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Analysis of Reliability Prediction and Maintainability Activities of an Earth Station System using Parallel Configurations

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Abstract. The recent news regarding the Malaysian satellite, MEASAT-3; which suffered an anomaly has caused the satellite to drift out of its geostationary orbit, and the uncontrolled re-entry of the Chinese Long March 5B rocket in 2021 had sparked high alarms in satellite operators industry. Due to the satellite communication system failure, the government had loss a massive amount of money. Hence, it is essential to equip the system with a sustainable framework design which can be achieved through an optimum system reliability and maintainability. Subsystem redundancies, multiple testing during the planning stage, and selection of only the best components for its subsystems can improve the system reliability. Also, relevant maintenance activities should be performed frequently to avoid cost overruns and unforeseen failures. This paper presents an analysis of the reliability and maintainability of an Earth Station system using Monte Carlo simulations. The results show that the highest reliability value is obtained for the 3-parallel configuration. Suitable maintenance activities are also suggested to assist with the maintainability of the Earth Station system.

Keywords: reliability, maintainability, earth station system, mean time between failure, Monte Carlo simulation

1. Introduction

Over time, communications satellites have been serving billions of users worldwide; mainly used in television, telephone, and internet applications. The satellites can deliver mobile connectivity in geographic areas where traditional wired or wireless infrastructures are difficult to deploy [1]. Uplink signal is received from a transmitting Earth Station and amplifies it before re-transmitting it to at least one Earth Station. An example of a satellite application is live broadcasting coverage, which is only possible with a dependable satellite communication system [2]. Yet, failures that result in system abnormalities and breakdowns are to be expected. Data loss in the systems is a common example of failure, which could be caused by wireless link distortion and irregular connectivity during cell handovers in cellular networks [3]. As mentioned in [4], statistical analyses of satellite reliability are scarce in the literature. Hence, more explorations need to be done in this area to fill in the gap. The reliability of an Earth Station system can be improved through the subsystem redundancies, multiple testing during the planning stage, and the selection of only the best components for its subsystems. Additionally, incomplete data combined with indistinct expert judgments introduce imprecision and evidential uncertainties into component performance characterization which must be considered when evaluating system reliability [5]. Furthermore, relevant maintenance activities must be performed on a timely basis to avoid any cost overruns and unforeseen failures.

Fundamentally, satellite failures can be caused by electronic circuit failure, malfunctioning fuel system, or even the environment [6]. The cause of satellite failures and the reliability of satellite communication system are major concerns because failed satellites typically remain in orbit or will be fragmented upon re-entry. Each subsystem in the satellite communication system has its own failure rate, which is a measure of the functionality of the subsystem [6]. A catastrophic event like satellite explosion, results in huge financial loss for the satellite service provider. Thus, the satellite communication system design is critical in ensuring that the operation service runs smoothly.

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This paper will focus on an analysis of reliability of an Earth Station system and its relevant maintenance activities using 2-parallel and 3-parallel configurations. The following is how our paper is structured: Section II presents the literature review of an Earth Station system comprising description about the basic Earth Station system, parallel structures, reliability of a satellite Earth Station system, Mean Time Between Failure (MTBF) and maintainability of a satellite Earth Station system; Section III explains the research methodology done for this research; Section IV discusses the results and analysis and lastly Section V concludes the research provided with the recommendation for future work.

2. Literature Review

2.1. Basic Earth Station System

A basic satellite communication system model is made up of both repairable and non-repairable components. The repairable components are found in Earth Station and satellite subsystems, while non-repairable components are found in satellite transponders [2]. A basic Earth Station system model is used in this research study because it is repairable, whereas non-repairable components result in different system design outcome.

The basic Earth Station system consists of two components: transmitters and receivers. There are a total of 20 subsystems available. Each transmission and receiving station have ten subsystems. Direct Access Cross Connect System (DACCS) and Digital Circuit Multiplication Equipment (DCME) are two similar subsystems for both transmitter and receiver. Modulator, Multiplexer, Up Converter, and Power Amplifier are components of the transmission part, meanwhile Low Noise Amplifier, Down Converter, Demodulator, and Demultiplexer are components of the receiving part [7].

The configuration of a basic Earth Station model is straightforward. Each component mentioned plays a role in the uplink and downlink processes, which is why the system has two Modulators, Multiplexers, Up Converters, and Power Amplifiers for the transmission part, and a Low Noise Amplifier, Down Converter, Demodulator, and Demultiplexer for the receiver part [2].

2.2. Parallel Structures for the Repairable Parts in the Earth Station System

The satellite receives uplink signals from the Earth Station's antenna. The signals are amplified to an optimal level using a power amplifier before being re-transmitted to the Earth via transponders [8]. The signal from the satellite is then received by the Earth Station and then, amplified once more for a communication purpose. This process demonstrates the importance of the Earth Station system in both transmitting and receiving signals from and to the Earth Station [8].

The n-parallel configurations are the subject of this research study. In this research study, 2-parallel and 3-parallel configurations are selected. The reason is because the reliability performance will be analysed, and consequently, the maintenance activity of each subsystem will be proposed. The 2-parallel configuration is visualised in Figure 1. Each station in the 2-parallel configuration has two redundant units. This configuration appears to be less expensive than the 3-parallel configuration, but it is more prone to failure. The system's mean-time-between-failure (MTBF) is also taken into account - as the higher the MTBF, the higher the system's reliability is [7]. The term MTBF measures the average timeframe that a system is functioning between failures [9]. Further discussion regarding MTBF will be elaborated in Section D.

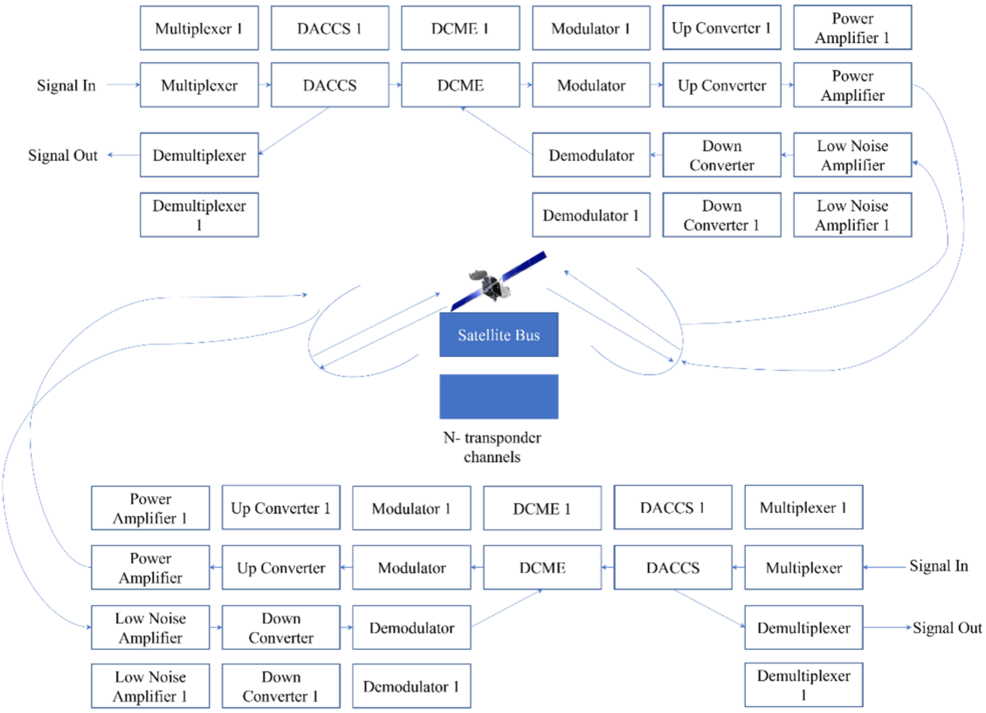

Fig. 1: 2-Parallel Earth station system model. [3]

2.3. Reliability of A Satellite Earth Station System

As mentioned in [10], it is common for a complex system mission to be decomposed into successive phases. Such system is often referred as a phased-mission system (PMS). During each of these phases, the system must complete a specific task while being subjected to varying stresses and dependability requirements, justifying the use of different reliability assessment models. Therefore, optimization is urgently needed when a design problem arises. For an example, optimization is required when determining a set of systematic parameters for the design of a satellite system. Such a problem will demand a comprehensive computational approach as well as multidisciplinary analysis [11].

Reliability is essentially the probability of the system performing its designated function over a specified period of time [12]. In other words, reliability is the probability of performing the designated functions without failure and under certain conditions over a specified period of time [13]. Reliability is regarded as one of the most important engineering technologies and is classified as the performance probability within a given period and the optimum product functionality after its launch of service [14].

Improved reliability can be attained through redundancy, greater prelaunch testing, or better design and parts selection [15,21]. Few approaches that have been introduced in the past research include a maximum likelihood estimation (MLE) approach to conduct parametric fits with the Weibull distributions along with the extensive use of the Kaplan-Meier estimator for calculating the reliability functions [4]. In addition, a past study by [16] on reliability characteristics of a satellite Earth Station had been investigated which also includes the failures which the systems have experienced. The transition state probabilities, meantime to failure (MTTF), reliability, availability, cost effectiveness and sensitivity analysis are obtained by utilizing Markov process theory and Laplace transformations. It is evidential that the key to satellite communication system reliability analysis is the reliability model [17].

Nonetheless, there are other various modelling techniques in determining the system reliability: Reliability Block Diagram models, Markov chains, and Monte Carlo simulation. In this research study, Monte Carlo simulation offers the highest level of accuracy and flexibility [9, 22]. The Monte Carlo model is "simulated" many times for a predefined system lifecycle. Whereas lifetime failure statistics from many simulation "samples" are summarized to generate system performance statistics [9].

On the ground, a control and management subsystem comprised of network control centres (NCCs) and network management centres (NMCs) provides real-time functions to regulate satellite terminal admission and resource utilization for reliable network service [18]. This research on reliability will focus on the ground station system which consists of 20 subsystems. These subsystems are divided into two, where 10 subsystems are at the transmission part and another 10 are at the receiving part. Then, further research is done on the ground station system configurations where the parallel redundancies are added. The parallel configurations that considered are: 2-parallel and 3- parallel configurations. These three (one with the original configuration and 2 other) configurations are chosen to see the effect of the reliability for each configuration.

2.4. Mean-Time-Between Failures, MTBF

The most important factor in achieving system operational feasibility is the reliability design [9]. The reliability of an Earth Station system can be defined as the possibility that the system will perform its acquired functions satisfactorily when used within the specified operating parameters and for a specified period. The failure rate of the system is related to its reliability. The failure rate is the frequency at which failures occur over a given time interval [11]. The failure rate per hour is denoted by

$$.\lambda = \frac{(\text{number of failures})}{(\text{total operating hours})} \tag{1}$$

where lambda (λ) is known as a failure rate.

Failure rate can be expressed in a variety of ways, including failures per hour, percentage of failures per 1,000 hours, and failures per million hours [11]. In the case of electrical and electronic devices, the distribution is exponential, and the system mean life or the MTBF is

$$M = \frac{1}{\lambda} \tag{2}$$

Thus, reliability can be defined as

$$R(t) = e^{-t/M} = e^{-\lambda t} \tag{3}$$

where λ is the instantaneous failure rate and M is the MTBF [11].

2.5. Maintainability of A Satellite Earth Station System

Maintainability refers to a system's ability to be maintained; however, maintenance is a series of steps taken to maintain or re-establish a successful operational state of the system [12]. Maintainability is primarily built into the design, whereas maintenance is the result of the design [12]. Maintainability can be classified into two categories of maintenance: preventive maintenance and corrective maintenance.

Preventive maintenance or preventative maintenance can also be called as scheduled maintenance. It is the maintenance that is frequently performed on an equipment to reduce the possibility of it failing. It is performed in a working system so that the equipment does not break down unexpectedly [19]. In Earth Stations, preventive maintenance prone to be complex like in the systems design. It is because of different manufacturers have different software and hardware, and disturbances are commonly exclusive in nature. Thus, a functional operation in this area acquires a specifically well plan with a competent organization. The plan should identify responsibilities for specialized system's needs, maintenance function, and the routine activity procedures. Moreover, this is also comprised of routine activities that can be performed via remote based on standardized assessment and test equipment, as well as the basic maintenance procedures such as adjusting power levels and replacing air filters [19].

Whereas, corrective maintenance is the unscheduled maintenance, or the maintenance acts performed to identify and make a correction to a fault so that the failed part can be restored to an operational condition within the restrictions established for in-service operations [15]. In earth stations, there are numerous means for failures to occur. Satellite footprints and links are made up of a simple design which is in contrast of the technical complexity of the required capabilities components and systems. This type of maintenance refers to the ability to monitor the satellite and its surrounding that provide easier ways to identify and removes the cause in a short period. The most challenging part in a corrective maintenance is to identify the problem source. In this research, the study is to identify a suitable maintenance framework or activities based on the stipulated time.

Maintenance is ought to be performed based on the three main stages: data acquisition usage of sensors, signal processing by utilizing various means of data processing and feature production which includes acquiring parameters to develop the monitored equipment status [20].

3. Research Methodology

The purpose of this research study is to investigate the reliability and maintainability of a potential modelling concept using MATLAB simulation. An Earth Station system model of 2-parallel and 3-parallel configurations are highlighted to obtain the MTBF of 1 year, 3 years, 5 years, 7 years, and 10 years. The reliability curves for each MTBF are shown for both configurations. The plausible numbers are generated to retrieve data for the analysis. Due to the sheer confidentiality and availability of the Earth Station system data, real data were not used. The secondary data were collected using MATLAB's Monte Carlo generator to generate random numbers to analyze the reliability and maintenance time. The flowchart of the research methodology is plotted in Figure 2. The research activity includes, exploring the different problems occurring in the Earth Station system and addressing the significant research gaps.

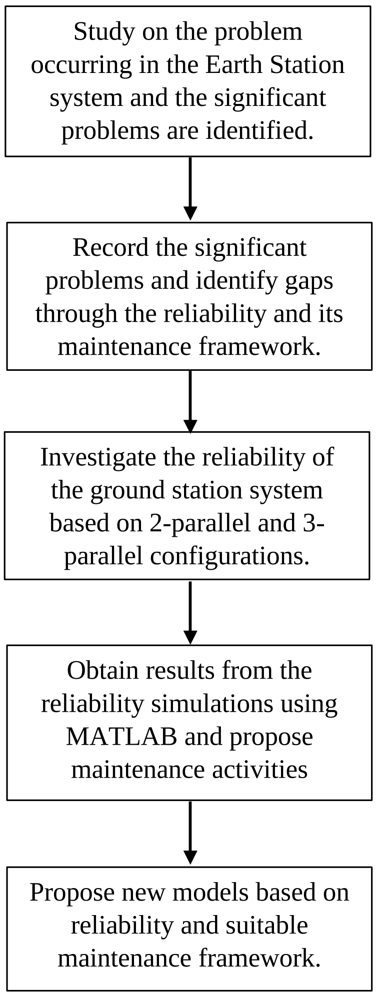

Fig. 2: Research Methodology.

The system reliability of 2-parallel and 3-parallel configurations was investigated based on the plausible numbers obtained from the past research papers and books [14]. Thus, simulation runs were performed on the system reliability using MATLAB. The reliability for each subsystem in the Earth Station system is calculated, and the graphs will be plotted against the lifecycle of the satellite system. Thus, an ideal design of the Earth Station system based on the reliability analysis and the suitable maintenance activities is proposed.

The flowchart of the technical simulation to determine the reliability using the Monte Carlo generator is shown in Figure 3. The technical simulation generates results for failure and repair activities. The key to this research goal is the technical simulation, which will be used to analyze the reliability of Earth Station system in 2-parallel and 3-parallel configurations over the time.

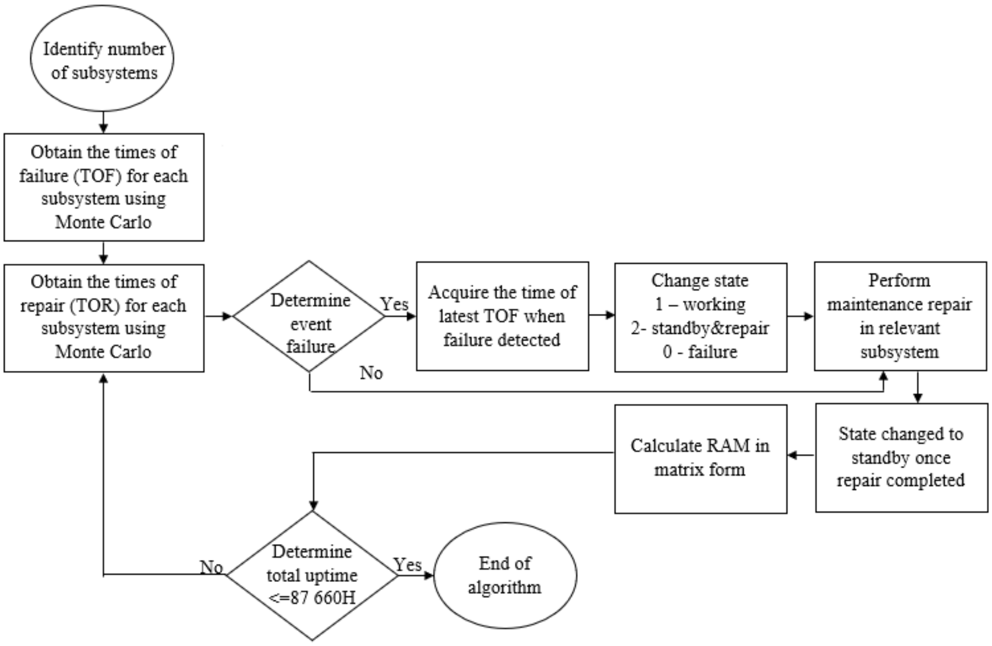

Fig. 3: Flowchart of the technical simulation to determine the reliability by using Monte Carlo.

4. Results and Discussion

The reliability curves are derived from the analysis using random numbers generated in MATLAB and with MTBF values of 1 year, 3 years, 5 years, 7 years, and 10 years respectively. The highest reliability value obtained in both parallel configurations is MTBF of 10 years. The reason is because lesser failure occurs in a system with high MTBF value which provides longer system functionality and better system reliability. The findings are depicted in Figures 4 and 5.

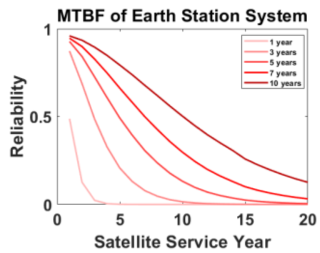

Fig. 4: The reliability graph of 2-parallel configuration with MTBF of 1 year, 3 years, 5 years, 7 years and 10 years.

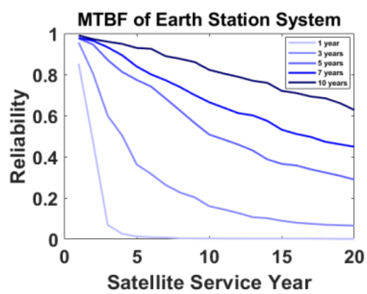

Fig. 5: The reliability graph of 3-parallel configuration with MTBF of 1 year, 3 years, 5 years, 7 years and 10 years

Figure 4 illustrates the reliability graph of a satellite Earth Station system in a 2-parallel configuration with 5 types of MTBF. The highest reliability can be found for MTBF of 10 years. It is because the reliability value is 0.96 for the 1st year of the satellite service. It is then significantly degraded as the satellite service year progresses to the 10th year with the reliability value of 0.50. This value is nearly half of the system reliability because the overall system functionality will encounter more frequent failure over the years until the end of its lifecycle.

Whereas Figure 5 shows the reliability graph of an Earth Station system in a 3-parallel configuration also with 5 types of MTBF. It can be proven that this configuration provides the best reliability of the Earth Station system. It is because the reliability of the 1st year of satellite service with MTBF of 10 years is 0.99 which is higher than the one in the 2-parallel configuration. It is then fell to 0.82 at 10th year which is very minimal in this case if compared to the 2-parallel configuration. The reason is because the 3-parallel configuration provides more redundancies which lower the rate of failure frequency.

The equipment that must be considered when looking for the best maintenance activities is identified. In addition, the suggested operation and maintenance requirements have been investigated. Table 1 depicts the operational and maintenance requirements for the Earth Station's functional area or subsystem, as well as the maintenance activities. According to Table 1, the best maintenance activities for each piece of equipment listed are usually determined by the condition of the subsystem itself. When a subsystem fails to function, a replacement part is installed. The listed maintenance activities must be performed on a regular basis [9].

Table 1: Station O&M Requirements by Functional Area or Subsystem and the Required Maintenance Activities

Component	Required Maintenance
Antenna system	Regular inspection on its physical features, alignment, and system performance
RF terminal electronics	Close monitor on electronic equipment and its functionality
Baseband multiplexing	Periodic inspection of optimum bit rate transmission
Computers and peripherals	Configure computer management with only the best software and upgrade frequently
Facilities systems	Periodic environment check-ups on building, supplies and tools needed

5. Conclusion and Recommendation

In summary, 2 main elements consisting of the reliability and maintainability are vital to represent a sustainable framework of a satellite communication system. The optimal value of MTBF must be achieved to escape any unwanted failures. This value can be obtained via the incorporation of the redundancies, various testing in the planning stage and the favored choice of the best components for its subsystems. From this paper, it can be concluded that, the 3-parallel configuration yields better system design for an Earth Station with 0.99 of reliability from the 1st year of the satellite service and drops slightly to 0.82 for the 10th year of the satellite service. In contrast to the 2-parallel configuration, which yields 0.96 for the 1st year of the satellite service and degrades significantly to 0.50 at the 10th year of the satellite service.

Moreover, the suitable maintenance activities are also proposed in this research study. The suggested maintenance activities highlight 5 most essential functional areas or subsystems of the Earth Station system which are antenna system, RF terminal electronics, baseband multiplexing, computers and peripherals, and facilities systems.

Thus, to progress with this research study, the reliability model must be developed in regulating the probability of the satellite communication system performance periodically. Apart from that, a 4-parallel configuration may be introduced to analyze the reliability of the Earth Station system. Furthermore, it is also recommended to compute a total system cost which plays a vital role in determining whether the suggested maintenance activities and the new developed reliability model are worth to be spent or not.

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