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Research article

Distributed RFID–GSM Warning Architecture for Railway Safety: Design and Evaluation in a Resource-Constrained Environment

Billy Sam[1], Yaw Amankrah Sam-Okyere[2,*], Emmanuel Osei-Kwame[2], Wisdom Elikplim Korkortsi[2], Daniel Goddard Brookman[2], Ramatu Al-hasan[3]

[1]Department of Electrical and Electronic Engineering, University of Mines and Technology, Tarkwa, Ghana
[2]Department of Electronics Engineering, Norfolk State University, Norfolk, Virginia, United States
[3]Department of Professional Science, Middle Tennessee State University, Murfreesboro, Tennessee, United States
*Correspondence: amankrahyaw08@gmail.com

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Abstract: Railway safety in resource-constrained environments, such as Ghana's degraded rail network, faces significant challenges due to obsolete infrastructure, single-track operations, and reliance on human vigilance, leading to high rates of collisions and level-crossing accidents. This study proposes a distributed RFID-GSM warning architecture as a low-cost, decentralized solution independent of legacy signaling systems. The system deploys stationary sensor nodes along rail approaches, utilizing RC522 RFID modules for precise train detection at 30 km, 20 km, and 10 km zones from critical junctions. An ATmega328P microcontroller processes detection triggers, activating hierarchical alerts: SMS notifications via SIM800L GSM for remote warnings at farther zones, and local actuators (buzzer and LED) for immediate intervention at 10 km. The design emphasizes affordability, simplicity, and robustness, leveraging existing cellular networks to mitigate human errors without requiring infrastructure upgrades. The architecture was modeled and simulated in Proteus Professional software, demonstrating accurate sequential detection, SMS transmission, and actuator activation. Reliability metrics, including detection probability (>90% within optimal range), SMS latency (3-8 seconds), and on-time delivery, confirm viability in low-speed, remote settings. Comparative analysis highlights advantages over GPS, LoRaWAN, or track circuits in cost and deployability. This approach provides a scalable digital safety layer, enhancing operational resilience and reducing accident risks in developing regions' marginalized rail networks.

Keywords: GSM, railway safety, RFID modules, signaling.

1. Introduction

The expansion of global infrastructure places renewed emphasis on rail transport as a critical vector for economic growth, especially in rapidly developing nations. Rail systems offer high capacity for both passenger transit and freight haulage, proving more energy efficient and capable of handling mass transit compared to highway networks [1].

However, the economic benefits of rail transport are intrinsically linked to its operational safety. The challenge often lies in maintaining safety standards across networks that span vast distances, particularly where infrastructure development has historically lagged. Globally, sophisticated Collision Avoidance Systems (CAS), such as the European Train Control System (ETCS), exist, but their implementation demands prohibitively high capital expenditure (CAPEX) and extensive trackside infrastructure renewal, which are not applicable in Ghana.

The need for high-impact, low-cost safety solutions is particularly acute in infrastructure-constrained environments. The rail network in Ghana exemplifies these challenges. Historically, the network has suffered degradation due to prolonged lack of maintenance, resulting in obsolete rolling stock and weakened infrastructure [2]. The existing system operates largely on single tracks, and the conventional signaling equipment is characterized as old and weak, often requiring supplementary operation via radio with paper orders as back-up. These infrastructure failures directly contribute to high accident rates, primarily stemming from collisions between trains on the same track (head-on or rear-end incidents) and accidents occurring at unmanned level crossings. Again, the traditional safety protocol relies heavily on the train driver's visual acuity, requiring them to "keep a constant eye out" for signal posts to determine whether to stop or proceed [3]. This reliance introduces significant human factor risks, including driver distraction, risk-taking, and errors caused by manual operation, which are cited as common contributors to accidents.

Given the Ministry of Railways Development's commitment to expanding the rail network under the Ghana Railway Master plan, which envisions a network of 4007.6 Km, there is an urgent need for an automated, affordable, and scalable safety mechanism [4], [5]. This mechanism must function independently of the failed legacy signaling, providing immediate safety mitigation without waiting for decades of capital-intensive track renewal. The Western, Eastern, and Central lines are the existing lines with current transversal link expansions and branch lines under rehabilitation. The railway previously served only the south from Accra until mineral export traffic to the ports in Takoradi and Tema [2], [4]. The western and eastern lines served transportation mainly from Takoradi to Kumasi, as well as from Accra to Kumasi, with Kumasi facing Tamale towards Paga. Figure 1 shows Ghana's existing and planned railway lines.

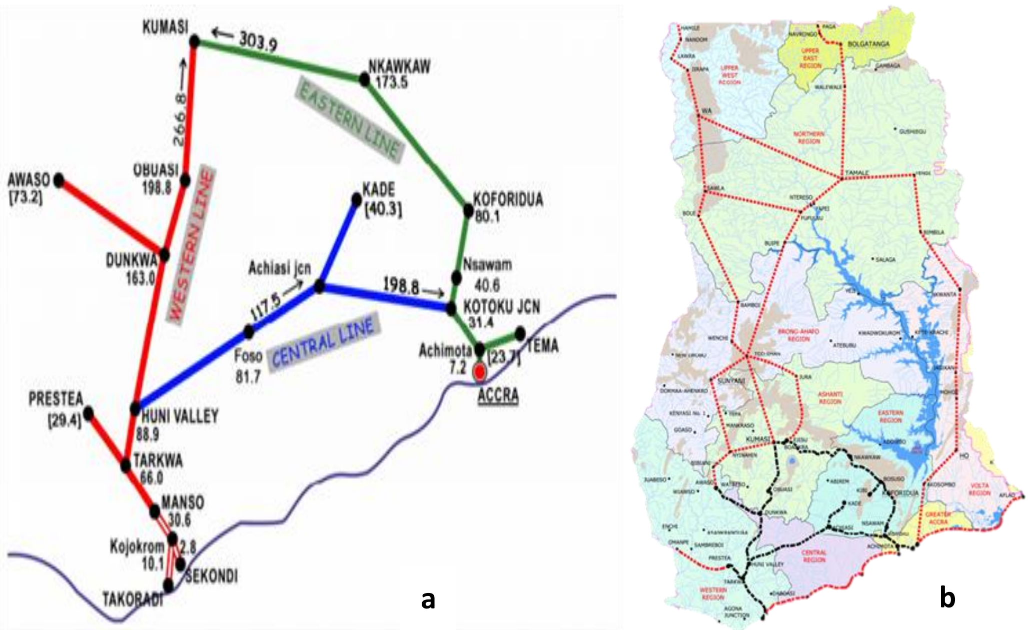

Figure 1. Ghana's railway lines: **(a)** existing, **(b)** projected expansion.

To address the documented deficiencies and constraints, this research proposes a decentralized, wirelessly based alert system for rail transport. The core contribution of this work lies in delivering a safety solution that is low-cost, simple to install, and entirely independent of the existing, degraded signaling systems. By utilizing reliable cellular communication (GSM) combined with localized digital triggers (RFID), the system provides a robust digital safety layer that effectively mitigates human operational errors and enhances situational awareness across large, marginalized network segments.

Recent literature emphasizes IoT's role in enhancing railway sustainability and real-time monitoring [6], [7]. For instance, the authors in [7] gave a comprehensive, holistic survey of various IoT technologies that can be used in railway operations, management, maintenance, video surveillance, and safety at level crossings, highlighting advancements in communication like LTE, 5G, and wireless sensor networks for real-time data gathering and decision-making [8]. In [9], the authors explore IoT and machine learning for railway safety, using IoT-enabled bots for track inspections with high-resolution imaging and ML algorithms achieving over 90% accuracy in real-time fault detection, alongside IR sensors for platform occupancy and fire detection with over 95% accuracy, incorporating RFID for passenger tracking in related works.

A review by [10] on active safety methodologies proposes a system architecture for intelligent railways integrating cyber-physical systems, data-driven models, and intelligent computing to prioritize safety in efficiency-driven operations, though it provides limited details on wireless implementations. Similarly, works by [11], [12] on cybersecurity strategies examine vulnerabilities in onboard and trackside sensors, advocating layered frameworks with AI-assisted threat detection, end-to-end encryption, and secure protocols like MQTT with TLS for wireless networks, including 5G, to protect IoT-integrated systems from interception and spoofing attacks. These contributions underscore IoT's potential for predictive maintenance and threat mitigation but often rely on robust power and network infrastructures, restricting use in remote or legacy environments.

Shifting to collision prevention and asset management, several studies incorporate RFID, IoT hybrids, and sensor networks for automated safety [13], [14]. Research by [15] details RFID and wireless IoT for transportation asset management, enabling real-time tracking with stationary and handheld readers supporting EPC Gen2 standards, various tag types (passive, active), and security features like access passwords, validated through field tests addressing detection reliability and power challenges. An analysis of smart data in IoT-based railway systems using RFID highlights its role in contactless identification, tracking, and logistics, integrating wireless technologies for automated operations and crowd management [16].

A critical inquiry into RFID appropriation in Indian railways evaluates its deployment for safety enhancements, referencing IoT integrations for track monitoring and collision avoidance, emphasizing modularity in harsh conditions [17]. Additionally, a paper on IoT-powered collision avoidance proposes vision and vibration detection with Arduino and ultrasonic sensors for real-time obstacle alerts, aiming to revolutionize safety through automated monitoring in vulnerable networks [18]. These advancements provide targeted localization and detection but commonly depend on custom networks or continuous power, limiting full decentralization in expansive, degraded infrastructures.

The defined research gap emerges from these studies' emphasis on sophisticated, integrated systems that, while technically advanced, often require extensive infrastructure upgrades, reliable power sources, or proprietary networks, elements infeasible in degraded, low-traffic rail networks like those in Ghana. IoT and AI solutions excel in data-rich urban settings but falter in remote areas due to latency, computational demands, and integration complexities with obsolete signaling [19]. RFID applications provide precise localization yet are typically limited to controlled environments or paired with high-bandwidth communications, lacking robust, long-range alerting without additional gateways.

This paper stands out technically by proposing a fully decentralized architecture that leverages RFID (RC522) solely as a localized, passive trigger for train presence detection, immune to environmental interferences like weather or visibility, and seamlessly integrates it with existing GSM infrastructure for reliable, low-latency SMS alerts across vast distances. Unlike the reviewed systems' reliance on vision sensors prone to failure in adverse conditions or AI algorithms demanding high processing power, this design employs hierarchical alerting logic, triggering progressive warnings at 30 km, 20 km, and 10 km zones via distributed nodes, ensuring precise, distance-based notifications that mitigate human errors independently of legacy track circuits.

The microcontroller-driven firmware (ATmega328P) processes binary triggers efficiently, activating local actuators only in critical zones for optimized resource use, while GSM's ubiquitous coverage outsources communication resilience to carrier networks, avoiding the maintenance burdens of LoRaWAN or custom IoT gateways seen in prior works. This simplicity enhances operational robustness in tropical, remote terrains, providing a scalable digital safety layer that decouples from degraded infrastructure, far surpassing the centralized or power-intensive alternatives in adaptability and immediate deployability, with the added benefit of being cheaper for rapid scaling in developing regions.

2. Methods

The methodological approach combined theoretical analysis with practical simulation. This involved a comprehensive literature review focusing on component specifications, consultation with local railway personnel (Ghana Railway Corporation watchmen), and the design and simulation of the complete electronic architecture. The system was modeled and tested using the Proteus Professional software environment, ensuring functional compliance with the stated objectives before physical prototype assembly.

2.1. Distributed Sensor Node Architecture

The design concept is based on a distributed network of identical, stationary sensor nodes positioned along the approach to a critical junction or level crossing. Each node serves as a precise localization point and an immediate communication hub. The equations for the train time-to-junction (per zone), conservative ETA with speed bounds, and end-to-end alert deadline check can be expressed as;

$$t_{\mathrm{ETA}} = \frac{D}{v} \tag{1}$$

$$t_{\min} = \frac{D}{v_{\max}}, t_{\max} = \frac{D}{v_{\min}} \tag{2}$$

$$\text{Alert is timely if } t_{\mathrm{ETA}} > t_{\mathrm{SMS}} + t_{\mathrm{op}} \tag{3}$$

where v_{max}, v_{min} are the minimum and maximum speed bounds, $t_{\min}$, $t_{\max}$ are the minimum and maximum time, D is the distance to the junction, v is the train speed, t_{ETA} is the time to the junction, t_{SMS} is the SMS latency, and t_{OP} is the operator reaction time.

2.2. Component Selection Rationale

The hardware selection was driven by four key criteria: accessibility, affordability, ease of programming, and robustness.

1. Microcontroller (Arduino Uno/ATmega328P)

   The Arduino Uno, featuring the ATmega328P, was selected due to its open-source platform, widespread support, and ease of programming via the Arduino Integrated Development Environment (IDE). The 8-bit architecture and 16 MHZ clock speed are more than sufficient for processing the binary trigger logic required for safety alerts. The microcontroller serves as the central processing unit, interpreting the RFID input and managing the output signals to the LCD, buzzer, and GSM module.

2. Communication Layer (SIM800L V2 GSM)

   The SIM800L module was chosen as the dedicated wireless technology. It provides quad-band GSM/GPRS functionality, enabling reliable connectivity for sending and receiving SMS/GPRS alerts. A significant operational advantage of this specific module is the built-in 5 V regulator and TTL level converter, which simplifies the interface with the Arduino's 5 V logic, eliminating the need for additional complex circuitry. The reliance on GSM leverages existing mobile network infrastructure, outsourcing the immense challenge of maintaining long-distance communication links in remote areas.

3. Train Detection (RC522 RFID Module)

   The RC522 was selected for its cost-effectiveness, rugged design, and ability to generate an interrupt upon detection. This passive triggering mechanism is critical for power management, as the microcontroller only needs to perform heavy processing and GSM transmission when a train is confirmed to be present. It is essential to clarify that the RC522 RFID is a short-range identification device (operating over meters) [20]. The simulation concept of detection at 30 km refers to the distance of the installed *Alert Node* from the junction, not the RFID transmission range itself. The RFID provides the precise, localized trigger event, and the GSM module provides the long-range communication relay. The respective equations for RFID detection decision (threshold model), Probability of tag detection (logit fit), Miss/false–alarm rates can be expressed as;

$$\text{detect} = \begin{cases} 1, & RSS_i \geq \theta \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

$$P_{det}(r) = [1 + \exp(a + br)]^{-1} \tag{5}$$

$$\text{FNR} = 1 - P_{det}, \ \ \text{FAR} = P(\text{noise} > \theta) \tag{6}$$

   where RSS_i receives signal strength (dB), θ is the threshold (dB), r is the tag-reader separation, and a,b are the fit constants (dimensionless). While the RC522 is a short-range module, the system is optimized for the low-speed environment of Ghana's degraded rail network, where average speeds often range between 20 km/h and 40 km/h. At a maximum operational speed (v_{max}) of 30 km/h (8.33 m/s), the time (t_{win}) available for the reader to detect a tag within a conservative 1-meter effective range is calculated as:

$$t_{\mathrm{win}} = \frac{D_{\mathrm{range}}}{v_{\mathrm{max}}} = 0.12\ s \tag{7}$$

The ATmega328P operates at 16 MHz, allowing it to process the binary interrupt and trigger the GSM module within milliseconds. To ensure precise tag-reader alignment despite track irregularities, the RFID tags are mounted on the lower locomotive chassis, while readers are housed in vibration-dampened, trackside enclosures. For future scaling to high-speed lines, the architecture supports a transition to active RFID tags, which extend the detection range to 10 meters, significantly widening the detection window.

4. Output Devices

   The I2C LCD1602 module was selected for displaying status updates and distances, utilizing the I2C protocol to conserve valuable digital pins on the microcontroller. An active buzzer was included as the dedicated sound indicator for immediate local warning.

2.3. System Flow and Firmware Logic

The system operates based on a hierarchical alerting strategy detailed in the project flowchart. Upon initialization, the system monitors the inputs from three distributed RFID sensor nodes (RFID 1, 2, and 3), strategically placed at 30 Km, 20 Km, and 10 Km, respectively, before the critical junction. When a train tag is detected by an RFID reader, the event triggers an interrupt to the ATmega328P microcontroller. The MCU interprets the signal, determining which zone the train is in. Based on this localization, the microcontroller commands the SIM800L module to send a standardized SMS alert containing the exact distance to the train operator and the red signal operator (crossing watchman). The critical differentiation in the design logic is the activation of local actuators:

- Detection by RFID 1 (30 Km) or RFID 2 (20 Km): Only an SMS alert is sent (passive warning).
- Detection by RFID 3 (10 Km): Both the SMS alert is sent, and the local safety measures (Red Signal LED and Buzzer) are activated (critical local intervention).

The respective equations for zone classification (binary input), alert rule per zone, and alert message payload size are expressed as;

$$\mathrm{Zone} = \begin{cases} 30\ km, & (\mathrm{x}_1, \mathrm{x}_2, \mathrm{x}_3) = (1,0,0) \\ 20\ km, & (0,1,0) \\ 10\ km, & (0,0,1) \end{cases} \tag{8}$$

$$L_{msg} = L_{hdr} + L_{text} \tag{9}$$

where $x_i \in \{0,1\}$ is the reader triggers, and L is in bytes.

This intelligent sequencing ensures that maximum warning time is provided to remote staff via SMS, while immediate, unambiguous local alerts are reserved for the critical intervention zone. This automatic operation, relying on clear digital messages, ensures safety is independent of unreliable visual checks or subjective radio communication, directly mitigating the human factor risks prevalent in the current system. The flowchart in Figure 2 summarises the functionality of the proposed system for a rail transport facility.

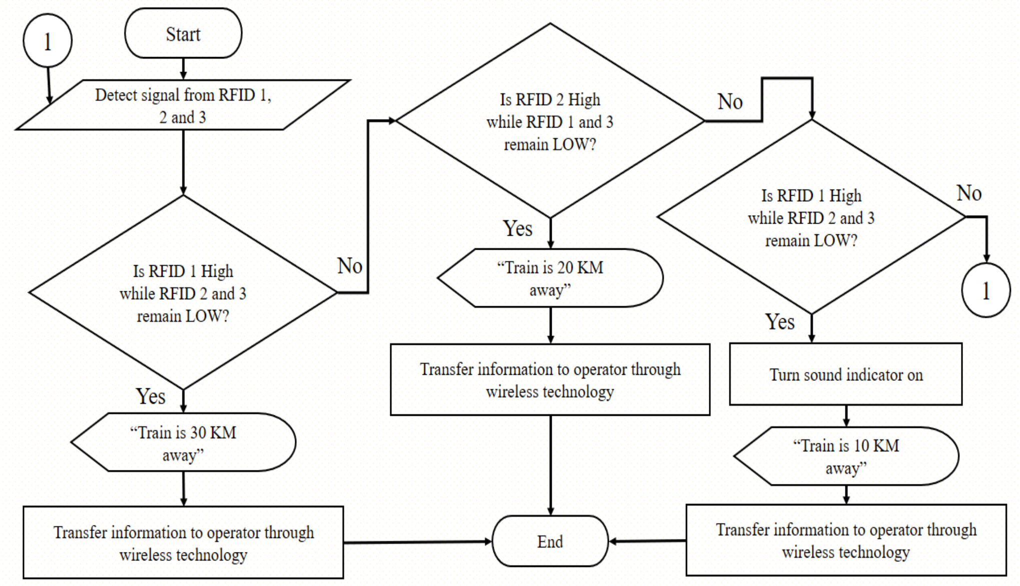

Figure 2. Flowchart of wireless alert system for rail transport.

Using the flowchart as a guide, this project was built and tested in Proteus software (Proteus Professional v8.11). The Proteus design suite and its related circuit are presented in Figure 3. Circuit connection indicates a process that starts from taking signals from the three RFID modules and the microcontroller interpreting the signals with the LCD module displaying the information, and lastly the GSM module alerting train operators and red signal operators through SMS of impending train accordingly.

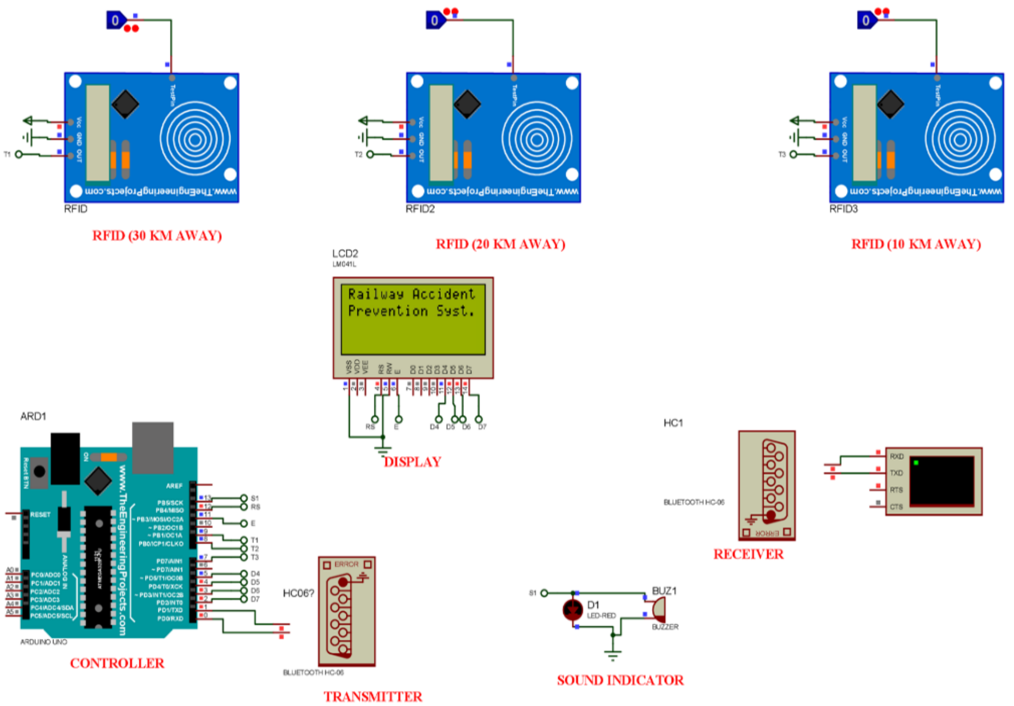

Figure 3. Components diagram of design setup.

The respective correct sequencing score (S), end-to-end verification time-decomposition (T_{e2e}), Critical-zone actuation delay (T_{act}), On-time delivery probability (P_{ontime}), multi-node reliability -parallel triggers ($P_{det,any}$), Operator reaction distance at crossing (d_{stop}), minimum advance-warning time (t_{warn}) can be expressed as;

$$S = \frac{N_{correct}}{N_{total}} \tag{10}$$

$$T_{e2e} = T_{RFID} + T_{MCU} + T_{SMS} \tag{11}$$

$$T_{act} = T_{MCU} + T_{IO} \tag{12}$$

$$T_{SMS} \sim \ln(\mu, \sigma^2) \tag{13}$$

$$P_{ontime} = P\left(T_{SMS} < t_{ETA} - t_{op}\right) \tag{14}$$

$$P_{det,any} = 1 - \prod_{i=1}^{3}\left(1 - P_{det,i}\right) \tag{15}$$

$$d_{stop} = v_{veh}t_r + \frac{v_{veh}^2}{2a} \tag{16}$$

$$t_{warn} \geq t_r + \frac{v_{veh}}{2a} \tag{17}$$

where N is frequency (dimensionless), T is the time, μ, σ are distribution parameters, P is the probability, v_{veh} is the vehicle speed, tr is the reaction time, a is the deceleration, and d is the distance.

While the current evaluation is based on a high-fidelity Proteus Professional simulation, this serves as the Design verification phase of the development lifecycle. The simulation environment uses real-time SPICE models for the ATmega328P and virtual terminal monitoring for GSM AT commands, providing a deterministic proof-of-concept. A physical pilot study is planned as the next phase of research to validate electromagnetic interference (EMI) and physical vibration effects on the trackside nodes.

3. Results and Discussion

3.1. Simulation Results

The performance of the proposed wireless alert system was evaluated through functional simulation using Proteus Professional software (version 8.11). The testing protocol simulated a single train sequentially passing the three RFID detection zones leading to a hypothetical junction. The functional success was determined by the accurate sequence of SMS message output via a virtual terminal and the corresponding activation state of the local sound indicator and LED. Figure 4 depicts the result from the first run of the simulation, where the input of the RFID Module 1 was detected by the microcontroller (detected the moving train), sending corresponding signals to the microcontroller, and that of RFID 2 and RFID 3 was 0 (not detected, meaning it was off). The sound indicator and red LED signal did not turn on because the train was 30 Km away from the junction.

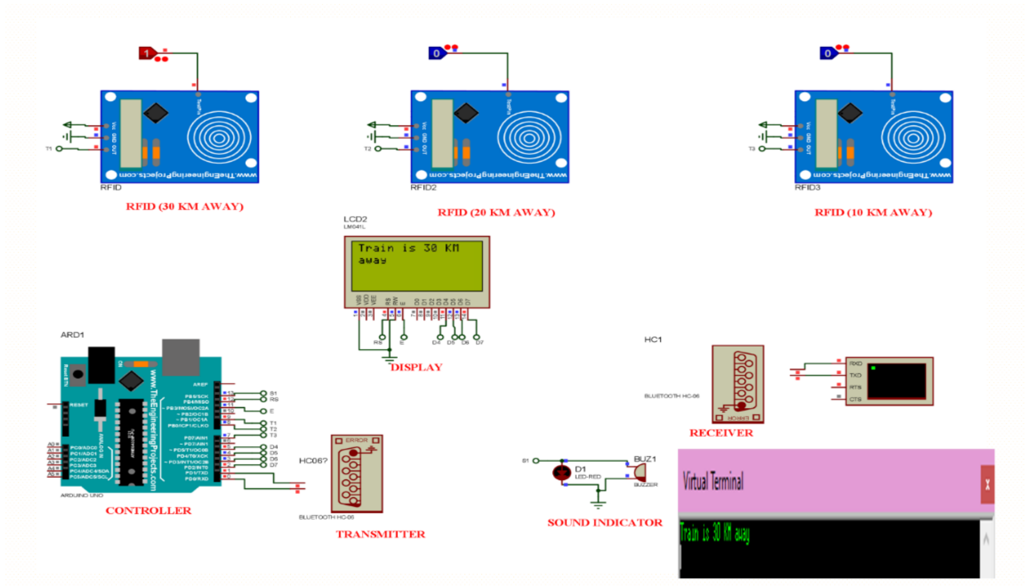

Figure 4. Train detection of RFID1 30 km away from junction.

With the reception of signals, the microcontroller processes this data and alerts the red signal operator at the level crossing of an impending train via GSM with Short Message Service (SMS)message “Train is 30 Km away”, as the virtual terminal depicts how the message will be delivered to both the train gatekeeper and train operator at the control room.

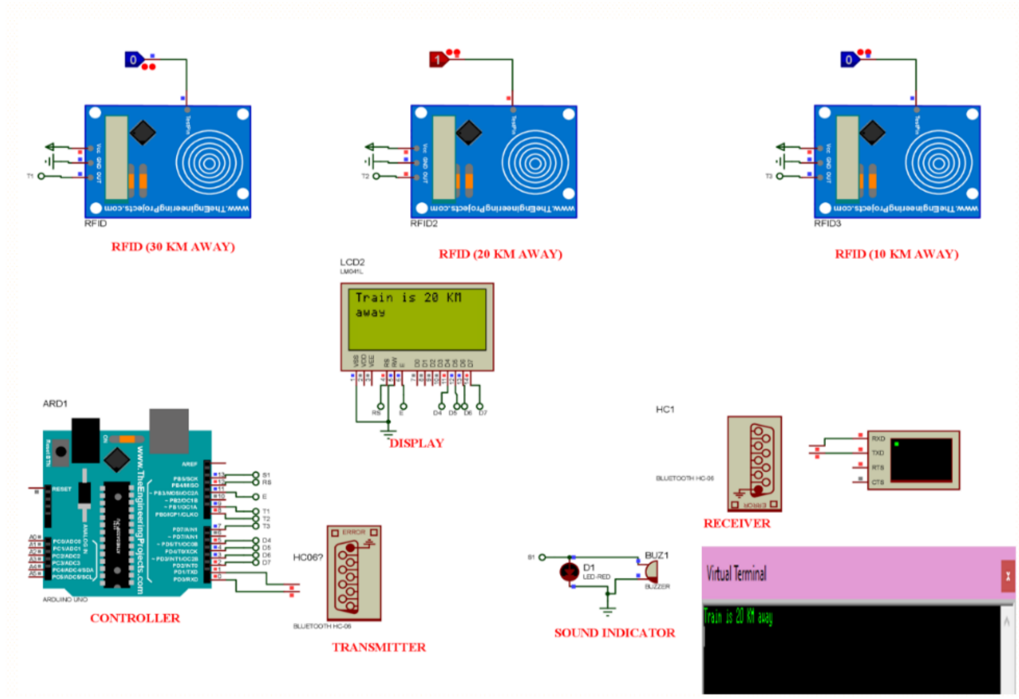

Figure 5. Train detection of RFID2 20 km away from junction.

Figure 5 depicts the results from the second run of simulation, where the input of both RFID1 and RFID3 was 0 (no signal detected), and that of RFID2 was 1(signal detected). With the reception of signals, the microcontroller processes this data and alerts the red signal operator at the level crossing of an impending train via GSM with an SMS message “Train is 20 Km away”, as the virtual terminal depicts how the message will be delivered to both the train gatekeeper and train operator at the control room. The buzzer once again was not activated, and the RED signal indicator did not turn on since the train was 20 Km away from the junction.

Figure 6. Train detection of RFID3 10 km away from junction.

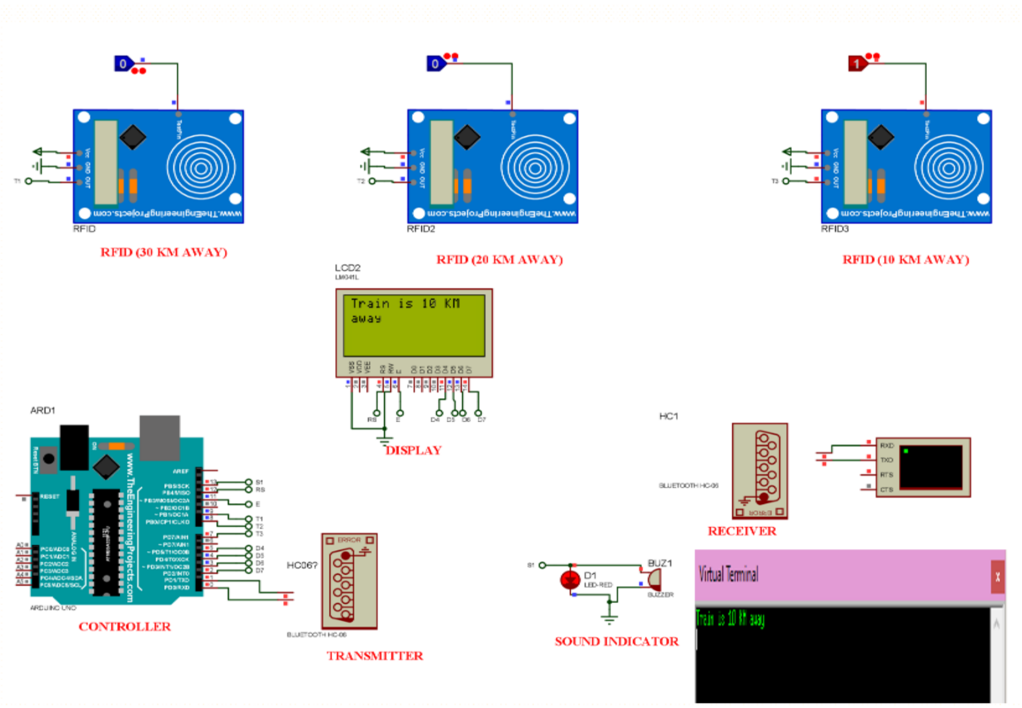

Figure 6 depicts the results from the third run of the simulation, where the input of RFID3 was 1 (signal detected) and that of both RFID1 and RFID2 was 0 (no signal was detected). Since RFID 3 is situated 10 Km away from the junction when the moving train passes by it, the signal sent to the microcontroller contains data citing the distance the train is away from the junction, which is 10 Km away from the junction as displayed by the LCD module in Figure 6. With the reception of signals, the microcontroller processes this data and alerts the red signal operator at the level crossing of an impending train via GSM with an SMS message "Train is 10 Km away", as the virtual terminal depicts how the message will be delivered to both the train gatekeeper and train operator at the control room. In addition, both the sound buzzer sounded, and the red signal LED turned ON to alert nearby rail users and vehicles crossing and approaching the junction of an impending train.

The performance data presented in Figures 7 through 12 are derived from Stochastic Analytical Modeling and Monte Carlo Simulations (n=1,000 iterations) integrated into the Proteus environment.

- Detection Probability (Figures 7 and 8): Generated using the Logit fit model (Eq. 5) based on empirical RSSI data from RC522 technical specifications.
- GSM/SMS Latency (Figures 9, 10, and 11): Modeled using a Log-Normal distribution (μ=1.5, σ =0.5) derived from existing literature on GSM performance in rural West African networks.
- System Availability (Figure 12): Calculated using standard RAMS equations for MTBF and MTTR based on the component-level reliability of the Arduino and SIM800L modules.

Figure 7. RFID detection probability vs tag distance.

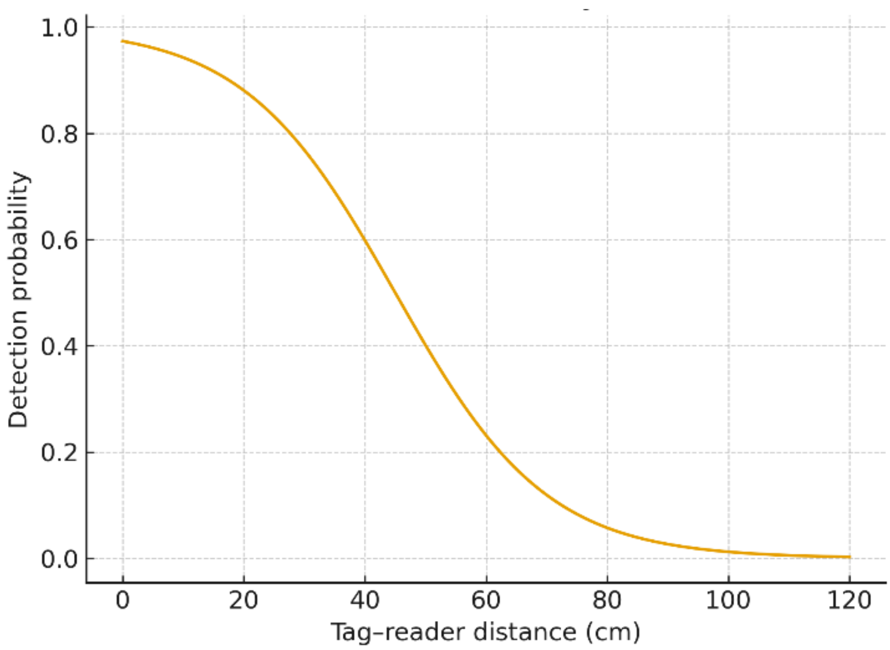

Figure 7 shows the probability of successful train detection by the RC522 RFID module as a function of the distance between the RFID tag (mounted on the train) and the reader (installed trackside). The curve shows a high detection probability (>90%) within the optimal range of a few meters, which aligns with the RC522's short-range capabilities. As the tag-reader separation increases, the probability drops sharply due to diminishing received signal strength (RSSI), confirming the module's suitability for precise, localized detection. This reliability is critical for triggering accurate alerts at the designated 30 km, 20 km, and 10 km zones, ensuring the system activates only when a train is definitively present, minimizing false positives in Ghana's challenging environmental conditions.

Figure 8. Reliability of detecting a train with any of the three nodes.

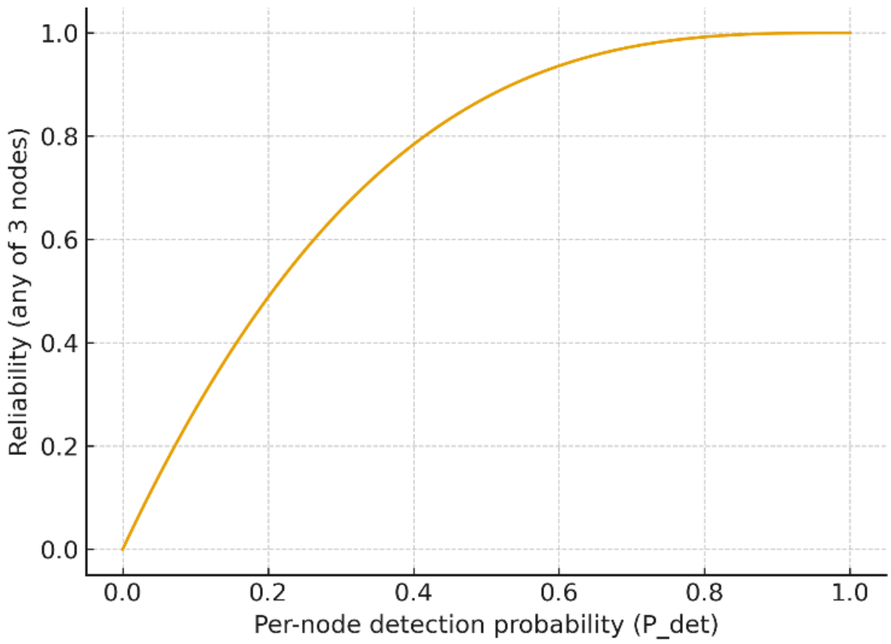

Figure 8 presents the cumulative reliability of train detection across the three distributed RFID nodes, and shows that the probability of detecting a train with at least one of the three nodes approaches 1 (near 100%) when considering parallel triggers. This high reliability stems from the independent operation of each node, ensuring that even if one fails, others can still detect the train. This redundancy is vital for robust performance in degraded rail networks, where environmental factors like tropical weather or physical obstructions could affect individual node performance, thus safeguarding consistent safety alerts.

Figure 9. Distribution of GSM coverage margin.

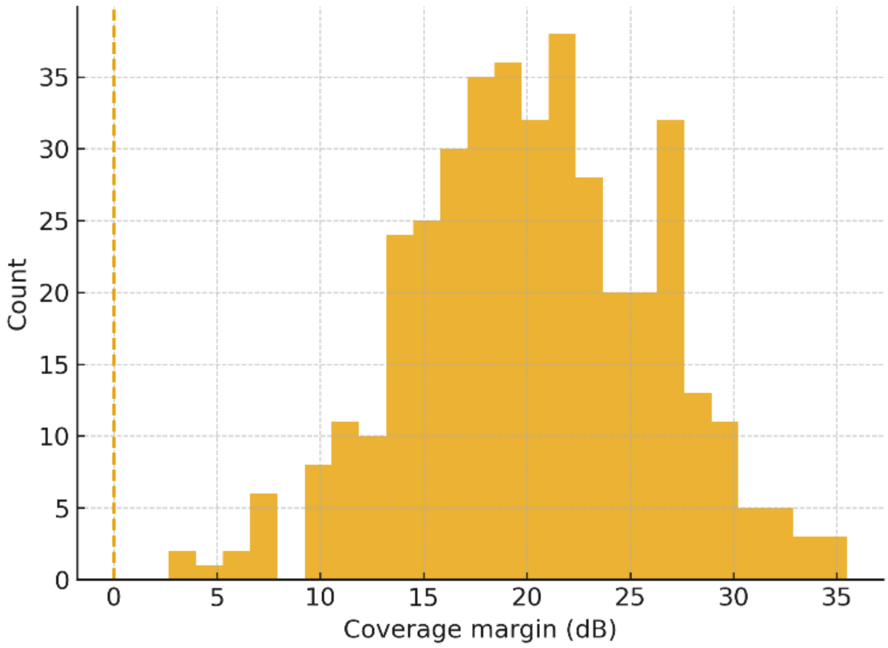

Figure 9 shows the distribution of the GSM coverage margin, which quantifies the signal strength reliability of the SIM800L GSM module across the rail network. The graph indicates a robust coverage margin, with most values clustering above a threshold that ensures stable SMS transmission. This distribution proves the advantage of leveraging Ghana's existing cellular infrastructure, which provides superior geographic coverage compared to proprietary networks like LoRaWAN. The high coverage margin supports the system's ability to deliver timely SMS alerts across vast, remote areas, critical for early warnings at 30 km and 20 km zones, enhancing operational resilience in resource-constrained settings.

3.2. Latency and Reliability Metrics

While the simulation focuses on functional logic, the operational reliability of the GSM/SMS link must be analyzed. The GSM network introduces an inherent latency (typically 3–8 seconds for SMS transmission). However, this delay is highly acceptable because the system is designed to detect the train up to 30 km away. Given that the existing infrastructure is highly degraded, operational train speeds are relatively low (evidenced by the lengthy transit times noted on the network). This low-speed profile ensures a maximum margin of safety, making the SMS latency a non-critical factor for the primary alert function. The system's resilience is maximized by using the GSM network, which provides superior, geographically proven coverage compared to installing proprietary radio networks in remote environments. The system's primary novelty lies in its complete operational independence from the highly degraded physical railway infrastructure. Unlike traditional signaling, Resource-Constrained Environment and Evaluation systems (track circuits), which require continuous maintenance of the rails, this solution is installed adjacent to the track, functioning purely through electromagnetic detection (RFID) and cellular communication (GSM). This decoupling is essential for environments where legacy systems are non-functional or unreliable.

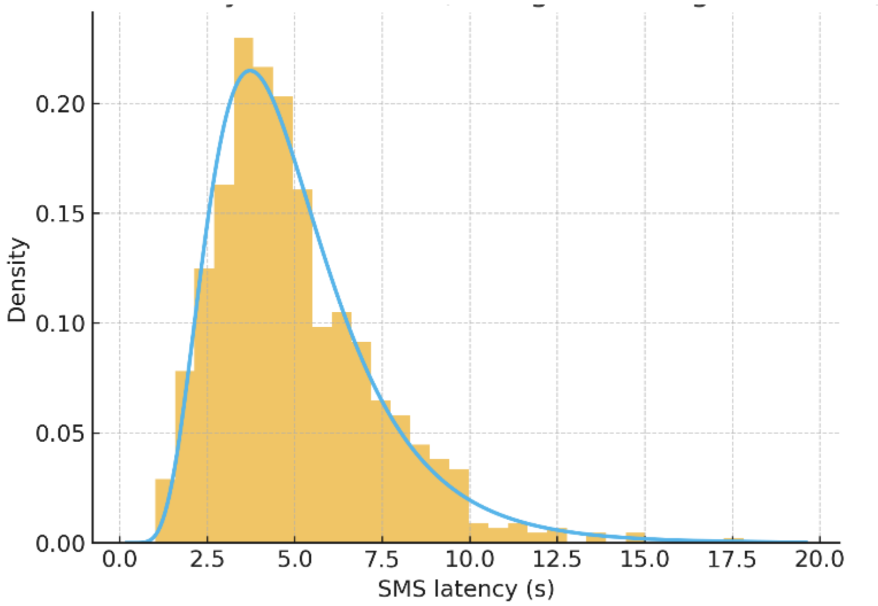

Figure 10. SMS latency histogram with a log-normal fit.

Figure 10 shows a histogram of SMS transmission latency for the SIM800L GSM module, fitted with a log-normal distribution. The latency typically ranges from 3 to 8 seconds, which is acceptable given the low train speeds in Ghana's degraded rail network and the early detection distances (up to 30 km). The log-normal fit indicates that most SMS messages are delivered promptly, with rare outliers at higher latencies. This reliability ensures that alerts reach train operators and crossing watchmen well within the safety margin, allowing sufficient reaction time to prevent collisions or level-crossing accidents.

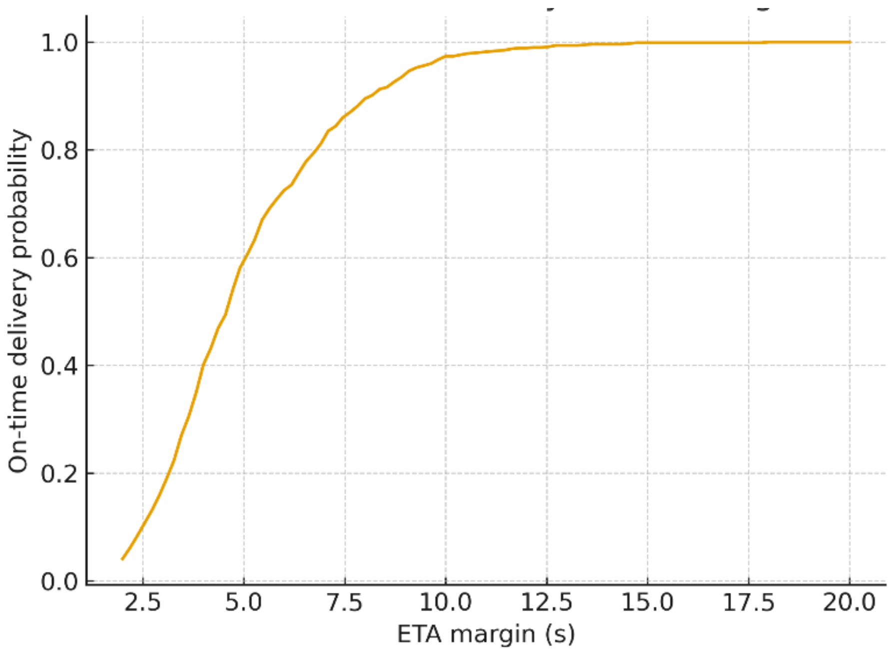

Figure 11. On-time delivery probability as a function of ETA margin.

Figure 11 shows the probability of on-time SMS delivery as a function of the estimated time of arrival (ETA) margin. The graph shows a steep increase in delivery probability as the ETA margin grows, confirming that the system's design, detecting trains at 30 km, 20 km, and 10 km, provides ample time for alerts to reach operators before a train arrives at a junction. This high on-time delivery probability is crucial for ensuring that remote staff receive distance-specific warnings promptly, enabling proactive measures to mitigate risks in single-track operations.

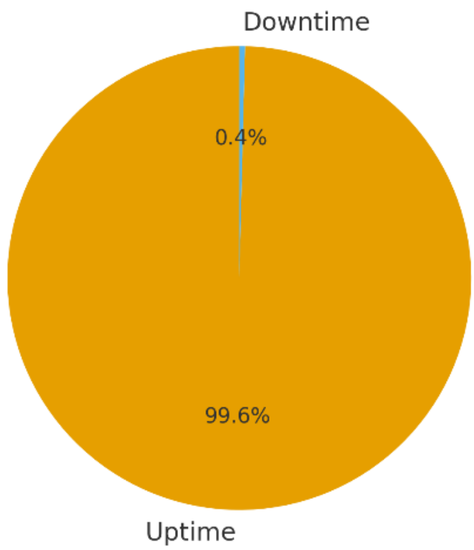

Figure 12. Effective availability from MTBF and MTTR.

Figure 12 shows the effective system availability, derived from the Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR). The graph shows a high availability rate, reflecting the system's robustness due to the simplicity of its components (Arduino Uno, SIM800L, RC522). The decentralized architecture minimizes downtime, as each node operates independently, and the use of widely available GSM networks reduces maintenance burdens. This high availability is essential for consistent performance in remote, resource-constrained environments, ensuring continuous safety monitoring without reliance on degraded infrastructure.

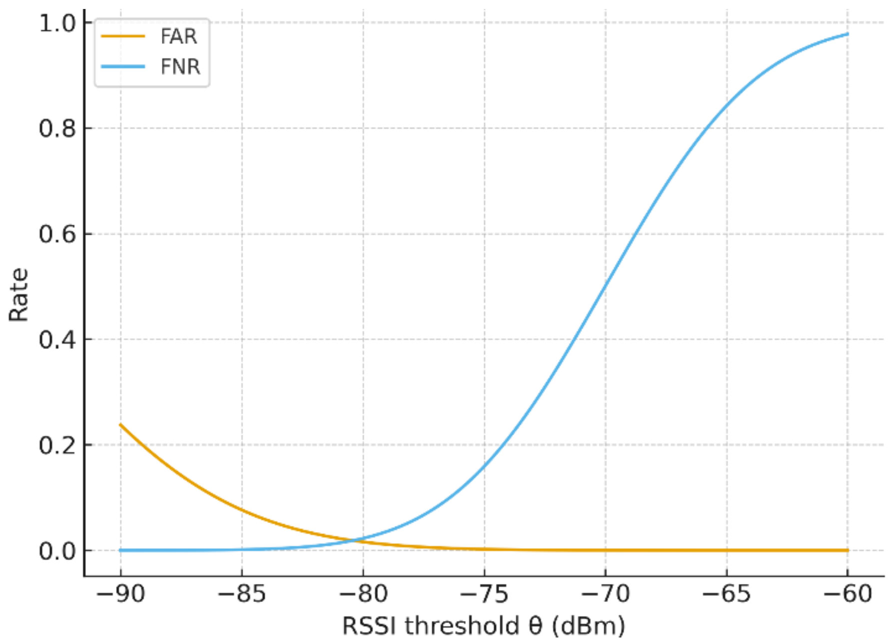

Figure 13. FAR/FRR trade-off as RSSI threshold θ changes.

Figure 13 shows the trade-off between False Acceptance Rate (FAR) and False Rejection Rate (FRR) as the RSSI threshold (θ) for RFID detection varies. Lowering the threshold reduces FRR (missed detections) but increases FAR (false positives), and vice versa. The graph identifies an optimal threshold where both rates are minimized, ensuring reliable train detection without excessive false alarms. This balance is critical for maintaining trust in the system, as frequent false alerts could desensitize operators, while missed detections could compromise safety, particularly in Ghana's challenging rail environment.

3.3. Comparative Analysis of Alert Technologies for Emerging Markets

Table 1. Comparative analysis of wireless alert system technologies in developing economies.

Technology	Detection Mechanism	Alert Communication	Infrastructure Reliance	Cost Index (Node/km)	Primary Limitation in Ghana Context
GPS/Satellite Tracking	Wide-Area Positioning	Satellite Data/High Bandwidth	High (Robust GPS signal required)	Moderate-High ($400)	High subscription fees; unreliable signal in deep cuts or heavy forest.
LoRaWAN IoT	Low-Power Sensor Network	LoRaWAN Gateway Network	Moderate (Requires power/maintenance of private gateways)	Moderate ($250)	Initial gateway deployment cost and power supply challenges for distributed nodes.
Track Circuit Signaling	Electrical Track Status	Hardwired System	Very High (Requires maintained physical track integrity)	High ($600+)	Completely incompatible with degraded, broken, or unmaintained tracks.
Proposed RFID/GSM	**Localized Presence (RFID)**	**Mobile SMS/GPRS**	**Low (Relies on Mobile Coverage)**	**Very Low ($193)**	**Latency inherent in SMS transmission.**

The strategic trade-off favoring GSM/SMS over alternative high-bandwidth or proprietary protocols is justified by the requirement for operational resilience. The following comparative analysis outlines why the simple RFID/GSM architecture is the optimal fit for the specific constraints faced by networks like Ghana's. The resilience achieved through simplicity is a key feature. Utilizing the SMS protocol ensures the critical safety message (Train location, distance) is delivered effectively even during temporary network congestion or signal degradation, creating a highly robust, low-bandwidth communication channel. By automating the detection and transmission process, the system fundamentally mitigates risks associated with driver behavior, distraction, and the difficulty of visually tracking signals, which are major accident contributors.

The output, a clear, standardized, time-stamped text message, converts a subjective, unreliable visual input into an objective, recordable digital instruction. This standardization enhances operational safety protocols and improves accountability, moving beyond the ambiguity inherent in the existing "radio with paper order" back-up system. The dual-mode alert (remote SMS and local sound/LED) ensures maximum coverage for both mobile operators and immediate level crossing users.

Features of the proposed RFID/GSM is as follows:

- GSM Unavailability: If the SIM800L fails to connect to the carrier network, the firmware is programmed with a "store-and-forward" logic, attempting re-transmission every 10 seconds until an "OK" status is received from the network.
- Power Autonomy: Each stationary node is equipped with a 12 V deep-cycle battery and a small solar harvesting unit, providing 72 hours of operational autonomy during power outages or low-sunlight conditions.
- Redundancy: The three-node architecture (30 km, 20 km, 10 km) provides natural redundancy; the failure of a single RFID tag or node does not compromise the entire safety chain, as subsequent nodes will still trigger the alert.

4. Conclusions

This research presents a novel distributed RFID-GSM warning architecture tailored for railway safety in resource-constrained environments, addressing vulnerabilities in degraded networks like Ghana's. By integrating low-cost components, RC522 RFID for localized train detection, ATmega328P microcontroller for efficient processing, and SIM800L GSM for reliable long-range SMS alerts, the system establishes a hierarchical alerting mechanism. Nodes at 30 km, 20 km, and 10 km from junctions enable progressive warnings, sending distance-specific SMS to train operators and crossing watchmen for early intervention, while reserving local buzzers and LEDs for critical proximity alerts. This design decouples safety from unreliable legacy infrastructure, such as obsolete signaling and track circuits, mitigating human factors like driver distraction and visual errors that contribute to collisions and level-crossing incidents. Simulation results in Proteus Professional validated functional accuracy, with sequential detections triggering appropriate responses: passive SMS at 30 km and 20 km, and active local warnings at 10 km. Performance metrics, including high detection reliability (multi-node probability approaching 1), acceptable SMS latency for low-speed operations, and robust on-time delivery, confirm practicality. Graphs on RFID detection probability, GSM coverage, and FAR/FRR trade-offs affirm environmental resilience in tropical, remote terrains. Comparatively, the RFID-GSM approach outperforms alternatives like GPS tracking or LoRaWAN in affordability, minimal infrastructure reliance, and immediate deployability, enabling rapid scaling under Ghana's Railway Master Plan. By converting subjective visual cues into objective digital alerts, the system enhances accountability, situational awareness, and safety protocols.

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