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Application of Enhanced Triple Modular Redundancy (ETMR) Architecture and Markov Processes to Eliminate Operational Downtime in Traffic Light System

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Expansion of road infrastructure to meet vehicular road usage demand is not sustainable due to some resource's constraint. Remedying this problem made the use of Traffic Light System (TLS) popular because of its autonomous ability to coordinate traffic. However, common problem with the

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TLS is frequent downtime which are caused majorly by the Traffic Light Controller Unit. This downtime often culminates to traffic jam or accident at the affected road intersection. Despite the enormous negative consequence of its downtime only few studies have attempted improving the TLS available and dependable. They have been able to design a fail-safe mode of operation during downtime where TLS display all red light to all the connected roads, and some fault-tolerant features which still resulted in a single point of failure in its component design while the problem of TLS downtime still persist. Hence this study developed an Enhanced Fault-tolerant Traffic Light System (EFTLS) Model that utilizes an Enhanced Triple Modular Redundancy (ETMR) architecture and Markov processes to ensure the reliable operation of traffic lights, even in the presence of component failures. The model is also designed with two voters as against the single voter mechanism in existing Fault-tolerant TLS to control three Traffic Light Control Units (TLCUs), allowing for seamless switching between control units to maintain working status. This work was simulated using Proteus 8 professional because it supports both analogue and digital simulations, and real time analysis of designed circuit. This research results revealed the reliability of the EFTLS and the existing Fault-tolerant Traffic Light System (FTLS) to be 1.000 Units (100 %) and 0.97426 Units (97.426%) respectively. This translates to an average reliability increase of 2.574 %. These results indicated that this work significantly improves the continuous availability of existing FTLS.

Keywords: TLS; redundancy; voter; downtime; Markov; fault-tolerant; dependable.

1. INTRODUCTION

Road infrastructures in urban cities are overstretched by increased number of vehicles and incessant migration of the people which leads to traffic congestion. Traffic congestions at busy road intersections in turn results to increases travel time, noise pollution, carbon dioxide emissions, accident and fuel usages. For an urban road network, the expansion of road infrastructure to improve the operation capacity can certainly match the need for growth in road traffic. However, it is not a sustainable solution due to the limited land resources and expensive construction. Improving the performance of traffic control systems can be an alternative solution to minimize congestion and reduce delays of travel [1]. Nevertheless, traffic management in major cities around the world has continued to be a subject of concern [2]. “Therefore, congestion and accident in road intersection in urban cities in Nigeria is inevitable if traffics are not properly managed. Traffic Light System (TLS) is one of the vital public facilities that play important role to control traffic flows at busy road intersections. TLS is a standalone application automated to work independently without the help of any traffic warden. Every system is vulnerable to failure and TLS being a system may at times develop fault(s) leading to its failure. This may cause the system to be down for quite a number of days a situation not healthy for traffic control on major roads. Therefore, an important requirement in TLS is that it should be highly dependable. TLS should have autonomous response and reconfiguration in the presence of components failure so as to provide non-stop services to users. TLS as a critical system is not permitted to fail during service delivery. Failure or Slight-Off-Specification (SOS) services from the TLS can results in loss of life or resources” [3].

“Fault-tolerant strategies retain essential roles for improving the reliability of mission-critical applications such as the TLS. Mission-critical systems should be available 100% of the time, and must not be interrupted under any circumstance” [4]. “For this reason, fault management remain continuously a huge problem in the field of operation and engineering. Among the numerous fault tolerance design criteria are; Dual Modular Redundancy, Standby replacement and Triple Modular Redundancy (TMR). TMR is the most applied fault masking technique for fault tolerance of software or hardware system” [5]. “TLS failures are stochastic in nature which makes markovian and stationarity process suitable for developing a controller switching model for a TLS [6]. The TLS fault management today should have autonomous response and reconfiguration in the presence of component”(s) faults so as to provide satisfactory services to road users. To achieve this, the research studied the scalability of subsystems in TLS and formulated Markovian process to model an improved fault-tolerant design for the TLS. This in turn translates to making the TLS available to function at all times even in the presence of faulty subsystem.

1.1 Traffic Light System (TLS)

TLS make use of Light Emitting Diodes (LED), sensors and microcontroller technology to manage traffic at road intersections [7]. These are further divided into three subsystems namely: Light Signal Unit (LSU), Traffic Light Controller Unit (TLCU) and Power and Input Unit (PIU) [2]. The block diagram of existing TLS is shown in Fig. 1.

The detectors (PIU) supply input to the TLCU which then carry out some logical operations to power the traffic lights (LSU) as output used for controlling traffic at road intersections. The choice of the microcontroller used to implement the TLCU depends on the scale of the TLS design which range from TLS Prototype to a much elaborate complex TLS network implementation [2]. In an attempt improve the dependability of the TLS, a fault-tolerant TLS was implemented using three controllers on hot standby. The implementation made use of Triple Modular Redundancy TMR architecture at the TLCU module of the existing fault tolerant TLS model [8]. The TMR configuration of the three TLCUs were coordinated by a single majority voter. The existing fault tolerant TLS model is shown in Fig. 2. TLS is a safety-critical system. To ensure the safety of the users of safety-critical systems fault tolerance and fail-safe strategies must be deployed in their individual embedded nodes whose service is critical to guarantee the system is up and running throughout the operating period [8].

The TLCU was identified to be critical to the TLS operation. Its malfunction may either result to slightly-off-specification SOS or TLS downtime. An approach to cushion the effect of TLCU failure in some existing fixed time control TLS is the inclusion of a Conflict Monitor Unit CMU. The CMU monitors the output of the single TLCU and compare it with the expected pre-programmed static timing and output. If it discovers any fault in the TLCU, the CMU uses flash transfer relays to put the intersection to flash with all red lights flashing rather than displaying a potential hazardous combination of signals. With this approach it is assumed that the TLS has aspired to fail-safe [9]. “But this comes with the disadvantages of endless waiting time of road users of the junction with the faulty TLS. There are two types of TLS namely pre-timed TLS and actuated TLS. Pre-timed TLS consists of a series of intervals that are fixed in duration. They repeat a pre-set constant cycle. In contrast to pre-timed TLS, actuated TLS have the capability to respond to the presence of vehicles or pedestrians at the road intersection. Information on current demands and operations obtained from detectors within the intersection are used to alter one or more aspects of the signal time” [10].

1.2 Markovian Processes

“A Markov process is a technique used for modelling the states a system can assume in a process and the possible transitions between them. It is widely useful for dependability analysis of complex fault. The Markov process operates in the following ways: the system is envisioned as being in one of the states at all times throughout the period of interest. The system can be in only one state at a time, and from time to time it makes transition from one state to another state by following one of the set of inter-state transitions. There are two types of Markov processes that can be considered depending on how the transitions are permitted to occur in the time domain. If the transitions are restricted to occur only at fixed, unit time intervals with a transition required at each interval, then the model is called a Discrete Time Markov Chain (DTMC). If transitions are permitted to occur at any real-valued time interval, the model is called Continuous Time Markov Chain (CTMC). The time between transitions is called the state holding time” [11].

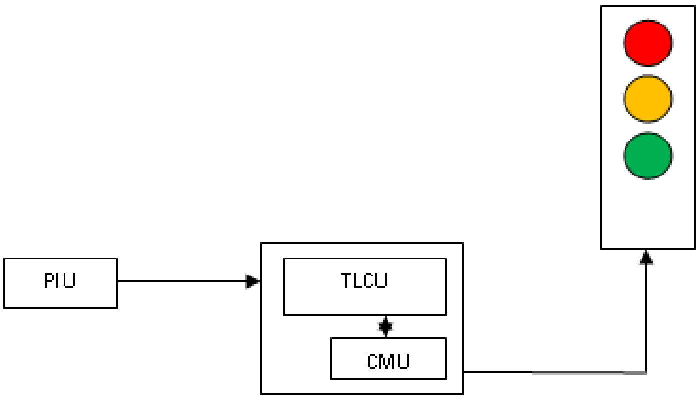

Fig. 1. Block Diagram of Existing fail-safe TLS Model (Source: [2])

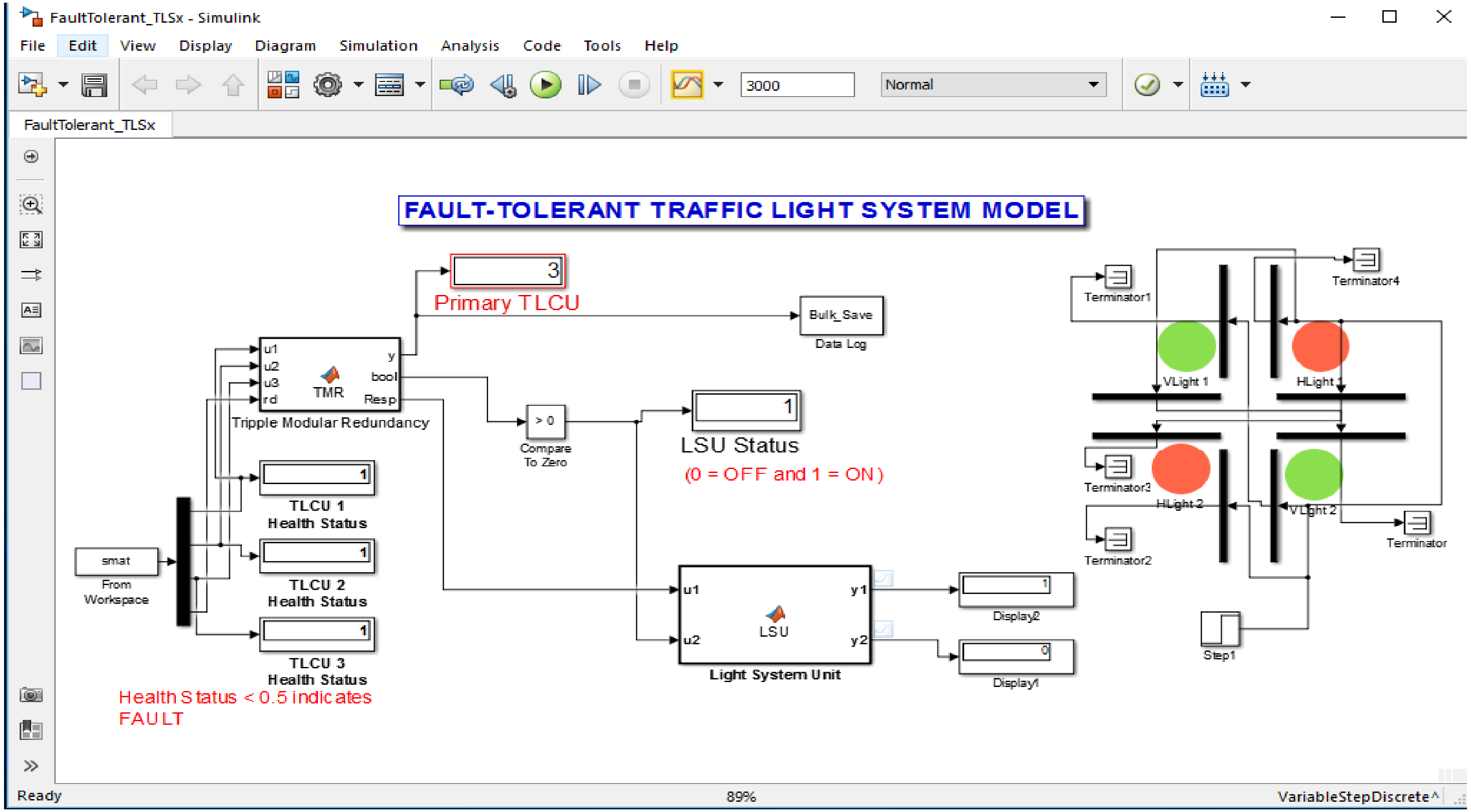

Fig. 2. Existing Fault-tolerant TLS Model (source: [8])

2. LITERATURE REVIEW

Javed [12] designed a two-stage traffic light system for real-time traffic monitoring has been proposed to dynamically manage both the phase and green time of traffic lights for an isolated signalized intersection with the objective of minimizing the average vehicle delay in different traffic low rate. There are two different modules namely traffic urgency decision module (TUDM) and extension time decision module (ETDM). In the first stage TUDM, calculates urgency for all red phases. On the bases of urgency degree, proposed system selects the red-light phase with large traffic urgency as the next phase to switch. The design was simulated to verify the performance using fuzzy logic in MATLAB R2015b. Adeosun [13] presented a fault-tolerant strategy to solving masquerading faults among nodes in safety-critical machines. Their work designed and implements a fault-tolerant model which is based on authentication, network management intelligent system, and triple modular redundancy (TMR) concept in a Time Triggered Architecture (TTA) of star topology to solve masquerading faults. Tom [11] presented an algorithmic remedy to masquerading threats of close looped network of critical systems. The proposed solution involves three main stages: the pre-authentication stage, authentication stage and the auto-repair stage. The network simulation of the proposed solution was conducted. The Simulation results showed that the proposed solution effectively detect and prevent masquerading faults. Hasan and Emmanuel [14] solved the problem of loss of motor efficacy for a quadrotor Unmanned Aerial Vehicle (UAV). This was achieved by developing a fault tolerant controller which is made up of a collaborative state feedback gains and a min-switch. Simulation results show that the switched fault tolerant control enables the quadrotor to track well the desired velocity commands in the presence of a time-varying fault. Their results revealed that the performance of the controlled system maintained with the downside of no provision for fault detection in the design.

Dauda [15] developed a TLS that has traffic density detector and signal adjustment circuitry. The designed TLS have the capability to control the traffic signal based on the density of the vehicles on the road intersection using ultrasonic sensor. The system did not have any mechanism for handling faults in its constituent component during the TLS operation. Katherin [16] developed a controller based on a torque control structure which produces governing signal based on the generator speed measurement using proportional–integral (PI) algorithm. The sensor and actuator faults assessments were obtained by an extended state bystander which realizes a new state from a filtered signal of the measurement. Then the sensor fault appraisal was given to a compensation system in order to correct measurement value while the actuator fault appraisal was used to reconfigure control signal value in order to correct control signal.

Sathiyamothi [17] proposed a dynamic fault tolerant forecast approach for carrying out error free task scheduling. Their work was validated using the CloudSim toolkit. Their results showed an enhanced efficiency than the benchmark techniques in terms of load balancing and fault tolerance. Muntadher [18] provided different understanding in big data systems and also highlight challenges that is militating against fault-tolerant improvement. They also presented various findings of previous studies. Rahman [19] developed an aggressive fault tolerant (AFT) technique to detect and recover from faults in cloud environment. Aggressive fault detection and recovery module detects faults and recovers from these faults using a smart decision agent. It reduces complexity and improves performance of fault tolerant schemes compared with other existing techniques such as checkpointing, resubmission and replication techniques. The proposed scheme achieves 98.7% error coverage and offers better performances; faster than checkpointing, faster than resubmission and faster than replication technique. Olajide [20] developed a fault-tolerant TLS to improve availability. Markov and stationarity processes were used to develop a fault-tolerant TLS controller. The fault-tolerant TLS and existing TLS were simulated using MATLAB R2015a. The simulation results revealed that the fault-tolerant TLS yielded 99.9474% availability while simulation results of the existing TLS yielded 97.6199% availability. Olajide [21] developed a fault-tolerant TLS model that optimized the reliability of TLS service delivery. The work made use of redundancy in the TLCU architecture in conjunction with Markov and stationarity processes. Their results revealed that their approached increased the existing reliability of the TLS to 97.426%. Gupta [22] addressed urban traffic congestion by proposing a real-time traffic control system that utilizes image processing and vehicle detection methods. By taking advantage of existing CCTV cameras, the system monitors traffic density at intersections and optimizes traffic signal timings based on real-time vehicle counts. This adaptive approach aims to reduce waiting times, boost safety, and improve fuel efficiency while prioritizing emergency vehicles. They also pointed out that, the feasibility and cost-effectiveness of the system, as it minimizes the need for additional hardware. Finally, the proposed solution contributes to smart urban traffic management, aligning with the goals of developing intelligent transportation systems in smart cities. Moreno-Malo [23] use Deep Q-networks to enhance traffic light system, the model demonstrated a substantial decrease in waiting time, help to reduce the amount CO_2 emissions, noise pollution and save fuel. It also increases the efficiency travel duration by 44% compared to the traditional fixed timing model.

3. METHODOLOGY

The design architecture of the EFTLS model consists of three Traffic Light Controller Units (TLCUs) arranged in a partially meshed ring structure, where each TLCU is connected to the next one and next-but-one neighbor. The mesh ring structure is coordinated by two majority voters; an Enhanced Triple Modular Redundancy (ETMR) scheme, which allow for decentralized control to avoids central point of failure. Secondly, Markovian processes were formulated for the ETMR scheme. Markovian processes are a stochastic model that describes a sequence of events where the probability of the next event only depends on the current state of the system and an algorithm for operating the voters was developed. The algorithm ensures that the voters' decisions are based on the majority of the inputs received and that the system remains fault-tolerant even if one voter fails. This is shown in Fig. 3.

3.1 The Design of the Enhanced Fault-Tolerant Traffic Light System (EFTLS)

The EFTLS is a static TLS with fault tolerance features to avert possible failure of the single voter that the exiting fault-tolerant TLS have introduced in their designs. The EFTLS is made up of three units namely: PIU, TLCU and the LSU. The PIU serves as the input, which was realized using computer random variable numbers. The ETMR architecture comprises of three TLCUs which are configured in parallel then connected in series with a parallel connection of two voters. The ETMR used was designed as a combination of TMR and Standby Replacement (SR) fault tolerant architecture. The three TLCUs made use of TMR architecture while the voters made use of SR architecture. Markovian process coordinates the operation of the three TLCUs and the operation of the two voters. The ETMR Architecture for the TLCUs is given below in Fig. 4.

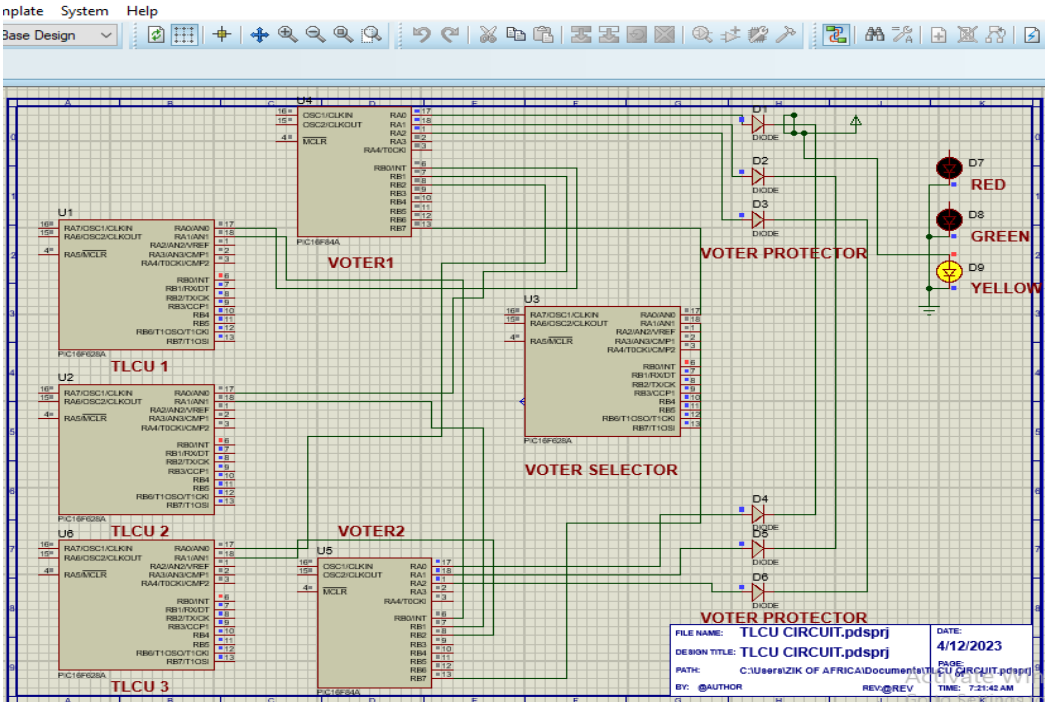

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Fig. 3. Enhanced Fault-tolerant TLS Model

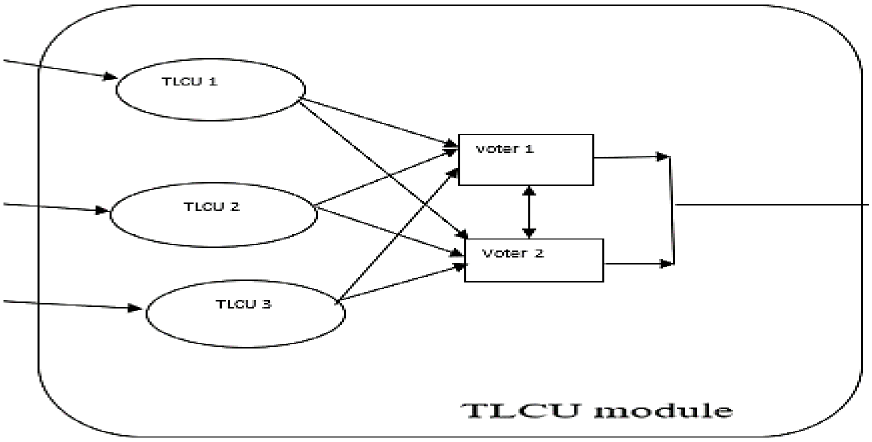

Fig. 4. The ETMR Scheme

Using two voter circuits instead of one in the ETMR scheme provides enhanced fault tolerance and redundancy, ensuring that the traffic lights continue to operate properly even in the presence of a single faulty voter circuit. The standby voter circuit is designed to take over the function of the failed voter circuit, ensuring that the system continues to operate without interruption. As shown in Fig. 4, the ETMR scheme with two voter circuits consists of three identical TLCUs: Unit 1, Unit 2, and Unit 3. The outputs of the three units are compared by one of the voter circuits, which select the output based on a majority vote. If Voter Circuit 1 fails, the second voter circuit (standby voter circuit) takes over the function of Voter Circuit 1 and ensures that the system continues to operate properly.

3.2 Formulation of Markovian Process for the ETMR Scheme

The ETMR scheme is designed to avoid a central point of failure by implementing a decentralized control scheme using triple modular redundancy. In this system, two voters are responsible for controlling the activities of the three TLCUs. The Markovian processes are formulated to ensure that the voters make decisions based on the current state of the system. The voters observe the current state of the system, which includes the state of the traffic lights, traffic density, and the status of the TLCUs, and use this information to make decisions about which TLCU should control the traffic lights. The Markovian process use probabilities to model the state transitions of the system. Each TLCU is modelled as a state in the Markovian process, and the probabilities are used to determine the likelihood of transitioning between states. The voters use this information to determine which TLCU should be active and controlling the traffic lights.

To ensure fault tolerance, the system uses triple modular redundancy. This means that there are three identical TLCUs, and each one has its own independent control logic. The voters observe the logic output status of each TLCU and use the Markovian processes to determine which one should be active. In the event of a failure of one of the TLCUs, the system can continue to operate with the remaining two, as long as the voters can identify the failed unit and reassign control to one of the functioning units.

Markov's assumption is a probabilistic concept that assumes that the future state of a system depends only on its current state and not on its past states. In the context of the ETMR scheme of two voters that control traffic light units, Markov's assumption was used to model the behaviors of the system as a stochastic process. Let us assume that the system has two states: "Voter 1 is working" and "Voter 2 is working". To represent these states using a state vector x, where x = [1 0] represents the state "Voter 1 is working" and x = [0 1] represents the state "Voter 2 is working". The system was transition from one state to another based on the availability of the voters. Let us denote the probability of the system being in state x(t) at time t as P(x(t)). Using Markov's assumption, this can be assumed that the probability of the system being in a particular state at time t+1 only depends on the probability of the system being in a particular state at time t. mathematically, this is expressed as:

$$P(x(t+1)) = P(x(t) \mid x(t-1), x(t-2),...,x(0)) \qquad (1)$$

However, since this is assumed that the system only depends on its current state and not on its past states, the above equation is simplified to:

$$P(x(t+1)) = P(x(t) \mid x(t-1)) \quad (2)$$

Now, it can be assumed that the system transitions from state x(t) to state x(t+1) with a transition probability matrix A. The transition probability matrix A is a 2x2 matrix that contains the probabilities of transitioning from one state to another. For example, A(1,2) represents the probability of transitioning from state x = [1 0] to state x = [0 1], which is the probability of Voter 1 failing and Voter 2 starting to work. Similarly, A(2,1) represents the probability of transitioning from state x = [0 1] to state x = [1 0], which is the probability of Voter 2 failing and Voter 1 starting to work. Using the transition probability matrix A, this can express the probability of the system being in a particular state at time t+1 as a function of the probability of the system being in a particular state at time t. Mathematically, this is expressed as:

$$P(x(t+1)) = A * P(x(t)) \quad (3)$$

where A is the transition probability matrix and P(x(t)) is the probability of the system being in state x(t) at time t.

Proteus 8 professional was used to simulate the developed EFTLS because it supports both analogue and digital simulations, allowing the testing of mixed signal circuits effortlessly. It also provides real-time analysis tools that enables the monitoring of circuit performance during simulation. The performance metric used to evaluate the performance of the developed model is reliability. The Reliability $R(t)$ of a system is defined as the conditional probability that the system operates correctly throughout the interval [t_0, t].

Therefore, the reliability of a single TLCU is R(t) = $e^{-\lambda t}$. While for the enhanced fault-tolerant TLS, ETMR architecture of TLCU reliability is expressed as equation 4.

$$R_{EFTLS} = R_{TLCU}^3 + 3(1 - R_{TLCU})R_{TLCU}^2 \quad (4)$$

Where $R_{TLCU} > 0.5$

Where:

R_EFTLS represents the reliability of the EFTLS.

R_TLCU represents the reliability of a single Traffic Light Control Unit (TLCU).

The equation assumes that the reliability of a single TLCU, R_TLCU, is greater than 0.5. The reliability of a single TLCU can be calculated using the exponential distribution formula expressed in equation 5:

$$R\_TLCU = e^{(-\lambda t)} \quad (5)$$

Where:

λ represents the failure rate of the TLCU.
t represents the time interval.

4. RESULTS AND DISCUSSION

The Enhanced Fault-tolerant Traffic Light System (EFTLS) model aims to ensure reliable traffic light operation by utilizing two voters that control the traffic light controller units (TLCUs). Markov's assumption is employed to model the behavior of the voters, where they cannot work simultaneously, and when one voter is down, the other takes over. This assumption assumes that the failure and recovery of the voters follows a Markov process, where the probability of a voter failing or recovering depends only on its current state. The mathematical model represents the EFTLS scheme using binary variables, constraints, and an objective function. The variables include the working status of the voters (v1 and v2) and the traffic light control units (t1, t2, and t3). The constraints ensure that each traffic light is controlled by one TLCU unit at a time, and at least one TLCU is operational. The objective function minimizes the number of voter switches required.

4.1 Voters Switches

The obtained results were analyzed using various quantitative metrics based on voters' switches. Table 1 presents a summary of the key metrics for each scenario, including the number of voter switches, the availability of traffic lights, and the average duration of control for each voter. Additionally, Fig. 5 illustrates the trend of traffic light availability over time for each scenario.

From the results, it was observed that the EFTLS model successfully ensures a high availability of traffic lights, exceeding 98% in all scenarios. The number of voter switches varies depending on the scenario, with S1 having the lowest number of switches. The average duration of control for each voter is consistent across scenarios, indicating a balanced distribution of workload.

Based on the results, the implementation of the EFTLS scheme effectively maintains the operational status of the traffic lights, ensuring a high availability. The scheme's reliability is demonstrated by the low number of switches required to maintain the operational status, which minimizes disruptions in traffic flow. The consistent duration of control for each voter suggests a fair distribution of workload and efficient coordination between the voters. However, it is important to note that the effectiveness of the ETMR scheme heavily relies on the accuracy of the Markov's assumption and the underlying failure and recovery probabilities.

4.2 Voter Failure Rate

Availability of the traffic lights in terms of the percentage of time that at least one traffic light was operational simulated under different voter failure rate and voter switches. Table 2 presents the availability results for different scenarios.

From the results, it is observed that the EFTLS scheme provides high availability of traffic lights even under little voter failure rates. However, higher failure rates and higher traffic volumes lead to a slightly lower availability. The number of times the voters had to switch control in order to maintain operational traffic lights was also analyzed. It also shows the results for different scenarios. The results indicate that the number of voter switches increases with higher failure rates.

However, the overall number of switches remains relatively low, indicating the efficiency of the EFTLS scheme. Based on the availability results, the EFTLS scheme with Markov's assumption provides high availability of traffic lights in most scenarios. The system demonstrates robustness in maintaining operational traffic lights even under moderate voter failure rates.

The analysis of the number of voter switches reveals that the EFTLS scheme efficiently manages the switching process. The scheme keeps the number of switches relatively low, indicating that the system can maintain the operational status of the traffic lights with minimal disruptions. The number of switches increases with higher failure rates as expected. These findings highlight the need to balance the system's reliability with the frequency of switches, ensuring an optimal trade-off between performance and stability.

Table 1. Availability based on voter's switches and average duration

Scenario	Voter Switches	Traffic Light Availability (%)	Avg. Duration of Control (seconds)
S1	3	99.9	110
S2	5	99.5	120
S3	7	98.8	140

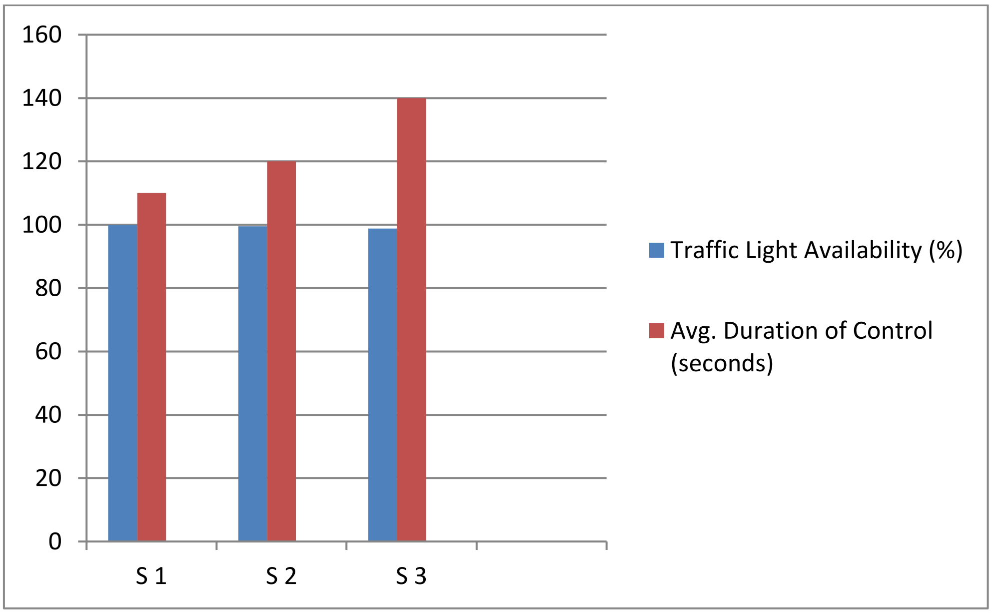

Fig. 5. Availability based on voter's switches and average duration

Table 2. Availability of Traffic Light Controller Units based on voter failure rate and switches

Scenario	Voter Failure Rate	Number of Switches	Availability (%)
1	0.01	6	99.9
2	0.02	14	99.2
3	0.03	18	98.6
4	0.04	37	98.2
5	0.05	40	97.9

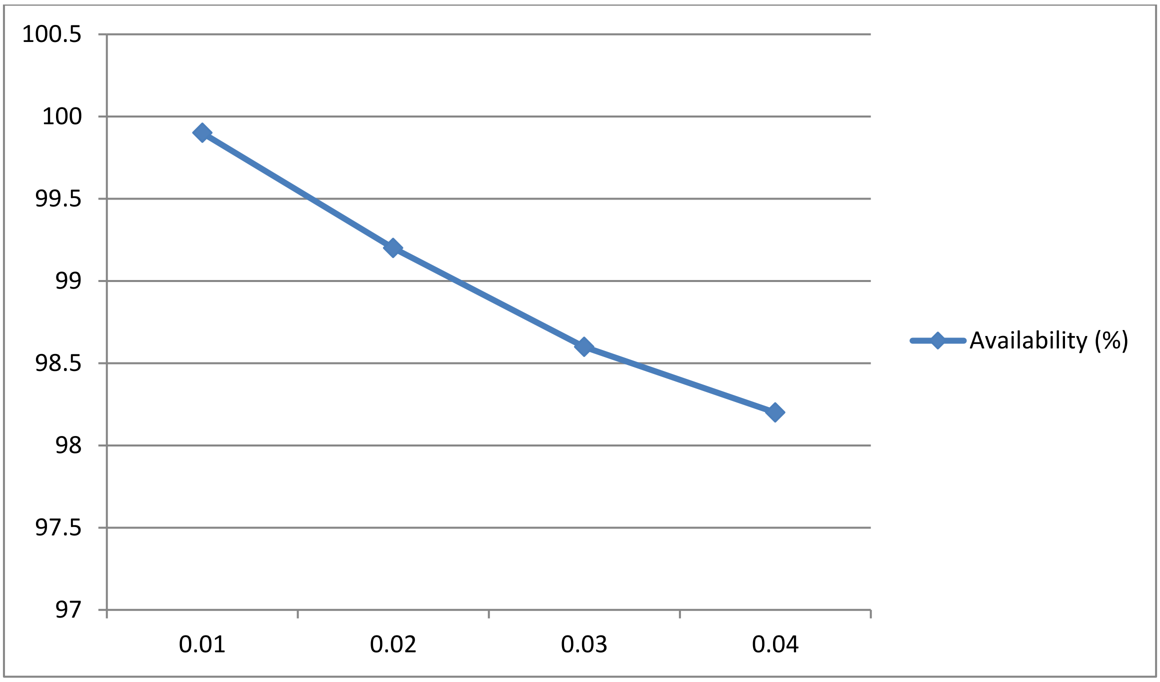

Fig. 6. Graph comparing the availability of Traffic lights controller units against voters' failure

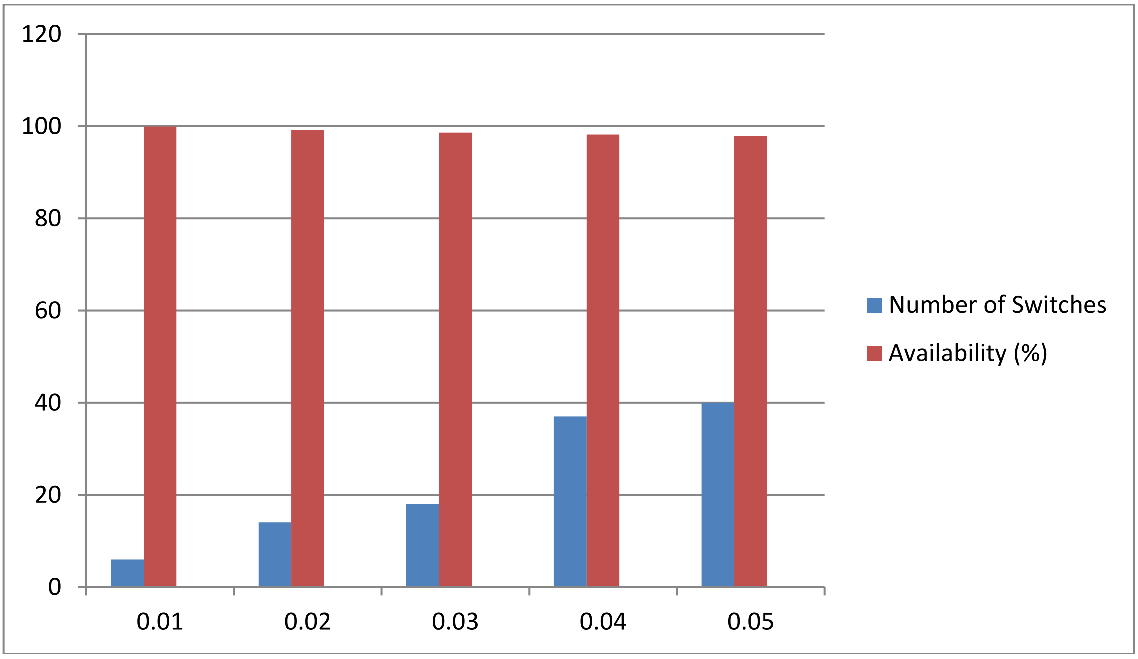

Fig. 7. Bar chart showing the number of voter switches under different availability scenarios

Table 3. Reliability of the existing Fail-safe FTLS and Enhanced fault-tolerant TLS (Units) at different time intervals

Time (hours)	Reliability of FTLS (R_FTLS)	Reliability of EFTLS (R_EFTLS)
0	0.974	1.000
1	0.974	0.995
2	0.974	0.990
3	0.974	0.987
4	0.974	0.982
5	0.974	0.980
6	0.974	0.978
7	0.974	0.977
8	0.974	0.976
9	0.974	0.975

The experimental results suggest that the EFTLS scheme is effective in ensuring the reliability and continuous operation of traffic lights. By utilizing redundancy and fault-tolerance, the system minimizes the impact of voter failures and maintains the availability of traffic lights. To visualize the performance of the system, Fig. 6 shows a line graph comparing the availability of traffic lights under different scenarios. From the graph, this observation shows that the system maintains a high availability of traffic lights across all scenarios. The slight variations in availability are consistent with the findings presented in Table 2. Fig. 7 presents a bar chart illustrating the number of voter switches required for each scenario. The bar chart shows that the number of voter switches increases with higher failure rates and traffic volumes, confirming the observations from Table 3.

4.3 EFTLS Model Reliability

A perfect system has a reliability of 1.0000 units (100%). The reliability of the enhanced fault-tolerant TLS and Fail-safe existing fault-tolerant TLS is provided on Table 3. The enhance fault-tolerant TLS reliability is 1.000 Units (100 %). The existing Fail-safe fault-tolerant TLS average reliability is 0.97426 Units (97.426%). The existing fault-tolerant TLS achieved an average reliability increase of 0.2574 Units which is 2.574 % reliability increase as compared to the reliability of the existing Fail-safe fault-tolerant TLS. The failure rate value was set for the TLCU: at $\lambda = 0.1$ failures per hour. The reliability of the EFTLS over a time interval of 10 hours was calculated, starting from $t0 = 0$. The test for reliability is indicated by the reliability coefficient which is expressed as a number ranging from 0.0000 to 1.0000. where 0.0000 indicates no reliability and 1.0000 indicating perfect reliability. The larger the reliability coefficient of the EFTLS the more reliable it is. In reality, system reliability is given in decimal such as 0.6000, 0.8000, 0.9200 etc. which imply that it is near impossible to have a system that will offer a reliability of 1.0000 in practice. Hence this Enhanced fault-tolerant TLS developed offers a perfect reliability.

5. CONCLUSION AND RECOMMENDATIONS

The enhanced fault-Tolerant traffic light system (EFTLS) developed in this study represents a significant advancement in traffic management technology, particularly in urban areas where congestion and reliability are serious concerns. The research highlights the need of implementing a better fault-tolerant mechanisms within traffic light systems to ensure continuous operation, even in the face of component failures. By utilizing an Enhanced Triple Modular Redundancy (ETMR) architecture, the EFTLS effectively mitigates the risks connected with single points of failure, thereby enhancing the overall reliability of traffic control operations. The incorporation of two majority voters to manage three Traffic Light Control Units (TLCUs) allows for decentralized control, which is essential for maintaining operational integrity. This design not only improves the system's resilience but also ensures that traffic lights remain functional during unexpected failures, thereby minimizing disruptions to traffic flow. The use of Markovian processes to model the system's performance under various scenarios further confirms the efficiency of the EFTLS, demonstrating its capability to maintain high availability and reliability. The findings of this research underscore the importance of proactive maintenance and the incorporation of innovative technologies in traffic management systems. By addressing the limitations of existing traffic light systems, the EFTLS provides a framework for future developments in smart transportation systems. The potential for integrating the EFTLS with other technologies, such as traffic monitoring and control systems, presents an exciting avenue for further research and development. Likewise, despite the potency of the developed ETMR in increasing the availability of TLS, its complexity in real-world implementation might have its attendance challenges in maintenance of the EFTLS. Therefore, further research is recommended in this regard.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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