EAI Endorsed Transactions
on Scalable Information Systems

Research Article EAI.EU

IoT and Relaying Aided Transmission Technologies for Monitoring Electrical Equipment Status

Yawen Yi[1], Chuan Chen[2,*], Ziran Chen[1], Ganxin Jie[2], Yong Tu[1], and Qijun Zhang[1]

[1]Yangtze Power Corporation Xiangjiaba Hydroelectric Power Plant, Yibin, Sichuan, China, 644612
[2]National Key Laboratory of Environmental Adaptability for Industrial Products of China Electric Appliance Research Institute Co., Ltd., Guangzhou, Guangdong, China, 510600

Abstract

This paper presents a novel approach to monitor the status of electrical equipment using Internet of Things (IoT) and relaying-aided transmission technologies, where the data rate is used as the metric for evaluating the system monitoring performance. In this framework, relaying plays a pivotal role, enhancing the efficiency of data transmission in the monitoring process. We employ the optimal relay selection criterion to choose the most effective relay to assist the data transmission, thereby optimizing the communication link between the electrical equipment and the monitoring system. To provide a comprehensive understanding of the system performance, we delve into the analytical aspects by deriving an analytical expression for the data rate. This expression offers some insights into the theoretical performance limits and the factors influencing the efficiency of the system. The theoretical framework is further complemented by a series of simulations. These simulations validate the analytical expression developed in the study, and provide practical scenarios to demonstrate the real-world applicability and effectiveness of the proposed IoT and relaying-aided transmission technologies in monitoring electrical equipment.

Received on 13 January 2023; accepted on 19 February 2024; published on 23 February 2024

Keywords: IoT, relay selection, analytical data rate

doi:10.4108/eetsis.4839

1. Introduction

Internet of Things (IoT) networks have fundamentally reshaped industries, particularly in the realm of industrial IoT (IIoT) and the monitoring of electronic equipment [1–3]. These networks, built upon wireless connectivity and often designed for low-power operation, serve as the backbone for data-driven insights and real-time monitoring in industrial settings. IIoT harnesses the power of IoT networks to collect and analyze data from sensors and connected devices, enabling predictive maintenance and minimizing downtime by detecting potential electronic equipment failures early [4–7]. Remote monitoring capabilities, coupled with robust security measures, ensure that operators can access critical information securely and make informed decisions promptly. Scalability and flexibility are key attributes of IoT networks, accommodating the evolving needs of electronic equipment monitoring and providing customized solutions that integrate sensors, actuators, and advanced analytics tools [8–11]. Furthermore, the convergence of data analytics and AI techniques within IoT networks helps extract valuable insights from the copious data generated, paving the way for more efficient decision-making, enhanced performance optimization, and the proactive management of critical machinery. As IoT technology continues its evolution, its application in electronic equipment monitoring holds the promise of further enhancing operational efficiency, reducing costs, and ensuring the seamless operation of electronic equipment in industrial and commercial contexts alike.

Relaying techniques, at the heart of modern communication systems, are instrumental in overcoming signal propagation challenges and enhancing data transmission performance[12–15]. The usage of relay selection, involves the strategic choice of relay nodes to assist in data transmission, significantly impacting data rates and overall system performance [16–19]. Relays act as

*Corresponding author. Email: Chenchuangcess@126.com.

intermediaries, extending coverage, improving signal quality, and mitigating issues like signal attenuation or fading. Relay selection algorithms assess relay nodes based on factors like channel quality, signal-to-noise ratio, and distance to optimize the data rate while minimizing packet loss and retransmissions [20–23]. This enhancement in data rates is crucial for applications such as wireless sensor networks, industrial IoT, and mobile communications, where maintaining high-speed data exchange is essential for real-time monitoring, control, and seamless connectivity. Striking a balance between the complexity and performance, relay selection methods aim to offer optimal relay choices with minimal computational overhead. In essence, relay selection is a vital component of relaying techniques, shaping data rates and improving communication system performance, making it indispensable for wireless networks and IoT applications, as ongoing research continues to refine and innovate these strategies to meet evolving network demands.

In this study, we introduce an innovative method for monitoring the status of electrical equipment through the integration of IoT and relay-assisted transmission technologies. The effectiveness of this system is primarily measured by the data rate, which serves as a critical metric of monitoring performance. A key element in this system is the strategic use of relaying, which significantly enhances the efficiency of data transmission during the monitoring process. The optimal relay selection criterion is used to choose the most effective relay, thus maximizing the efficiency of the communication link connecting the electrical equipment with the monitoring system. To thoroughly understand the system performance, our study delves into detailed analytical examination, formulating an analytical expression for the data rate. This expression provides deep insights into the theoretical performance boundaries and the variables affecting system efficiency. Complementing our theoretical analysis, we conduct a series of simulations. These simulations not only corroborate our analytical models but also offer practical demonstrations of how our proposed IoT and relay-assisted transmission methods can be effectively applied in real-world settings for monitoring electrical equipment.

2. System model

Fig. 1 illustrates the system model of the two-hop relay-assisted wireless network. This network architecture comprises several essential components: a single source node S, an array of N half-duplex decode-and-forward (DF) relays, and a single destination D. A fundamental characteristic of this setup is the absence of the direct communication between the source S and the destination D. Consequently, to establish effective

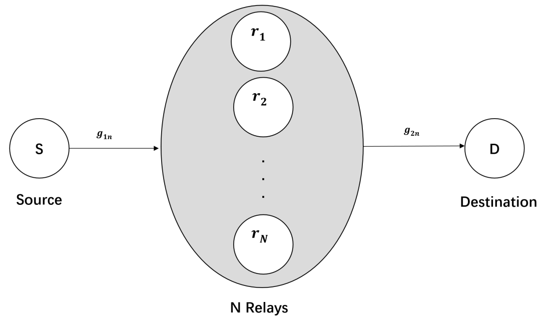

Figure 1. System model of two-hop relay-assisted wireless network, where there exists one source S, N half-duplex relays, and one destination receiver D.

communication between these endpoints, the source S must rely on the assistance of one specific relay from the set of relays denoted as $\{r_n | 1 \leq n \leq N\}$ [24–27], which underscores the significance and relevance of this system model in contemporary research and practice.

Moreover, the wireless communication within this model is intricately characterized by two distinct channels: g_{1n} and g_{2n}. These channels play pivotal roles in data transmission within the network. Specifically, g_{1n} represents the wireless channel through which data originates at the source S and is conveyed to the selected relay r_n. In addition, g_{2n} embodies the wireless channel utilized for the transmission of data from the relay r_n to the destination D. The specific nature and quality of these wireless channels profoundly impact the overall performance and efficiency of the communication link.

In further, the relay r_n operates in the DF protocol to meticulously handle the transmission of signals originating from the source S and destined for the receiver D. The DF protocol, known for its effectiveness in relay communication systems, is instrumental in decoding and forwarding these signals, ensuring they reach the destination D with reliability and integrity. This entire system model encapsulates a complex and highly relevant framework for the study and analysis of relay-assisted wireless networks, offering valuable insights into the dynamics of multi-hop communication scenarios.

The probability distribution functions (PDFs) of g_{1n} and g_{2n} are given as, respectively,

$$f_{g_{1n}}(x) = \begin{cases} \frac{1}{\alpha_1} e^{-\frac{x}{\alpha_1}}, & x \geq 0, \\ 0, & x < 0, \end{cases} \tag{1}$$

$$f_{g_{2n}}(x) = \begin{cases} \frac{1}{\alpha_2} e^{-\frac{x}{\alpha_2}}, & x \geq 0, \\ 0, & x < 0, \end{cases} \tag{2}$$

where α_1 and α_2 are the average channel gain of g_{1n} and g_{2n}, respectively.

3. Data rate analysis

The transmission rate from the source S to destination D through relay r_n is,

$$R_n = \frac{1}{2}\min\left\{\log_2\left(1+\frac{P}{\sigma^2}g_{1n}\right), \log_2\left(1+\frac{P}{\sigma^2}g_{2n}\right)\right\} \tag{3}$$

$$= \frac{1}{2}\log_2\left(1+\frac{P}{\sigma^2}\min\{g_{1n}, g_{2n}\}\right), \tag{4}$$

where P is the transmit power at the source S and relays, and σ^2 denotes the variance of the additive white Gaussian noise (AWGN).

For this system, the source S chooses one of the relay r_{n^*} among N relays based on the max-min criterion. Then, the system transmission rate is,

$$R_{n^*} = \max_{n\in N} R_n \tag{5}$$

$$= \max_{n\in N}\log_2\left(1+\frac{P}{\sigma^2}z_n\right) \tag{6}$$

$$= \log_2\left(1+\frac{P}{\sigma^2}\max_{n\in N} z_n\right) \tag{7}$$

$$= \log_2\left(1+\frac{P}{\sigma^2}\max z_{n^*}\right), \tag{8}$$

where $z_{n^*} = \max_{n\in N} z_n$ and $z_n = \min\{g_{1n}, g_{2n}\}$. Subsequently, we derive the cumulative distribution function (CDF) of z_{n^*} as

$$F_{z_{n^*}}(Z) = P\{z_{n^*} \le Z\} \tag{9}$$

$$= P\{z_1 \le Z\}\cdot P\{z_2 \le Z\}\cdots P\{z_n \le Z\} \tag{10}$$

$$= \sum_{i=1}^{N} C_N^i\Big(-e^{-\frac{\alpha_1+\alpha_2}{\alpha_1\alpha_2}Z}\Big)^i, \tag{11}$$

Similarly, the PDF of z_{n^*} is

$$f_{Z_{n^*}}(Z) = \frac{dF_{z_{n^*}}(Z)}{dZ} \tag{12}$$

$$= \sum_{i=1}^{N} C_N^i(-1)^i(-i)\frac{\alpha_1+\alpha_2}{\alpha_1\alpha_2}e^{i\frac{\alpha_1+\alpha_2}{\alpha_1\alpha_2}z}. \tag{13}$$

Based on (13), the system transmission data rate through N relays with the optimal relay selection is derived as

$$R = \frac{1}{2}\int_0^\infty \log_2\left(1+\frac{P}{\sigma^2}z\right)f_{z_{n^*}}(z)dz \tag{14}$$

$$= \frac{1}{2}\int_0^\infty \log_2\left(1+\frac{P}{\sigma^2}z\right)\sum_{i=1}^{N} C_N^i(-1)^i(-i)\frac{\alpha_1+\alpha_2}{\alpha_1\alpha_2} \times e^{-iz\frac{\alpha_1+\alpha_2}{\alpha_1\alpha_2}}dz \tag{15}$$

$$= -\int_0^\infty \sum_{i=1}^{N} C_N^i(-1)^i e^{-iz\frac{\alpha_1+\alpha_2}{\alpha_1\alpha_2}}\frac{1}{z+\frac{\sigma^2}{P}}dz \tag{16}$$

$$= \frac{1}{2\ln 2}\sum_{i=1}^{N}\frac{C_N^i(-1)^i}{e^{-\frac{i\sigma^2(\alpha_1+\alpha_2)}{P\alpha_1\alpha_2}}}E_i\Big(-\frac{i\sigma^2(\alpha_1+\alpha_2)}{P\alpha_1\alpha_2}\Big), \tag{17}$$

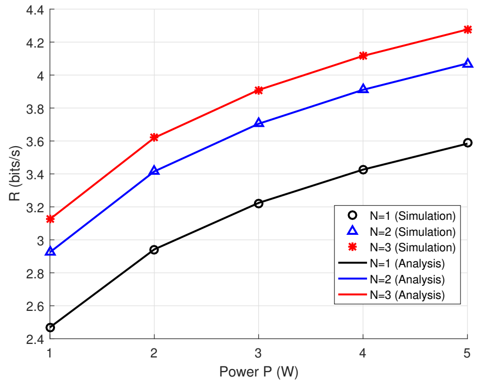

Figure 2. Effect of transmit power P on the transmit data rate.

where $E_i(x) = \int_{-\infty}^{x}\frac{e^t}{t}dt$ with $x<0$ is the exponentially integral function.

Note that the above derived analytical expression for the data rate is a crucial tool in the field of communication systems, serving as the cornerstone for system design, optimization, and performance evaluation. It can help make informed decisions regarding resource allocation, capacity planning, and quality of service guarantees. Moreover, it plays a pivotal role in the spectrum efficiency assessment, error rate analysis, and comparative evaluations of different communication technologies.

4. Simulation Results and Discussions

In this section, a series of simulations have been meticulously executed to rigorously validate the accuracy and effectiveness of the analytical results obtained in (17). These simulations serve as a critical step in corroborating the theoretical findings and ensuring their applicability to real-world scenarios. To provide a concrete context for the simulations, specific parameter values have been employed. If not specified, both the transmit power at the relay and the source have been set at a consistent power level of 1 Watt (1 W). This standardized power setting ensures a consistent basis for performance evaluation. Additionally, the noise power, represented by the parameter σ^2, has been configured at a value of 0.01 Watt (0.01 W). This level of noise power represents the background interference and thermal noise in the communication channel, a critical factor that can significantly affect the system performance. Through these simulations, the research aims to bridge the gap between theoretical predictions and practical outcomes, providing a comprehensive assessment of the proposed analytical model's effectiveness in real-world communication scenarios.

Fig. 2 and Table 1 present the effect of transmit power P on the transmit data rate, where P varies

Table 1 Numerical effect of transmit power P on the transmit data rate.

P	1	2	3	4	5
Sim $N=1$	2.4665	2.9383	3.2181	3.4276	3.58
Ana $N=1$	2.4688	2.9420	3.2243	3.4262	3.58
Sim $N=2$	2.9269	3.4150	3.7062	3.9111	4.06
Ana $N=2$	2.9245	3.4153	3.7046	3.9105	4.07
Sim $N=3$	3.1269	3.6206	3.9079	4.1165	4.27
Ana $N=3$	3.1253	3.6192	3.9097	4.1162	4.27

from 1W to 5W. From this figure and table, one can find that as the transmit power increases, there is a corresponding increase in the transmission data rate. This correlation is imperative in communication systems, as a higher power can help enhance the transmission quality. Moreover, it is illustrated that the number of relays N plays a significant role in augmenting the data rate. The addition of relays in a communication system can increase its transmission data rate by improving diversity and path selection. With more relays available, the system can choose a better suitable relaying path, resulting in potential enhancements in signal strength and quality. This can lead to a higher-data rate communication channel, as the system can dynamically adapt to select the best possible transmission paths based on the channel conditions. In further, the simulation and analysis results have a remarkable resemblance, which indicates that the theoretical analysis is reliable. This also suggests that the analytical model can correctly predict the performance of the system. These results indicate that multiple transmission paths can lead to diversity gain, which is a significant advantage for signal propagation in wireless communication systems. Such systems can efficiently select the most appropriate relay for signal propagation. This process can lead to improved signal quality and enhanced system data rate.

Fig. 3 and Table 2 illustrate the relationship between the transmission data rate R and the average channel gain α_1 for the first hop within the two-hop relay-assisted wireless network. We can find from this figure and table that with varying quantities of relays, specifically $N = 1$, $N = 2$ and $N = 3$, an increase in the average channel gain α_1 for the first hop is directly proportional to an enhancement in the channel data rate R for various numbers of relays. Moreover, it is evident that, for a given channel gain, the augmentation in the channel data rate R is substantial with an increase in the number of relays. Additionally, Fig. 3 and Table 2 show that the results of our analysis match the simulation results very well, thereby validating the theoretical model with empirical data.

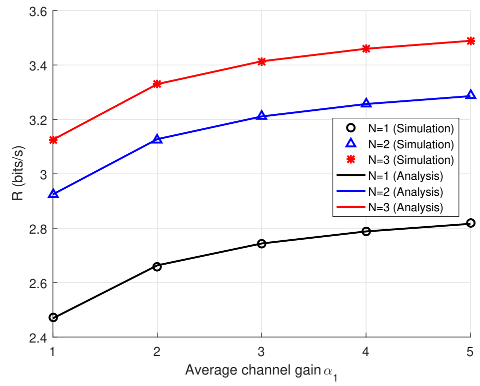

Figure 3. Impact of the average channel gain α_1 on the transmit data rate R.

Table 2 Numerical impact of the average channel gain α_1 on the transmit data rate R.

α_1	1	2	3	4	5
Sim $N=1$	2.4709	2.6597	2.7440	2.7881	2.81
Ana $N=1$	2.4688	2.6635	2.7440	2.7882	2.81
Sim $N=2$	2.9232	3.1235	3.2115	3.2580	3.28
Ana $N=2$	2.9245	3.1275	3.2109	3.2566	3.28
Sim $N=3$	3.1245	3.3301	3.4125	3.4609	3.48
Ana $N=3$	3.1253	3.3298	3.4138	3.4598	3.48

Similar to Fig. 3 and Table 2, Fig. 4 and Table 3 show the transmit data rate R of the two-hop relay-assisted wireless network versus the average channel gain α_2 of the second hop with different relay numbers. This figure and table clearly demonstrate that an increment in the average channel gain α_2 is helpful for the elevation in the transmit data rate R for various relay numbers. Moreover, it is evident that, for a given channel gain, the augmentation in the channel data rate R is substantial with an increase in the number of relays. In further, Fig. 4 and Table 3 show that the results of our analysis match the simulation results very well, thereby validating the theoretical expression with empirical data.

Fig. 5 and Table 4 present the impact of the number of relays N on the transmit data rate R with the average channel gain $\alpha_1 = \alpha_2 = 1$, 2 or 3, where N

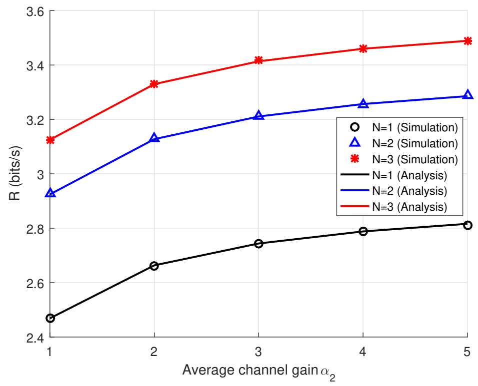

Figure 4. Impact of the average channel gain α_2 on the transmit data rate R.

Table 3 Numerical impact of the average channel gain α_2 on the transmit data rate R.3mm

α_2	1	2	3	4	5
Sim N = 1	2.4693	2.6621	2.7438	2.7885	2.81
Ana N = 1	2.4688	2.6635	2.7440	2.7882	2.81
Sim N = 2	2.9254	3.1290	3.2113	3.2554	3.28
Ana N = 2	2.9245	3.1275	3.2109	3.2566	3.28
Sim N = 3	3.1237	3.3311	3.4165	3.4604	3.48
Ana N = 3	3.1253	3.3298	3.4138	3.4598	3.48

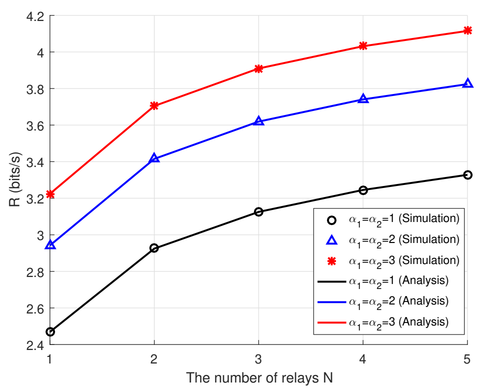

Figure 5. Transmit data rate R versus the number of relays N.

varies from 1 to 5. As show in Fig. 5 and Table 4, no matter $\alpha_1 = \alpha_2 = 1$, 2 or 3, the transmit data rate R increases with the increase of the number of relays N. The reason is that when the channel gains of g_1 and g_2 are the same, an increased number of relays enhances the channel diversity from the source to the destination.

Table 4 Numerical transmit data rate R versus the number of relays N.

N	1	2	3	4	5
Sim $\alpha_1 = \alpha_2 = 1$	2.4687	2.9259	3.1272	3.2452	3.32
Ana $\alpha_1 = \alpha_2 = 1$	2.4688	2.9245	3.1253	3.2453	3.32
Sim $\alpha_1 = \alpha_2 = 2$	2.9424	3.4141	3.6191	3.7398	3.82
Ana $\alpha_1 = \alpha_2 = 2$	2.9420	3.4153	3.6192	3.7405	3.82
Sim $\alpha_1 = \alpha_2 = 3$	3.2222	3.7062	3.9083	4.0319	4.11
Ana $\alpha_1 = \alpha_2 = 3$	3.2243	3.7046	3.9097	4.0314	4.11

This diversity allows the system to choose a better relay to assist the data transmission. As a result, the system transmit data rate is higher with an increased number of relays. Moreover, we can perceive that the transmit data rate R increases steadily with the increase of α_1 and α_2. In addition, the analysis results can well match the simulation results and validate the derived closed expressions for the transmit data rate of the system.

5. conclusion

This paper presented a novel approach to monitor the status of electrical equipment using IoT and relaying-aided transmission, where the data rate was used as the metric for evaluating the system monitoring performance. In this framework, relaying played a pivotal role, enhancing the efficiency of data transmission in the monitoring process. We employed the optimal relay selection criterion to choose the most effective relay to assist the transmission, thereby optimizing the communication link between the electrical equipment and the monitoring system. To provide a comprehensive understanding on the system performance, we delved into the analytical aspects by deriving expressions for the data rate. The analytical expression offered insights into the theoretical performance limits and the factors influencing the efficiency of the system. The theoretical framework was further complemented by a series of simulations. These simulations validated the analytical models developed in the study, and provided practical scenarios to demonstrate the real-world applicability and effectiveness of the proposed IoT and relaying-aided transmission in monitoring electrical equipment.

Acknowledgment

This work was supported by China Changjiang Electric Power Co., Ltd., with Grant number 422220006.

5.1. Copyright

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