International Journal of Railway Research, Vol. 8, No. 1, (2021), 15-24

Iran University of Science and Technology

International Journal of Railway Research

ISSN: 2423-3838

Reliability Analysis, Modeling and Simulation of Optical Transmission Network (Case study: railway optical telecommunication)

Maziar Yazdani[*1], Fatemeh Hajizadeh[1,*], Saeed Ghazi Maghrebi[2], Mohammad Ali Afshar Kazemi[3]

[1]Railway Technical & Infrastructure Dept, Tehran, Iran, yazdani_maziar@yahoo.com & fahajizadeh@hotmail.com

[2]Department of Communications, Islamic Azad University, Yadegar-e-Imam Khomeini (RAH) Shahr-e-Rey Branch, Tehran, Iran, S_ghazi2002@yahoo.com

[3]Department of Management, Islamic Azad University, Qeshm Branch, dr.mafshar@gmail.com

ARTICLE INFO

Article history:

Received: (07.02.2021)

Accepted: 02.12.2021

Published: 05.12.2021

Keywords:

Reliability

RBD model

MTBF

Railway Optical Transmission Network

Monte Carlo Simulation

A B S T R A C T

Today, huge amounts of data are transmitted around the world through the high capacity of the optical telecommunication networks. In railways, optical transmission networks play an important role in transmitting vital rail data too. Improving the reliability of telecommunication infrastructures is essential to increase productivity, maintain traffic safety and reduce maintenance costs. In this paper, first the reliability of the optical transmission telecommunication network has been modeled and calculated analytically through RBD method and then its results have been approved through Monte Carlo simulation. Due to the importance of the optical transmission network in railway safety, the probability of optical transmission network outages and the Mean Time between Failure (MTBF) for 3 years have been calculated and simulated. A case study for this research was performed by using the real breakdown statistics of the network based on the optical telecommunications of the high-traffic railway area in "Azerbaijan District", one of Iranian Railways network in north-west of Iran.

1. Introduction

Optical transmission networks play a key role in the railway safety guarantee and rail accidents prevention [1]. Increasing the reliability of these networks has significant importance in the railway network performance [1-2-3]. Reliability engineering and its different aspects have been considered in various researches. Various articles have been reviewed on reliability [4-5-6]. Authors in [7] presented review research on "Reliability, Availability, Maintenance, and Safety RAMS engineering" based on researches from 1998 to 2005. Authors in [8] proposed system and subsystem reliabilities and maintenance modeling via Reliability Block Diagram (RBD) method. Authors in [9] have modeled and analyzed reliability in rail signaling. Authors in [10] studied different methods of reliability modeling such as RBD, Fault Tree, Markov Chains in telecommunication networks as well as communication base train control)CBTC(. Many researches have been done to assess the reliability of the main railway infrastructure [11-12-13-14], but there are no researches on the reliability of the railway optical communication systems.

Rail stations are connected to each other through the fiber-optic transmission network [3]. The most important services which are implemented through this network includes telephone signal and VOIP signals, CCTV signals, train control signals, and dedicated rail

*Corresponding author
Email address: yazdani_maziar@yahoo.com

[DOI: 10.22068/ijrare.281]

software data such as graphs, consignment note, etc. Therefore, the interruption of the network will lead to the interruption of the services and ultimately reduce rail safety [1-2-3].

In this study, the probability of simultaneous failure at main and backup fiber-optic network members, network outages during three years, and MTBF are simulated by the Monte Carlo method. We used the failure statistics of Azerbaijan with 16 stations obtained through "Kazvin" software owned by railway during three years (2018-2020).

Network topology and reliability analysis have been presented in Sections 2 and 3, respectively. Reliability modeling and Monte Carlo simulation have been done in Sections 4 and 5, respectively. Finally, the results of modeling and simulation have been presented in Section 5.

2. 2. Materials and methods

2.1. Network Topology

The railway transmission network, as shown in Figure 1, includes stations and their optical communication lines for telecommunication signals. Each station includes an AC power supply and its backup power generators (*R1* and *R2*), rectifier and batteries (*R3* and *R4*), optical transmission equipment containing main and their backup, synchronous digital hierarchy / Dense wavelength division multiplexing/Optical transport networks (SDH/DWDM/OTN)-(*R5* and *R6*). Furthermore, the connection between the stations, located across the railway route through the optical fiber cable on both sides of the rail lines, is called Line (1) and Line (2) [1-2-3].

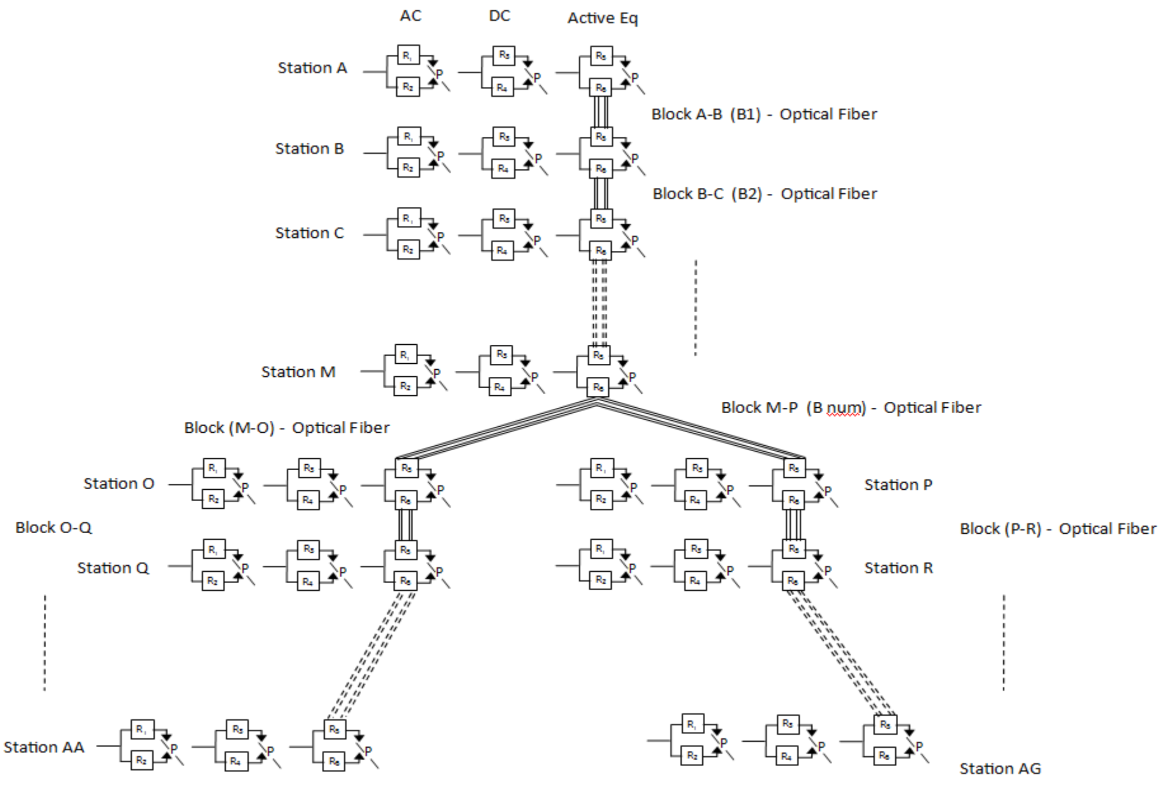

Fig. 1. Railway Optical Transmission Network Topology

[DOI: 10.22068/ijrare.281]

2.2 Reliability Analysis

Reliability of the system is defined as the probability of desired system function under certain conditions in a specified interval of time. [7-13]

2.1.1. Reliability

We define $R(t)$ as a complement of the cumulative probability distribution function $F(t)$ and also $f(t)$ as a probability distribution function. In this research, to calculate the network reliability, the exponential distribution function is used as bellow [13-17]:

$$f(t)= \lambda e^{-\lambda t} \quad (1)$$

Then $F(t)$ is:

$$F(t) = 1- e^{-\lambda t} \quad (2)$$

Therefore, the reliability of these systems will be as bellow [6-7]:

$$R(t)= \int_t^{\infty} \lambda e^{-\lambda t}\, dt = 1 - \int_0^t \lambda e^{-\lambda t} dt = e^{-\lambda t} \quad (3)$$

As a result, unreliability is shown with Q(t) and will be [7-13-15]:

$$Q(t) + R(t)= 1 \Longrightarrow Q(t)= 1-R(t) \quad (4)$$

$$Q(t)= F(t) = \int_0^t f(t).dt = 1 - e^{-\lambda t} \quad (5)$$

2.1.2. Failure Rate

The failure rate $h(t)$ is the failure probability in Δt time interval under the condition that no failure has occurred before time t. In most systems, the lifecycle behaves according to figure 2, which is known as the bathtub curve [17-18]. In this research, $h(t)$ is considered between two times t_1 and t_2. It is known as the random failure part that shows steady operation after fixing the defects. In the intended range, failure is random, and the failure of each component occurs independently of other components.

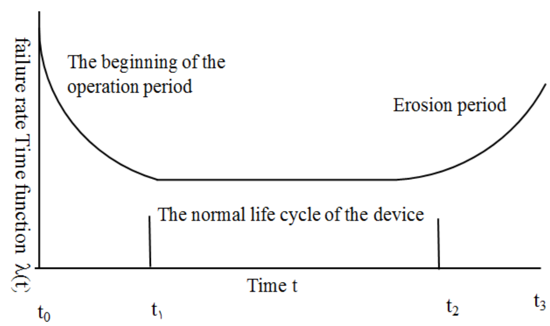

Fig.2. Bathtub curve of failure rate [17]

The failure rate for exponential distribution function can be described as bellow[17-18]:

$$h(t)= \frac{f(t)}{1-F(t)} = \frac{f(t)}{R(t)} = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda \quad (6)$$

In this case, $h(t)$ is a constant value of λ and λ is [10]:

$$\lambda = n/(T \times N) \quad (7)$$

Where n is the number of failures, N is the number of equipment, and T is the total time.

$$\lambda_s = \sum_1^n \lambda_i \quad (8)$$

[DOI: 10.22068/ijrare.281]

Where n is the total number of system units, λ_s is the total of λ's, and λ_i is the failure rate of each unit.

2.2.3. Mean Time between Failures (MTBF)

MTBF is the average time between failures of a System. [10] By using (3), it will be as bellow:

$$MTBF=\int_0^\infty \boldsymbol{R(t)dt} = \int_0^\infty \boldsymbol{e^{-\lambda t}.dt} = \frac{\mathbf{1}}{\boldsymbol{\lambda}} \quad (9)$$

2.1.3. Reliability Block Diagram Model (RBD)

In the RBD model, to model a system and calculate reliability, we use a diagram with connected blocks. Each block consists of input and output terminals [8-10]. We divide systems as series systems, parallel systems, systems with standby units, and combined systems.

- **Series Systems**

In series systems, the performance of the complete system depends on the performance of all components, and if one of them fails, the complete system stops. In this system type, main parameters are computed as bellow [10-18-19]:

$$R_{series}(t)= Pr\left(\bigcap_{i=1}^{n} Ai\ (t)\right)=\prod_i^n R_i(t) \quad (10)$$

$$Q_{series}=1- \prod_i^n R_i\ (t) \quad (11)$$

$$MTBF_{series}= \int_t^\infty R_{SS}\ (t)dt \quad (12)$$

$$MTBF_{series}= \int_t^\infty e^{\sum_{i=1}^{n} \lambda i\ (t)}\ dt = \frac{1}{\sum_{i=1}^{n} \lambda i} \quad (13)$$

Where n is the number of system units, R_i is the Reliability of each unit, and λ_i is the failure rate of each unit.

- **Parallel Systems**

In a Parallel system, all members are active simultaneously so that in case of the correct function of one member in each unit, the whole system will have the desired performance. In this system type, main parameters are computed as bellow [10 -18-19]:

$$R_{parallel}(t)= Pr\left(\bigcup_{i=1}^{n} A_i\ (t)\right)=1-\prod_{i=1}^{n}(1 - R_{i\ (t)}) \quad (14)$$

$$Q_{parallel} =\prod_{i=1}^{n} Q_{i(t)} \quad (15)$$

$$MTBF_{parallel} =\int_0^\infty R_{parallel}\ (t)\ dt \quad (16)$$

$$MTBF_{parallel}=\int_0^\infty [1 - (1 - e\text{-}\lambda t)\ n\ ]dt \quad (17)$$

$$MTBF_{parallel} = \frac{1}{\lambda}\sum_{i=1}^{n}\frac{1}{i} \quad (18)$$

Where R_i is the Reliability of each unit and n is the total number of system units.

- **Systems with Standby unit**

  In systems with surplus members, despite the availability of parallel members, only one of them is active. The other members are kept on standby, and they will be activated only when their working member fails. In these systems, main parameters are computed as below [10-18-19]:

[DOI: 10.22068/ijrare.281]

$$R_{sbs}(t)=\sum_{i=0}^{k}[\frac{(\lambda t)^{i}.(e^{-\lambda t})}{i!}]= e^{-\lambda t}\times(1+\lambda t) \quad (19)$$

$$Q_{sbs}=1- e^{-\lambda t}\times(1+\lambda t) \quad (20)$$

$$MTBF_{sbs}= \int_{.}^{\infty} R\ sbs\ (t)dt \quad (21)$$

$$MTBF_{sbs} = \int_{.}^{\infty} R\sum_{i=0}^{k}[\frac{(\lambda t)^{i}.(e^{-\lambda t})}{i!}]dt \quad (22)$$

$$MTBF_{sbs} =\frac{k+1}{\lambda} \quad (23)$$

Where $R_{sbs}(t)$ is system reliability, $k + 1$ is the number of units which k of them are standby units.

The above relations have been written based on the following assumptions:

1. An assumption in our standby system is that fault detection and switching from faulty components to normal units will never fail.

2. All units (components) are independent and similar.

3. Standby units do not fail in standby mode.

• Combined system

A combined system is a combination of the above systems, and it is defined as three bellow categories (24, 25, 26) [10-18-19]:

$$R_{parallel-series} =Pr\ (\bigcup_{i=1}^{M}\bigcap_{j=1}^{N}A_{ij}(t))=1- \prod_{i=1}^{M}(1-\prod_{j=1}^{N}(R_{ij}\ (t)))A \quad (24)$$

$$R_{series-parallel}= Pr\ (\bigcap_{ji=1}^{N}\bigcup_{j=1}^{M}A_{ij}(t))= \prod_{i=1}^{N}(1-\prod_{j=1}^{M}(1-R_{ij}\ (t))) \quad (25)$$

Where N is the number of first series units, M is the number of second series units

$$R_{series-standby}=\prod_{i=1}^{N}(\sum_{i=0}^{k}[\frac{(\lambda t)^{i}.(e^{-\lambda t})}{i!}]) = \prod_{i=1}^{N}(e^{-\lambda t}\times(1+\lambda t)) \quad (26)$$

Where N is the number of series units, and k is the number of standby units.

3. Results and Discussion

In order to calculate the reliability of the optical transmission network, it can be divided into subsystems, station, and fiber optic, as shown in figure 1. In the first step, the reliability of each subsystem and then the reliability of the complete network is calculated.

3.1. Reliability of Station Subsystem

Figure 3 shows one of the equipment with a standby member, complete station components, and its topology.

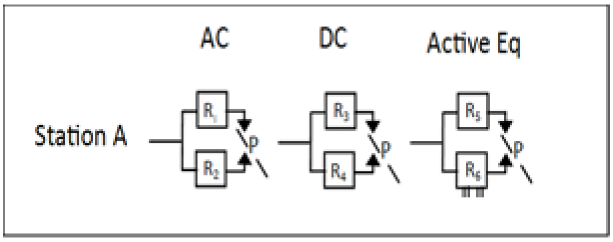

Fig. 3. Station equipment topology

According to figure 3, each station consists of two units, which one is working and the other is on standby mode. Therefore, the connection of each equipment with its backup member is in standby mode and in series with other equipment.

Reliability of equipment with its standby member using (7) and (19), for the period of 720 hours, i.e., one month, is calculated as below:

---

*Corresponding author
Email address: yazdani_maziar@yahoo.com

[DOI: 10.22068/ijrare.281]

$$R_{sbs}(t)= e^{-\lambda t}\,(1+\lambda t) = e^{-0.00002*720} \times (1+0.00002*720) = 0.9999 \qquad (27)$$

As a result, the reliability of one of the equipment with its standby member is equal to 0.9999.

Using (7) and (23), the MTBF of each equipment will be as bellow:

$$MTBF_{sbs}= \frac{k+1}{\lambda}= \frac{1+1}{0.00002}= 90909h \qquad (28)$$

Thus, the MTBF for single equipment of each station is 90909 hours (about ten years). According to figure 3, considering all of the equipment inside a station in series mode, the reliability of station A using (7) and (26), during 720 hours, will be:

$$R_{series-standby\ station)}\,(720) = \prod_{i=1}^{n}(e^{-\lambda t}\,(1+\lambda t)=(e^{-0.00002\times720} \times (1+0.\ 00002*720)) \times (e^{-0.00002\times720} \times (1+0.\ 00002*720))\times(e^{-0.00002\times720} \times (1+0.\ 00002*720\ )) =0.9997 \qquad (29)$$

Using (13), the MTBF at one station, including all of the equipment, will be:

$$MTBF_{series}= \frac{1}{n\lambda}= \frac{1}{3*0.00002}=16666h \qquad (30)$$

So, 16666 hours (about two years) is the MTBF of the station. Due to the similarity of equipment breakdown statistics, we obtain the same reliabilities for all stations.

3.2. The Reliability of Fiber-Optic Lines

According to Figure 1, the connection between the stations is established through the optical fiber network. The network consists of two series subsystems that act together in parallel [1-2-3].

Figure 4 shows the rate and the type of optical fiber failures in the railway, which has been extracted from "Kazvin" software and Hazard tables.

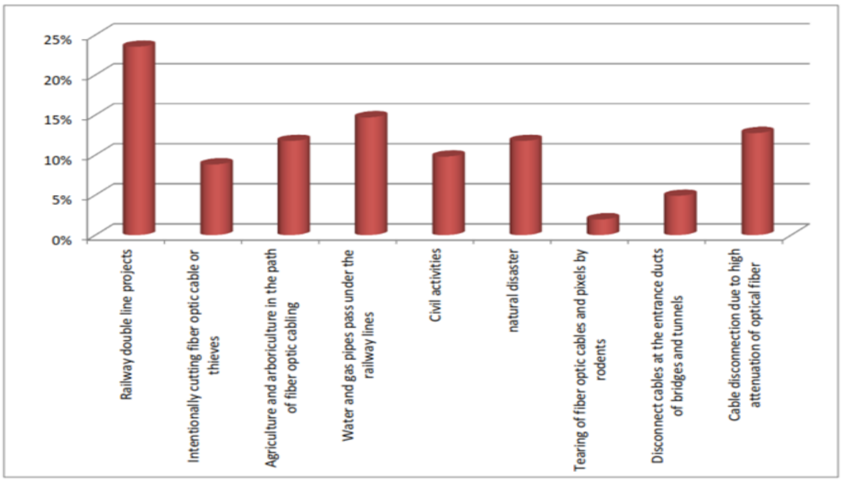

Fig.4. Rate and type of the railway optical fiber failures reasons

[DOI: 10.22068/ijrare.281]

Table (1) shows the number of failures of each of the series fiber optic blocks extracted from the "Kazvin" railway failure registration software. Through equations 8 and 10, the λ and R(t) of each fiber optic block are calculated separately. to calculate the $R(t)$ of optical fiber lines, first, the reliability of blocks (1) to (12) of both optical fiber lines

(Rb Line (1) and Rb Line (2)) are calculated separately by using (3) and (7) [48]. Then the

reliability of the whole network is calculated in parallel by using (7), (10), and (14) and Table 1.

Table 1- Analytical results of the system

block name	Number of failures		Lines (λ)		Lines R(t)	
	Line 1	Line 2	Line 1	Line 2	line 1	line 2
A-B	16	36	0.0006088	0.0006849	0.9945	0.9977
B-C	15	14	0.0005708	0.0005327	0.9981	0.9968
C-D	16	16	0.0006088	0.0006088	0.9977	0.9986
D-E	14	14	0.0005327	0.0005327	0.9981	0.9972
E-F	17	15	0.0006469	0.0005708	0.9963	0.9972
F-G	18	13	0.0006849	0.0004947	0.9959	0.9977
G-H	18	11	0.0006849	0.0004186	0.9963	0.9977
H-I	14	14	0.0005327	0.0005327	0.9968	0.9981
I-J	12	18	0.0004566	0.0006849	0.9977	0.9963
J-K	15	19	0.0005708	0.000304	0.9963	0.9963
K-L	14	23	0.0005327	0.000190	0.9972	0.9977
L-M	15	14	0.0005708	0.000342	0.9977	0.9959

According to Table 1, the reliability results of the optical fiber lines (blocks) are calculated as below:

A) $R_{b\ Line\ (1)} = \prod_{i=1}^{n} R_b\ Line\ (1) = R(b)_1 ... R(b)_{12} = 0.9197$ (31)

$Q_{b\ Line\ (1)} = 1 - R(t) = 1 - 0.\ 9197 = 0.0803$

B) $R_{b\ Line\ (2)} = \prod_{i=1}^{n} R_b\ Line\ (2) = R(b)_1 ... R(b)_{12} = 0.\ 0.9188$ (32)

$Q_{b\ Line\ (1)} = 1 - R(t) = 1 - 0.\ 9188 = 0.0812$

C) $R_{parallel\ Lines\ A\ \&\ B} = 1 - [\prod_{i=1}^{N} (1 - R_{i\ (t)})] = 1 - (1 - R_{b\ Line\ (1)})(1 - R_{b\ Line\ (2)}) = R_{b\ Line\ (1)} + R_{b\ Line\ (2)} - R_{b\ Line\ (1)} R_{bLine(2)} = 0.993$ (33)

$Q_{parallel\ Lines\ A\ \&\ B} = 1 - R(t) = 1 - 0.99 = 0.006$

Where, in Part A, the reliability of the first optical cable (Rb Line1) and in Part B, the reliability of the second optical cable (Rb Line 2) are calculated in series. In part C, the results of both parts A and B are calculated in parallel.

3.3. Monte Carlo Simulation

The Monte Carlo simulation process is used to predict the network behavioral algorithm over time. Monte Carlo simulation in this research is used to verify the computational results of the reliability in the RBD model. Also, it is used to obtain the number of concurrent outages of parallel optical fiber lines leading to the network blackout in the next three years as well as MTBF of the network.

In order to perform the reliability simulation, by using the analytical results of the RBD model from Table 1, the uniform distribution range for random numbers is divided proportionally to the probability of performance and failure. [21] For comparison, simulation results have been done in two rounds, as presented in Table 2.

Row A shows the unreliability of the first line of the optical fiber Line (1), row B shows the

*Corresponding author
Email address: yazdani_maziar@yahoo.com

[DOI: 10.22068/ijrare.281]

unreliability of the second line of the optical fiber Line (2), and row C shows the unreliability of Line (1) and Line (2) in parallel.

A) $Q_{b\ Line\ (1)} = 0.0812$
B) $Q_{b\ Line\ (1)} = 0.0803$
C) $Q_{system} = 0.0812 \times 0.0803 = 0.006$

Monte Carlo simulation, as shown in Figure 5, was performed through MATLAB software with 6000 samples. It is important to notice that in this simulation, a result similar to the reliability results in the RBD analytical calculation (uncertainty equal to 0.006) was obtained after the 3000[th] test. Moreover, the simulation results show that the probability of simultaneous failure for the two lines of the optical fiber network. (network outage) were seven times for three years. The simulation results are shown in Table 2.

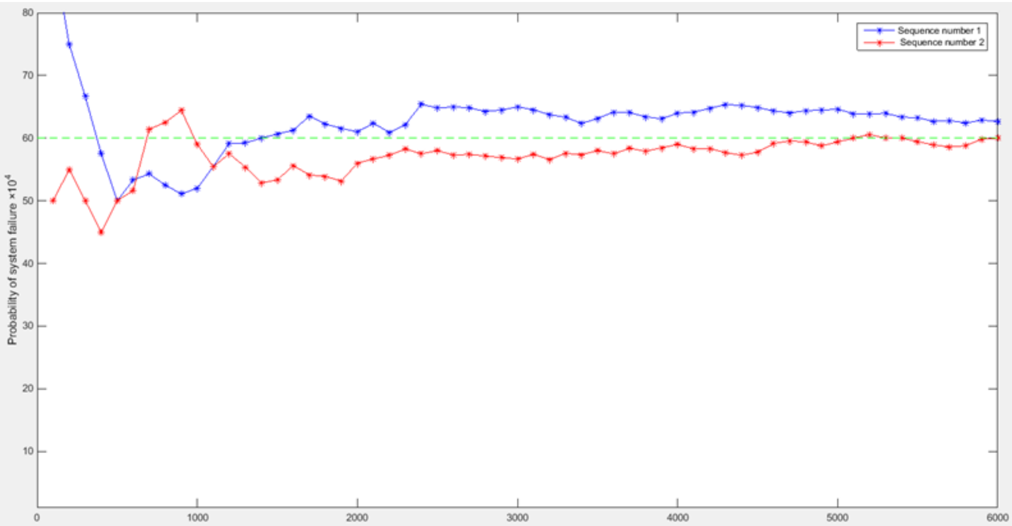

Fig.5. Optical fiber network reliability simulation

Table 2- Simulation results of system reliability

Cumulative number of tests	Cumulative number of the failures for each member		Number of failures with time intersection		Cumulative probability of system failures×104
Sequence (1)	1	2	cumulative	unique	
1000	56	49	6	6	70
2000	112	83	13	7	63
3000	181	128	19	6	66
4000	203	196	25	6	65
5000	267	243	30	5	62
6000	298	285	36	6	61
Sequence (2)					
1000	43	56	5	5	50
2000	86	91	10	5	53
3000	139	141	16	6	54
4000	153	166	22	6	58
5000	171	178	29	7	59
6000	188	198	36	7	60

Table 2 presents the simulation results for two sequences. The cumulative number of the failures for each member in each sequence, the number of the failures, and the cumulative probability of system failures for each sequence have been presented.

3.3.1. MTBF Calculation Based on Monte Carlo Results

The MTBF of the fiber-optic network is calculated by analyzing the network behavior in Monte Carlo simulation (number of network failures and its failure rate) shown in Table (2) and using equation (18) as follows:

[DOI: 10.22068/ijrare.281]

$$MTBF_{parallel\text{-}series} = \frac{1}{\lambda}\sum_{i=1}^{n}\frac{1}{i} = \frac{1}{\frac{n}{N\times T}}\times\sum_{i=1}^{n}\frac{1}{i} = \frac{1}{\frac{36}{2\times 26280}}\sum_{i=1}^{12}\frac{1}{12} = \frac{1}{0.0006849}\times 3.10321 = 4531\ h \quad (34)$$

Thus, the MTBF of the fiber optic network (2 parallel lines) was obtained at 4531h.

3.3.2. Analytical calculation results in RBD model and Monte Carlo simulation

The total results of the analytical calculation through RBD modeling, as well as the simulation, have been mentioned in Table 3.

Table 3- Analytical calculation results in RBD model and Monte Carlo simulation

path	Failure rate (λ)	R(t)	Q(t)	MTBF (h)	failures Number
Line(1)	0.0070	0.9197	0.0803	142	184
Line(2)	0.0072	0. 0.9188	0.0812	141	207
$system_{parallel}$	0.0006	0.993	0.006	4531	7

The number of optical fiber outages in lines (1) and (2) have been extracted from the railway failure recording software. The reliability and MTBF for each series' lines were calculated by using the RBD model. Moreover, the definite probability of the two parallel optical fiber lines simultaneously and MTBF for the network was obtained through the results of the RBD model and Monte Carlo simulation for three years. It is reminded that any breakdown in series lines leads to network outage, but in parallel lines, the simultaneous breakdown of the two lines leads to the network outage. Comparison of the results of the reliability of the series and parallel lines, the number of network outages in both cases, and their MTBF have been mentioned in Table 3.

For the first time in research, through Modeling and simulation of Monte Carlo, the behavior of the telecommunications transmission network has been predicted for a period of (3) years.

4. Conclusion

In this research, the reliability of the existing optical transmission network in the railway was modeled and analyzed analytically by using RBD model. The results of the analytical calculation were also verified by using Monte Carlo simulation. Based on the simulation results, the number of simultaneous outages of the optical fiber lines was *t* times of the total network outages and the MTBF, for a period of three years, was 4531 hours. Moreover, in this research, the statistics of actual failures recorded in three years were studied. Moreover, this research regarding the importance of safety in railway a viewpoint was provided to the network owners to implement a suitable solution to increase the network reliability in case of need for more reliability.

5. References

[1] Yazdani Maziar, in the book: "signaling & communication in the railway from yesterday to tomorrow," The Iranian Railway Training & research center, 2014.

[2] S. Ghazi Maghrebi and et al., "Examining Liberalization of Iranian Railway Communication Service," IEEE International Symposium on Networks, Computers and Communications (ISNCC), Turkey, 2019.

[3] Khodayi Ahmad and et al., "The liberation of rail telecommunication services," the Iranian railways training and research center, 2018.

[4] A. J. Bourne, "Book Review: Advances in Reliability Technology Symposium," The international journal of electrical Engineering & education, Volume: 26 issue: 4, pp. 376-376, 1989.

[5] E. N. Dialynas, "Book Review: 11th Advances in Reliability Technology Symposium", The international journal of electrical Engineering & education, Vol 29, Issue 2, pp. 132-132, 1992.

[DOI: 10.22068/ijrare.281]

[6] Smith, D, "Reliability, Maintainability and Risk," Elsevier Ebook, 9th Edition, 2017.

[7] S. Saraswat and G.S. Yadava, "An overview on reliability, availability, maintainability, and supportability (RAMS) engineering," International Journal of Quality & Reliability Management, VOL. 25, pp: 330-344, March 2008.

[8] K.D. Figiel, et al., 1990, "A generalized reliability block diagram (RBD) simulation," IEEE Simulation Conference Proceedings, USA.

[9] Yu Min And et al., "Reliability Model for Control Center of Railway signaling system based on SRN," IEEE Fourth International Conference on Digital Manufacturing & Automation, 2013, CHINA.

[10] W. Ahmed, et al., "Reliability Modeling and Analysis of Communication Networks," Elsevier Journal of Network and Computer Applications, Volume 78, pp. 191-215, 15 January 2017.

[11] M. Marco and et al., "Maintenance management of railway infrastructures based on reliability analysis," Elsevier Reliability Engineering & System Safety, Vol 104, pp. 71-83, August 2012.

[12] L. Jun Ting, D. Jian Wu, "Reliability Models of GSM-R Redundant Network on High-Speed Railway," Materials science & Engineering, vol.198-199, pp. 1783-1788, 2012.

[13] L. Chen and et al., "Verification of the safety communication protocol in train control system using colored Petri net," Reliability Engineering & System Safety, Vol. 100, Pages 8-18, April 2012.

[14] A. Maria, IEEE International Conference on Railway Safety Assurance: Management and Method in a Safe Network, "The introduction of common safety methods," London, UK, 2013.

[15] Seongwoo Woo in the book: "Reliability Design of Mechanical Systems," chapter "Modern Definitions in Reliability Engineering," (pp.53-99), ResearchGate, pp 53-99, 2020.

[16] Seongwoo Woo, In book: Modern Definitions in Reliability Engineering, Reliability Association of Korea, Seoul, Korea, pp.53-99, 2020.

[17] B. S. Dhillon, In book: Design Reliability: Fundamentals and Applications, University of Ottawa, Ontario, Canada, 1999.

[18] B.M. Ayyub, R.H. McCuen, "probability statistics and reliability for engineers and scientists," DOI: 10.1201/b12161, University of Maryland, College Park, January 2003

[19] Durga Rao Karanki and et al., "Advances in RAMS Engineering," book' Springer Nature Switzerland AG 2020.

[20] Ch. Panda, S. Narayan Patro, P. Kumar Gantayat, "Link Reliability in WDM Optical Network," Chinmayananda Panda et al. / Indian Journal of Computer Science and Engineering (IJCSE), Vol. 3 No. 1, Pp. 126-132, Feb-Mar 2012.

[21] Pierre Brémaud, "Markov Chains: Gibbs Fields, Monte Carlo Simulation and Queues, " 557 pages, Springer International Publishing, 2020.

[22] Eduardo Calixto, in Chapter 4 - Reliability, Availability, and Maintainability (RAM Analysis), Gas and Oil Reliability Engineering (Second Edition), Modeling and Analysis, 2016, Pages 269-470, Elsevier books, 2016.

[23] Ch. Panda, S. Narayan Patro, P. Kumar Gantayat, "Link Reliability in WDM Optical Network," Chinmayananda Panda et al. / Indian Journal of Computer Science and Engineering (IJCSE), Vol. 3 No. 1, Pp. 126-132, Feb-Mar 2012.

[24] A. Sayed, et al., "Reliability, Availability and Maintainability Analysis for Grid-Connected Solar Photovoltaic Systems," MDPI Journal, VOL 12, pp. 1-18, Energies 2019.

[25] G. Haitao, Y. Xianhui, "A simple reliability block diagram method for safety integrity verification," Reliability Engineering and System Safety, Elsevier, vol. 92, pages 1267-1273, 2007.

[DOI: 10.22068/ijrare.281]