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Probabilistic Determination of Substation Communication Network Reliability Parameters

Jackson Esabu, Samuel Amaechi Ike

Department of Electrical & Electronic Engineering, University of Benin, Benin City, Nigeria

Email address:
esabu03@yahoo.com (J. Esabu), sam.ike@uniben.edu (S. A. Ike)

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Abstract: Substation communication network consists of networking devices whose reliability is becoming one of the most prioritized by utility asset owners owing to the critical functions (that is power grid real time monitoring and control operations) perform by the substation communication network. This paper focused on the use of probabilistic approach to determine substation communication network reliability using statistical analysis, randomly derived statistical data, reliability theory and computing techniques. The paper also focused on the use of network nodes reduction technique to test the communication network redundancy. The findings of this paper are aimed at using networking device derived failure rate data to determine communication network reliability at the defined end of life of the network, and also to estimate the of Mean Time To Failure of the derived communication network. The result of this research has demonstrated that probabilistic approach can be use to successfully analysis and determine the reliability of a communication network within the defined network service (i.e. operational) life.

Keywords: Seamless Parallel Redundant Time Dependent (SPRTD) Network, Mean Time To Failure (MTTF), Reliability, Failure Rate (f(t)), Node Elimination Approach, and Parallel Redundant Protocol (PRP)

1. Introduction

The determination of substation communication network reliability parameters through deterministic approach might lead to inconsistent results owing to insufficient data about the communication network devices, design parameters and the network operational data. These networking devices are usually designed with semiconductor, with typical failure rate ranging from 10-10 to 10-7 h-1. Failures of these networking devices usually occur at the early stage of their operational life, and the chances of manufacturer defeat are relatively very low [1], but as these networking devices age, they eventually run into degrading performance with Mean Time Before Failure (MTBF) ranging typically from 100,000 to 1,000,000 (hrs). This underpins the need for a probabilistic approach, which provides a realistic engineering analysis and results that can be used to enhance the performances of the communication network.

Substation communication network reliability analysis through 'Probabilistic Approach', involves the use of statistical distribution to mathematically model the desired behavior of the communication network. Previous researches have shown that communication network redundancy can be easily achieved through Parallel Redundancy Protocol (PRP) [2]. PRP is essentially designed for substation automation application, to enables the duplication of communication network data simultaneously over uncorrelated (stochastically independent) medium.

Reliability Block Diagrams have been used successfully to evaluate the availability of different components of substation automation systems that utilize IEC 61850 protocol [3]. This same technique was successfully used in analyzing substation network architectures and the availability characteristics of the different redundancy schemes in the network [4]. Reliability theories and Monte Carlo Simulation technique have been used successfully to evaluate the reliability and availability of power system equipment [5]. Researches have also shown how to use algorithms, mathematical analysis and software tools to effectively evaluate, optimize the reliability of telecommunication networks [6] with full interoperability between the intelligent devices within the network [7, 8].

In this paper we briefly present a method for communication network architecture reliability estimation using the versatile Weibull statistical distribution and randomly derived statistical data. This method was applied to a redundant communication network considering the type of networking devices, component failure probabilities and the effect of communication network failures on monitoring and control of power system. We have also demonstrated in this paper how to use mathematical analysis and software to effectively evaluate the reliability of communication network, estimate communication network MTTF and comparing the reliability of the networks (derived network verses a typical non-redundant network reliability).

2. Communication Network Design Methodology

Typical digital protection system uses Ethernet switches, Ethernet interfaces and external time sources to interconnect intelligent devices (such as digital protective relays, universal remote I/O devices, etc.) [9]. These interconnected intelligent devices perform substation protection, monitoring and control functions [8] by sending GOOSE triggered data through the substation communication networks (mainly the Process Bus and Station Bus). These Process Bus and Station Bus have similar capabilities and functionalities as the well-defined and established LAN networks [10].

Substation communication network architecture could be a hybrid of the three main basic Ethernet switched architectures (that is Star, Ring and Cascaded) [11]. In this paper, the following hybrid communication architecture (that is Seamless PRP Redundant Time Dependent (SPRTD) communication network) shown in Figure 1 is formulated based on the basic operational theory of a typical Ethernet switched network. The proposed SPRTD network consists of Process Bus and Station Bus that are configured as a seamless redundant communication network linked via dedicated fiber optic link for an optimum point-to-point connection.

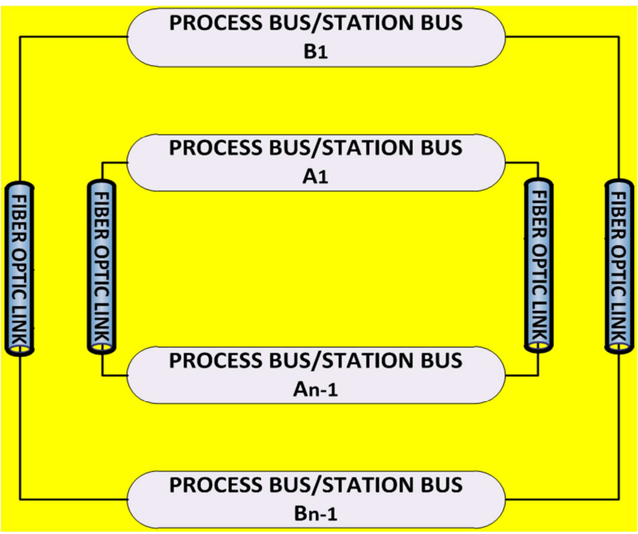


Figure 1. *Proposed SPRTD Communication.*

The statistical distribution [1] used in analyzing the proposed SPRTD network is carefully chose such that the distribution fit the network model, and accurately represents the SPRTD network. The statistical distribution is defined such that the proposed SPRTD network reliability and other network reliability metrics such as the network Mean Time To Failure (MTTF) are mathematically obtainable through computer aided program.

The proposed SPRTD network which consists of parallel and series connected independent networking devices is analyzed as a time-dependent network with defined operational state based on the individual component state variable $X_S(t)$. The modeled SPRTD communication network is assumed to be capable of providing the required network redundancy, capable of transferring network data seamless without any loss of network data and also capable of instant failure recovery.

The individual component state variable $X_S(t)$ of the modeled SPRTD network is used to defined the operational state of the network. These individual component state variables are defined independently as:

$$X_S(t) = \{^1_0 \quad (1)$$

where 1 denotes the probability that each SPRTD device is successful and 0 is the probability that each SPRTD device failed.

The semiconductor characteristic of the SPRTD networking devices allows the network to continually remain in a successful steady state at time t+Δt. With an operating time (t), the fundamental distribution of the networking devices reliability can be represented simply as:

$$R(t) = \int_t^\infty f(t)dt \quad (2)$$

where R(t) is the reliability of the network from time (t) to infinity and f(t) represents the probability density function of the network. The carefully chosen statistical distribution used in analyzing the proposed SPRTD network is defined such that the network R(t) is fully optimized. The SPRTD network reliability ($R_S(t)$), is defined as;

$$R_S(t) = 1 - f_S(t) \text{ for } t > 0; \quad (3)$$

where $f_s(t)$ denote the probability that the SPRTD network fails on interval of (0, t).

The SPRTD IEC 61850-enabled Process Bus and Station Bus are interconnected by intelligent devices, as illustrated in Figure 2. The SPRTD network GPS timeserver ($GPS_{TIMESERVER}$) uses its GPS receiver as a reference time source and distributes the received absolute time throughout the network to optimize the network. The Process Bus and Station Bus connected intelligent devices are assumed to be capable of exchanging the $GPS_{TIMESERVER}$ time sensitive data (that is 'Protection, Monitoring and Control' data) across the network for substation protection, monitoring as well as control purposes.

The RTUs of the SPRTD network are referred to as the station gateways, which are assumed to be capable of supporting master-slave and client-server functions. These master-slave and client-server functionalities eased the monitoring & control [12], and gateway functions of the network and also allows seamless communication between all connected intelligent devices within the IEC 61850 enabled Process $\text{Bus}_{A/B}$ and Station $\text{Bus}_{A/B}$ shown in Figure 2 without any direct connection between the LANs network, so as to avoid common mode failures.

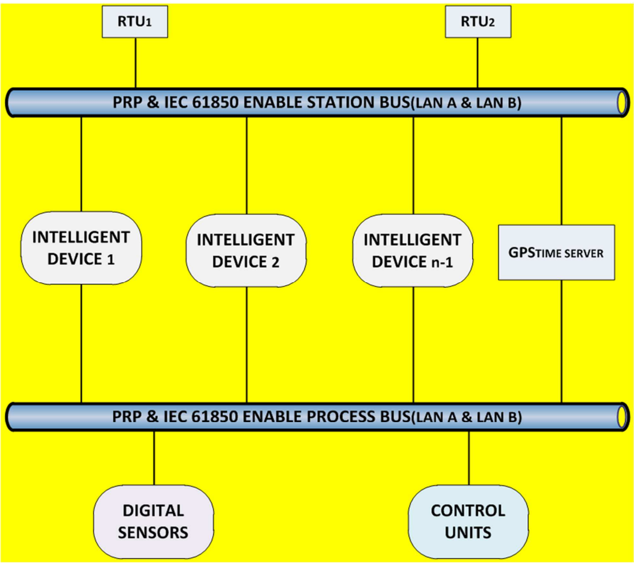


Figure 2. *Substation Communication Architecture.*

2.1. Formulated SPRTD Network Statistical Distribution Model

The formulated SPRTD communication network reliability analysis through a probabilistic approach is primarily based on the application of mathematical/statistical theories with a carefully well-defined and randomly chosen distribution limits. These distribution limits are defined such that the networking device failure rates are correlated with the shape of the distribution. The carefully chosen distribution coefficients [1] only tend to approach zero such that they never allow over-stretching and too narrowing of the distribution. These carefully chosen distribution coefficients limits are based on the assumption that the formulated SPRTD communication network devices do not experience any failure before their deployment due to their semiconductor properties. The probability density function of the statistical distribution is as follow:

$$f(x;\alpha,\beta) = \begin{cases} \frac{\beta}{\alpha}\left(\frac{x}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x}{\alpha}\right)^{\beta}} & x \geq 0 \\ 0 & x < 0 \end{cases} \quad (4)$$

The distribution coefficients limits (β) and (α) are within controlled ranges that ensure the formulated SPRTD network failure rate increase with time due to aging of the network devices are correlated to limit the network degradation rate.

2.2. Formulated SPRTD Network Modeling

The formulated SPRTD communication network reliability indices modeling is determined based on the reliability indices of the individual devices connected in series and/or parallel [1]. The reliability of SPRTD series connected device ($R_{SS}(t)$) is based on the assumption that the reliability of individually connected devices ($R_i(t)$) are independent and their distribution parameters are random variables [1] generated randomly within the defined distribution limits.

$$R_{ss}(t) = \prod_{i=0}^{n} R_i(t) \quad (5)$$

$$R_i(t) = e^{-\left(\frac{t-\gamma_{RanVar}}{\alpha_{RanVar}}\right)\beta_{RanVar}} \quad (6)$$

where $_{RanVars}$ are the randomly derived variables over a time t period.

The reliability of SPRTD parallel connected devices, ($R_{SP}(t)$) is derived as follow:

$$R_{Sp}(t) = 1 - \left(\left(\prod_{i=0}^{n}(1 - R_i(t))\right)\right) \quad (7)$$

$$R_{Sp}(t) = 1 - \left(\prod_{i=0}^{n}\left(1 - \left(e^{-\left(\frac{t-\gamma_{RanVar}}{\alpha_{RanVar}}\right)\beta_{RanVar}}\right)\right)\right) \quad (8)$$

The interconnected communication network is also represented by an equivalent probabilistic function ($R_S(t)$) which is defined as:

$$R_S(t) = \sum\left[\prod_{i=0}^{n} R_{ss_i}(t)\, R_{Sp_i}(t)\right] \quad (9)$$

The SPRTD communication network PRP capability was modeled as a consecutive k-out-of-n network [1] and tested. This is to ensure that the networks include sequences for network redundancy.

$$R_{S(k,n,R)} = \sum_{r=k}^{n}\left(\frac{n!}{k!(n-k)!}\right) R^r (1-R)^{n-r} \quad (10)$$

where R denotes the reliability of the statistical independent and identical components.

The modeled SPRTD communication network minimized its number of connections to at least eight possible minimum paths (MP) for R_S to converge and also ensures that at least one path out of the derived MPs is required for the SPRTD network to converge (that is the SPRTD network components are both statistically independent and identical) at every iteration. The k-out-of-n connected network was tested and verified given that for the numbers of network elements |ε| is the number of nodes in ε for R_S to converge.

Also, the modeled SPRTD network Mean Time To Failure ($MTTF_S$) was derived based on the assumption that the semiconductors' used in designing the networking devices are non-repairable, non-maintainable, cannot be reused once failed [13] and the networking devices are connected in series/parallel [14] configuration. For this reason, the PRP enabled communication network, which is inclusive of the IEC 61850 enabled Process $\text{Bus}_{A\&B}$ and Station $\text{Bus}_{A\&B}$, are assumed to be non-repairable. The SPRTD network time to fail is therefore defined as:

$$MTTF_S = \int_0^{\infty} R_S(t)dt \quad (11)$$

$$MTTF_S = \int_0^{\infty} \prod_{i=0}^{n} R_{ss_i}(t)\, R_{sp_i}(\mathrm{t})\, \mathrm{dt} \quad (12)$$

The derived $MTTF_S$ represents an integral function of the SPRTD communication network reliability function from zero to infinity limit within the defined probability density function.

The modeled SPRTD network has the following assumed design characteristics:

a) Flexibility and scalability
b) Robust, Redundant and fault-tolerance
c) Simplified data integration and interpretation
d) Simultaneous data transfer over uncorrelated channel
e) Correlated and collective computation

3. Modeled SPRTD Network Result & Discussion

The SPRTD reliability model is created with event and the model takes into account all networking devices connection mode (i.e. series or parallel). The SPRTD network reliability model includes the analysis of the initiating events (network faults). The modeled SPRTD communication network was simulated by simulating the reliability of individually connected (that is series/parallel connection) components and assuming network end of life of fifteen years. All connected intelligent devices, as illustrated in Figure 2, are assumed to be receiving and transmitting sensitive data seamlessly without incurring any data loss through the IEC 61850 enabled and PRP Process $Bus_{A/B}$ & Station $Bus_{A/B}$.

3.1. Modeled SPRTD Network Simulation Steps Overview

The simulation steps for the proposed SPRTD network is summarized below:

initialization: sample chosen distribution
set $i \neq 0; j \neq 0$
step 1: compute $\beta(i, j)$ = rand [2.6, 3.7]
step 2: compute α (i, j) = rand [14, 22]
step 3: if true, perform steps 4-6
step 4: compute $R_i(t)$ for individual component.
step 5: compute $R_{ss}(t)$ for series connections and $R_{sp}(t)$ for parallel connection(s) where applicable
step 6: test the network redundancy using $R_{S(k,n,R)}$ using unconnected graph G for the connected network, such that G = (v, ε); where v is the set of available nodes in the network and ε is the link.
$v = \{v_1, v_{2,...,} v_m\}$;
$s = v_1; t = v_m,$
$\varepsilon = \{\varepsilon_1, \varepsilon_{2,...,} \varepsilon_n\}$;
where s is the source node and t is the end node.
step 7: converge network
step 8: compute the derived network $R_S(t)$
step 9: repeat steps 1-8
step 10: compute the network $MTTF_S$

3.2. Simulation Results & Discussion

We performed simulations using the derived equations, randomly chosen distribution limits and the assumed design characteristics in Section 2 to evaluate the reliability parameters of the modeled SPRTD network. We used k-out-of-n framework to test the network redundancy. We consider a defined end of life of fifteen years for the network and carefully chose a statistical distribution whose limits (i.e. β & α) are randomly generated for every iteration.

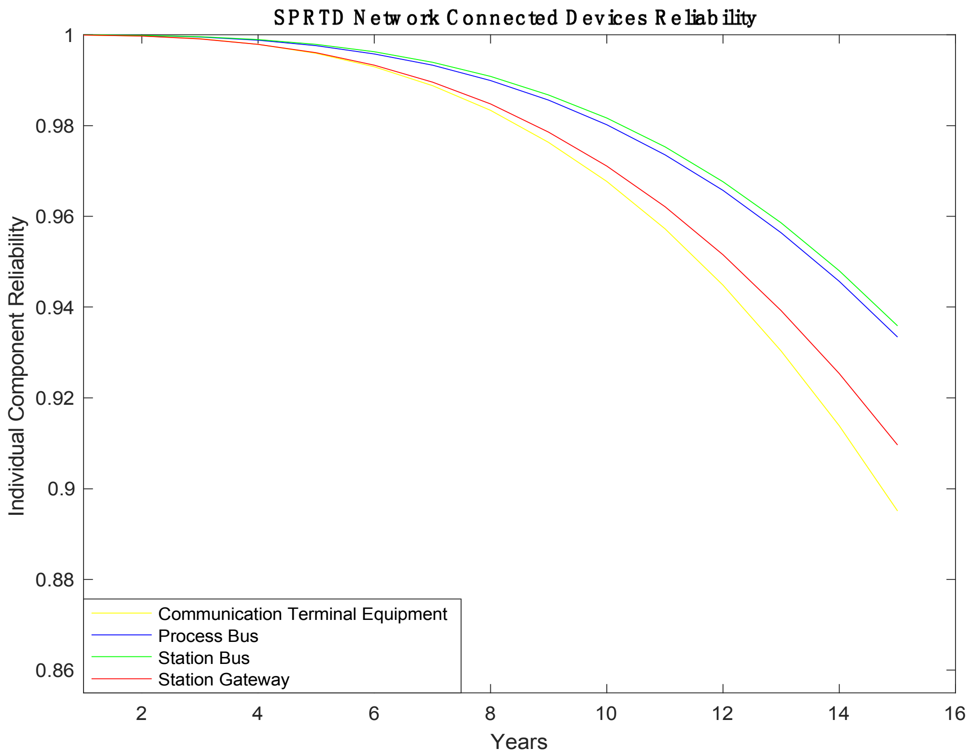


Figure 3. *SPRTD Network Connected Devices Reliability.*

The reliability of the individual components as shown in Figure 3, shows that each network component reliability decreases over time due to wear, fatigue and continuous operation of the SPRTD network. The network simulation result helped us to better understand the expected performance of the different components of the network over the network-defined life.

The level of SPRTD network reliability and availability is best estimated by analyzing the availability of the network access layer. The modeled PRP capable k-out-of-n network result as shown in Figure 4 meets utilities acceptable service level because of the network high reliability of approximately five nines reliability within the first five years of operation and approximately a two nines reliability toward the network defined end of life. This shows that the modeled SPRTD network is technically capable of supporting and providing the required protection, monitoring and control functions of the station at utilities acceptable service level.

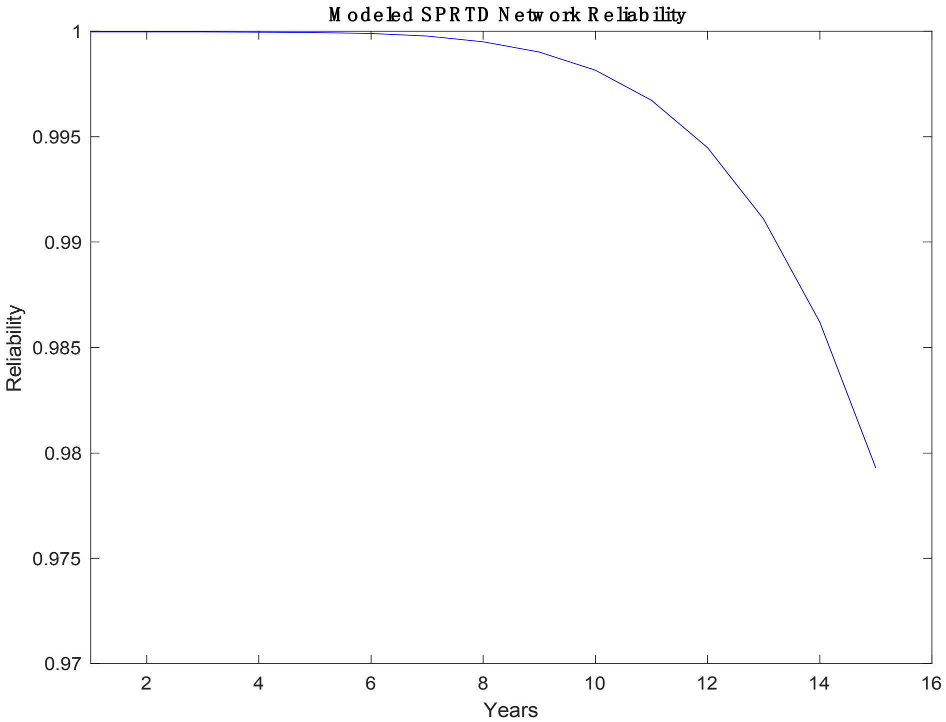
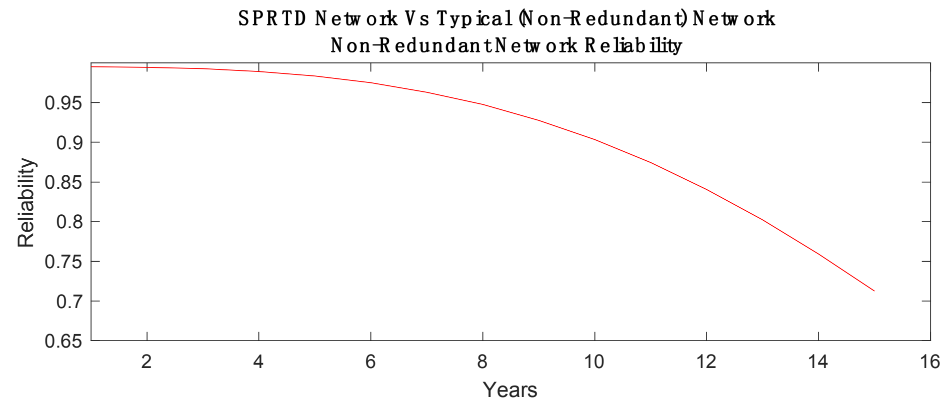


Figure 4. *SPRTD Network Reliability.*

The performance of the modeled SPRTD network was compared with a typical (that is non-redundant) network whose components (i.e. connected network devices) are assumed to have the same properties and characteristics as the proposed SPRTD network connected devices. The results as shown in Figure 5, shows that the reliability of the proposed SPRTD network at approximately the network defined end of life (i.e. 14th year) is almost what is achievable by a typical communication network during its 1st year of operation. This is a clear indication of the need for a redundant capability as proposed in the modeled SPRTD network. The differences in the networks reliability comparison results are mainly attributed to SPRTD network ability to duplicate communication network data simultaneously over it uncorrelated channel and the available optimum MPs for network convergence in the proposed SPRTD network.



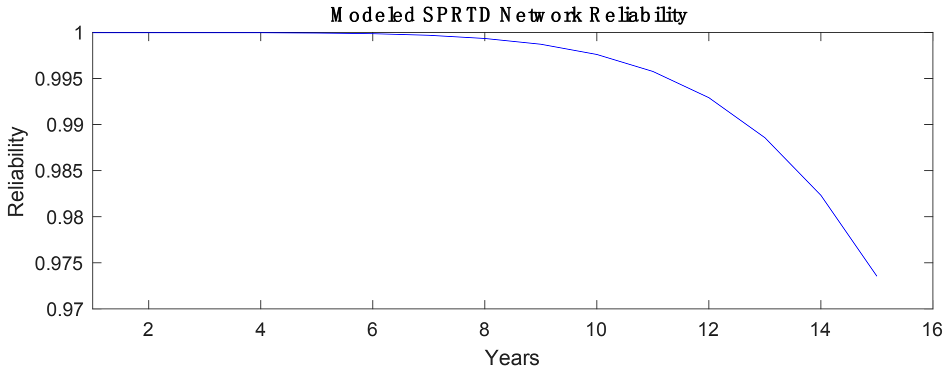


Figure 5. *Network Reliability Comparison.*

The modeled SPRTD communication network was also simulated to determine the network MTTF. The network MTTF, which is an important indicator of the expected performance of the SPRTD network, shows that the modeled SPRTD network as shown in Figure 6 has an estimated MTTF of approximately 3,723,000 hrs for the network defined end of life. The SPRTD network MTTR result shows that the probability of encountering manufacturing defect by the network devices is significantly very low and if any of these network device does fail, it is most likely due to physical mishandling of the device.

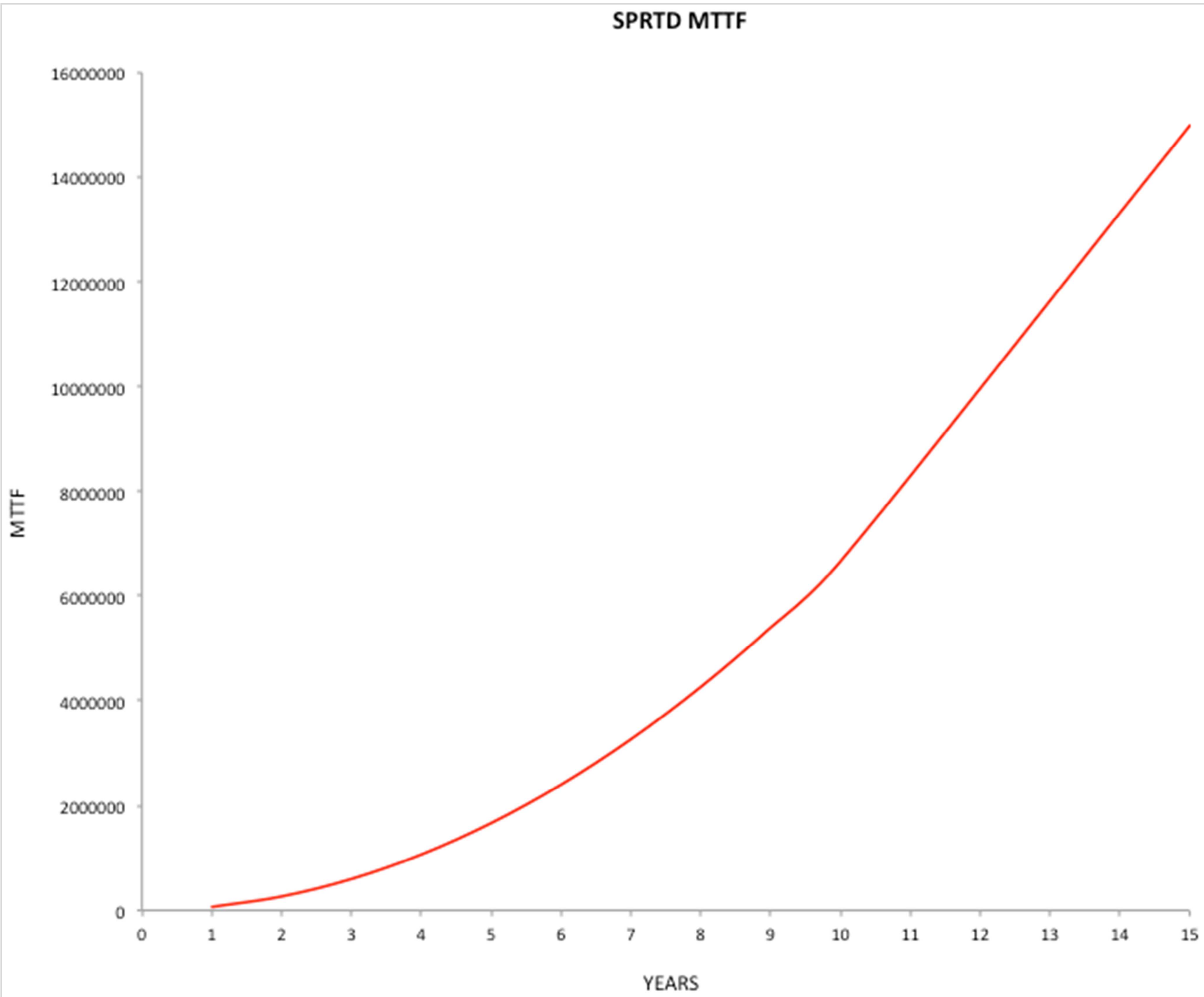


Figure 6. *SPRTD Network MTTF.*

4. Conclusion

Substation communication network has become a key aspect of modern power grid component due to increasing demand for reliable and robust communication of time sensitive data. We've proposed a reliable and robust communication network that is expected to play an important role in providing the desired reliable source for substation monitoring, control and protection functions. This article also discussed the reliability analysis of individually connected communication network devices, compared the reliability of the proposed SPRTD network with a non-redundant network and discussed the reliability of the compared network.

Considering the defined requirements of the communication network, we've demonstrated that probabilistic based reliability assessment method is opined to be a viable method to determine communication network reliability parameters, owing to its ability to mathematically model the desired attributes of the network. We've have also shown in this paper that though the formulated SPRTD network performance may degrade slightly over the network defined life due to aging of networking devices, but the chances of experiencing manufacturing early defect is very low.

In addition, this study has validated the successful use of computer based simulation software to simulate/visualize the reliability of a substation communication network.

Nomenclature

GOOSE	Generic Object Oriented Substation Event
GPS	Global Positioning System
IED	Intelligent Electronic Device
IEC	International Electrotechnical Commission
LAN	Local Area Network
MTBF	Mean Time Before Failure
MTTF	Mean Time To Failures
PRP	Parallel Redundant Protocol
RIO	Remote I/O
RTU	Remote Terminal Unit
SPRTD	Seamless PRP Redundant Time Dependent
TCP/IP	Transmission Control Protocol/Internet Protocol

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