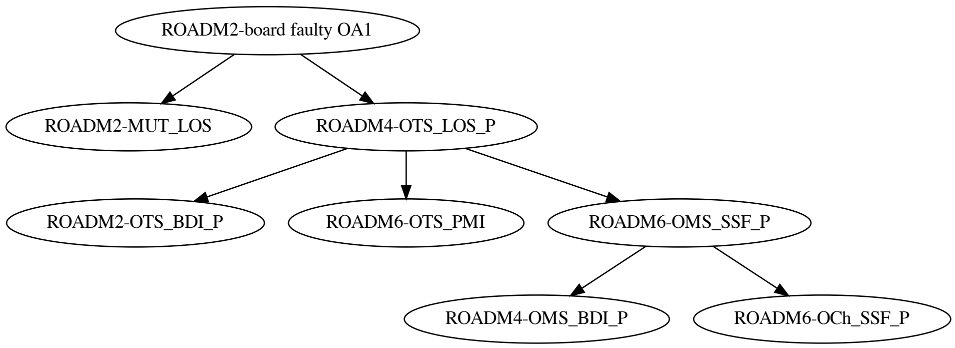


Figure 5.17: aAFDG of Test Case 6 OA Board Faulty

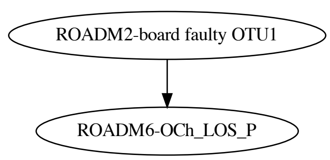


Figure 5.18: aAFDG of Test Case 6 OTU Board Faulty

5.7 Test Case 7

In test case 7, network physical topology, OTS, and OMS virtual topologies are shown in Fig. 5.1. This test case is a multi-failure example with failure suppression.

- **Network State**

  The network state is the same as that in Fig. 5.2.

- **Analysis of Generated Alarms**

  Since $Fiber_{7\to 2}$ fails at time step zero and $Fiber_{1\to 7}$ breaks down at time step one, the former failure will suppress alarms that are due to the later one. Thus, alarms OTS_PMI, OMS_SSF, OMS_BDI, and OCh_SSF will not be reported.

The results of collected alarms can be expected according to the predefined alarm generation rules, where are summarized in Table 5.31.

Node Name	Board Name	Reported Alarm	time step
ROADM2	FIU1	OTS_LOS	1
OLA1	FIU1	OTS_LOS	2
OLA1	FIU2	OTS_BDI	2
ROADM4	FIU1	OTS_PMI	2
ROADM4	OD1	OMS_SSF	2
ROADM1	FIU2	OTS_BDI	3
ROADM2	OM1	OMS_BDI	3
ROADM6	OTU1	OCh_SSF	3

Table 5.31: Collected Alarms in Test Case 7

- **Simulator Result**

  The alarm flow table given in Table 5.32 forms the basis for AF_{GT} in Table 5.33 and aAFDG in Fig. 5.19.

start	destination	alarm flow	time step
Fiber2-fiber1	ROADM2-FIU1	Fiber2-fiber cut;ROADM2-OTS_LOS	1
Fiber1-fiber1	OLA1-FIU1	Fiber1-fiber cut;OLA1-OTS_LOS	2
ROADM2-FIU1	OLA1-FIU2	ROADM2-OTS_LOS;OLA1-OTS_BDI	2
ROADM2-FIU1	ROADM4-FIU1	ROADM2-OTS_LOS;ROADM4-OTS_PMI	2
ROADM2-FIU1	ROADM4-OD1	ROADM2-OTS_LOS;ROADM4-OMS_SSF	2
OLA1-FIU1	ROADM1-FIU2	OLA1-OTS_LOS;ROADM1-OTS_BDI	3
ROADM4-OD1	ROADM2-OM1	ROADM4-OMS_SSF;ROADM2-OMS_BDI	3
ROADM4-OD1	ROADM6-OTU1	ROADM4-OMS_SSF;ROADM6-OCh_SSF	3

Table 5.32: Alarm Flow Table of Test Case 7

Boards	Fiber2-fiber1	ROADM2-FIU1	Fiber1-fiber1	OLA1-FIU1	OLA1-FIU2	ROADM4-FIU1	ROADM4-OD1	ROADM1-FIU2	ROADM2-OM1	ROADM6-OTU1
Fiber2-fiber1	0	1	0	0	0	0	0	0	0	0
ROADM2-FIU1	0	0	0	0	1	1	1	0	0	0
Fiber1-fiber1	0	0	0	1	0	0	0	0	0	0
OLA1-FIU1	0	0	0	0	0	0	0	1	0	0
OLA1-FIU2	0	0	0	0	0	0	0	0	0	0
ROADM4-FIU1	0	0	0	0	0	0	0	0	0	0
ROADM4-OD1	0	0	0	0	0	0	0	0	1	1
ROADM1-FIU2	0	0	0	0	0	0	0	0	0	0
ROADM2-OM1	0	0	0	0	0	0	0	0	0	0
ROADM6-OTU1	0	0	0	0	0	0	0	0	0	0

Table 5.33: AF_{GT} of Test Case 7

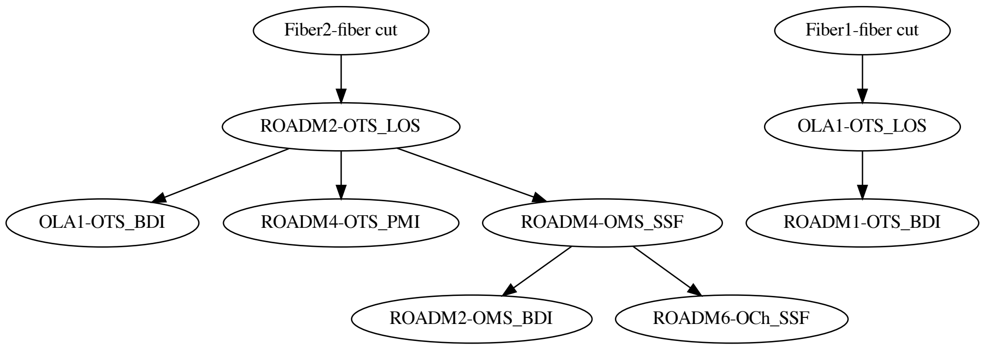


Figure 5.19: aAFDG of Test Case 7

5.8 Test Case 8

In test case 8, network physical topology, OTS, and OMS virtual topologies are as shown in Fig. 5.1. This test case is a multi-failure example without failure suppression.

- **Network State**

  The network state is the same as that in Fig. 5.2.

- **Analysis of Generated Alarms**

  Since $Fiber_{1\to7}$ fails at time step zero and $Fiber_{7\to2}$ breaks down at time step two, all alarms can propagate orderly without failure suppression.

  The results of collected alarms can be expected according to the predefined alarm generation rules, where are summarized in Table 5.34.

Node Name	Board Name	Reported Alarm	Time Step
OLA1	FIU1	OTS_LOS	1
ROADM1	FIU2	OTS_BDI	2
ROADM2	FIU1	OTS_PMI	2
ROADM2	OD1	OMS_SSF	2
ROADM2	FIU1	OTS_LOS	3
ROADM1	OM1	OMS_BDI	3
ROADM6	OTU1	OCh_SSF	3
ROADM2	FIU2	OTS_BDI	4
ROADM4	FIU1	OTS_PMI	4
ROADM4	OD1	OMS_SSF	4
ROADM2	OM1	OMS_BDI	5
ROADM6	OTU1	OCh_SSF	5

Table 5.34: Collected Alarms in Test Case 8

- **Simulator Result**

  The alarm flow table given in Table 5.35 forms the basis for AF_{GT} in Table 5.36 and aAFDG in Fig. 5.20.

start	destination	alarm flow	time step
Fiber1-fiber1	OLA1-FIU1	Fiber1-fiber cut;OLA1-OTS_LOS	1
OLA1-FIU1	ROADM1-FIU2	OLA1-OTS_LOS;ROADM1-OTS_BDI	2
OLA1-FIU1	ROADM2-FIU1	OLA1-OTS_LOS;ROADM2-OTS_PMI	2
OLA1-FIU1	ROADM2-OD1	OLA1-OTS_LOS;ROADM2-OMS_SSF	2
Fiber2-fiber1	ROADM2-FIU1	Fiber2-fiber cut;ROADM2-OTS_LOS	3
ROADM2-OD1	ROADM1-OM1	ROADM2-OMS_SSF;ROADM1-OMS_BDI	3
ROADM2-OD1	ROADM6-OTU1	ROADM2-OMS_SSF;ROADM6-OCh_SSF	3
ROADM2-FIU1	OLA1-FIU2	ROADM2-OTS_LOS;OLA1-OTS_BDI	4
ROADM2-FIU1	ROADM4-FIU1	ROADM2-OTS_LOS;ROADM4-OTS_PMI	4
ROADM2-FIU1	ROADM4-OD1	ROADM2-OTS_LOS;ROADM4-OMS_SSF	4
ROADM4-OD1	ROADM2-OM1	ROADM4-OMS_SSF;ROADM2-OMS_BDI	5
ROADM4-OD1	ROADM6-OTU1	ROADM4-OMS_SSF;ROADM6-OCh_SSF	5

Table 5.35: Alarm Flow Table of Test Case 8

Boards	Fiber1-fiber1	OLA1-FIU1	ROADM1-FIU2	ROADM2-FIU1	ROADM2-OD1	Fiber2-fiber1	ROADM1-OM1	ROADM6-OTU1	OLA1-FIU2	ROADM4-FIU1	ROADM4-OD1	ROADM2-OM1
Fiber1-fiber1	0	1	0	0	0	0	0	0	0	0	0	0
OLA1-FIU1	0	0	1	1	1	0	0	0	0	0	0	0
ROADM1-FIU2	0	0	0	0	0	0	0	0	0	0	0	0
ROADM2-FIU1	0	0	0	0	0	0	0	0	1	1	1	0
ROADM2-OD1	0	0	0	0	0	0	1	1	0	0	0	0
Fiber2-fiber1	0	0	0	1	0	0	0	0	0	0	0	0
ROADM1-OM1	0	0	0	0	0	0	0	0	0	0	0	0
ROADM6-OTU1	0	0	0	0	0	0	0	0	0	0	0	0
OLA1-FIU2	0	0	0	0	0	0	0	0	0	0	0	0
ROADM4-FIU1	0	0	0	0	0	0	0	0	0	0	0	0
ROADM4-OD1	0	0	0	0	0	0	0	1	0	0	0	1
ROADM2-OM1	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.36: AF_{GT} of Test Case 8

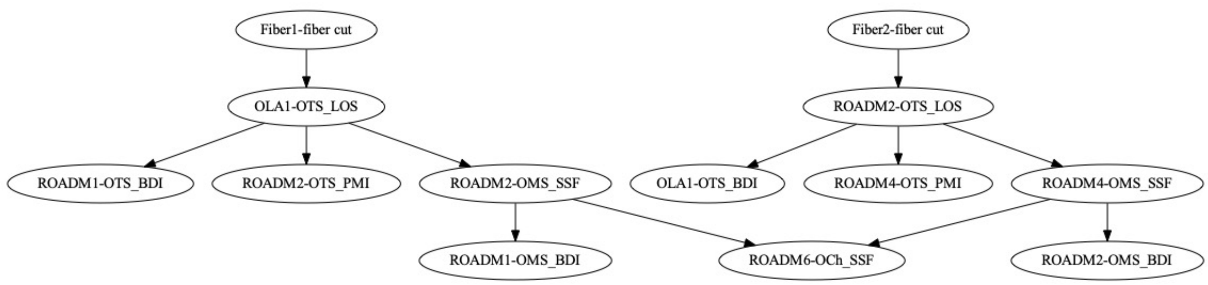


Figure 5.20: aAFDG of Test Case 8

Chapter 6

Conclusion

This thesis presents the detailed design of the failure propagation behavior, and the design of the simulator includes six single-failure and two multi-failure test cases used for the verification purpose. Also, the simulator provides plenty of ground-truth data for future researches and applications.

However, this simulator still has some limitations. For example, the alarm suppression, which multiple alarms can suppress into a single alarm, is not included in this simulator. Also, this simulator has not been tested by an extremely large network and large numbers of failures. Thus, the future studies are listed as follows.

- Perfect the OTN-based simulator and verify it with challenging test cases consisting of a large collection of failures. Also, the simulator needs to make the node-level subgraph change dynamically and automatically generate failures.
- Design the neural network model for root cause analysis.
- Design a mathematical model to obtain the hidden knowledge of failure/alarm propagation behavior.

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APPENDICES

Appendix A

Technical Document of OTN-based Simulator

The OTN-based simulator is the testbed for verifying the feasibility of all mentioned test cases in our report. The current simulator is feasible for the multi-failure scenario. This appendix section presents the input and expected output files from the simulator. Moreover, this appendix introduces the functionality of each code file and procedures for reproducing the results of existing test cases.

The description of the input and output files are given as follows:

- Input file 1: subgraph.txt

  Description: The node-level subgraph consists of all nodes upon the lightpaths. Each row records the node IDs traversed by the routing path per lightpath connection. The format of each lightpath is given by the start node, intermediate nodes as well as the end node.

  Example:

  ROADM1,OLA1,ROADM2,ROADM4,ROADM6

  ROADM1,ROADM3,ROADM2,ROADM4,ROADM6

- Input file 2: failures.txt

  Description: A failure is characterized by a row including node/fiber ID, failure name, faulty board, relevant parameters, the time step when failure occurred as well as board/fiber ID. The simulator is able to process multiple failures with failure suppression. This file lists all failures injected into the network for the purpose of testing.

Example:

Fiber1,fiber cut,fiber,None,0,fiber1

Fiber2,fiber cut,fiber,None,1,fiber1

Based on the given lightpaths, the fiber ID corresponds to a bi-directional fiber segment between the neighboring two NEs. The board named with "fiber1" represents the fiber following the direction of fiber segment in the table while "fiber2" indicates the reverse one.

- Output file 1: alarm_flow.csv

  This csv file collects the alarm flows concerning the injected failures due to the invoked atomic rules in the alarm generation database.

- Output file 2: alarms.csv

  This csv file records all alarms and their corresponding source nodes and boards.

- Output file 3: alarm_flow_matrix.csv

  This csv file records the ground-truth of alarm flow matrix AF_{GT}.

We developed the simulator under Python3 environment and the alarm generation database is built with MySQL 8.0. The simulator is composed of four python files and the function for each one is shown as below:

- Code file 1: main.py

  This block takes two input files and generates alarm_flow.csv, alarms.csv, and alarm_flow_matrix.csv.

- Code file 2: b_in_n.py

  This block defines boards/fibers inside each node/fiber.

- Code file 3: class_obj.py

  This block defines three types of class object including node-level object, board-level object and failure/alarm object.

- Code file 4: node_alarm_processing.py

  This block processes and generates alarms, alarm flows and AF_{GT}.

- Code file 5: transmit_down.py

  This block runs the operation of transmitting downstream.

- Code file 6: transmit_up.py

  This block runs the operation of transmitting upstream.

- Code file 7: to_board.py

  This block runs the operation of intra-site propagation.

- Code file 7: flow_graph.py This block generates the node-level network topology, which helps our main.py file.

- Code file 8: dep.py This block generates the aAFDG plot.

"Alarms.sql" contains all commands for loading the alarm generation database. The procedures for loading "Alarms.sql" are listed as follows:

1. Create an empty database in MySQL;

2. Run command "mysql -u [username] -p [name of database] < Alarms.sql" under the folder where "Alarms.sql" is located.

Please note that there need to carry out some modifications for the simulator when loading the rules. On line 1204 from "main.py", the host, user, password, and database name need to be changed when running this code on a different machine.

The step of running "main.py" is listed as follows:

1. Go to the directory of "main.py" on the terminal and enter command "python3 main.py";

2. to the directory of "dep.py" on the terminal and enter command "python3 dep.py" to get the aAFDG plot;

After running this code file, several csv files will be produced including "alarm_flow.csv", "alarms.csv" and "alarm_flow_matrix.csv". They collect all alarm flows, alarms and AF_{GT} for the given network state and failure(s).