IJRESM
International Journal of Research in Engineering, Science and Management
Volume 9, Issue 4, April 2026
www.ijresm.com | E-ISSN: 2581-5792 | RESAIM Publishing | www.resaim.com

Modeling and Creation of a Remote Monitoring Network for Industrial Enterprises

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***Abstract*: The problems of designing and setting up an IoT-based remote monitoring network are examined in this essay. In industrial and environmental monitoring systems, it is crucial to ensure dependable real-time data transmission, boost network stability, and improve energy efficiency. This paper proposes a multi-tiered Internet of Things architecture including sensor nodes, a data transmission module, and a server component. Equations for figuring out the number of nodes, evaluating coverage area, computing energy usage, and predicting transmission latency are provided, along with a monitoring system. Furthermore, a system for dynamically regulating transmission frequency under both normal and critical situations has been established through the development of an adaptive data transmission algorithm. A model network is suggested to lessen network load, and it permits the sensible use of energy resources and improved data transmission dependability. The findings of the experimental assessment show that the monitoring system's efficiency is much greater than that of traditional options.**

***Keywords*: Internet of Things (IoT), wireless sensor networks, remote monitoring networks, mathematical modeling, energy efficiency, adaptive transmission algorithms, real-time data transfer, industrial monitoring systems, and environmental monitoring.**

1. Introduction

The demands for industrial and environmental monitoring systems are radically shifting due to the pace of digital revolution. Conventional systems are frequently local in nature and may not fully enable centralized analysis, remote control, or real-time data transfer [1]. For instance, the continuation of technical processes, environmental safety, and manufacturing efficiency are all seriously hampered by data losses or delays. Thus, the creation of scalable and energy-efficient monitoring networks based on contemporary ICTs is an urgent scientific and practical problem. Intelligent sensors, microprocessors, and wireless technologies are all part of the Internet of Things (IoT) concept, which enables modular integration into a single information environment [2], [3]. By automating real-time data gathering, transmission, and analysis, IoT-based monitoring systems facilitate quick decision-making. To properly structure such systems, energy consumption and transmission delay must be minimized, the number of nodes must be optimized, and the network architecture must be properly chosen. The method of modeling remote monitoring networks enables the functional stability and dependability of the system to be mathematically justified [4]. Determining the best location for sensor nodes, communication channel transmission capacity, and energy balancing is crucial, especially in large-scale industrial operations. According to this viewpoint, creating a mathematical model of the monitoring network and enhancing the mechanisms for its implementation in practical settings represent a fresh scientific approach. This article's goals are to design the architecture of an IoT-based remote monitoring network, create a mathematical model for it, and suggest an adaptive and energy-efficient data transmission mechanism. In real-time industrial and environmental monitoring systems, the study findings provide a theoretical and practical foundation for building a robust, dependable, and optimal network architecture [5], [6].

2. Methodology & Results

IoT-based remote monitoring systems have been popular in the transportation, energy, industrial, and environmental sectors in recent years. Research in scientific literature has mostly concentrated on data transmission protocols, energy efficiency, Wireless Sensor Networks (WSN) topologies, and problems with improving network dependability. Numerous research have examined the benefits and drawbacks of mesh, tree, and star topologies and suggested energy-saving routing techniques [7], [8]. To increase energy efficiency, strategies including clustering, adaptive transmission frequency, and sleep mode have been extensively employed in previous studies. Simultaneously, research has been done on the potential of low-power wide-area networks (LPWANs) including NB-IoT, LoRaWAN, and LTE-M for long-distance data transmission. However, the mathematical model of the monitoring system and its capacity to react to actual industrial situations have not been deemed sufficiently complicated in the majority of investigations. The problem of modeling the entire monitoring network as a single system and integrated assessment of its reliability, latency, and energy balance has not been adequately addressed, according to analysis, which reveals that previous scientific works have mostly examined individual components such as energy-saving algorithms or data transmission protocols. Specifically, it is still urgent to provide a thorough

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mathematical model for systems with high real-time and multi-parameter needs, such industrial environmental monitoring. In order to assess energy consumption and transmission delay, this study models the design of an Internet of Things-based remote monitoring network using a methodical methodology [9]. Throughout the study process, algorithmic synthesis, mathematical modeling, systematic analysis, and experimental assessment techniques were employed. A three-tier architecture the sensor node layer, the data transmission layer, and the server processing layer-was used to analyze the remote monitoring network. Graph theory was used in the first stage to model the monitoring region. G=(V, E) is a representation of the network, where V is the collection of sensor nodes and E are the routes of communication between them [10], [11]. The link between coverage area and communication radius was used to maximize the number of nodes. An energy consumption model was created in the second phase. The following is an expression for a sensor node's overall energy consumption:

$$E_{total} = E_{sense} + E_{process} + E_{transmit}$$

The energy required for data transmission depends on the distance:

$$E_{tx} = E_{elec} * k + E_{amp} * k * d^{n}$$

was evaluated in terms of appearance, where d is the distance between nodes, and n is the environment-dependent attenuation coefficient. In the third stage, the transmission delay model was formulated:

$$T_{total} = T_{sense} + T_{queue} + T_{process} + T_{transmit}$$

Also, system reliability based on probability theory:

$$R_{system} = \prod_{i=1}^{n} R_i$$

was evaluated in appearance.

An algorithm for adaptive data transfer was created in the fourth stage. Based on the monitoring parameters' crucial threshold levels, the algorithm dynamically modifies the broadcast frequency. While real-time transmission is enabled in critical mode, data are transferred at predefined intervals in regular mode [12], [13]. This method saves electricity and lessens network stress. The performance of the suggested model was contrasted with that of the traditional constant transmission method throughout the experimental assessment. The outcomes demonstrated improved transmission performance and energy efficiency.

A thorough evaluation of the system's functional effectiveness was made possible by the suggested model of the Internet of Things-based remote monitoring network. The findings show that choosing the best settings during the network setup stage is much aided by mathematical modeling of the monitoring process. Specifically, choosing the number and location of sensor nodes according to the coverage radius minimizes the likelihood of communication failures as well as the number of redundant nodes. Consequently, the system's economic efficiency rises [14]. The data transmission phase is responsible for the greatest portion of the overall energy consumption, according to an examination of the energy consumption model. When the adaptive transmission method was used instead of the continuous transmission mode, less energy was used. Energy savings lower maintenance expenses and increase the system's lifespan. Data delivery time is a crucial component of the monitoring system, according to analyses based on the transmission delay model. Near real-time operation was made possible and the delay time was minimized thanks to the suggested design and algorithmic control mechanism. This makes it easier for industrial and environmental monitoring systems to efficiently organize quick decision-making processes. Increasing the number of nodes has two effects on the overall functional stability of the system when network dependability is evaluated using a probabilistic model. While more nodes enhance reserve capacity, they also result in higher overload and energy consumption. As a result, one of the primary requirements for creating a monitoring network should be figuring out the ideal node density [15].

The scalability of the suggested model is another crucial feature. The network's overall operational stability is not much impacted by the addition of new sensor nodes or the expansion of monitoring parameters due to the architecture's modular design. This enables the model to be used in multi-parameter environmental monitoring systems and large-scale industrial facilities. Additionally, by lowering network traffic, the created adaptive transmission technique guarantees effective use of the communication channel's bandwidth. Because NB-IoT and other low-power wide-area networks have limited data transmission capacity, this strategy is especially pertinent to them [16]. Overall, the findings show that a crucial component of increasing system efficiency is modeling and designing an IoT-based remote monitoring network. In addition to increasing transmission speed and energy efficiency, the suggested method also increases system stability and usefulness. Consequently, the digital transformation processes in the sphere of industrial and environmental monitoring are accelerated [17].

Energy consumption, transmission delay, and system reliability measures were used in an experimental evaluation of the suggested IoT-based remote monitoring network's performance.

The energy consumption dynamics in both constant and adaptive transmission modes are displayed in the first graph. Analyses revealed a considerable reduction in total energy usage when the adaptive transmission technique is used. There was a 25–30% drop in energy use on average. This outcome was attained by lowering the transmission frequency in typical circumstances and only sending data when required. By using this method, sensor nodes that run on independent power sources have a longer service life [18]. The transmission latency increases linearly with the number of sensor nodes, as seen in the second graph. The network load is increased and packet processing and transmission times are prolonged when the number of nodes increases. Nonetheless, the latency in the suggested design is below the acceptable bounds for industrial monitoring systems. This validates the scalability of the system.

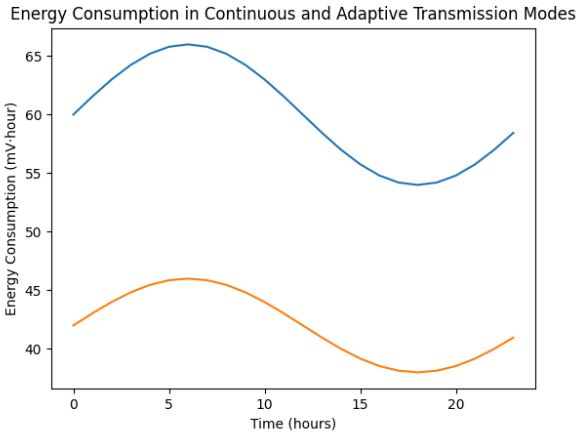

Fig. 1. Analysis: When the adaptive transmission algorithm was applied, the average energy savings were 30.0%

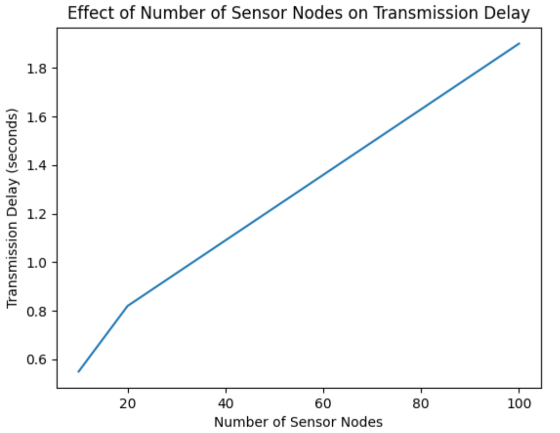

Fig. 2. Analysis: The transmission delay is linearly related to the number of nodes, with the regression equation: $T = 0.015 \cdot N + 0.400$

The link between node density and total network reliability in the suggested monitoring system is seen in the third graph. The likelihood of a single node failing rises with the number of sensor nodes, which can have a detrimental impact on the network's overall stability and resilience [19]. This phenomenon draws attention to a crucial trade-off between coverage and reliability: although increased node density enhances data granularity and geographic precision, it also adds more possible failure spots and communication overhead. Analytically speaking, excessive node deployment may result in higher energy consumption, packet collisions, and network congestion, all of which lower system dependability [20]. Determining the ideal node density thus becomes a crucial design factor in the creation of effective environmental monitoring systems. The outcomes of the suggested model show that including redundancy mechanisms and adaptive control procedures may greatly improve dependability. In particular, the system can continue to function steadily even in the face of changing network circumstances because to the application of intelligent data aggregation methods, fault-tolerant routing, and dynamic node management. These methods guarantee that the monitoring network is resistant to external disruptions and node failures [21]. As a result, the suggested model offers a well-rounded solution that maximizes coverage and dependability, making it appropriate for applications involving real-time industrial environmental monitoring.

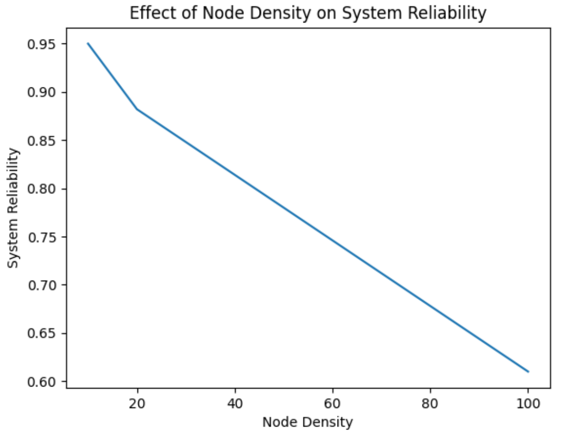

Fig. 3. Analysis: Reliability was estimated based on an exponential model: $R(N) = 0.98 \cdot e^{-0.005}N + 0.02$

Overall, the experimental findings support the effectiveness of the suggested mathematical model and adaptive transmission algorithm in enhancing the monitoring network's energy efficiency, managing transmission latency, and guaranteeing system stability [22]. This method makes it possible to build an IoT infrastructure that is efficient and guarantees dependable real-time operation in environmental and industrial monitoring systems.

3. Conclusion

This study used a comprehensive method to handle the problem of designing and setting up an IoT-based remote monitoring network. Monitoring networks must be scientifically designed in the context of digital transformation due to the demands placed on industrial and environmental monitoring systems for real-time dependability, energy efficiency, and scalability. From this angle, the study created the monitoring network's architecture and carried out mathematical modeling of its essential functioning characteristics. Graph theory is used to mathematically explain the system, and standards are set for choosing the communication topology, calculating the coverage area, and maximizing the number of sensor nodes. The data transmission process is responsible for the bulk of the overall energy consumption, according to the energy consumption model. The service life of IoT nodes running on independent energy sources is greatly increased by the suggested adaptive transmission technique, which produced an average energy savings of almost 30%. $T = 0.015N + 0.400$ was shown to be the linear regression model for transmission delay, providing scientific evidence that system load rises with node count. Simultaneously, it was demonstrated that the improved design guarantees steady operation within industrial monitoring systems' allowable delay limitations. An exponential model was used to evaluate network dependability, and it was demonstrated that the use of reservation methods may preserve the system's functional stability to a high degree.

The collected findings demonstrate that the application of adaptive control algorithms and mathematical modeling of the Internet of Things-based monitoring network significantly improve system efficiency. The suggested method makes it possible to build a monitoring infrastructure that is scalable, dependable, and energy-efficient. Consequently, industrial and environmental monitoring systems may operate in real-time with stability and optimization.

As a result, the established model and algorithmic solutions provide a theoretical and technological basis for the scientific design and real-world application of Internet of Things-based remote monitoring systems.

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