Regular paper

Availability analysis and comparison of different WDM systems

Ivan Rados

Abstract— We begin reasons why high system availability is important. Furthermore, the basic terms are introduced pertaining to the availability with particular review of the parallel structure. Then the availability of different wavelength division multiplexing (WDM) systems is analysed: point to point, chain and ring with 1+1 protection of the wavelength channel, plus the influence of availability of nodes and links on the total system availability. The data on failure intensity and mean time to repair of certain components were taken from various literature sources. We assumed in the analysis a WDM system with 16 wavelengths and 2.5 Gbit/s capacity per wavelength channel. Finally, results of calculation and comparisons of availability of different WDM systems and proposals for improvement of their availability are presented.

Keywords— WDM, wavelength channel, availability, protection.

1. Introduction

Modern industrialised societies are dependent on telecommunication services. Growth of data transmission and growth of internet traffic require transmission systems of huge capacities. Owing to the development of photonic technologies, wavelength division multiplexing (WDM) systems based have been introduced, offering high transmission speeds through a single fiber. In such networks, interruption of service for any reason, either defective equipment or human error, can cause isolation from telecommunication services and huge losses to both customers and network operators. Therefore, protection in such systems is extremely important for network operators [1]. The contracts between operators and their customers are always based on the service level agreements (SLAs), which are very strict regarding network availability and service quality. The possibility to guarantee high availability is the key for the operators in order to keep the existing and attract new customers, and is mainly reflected in the price of their services. Operators can invest a lot of money to equip their network with high quality hardware [2].

However, increase of quality of these elements above the level of current commercial systems is difficult and beyond their control. Far more acceptable way of guaranteeing high availability is the use of various protection strategies. Although there are several protection strategies, in this paper we will focus on 1+1 protection of wavelength channel which is very similar to path protection in synchronous digital hierarchy (SDH) networks [3]. In this paper we will first analyse the availability of link between two terminals of WDM system without protection (point to point, chain) and later the availability of WDM ring which uses 1+1 protection of wavelength channel.

2. On availability in general

The availability of some system A is the probability that the system will be functional in the given time, i.e., the ratio of time in which the system is operational compared to the total time. Unavailability U is a probability complementary to availability. When reporting on system performance, unavailability is frequently expressed as MDT (mean down time) in minutes per year:

$$\mathrm{MDT} = \frac{\mathrm{MTTR}}{\mathrm{MTTR}+\mathrm{MTTF}}, \tag{1}$$

where the MTTF (mean time to failure) is a mean time till the failure occurs and MTTR (mean time to repair) the mean time of repair [4]. In this paper we assume that the MTTF of the wavelength channel is constant regardless of a component age. The MTTF = $1/\lambda$, where λ is the failure rate, usually expressed in FIT (failure in time), where 1 FIT = 1 failure in 10^9 hours.

The main transport entity in the WDM systems is the wavelength channel. This is a one way connection type of a standard bit rate, for example 2.5 Gbit/s, between two nodes. Wavelength channel in the unprotected system (serial structure) in general passes through nodes which can be optical add/drop multiplexers and optical cross connects and optical links. Optical links consist of an optical cable and optical amplifiers which in terms of availability can be considered as one entity because they constitute a serial structure in which failure at any amplifier leads to interruption of communication between two nodes.

Availability of the serial structure is equal to the product of availabilities of individual elements, i.e.,

$$A_s = \prod_{i=1}^{n} A_i\,. \tag{2}$$

Such a structure does not have a possibility to restore communication between two nodes in case of failure of any element, i.e., the connection is functional if and only if all elements of the structure are working.

A significant improvement of availability can be achieved by applying a parallel structure, which means that besides the working path there is a protective one. Of course it is important that these two paths are completely independent, i.e., they do not have common elements [5]. If we mark the availabilities of the working and the protective paths as two completely independent events (w and p), then the availability of such a structure is a union of two nondisjunctive events, i.e., events which do not exclude each other mutually because complementary variables do not exist

$$A_p = P(w \cup p) \,. \tag{3}$$

For these events to be able to exclude each other mutually it is necessary to turn this union of nondisjunctive events into a union of disjunctive events in which complementary variables appear.

By conducting a simple analysis using De Morgan laws, one finds that the availability is [6] ruled by formula:

$$A = P\big\lfloor w \cup (\overline{w} \cap p)\big\rfloor \,. \tag{4}$$

By using the law of distribution and bearing in mind the union and intersection

$$A \cup (B \cap C) = (A \cup B) \cap (A \cup C) \tag{5}$$

we get that

$$A_p = P(w \cup \overline{w}) \cap (w \cup p) \,, \tag{6}$$

since $w \cup \overline{w} = 1$ (complete set), we can write:

$$A_p = P\Big[1 \cap (w \cup p)\Big] \,, \tag{7}$$

and according to the identity $1 \cap p = p$, we obtain:

$$A_p = P(w \cup p) \tag{8}$$

this being the availability of parallel structure.

The availability of connection for a given wavelength channel k is [7]

$$A_p = A_k = A_w + A_p - A_w A_p \,. \tag{9}$$

Connection between two nodes in case of 1+1 protection will fail if and only if there is a failure both of the working and protection paths. Of course, the connection fails if a failure occurs on terminal nodes because they are common elements for working and protection paths.

3. Availability analysis of different WDM systems

In this part we will first analyse the availability of WDM point to point system, chain (systems without redundancy) and WDM ring with 1+1 protection of wavelength channel.

We assume that network consists of N nodes and N links which connect those nodes [8]. In order to define the availability of wavelength channel between two nodes we introduce terms which refer to availability of the optical link connecting two nodes:

- a_{OL_i}, availability of ith link of the working path;
- a_{n_j}, availability of $j$the node, which belongs to the working path.

An optical link consists of an optical fibre and an optical amplifier (a_{OA}). In order for the connection to be functional, the optical fibre and amplifier must work properly. The most frequent cause of failure of the optical link is optical fibre cut. Usually all the fibres in the cable are cut, therefore instead of availability of the fibre the availability of the cable (a_{CA}) is used, since failures of fibre and cable are completely mutually dependent

$$a_{OL_i} = a_{CA}\, a_{OA} \,. \tag{10}$$

Nodes in which the wavelength channel is added/dropped are called “termination” nodes. The nodes through which wavelength channels pass from “west” to the “east” side, located between end nodes are called “transit” nodes. Since the wavelength channel passes through different components within these two types of nodes, their availability is different:

- $a_{n_j t}$, when termination node is working;
- $a_{n_j p}$, when transit node is working.

If the all nodes of the same type are the same, we have

- $a_{n_j t} = a_{nt}, \forall j$;
- $a_{n_j p} = a_{np}, \forall j$.

3.1. Availability of WDM point to point systems

Installation of a multiple SDH line systems between two nodes is expensive because large number of fibres is occupied, so a need arose for high capacity systems which require only two fibres. Such are WDM systems based on the multiplexing of wavelengths. Introduction of WDM technology begins with a point to point system. With such systems only end nodes are WDM nodes; between them the optical amplifiers are placed at certain distances. At the end nodes the wavelength channel passes through transmitter (TX), multiplexer (MUX), demultiplexer (DMUX), boost optical amplifier (BOA), optical preamplifier (POA) and receiver (RX), so the availability of the node is equal to the product of availability of several elements [9], i.e.,

$$a_{nt} = a_{TX}\, a_{MUX}\, a_{DMUX}\, a_{BOA}\, a_{POA}\, a_{RX} \,. \tag{11}$$

Optical link consists of optical cable and m optical amplifiers, so its availability is naturally equal to the product of the availability of cable and optical amplifiers

$$a_{OL_i} = a_{CA} \prod_{i=1}^{m} a_{OA_i} \,. \tag{12}$$

Total availability of the point to point system is equal to the product of availability of nodes and optical link [10]

$$a_{st}(P) = \prod_{i,j \in P} a_{OL_i}\, a_{n_j} = \prod_{i \in P} a_{OL_i} \prod_{j=1}^{2} a_{n_j}$$

$$= (a_{nt})^2 \left[\prod_{i \in P}^{m} a_{OL_i}\right] . \tag{13}$$

3.2. Availability of WDM chain

When instead of optical amplifiers we install optical add/drop multiplexers which have the possibility to separate wavelength channels, we will get a WDM chain which consists of termination nodes and transit nodes. At the termination nodes the wavelength channel passes through transmitter, multiplexer, demultiplexer, booster optical amplifier, optical preamplifier and receiver so that the availability of termination node is the same as for the point-point system.

At the transit nodes the wavelength channel passes through optical preamplifier, demultiplexer, multiplexer and booster optical amplifier, so the availability of the transit nodes is

$$a_{np} = a_{MUX}\, a_{DMUX}\, a_{BOA}\, a_{POA}\,. \tag{14}$$

A failure of any component within the nodes or the optical link leads to interruption of communication between termination nodes.

If the wavelength channel in the unredundant structure passes m optical links and nodes, availability of the communication between the termination nodes in such a structure is equal to the product of the availability of the optical links and nodes [10], i.e.,

$$\begin{aligned} a_{st}(P) &= \prod_{i,j\in P} a_{OL_i}\, a_{n_j} = \prod_{i\in P} a_{OL_i} \prod_{j\in P} a_{n_j} \\ &= (a_{nt})^2\, (a_{np})^{m-1} \left[\prod_{i\in P}^{m} a_{OL_i}\right]. \end{aligned} \tag{15}$$

It is important to stress here that the optical link consist of optical cable only.

3.3. Availability of WDM ring with 1+1 protection of wavelength channel

In the ring network which uses 1+1 protection of the wavelength channel, the wavelength channel in the source node is duplicated and transmitted simultaneously in both directions of the ring – the working and protection directions [11]. Under normal circumstances, the receiver at the termination node receives two copies of the signal (with different delay) and chooses the better one. In case of failure in the working path, the receiver selects the signal coming from the protection path. This is the so called **single ended** protection because switching is carried out at only one (reception) side. It is important here that working and protection paths do not have common elements, so a single failure does not cause total interruption of communication, and that means failures of the elements in the working and protection paths are completely independent. For each wavelength channel of the working path the appropriate wavelength channel of the protection path is reserved, and therefore we speak about 1+1 protection of the wavelength channel [8]. Since the wavelength channels on the protection path are reserved in advance, we speak about the so called **dedicated** (intended) protection where active cross connects are not necessary. Wavelength channels on working and protection paths can have the same wavelength but do not have to. If different wavelengths are used, wavelength converters which do not have significant influence on availability of WDM ring must be used.

Wavelength channel in the termination nodes passes through transmitter, splitter, multiplexer, booster optical amplifier, optical preamplifier, demultiplexer, switch and receiver, so the availability of the termination nodes is

$$a_{nt} = a_{TX}\, a_{SPL}\, a_{MUX}\, a_{DMUX}\, a_{BOA}\, a_{POA}\, a_{SW}\, a_{RX}\,. \tag{16}$$

Availability of transit nodes is the same as for WDM chain because wavelength channel passes throught the same components. If the wavelength channel of the working path P_0 passes m optical links between end nodes, availability of the working path is equal to the product of the availability of optical links and nodes through which the wavelength channel passes [10]

$$\begin{aligned} a_{st}(P_0) &= \prod_{i,j\in P_0} a_{OL_i}\, a_{n_j} = \prod_{i\in P_0} a_{OL_i} \prod_{j\in P_0} a_{n_j} \\ &= (a_{nt})^2\, (a_{np})^{m-1} \left[\prod_{i\in P_0}^{m} a_{OL_i}\right]. \end{aligned} \tag{17}$$

In case of failure in the working path, wavelength channel passes $N-m$ optical links and $N-m-1$ nodes at the protective path P_1 (Fig. 1).

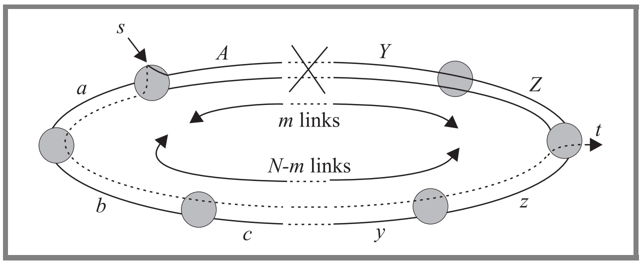


Fig. 1. 1+1 protection of the wavelength channel in case of working path failure.

Availability of the protection path is [10]

$$\begin{aligned} a_{st}(P_1) &= \prod_{i,j\in P_1} a_{OL_i}\, a_{n_j} = \prod_{i\in P_1} a_{OL_i} \prod_{j\in P_1} a_{n_j} \\ &= (a_{nt})^2\, (a_{np})^{N-m-1} \left[\prod_{i\in P_1}^{N-m} a_{OL_i}\right]. \end{aligned} \tag{18}$$

Availability of the wavelength channel between s and t nodes is completely determined by these two paths, so the availability of wavelength channel in case of 1+1 protection is calculated as availability of parallel structure A_{st} composed of two branches, whose failures are completely independent:

$$A_{st}(a) = a_{st}(P_0) + a_{st}(P_1) - \left[a_{st}(P_0)a_{st}(P_1)\right], \tag{19}$$

$$\begin{aligned} A_{st}(a) =& (a_{nt})^2(a_{np})^{m-1}\left[\prod_{i\in P_0}^{m} a_{OL_i}\right] \\ &+ (a_{nt})^2(a_{np})^{N-m-1}\left[\prod_{i\in P_1}^{N-m} a_{OL_i}\right] \\ &- \left\{\begin{matrix} (a_{nt})^2(a_{np})^{m-1}\left[\prod_{i\in P_0}^{m} a_{OL_i}\right](a_{nt})^2 \\ \times(a_{np})^{N-m-1}\left[\prod_{i\in P_1}^{N-m} a_{OL_i}\right] \end{matrix}\right\}, \end{aligned} \tag{20}$$

where a marks availability of optical links and nodes.

Although in the above equation's large brackets we have a product of two equal members $(a_{nt})^2(a_{nt})^2$, only one is present in the formula for availability $(a_{nt})^2$ because the cause of node failure is the same, so we get:

$$A_{st}(a) = (a_{nt})^2 \left\{\begin{matrix} (a_{np})^{m-1}\left[\prod_{i\in P_0}^{m} a_{OL_i}\right] \\ +(a_{np})^{N-m-1}\left[\prod_{i\in P_1}^{N-m} a_{OL_i}\right] \\ -(a_{np})^{N-2}\left[\prod_{i\in P_0,P_1}^{N} a_{OL_i}\right] \end{matrix}\right\}. \tag{21}$$

If we assume that optical links have equal lengths, their availability is equal, i.e.,

$$a_{OL_i} = a_{OL}, \forall i.$$

In this case the availability between nodes s and t is dictated by the following formula:

$$A_{st}(a) = (a_{nt})^2 \left[\begin{matrix} (a_{np})^{m-1}(a_{OL})^{m} \\ +(a_{np})^{N-m-1}(a_{OL})^{N-m} \\ -(a_{np})^{N-2}(a_{OL})^{N} \end{matrix}\right]. \tag{22}$$

4. Calculation and analysis of results

In order to calculate availability of WDM system it is necessary to know availability of nodes and optical links. For calculation of availability in general, it is necessary to know the failure rates and time to repair of certain elements. These data are taken from various papers previously published [9, 12].

As it can be seen in Tables 1, 2 and 3, decrease of time to repair of both the cable and equipment significantly decreases mean down time and influences availability of the entire system.

We will carry out an analysis of availability of systems, assuming they comprise 8 and 12 nodes, carry 16 wavelengths, 560 and 960 km long optical links and have 80 km spacing between optical amplifiers, i.e., nodes. We will also analyse the influence of reduction of cable and equipment repair time on system availability.

Table 1
Failure rate, unavailability and MDT for optical link
(MTTR = 21 and 15 h)

λ [FIT/km]	$U \times 10^{-6}$	MDT [min/year]
114	2.394	1.26
114	1.710	0.90

Table 2
Unavailability and MDT nodes for the system
point to point and chain

MTTR = 6 h	$U \times 10^{-5}$	MDT [min/year]
Termination	5.759	30.27
Transit	4.319	22.71
MTTR = 4 h		
Termination	3.840	20.18
Transit	2.880	15.14

Table 3
Unavailability and MDT nodes of the WDM ring
with 1+1 protection of wavelength channel

MTTR = 6 h	$U \times 10^{-5}$	MDT [min/year]
Termination	4.049	21.29
Transit	4.319	22.71
MTTR = 4 h		
Termination	2.700	14.19
Transit	2.880	15.14

As can be seen in Tables 4, 5, 6 and 7, the point to point system has the highest unavailability. Although the chain system has WDM nodes in places of optical amplifiers, its unavailability is somewhat smaller in comparison with to point to point system because of very high failure rates of optical amplifiers [9]. Naturally, the WDM ring with protection of wavelength channel has the lowest unavailability (35 times smaller compared to point to point and 31 times compared to chain system) which is understandable because we analyze a parallel structure where failures of certain elements are completely independent.

Table 4
Unavailability and MDT for different systems
(N = 8 nodes)

MTTR = 21 and 6 h	$U \times 10^{-5}$	MDT [min/year]
Point to point	191.82	1008.51
Chain	171.31	900.48
Ring (1+1)	8.16	42.91
MTTR = 15 and 4 h		
Point to point	136.54	717.83
Chain	120.64	634.02
Ring (1+1)	5.43	28.55

Table 5
Unavailability and MDT for different systems
(N = 8 nodes)

MTTR = 21 and 4 h	$U \times 10^{-5}$	MDT [min/year]
Point to point	188.02	988.33
Chain	158.86	834.89
Ring (1+1)	5.45	28.68
MTTR = 15 and 6 h		
Point to point	140.45	738.01
Chain	133.12	699.61
Ring (1+1)	8.13	42.77

Table 6
Unavailability and MDT for different systems
(N = 12 nodes)

MTTR = 21 and 4 h	$U \times 10^{-5}$	MDT [min/year]
Point to point	314.27	1651.76
Chain	265.78	1396.92
Ring (1+1)	556.64	29.26
MTTR = 15 and 6 h		
Point to point	230.75	1212.55
Chain	218.65	1149.01
Ring (1+1)	8.26	43.14

Table 7
Unavailability and MDT for different systems
(N = 12 nodes)

MTTR = 21 and 6 h	$U \times 10^{-5}$	MDT [min/year]
Point to point	318.13	1671.94
Chain	284.05	1492.79
Ring (1+1)	8.28	43.55
MTTR = 15 and 4 h		
Point to point	226.86	1192.37
Chain	200.32	1053.15
Ring (1+1)	5.49	28.87

Decrease of cable repair time from 21 to 15 hours significantly decreases unavailability of point to point system (around 27%) and chain system (around 22%), but difference for WDM ring is insignificant (less than 1%). The reason is that contribution of links to total unavailability is around 95% for a point to point system, around 80% for chain system and only between 0.5 and 1% for a ring with 1+1 protection of wavelength channel.

Decrease of equipment repair time from 6 to 4 hours causes largest decrease of unavailability of the ring structure, around 23%; for chain system the reduction is around 7% and for point to point around 2%. Such situation is due to significantly higher contribution of nodes to total unavailability of ring structure (between 98 and 99%) than of the chain (around 20%) and point to point (around 2%); therefore it is understandable that decrease of equipment repair time has exactly such effect. Of course, in the WDM ring the end nodes have the highest influence on the total unavailability because their failure leads to interruption of communication between two nodes. Termination nodes influence the unavailability of both point to point system and chain system, but the influence is smaller due to significantly higher influence of cable on the total unavailability.

The lowest system unavailability is obtained by decreasing the repair time of both cable (from 21 to 15 hours) and equipment (from 6 to 4 hours) and, expressed as percentage, it ranges from around 30% for point to point, to 29% for chain and 33% for ring. As it can be seen, the difference in the total decrease of unavailability is small because in certain cases the influence of cable is dominant, so almost the same decrease of unavailability is obtained by decrease of repair time of cables and nodes.

5. Conclusion

Results of analysis of presented the in this paper show that the point to point system has the lowest availability. Significant improvement of availability is achieved in WDM ring with 1+1 protection of wavelength channels, because it is actually a parallel structure, where failures of both paths are completely independent. Only after failure on both sides of the ring and at the termination nodes the system becomes unavailable. Point to point and chain systems have several times higher unavailability because they in fact have a serial structure in which failure of any component leads to interruption of communication between two nodes. It is also noticeable that, in general, the availability of different WDM systems decreases with increase of the optical link length and number of nodes, in particular for non-redundant systems. Significant availability improvement of all WDM systems can be achieved by decreasing the repair time both of optical links and equipment, e.g., by better organization of maintenance teams. We need to build ring systems because only this way we can offer the users services of high availability.

References

[1] C. Coltro, "Evolution of transport network architectures", *Alcatel Telecommun. Rev.*, pp. 10–18, 1st Quarter 1997.

[2] G. Willems, P. Arijs, V. W. Parys, and P. Demeester, "Capacity vs. availability trade-offs in mesh-restorable WDM networks", in *Proc. Des. Reliab. Commun. Netw. DRCN*, Budapest, Hungary, 2001.

[3] A. D. Schupke, "Reliability models of WDM self-healing rings", in *Proc. Int. Worksh. Des. Reliab. Commun. Netw. DRCN*, Munich, Germany, 2000.

[4] I. Jurdana and B. Mikac, "An availability analysis of optical cables", in *Proc. WAON'98*, Zagreb, Croatia, 1998, pp. 153–160.

[5] R. Inkret, "Shaping of entirely optical transmission network with wave multiplex". Masters thesis, Zagreb, Faculty of Electrical Engineering and Computing/IT, University in Zagreb, 1998.

[6] R. Inkret, "Availability modelling of multi-service all-optical transmission network". Ph.D. thesis, Zagreb, Faculty of Electrical Engineering and Computing, University of Zagreb, 2004.

[7] D. Arci, G. Maier, A. Pattavina, D. Petecchi, and M. Tornatore, "Availability models for protection techniques in WDM networks", in *Proc. Des. Reliab. Commun. Netw. DRCN*, Banff, Canada, 2003, pp. 158–166.

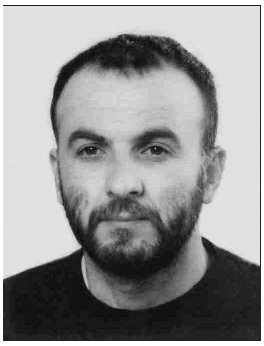
[8] M. R. Wilson, "The quantitative impact of survivable network architecture on service availability", *IEEE Commun. Mag.*, pp. 122–127, May 1998.

[9] R. Inkret and B. Mikac, "Availability analysis of different WDM network protection scenarios", in *Proc. WAON'98*, Zagreb, Croatia, 1998, pp. 121–128.

[10] I. Rados, "Influence of common path on availability of the ring network", *J. Telecommun. Inform. Technol.*, no. 3, pp. 71–75, 2004.

[11] P. Tomsu and C. Schmutzer, *Next Generation Optical Networks*. Upper Saddle River: Prentice Hall, 2002.

[12] W. D. Grover, *Mesh-Based Survivable Networks, Options and Strategies for Optical, MPLS, SONET and ATM Networks*. Upper Saddle River: Prentice Hall, 2004.



Ivan Rados received the B.Sc. degree in electrical engineering from the University of Split, Croatia, in 1983, and the M.Sc. degree from the University of Zagreb, in 2000. In 1985 he joined the PTT (Post and Telecommunication) at Tomislavgrad. Since 1992 he works at the Department of Transmission Systems of the HT Mostar (Croatian Telecommunication). His research interests include: digital transmission systems, optical systems and networks, availability and reliability of telecommunication systems. He has published 10 papers in international conference proceedings.

e-mail: Ivan.Rados@htmobilne.ba
HT d.o.o. Mostar
Kneza Branimira bb
88000 Mostar, Bosnia and Herzegovina