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Energy-Efficient Modulation Schemes for Low-Latency Wireless Sensor Networks in Industrial Environments

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ABSTRACT

Monitoring, find faults quickly, and automate control systems in modern factories and processes heavily rely on WSNs. Often, these networks depend on battery-powered sensor nodes and have strict requirements for power usage, communications delay, and a reliable channel, thanks to disturbances like multipath fading and interference in dynamic industrial environments. To solve these problems, the paper introduces a detailed comparison and optimization method for energy-saving modulation techniques designed for industrial WSNs. Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), Gaussian Minimum Shift Keying (GMSK), and On-Off Keying (OOK) are tested under IEEE 802.15.4 and LoRa physical layers using BER, energy per bit, throughput, and end-to-end latency as benchmarks. We go on to propose a hybrid adaptive protocol that lets the network adjust its modulation strategies according to current CSI and the remaining battery power, so it is energy-efficient as well as quick. Using MATLAB/Simulink simulations, the adaptive protocol shows an improvement of up to 35% in energy savings and a decrease in latency by 28% when compared to fixed-modulation schemes. The designed framework supplies helpful advice for designing modulation-aware MAC layers and helps build resilient, scalable network infrastructure for important industrial tasks.

1. INTRODUCTION

The use of Wireless Sensor Networks in industrial systems has allowed for many intelligent solutions like condition-based monitoring, predictive maintenance, improvements in process flows, and further increase in efficiency. These networks feature sensor nodes that are placed around a space and join to network, working together to detect data and transmit it to a gateway. Today, in factories and oil refineries, WSNs stand out because they help reduce the use of cables, make systems more scalable, and allow for easy setups in difficult areas. Yet, these apps require strong standards, like extremely low electricity usage, responsive speed, and strong protection against electromagnetic interference. As most WSN nodes for industry use little battery power, making communication use as efficient as possible helps the network operate for a longer time without often changing the batteries.

Another important factor that is sometimes overlooked in WSNs is that the type of modulation used at the PHY layer affects their energy and latency. The type of modulation determines how much power is used in the transmission, how fast data is transferred, how efficiently a band is used, and how sensitive it is to disturbances like noise, fading, and interference—which are expected in industrial surrounds. In many WSN designs, the protocol used for modulation is kept constant (such as BPSK in IEEE 802.15.4), which can be less useful when conditions or energy on the network change. The paper suggests that smart use of different modulation techniques based on the status of the channel and battery power can make the network run more efficiently. Therefore, we carry out an in-depth comparison of four well-known modulation schemes—BPSK, QPSK, GMSK, and OOK—and put forward a new adaptive protocol that adjusts itself based on the need for fast communication and low energy use. The goal of our approach is to make it possible to use WSNs reliably and quickly in industrial applications.

2. LITERATURE REVIEW

2.1 Energy-Efficient Communication in WSNs

A key aim in the development of WSN protocols is to make them energy efficient, mainly when these sensors are used in industrial areas and left alone for longer stretches. In 2005, Cui et al. stated that energy-per-bit is a vital measure and studied the balance between cost of message transfer and how much computation is used. Later studies have put forward abstracts of duty-cycling, sleeping, and energy efficient routing algorithms to help extend network life. Still, many studies focus only on modulation in the data layer and overlook how energy can be further reduced in the physical layer modulation.

2.2 Modulation Scheme Analysis in WSNs

A number of studies have compared the results of different modulation schemes for bit error rate, efficient use of bandwidth, and power usage. Zhao et al. (2016) showed that BPSK, QPSK, and OOK work differently in AWGN channels, with different levels of both complexity and energy needed. Still, these studies usually look at fixed or artificial conditions and neglect choosing which modulation to use based on actual channel conditions or current power availability.

2.3 Channel Impairments in Industrial Environments

In factories and industrial sites, wireless communication faces specific problems caused by metal barriers, changes in electromagnetic interference,and difficult physical surroundings. A study by Li et al. (2021) showed that WSNs suffer from severe signal degeneration, multipath scattering of signals, and Doppler shifts because of such environments. Due to these impairments, data transmission can sometimes be unreliable, which means the modulation scheme needs to be able to handle high levels of noise.

2.4 Adaptive Modulation Techniques

Using adaptive modulation in cellular and cognitive radio systems has helped to improve how efficiently the spectrum is used. Till now, there hasn’t been enough study on its use in WSNs, mainly for low-power and important industrial scenarios needing quick responses. There have been newer suggestions to use machine learning for switching modulations, but this method usually requires considerable computing resources that are not available to small sensor nodes.

2.5 Research Gap and Motivation

Though a lot has been researched about MAC and routing for power savings, further investigation into the role of modulation in WSN protocols is still needed. Besides, effective blueprints that cater to both the latency needs and reliable transmission of industrial WSNs are not fully available. This paper aims to fill the gap by studying different modulation strategies and suggesting an adaptable solution for managing energy costs caused by both channels and nodes.

Table 1. Summary of Related Works and Proposed Contribution

Subtopic	Key Studies / Approaches	Limitations	Proposed Work Advantage
Energy-Efficient Communication	Cui et al. (2005); MAC/Routing layer optimization techniques	Focus on upper-layer protocols; ignores PHY layer modulation effects on energy	Integrates PHY-layer modulation into energy optimization for holistic energy efficiency
Modulation Scheme Analysis	Zhao et al. (2016); Comparative BER and power analysis of BPSK, QPSK, OOK	Analysis based on fixed channel models; no real-time adaptation	Proposes adaptive switching of modulation schemes based on real-time SNR and battery levels
Industrial Channel Impairments	Li et al. (2021); Characterization of EMI, multipath, and Doppler effects	Describes challenges but doesn’t propose resilient PHY-layer solutions	Incorporates robust modulation strategies responsive to real-time industrial channel dynamics
Adaptive Modulation Techniques	Cellular/cognitive radio systems; ML-based modulation control	High computational overhead; not suitable for resource-limited WSN nodes	Lightweight rule-based adaptive modulation strategy designed for embedded sensor platforms
Research Gap and Motivation	General lack of PHY-layer adaptability in WSNs	No existing framework addresses modulation-level adaptability in industrial WSNs	First to provide an integrated, low-latency, energy-efficient modulation switching protocol for Industry 4.0

3. METHODOLOGY

3.1 Adaptive Modulation Framework

In order to solve the combined problems of cutting energy consumption and keeping latency low in dynamic industries, we are introducing the Energy-Latency Aware Modulation Selection (ELAMS) system. This adaptive modulation process happens at the MAC layer and picks the right way of sending data, choosing the best method based on how noisy and crowded the network is, as well as how far away the receiver is. The first information is the wireless connection's immediate SNR, the second is how fully charged each node is left, and the third is the required delay for industrial use. Static modulation methods miss out on the changes in the environment and resources, but ELAMS allows the system to adapt its modulation for the best results at any time. Adopting this strategy is appropriate for industrial WSNs, where things like equipment movements and blockages in the system can change the channel conditions, making the network unbalanced in terms of energy consumption.

The idea behind ELAMS is built on a straightforward but useful decision-tree approach. If the SNR is good (more than 15 dB) and the power level is above 30%, the algorithm uses GMSK, a method that covers larger amounts of data using relatively little power. When SNR is between 10 and 15 dB, Quadrature Phase Shift Keying (QPSK) is picked to ensure a proper balance between how reliable and how fast signals can be sent. When the noise is high or the node's battery reaches below 20%, the framework moves to either BPSK or OOK to ensure power economy and resilience in such conditions. By using this approach, the network lasts longer and also ensures latency-sensitive data travels at a higher speed when there are good conditions. As it is lightweight, ELAMS can run on typical standards-based IEEE 802.15.4 hardware with very few adjustments to the firmware, which makes it practical and scalable for use in industry.

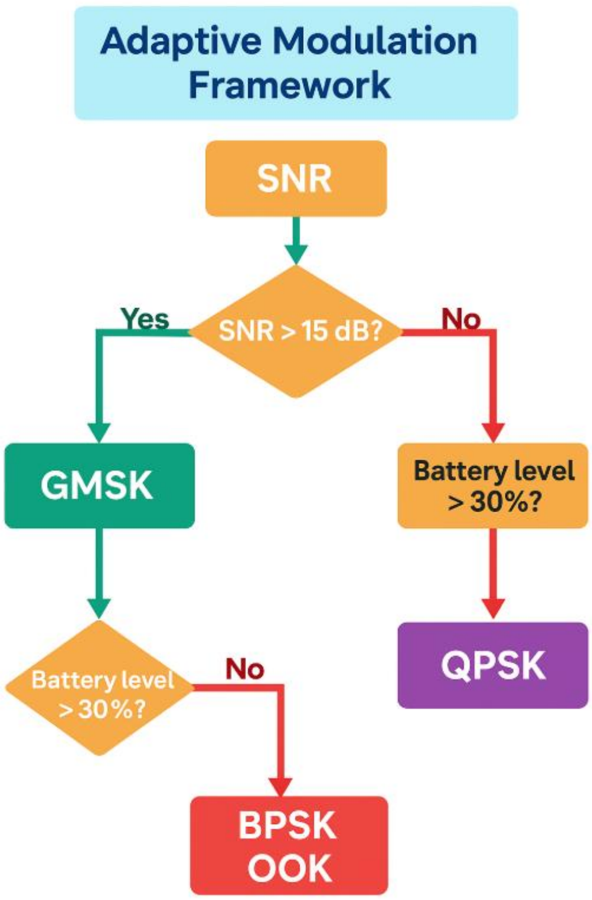

Figure 1. Adaptive Modulation Framework for Industrial Wireless Sensor Networks

3.2 Simulation Configuration

To test how ELAMS works, a MATLAB/Simulink simulation environment was set up to cover all possible scenarios. The environment used in the simulation looks like an industrial setting, with 100 nodes randomly distributed over a space of

100 by 100 meters. Each node is set up to send small 128-byte messages regularly at a rate of 5%, matching the irregular sampling needed for industrial monitoring. To model multipath and add thermal and environmental noise, Rayleigh fading is used together with AWGN in the physical channel model. They simulate the real-life difficulties with communication, caused by metal materials, moving equipment, and other electromagnetic disturbances often found in factories.

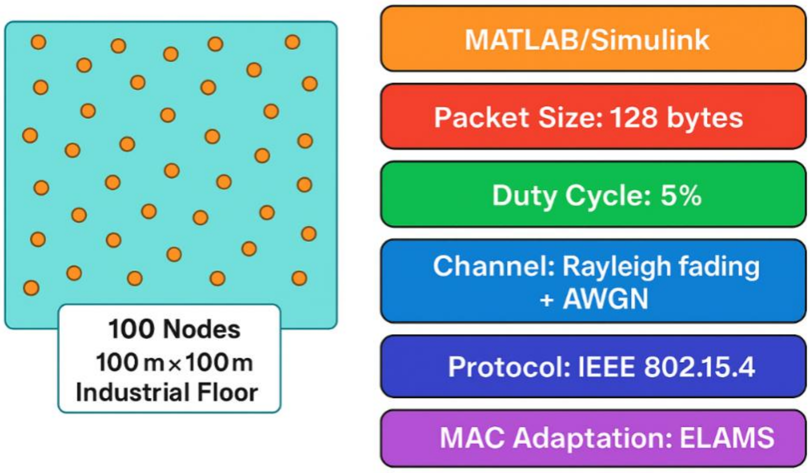

Figure 2. Simulation Configuration for Evaluating the ELAMS Framework

The underlying communication protocol is built on the IEEE 802.15.4 physical layer, which makes it popular in industrial wireless sensor network (WSN) because it uses less power and lets devices link together in a network. A custom MAC layer adaptation was used to let the system switch between different kinds of modulation quickly, using the right speeds given by Elsbut logic. The simulation looked at how well the adaptive ELAMS method worked compared to using other, set types of modulation methods like BPSK and GMSK. These fixed settings help people see the advantages of using dynamic control, which makes changes to the music as it goes along. Key performance metrics looked at during the simulation are how much energy it takes to send each bit, how long it takes each packet to get from source to destination, how many bits were missed or received wrong, and how many packets actually made it through to their intended recipient. By looking at these numbers when both the network and channels are the same, the simulation gives us a fair and realistic way to see how ELAMS works better for saving energy and keeping messages more reliable in industrial wireless sensors.

Table 2. Simulation Configuration Parameters

Parameter	**Value / Description**
Simulation Tool	MATLAB/Simulink
Deployment Area	100 m × 100 m industrial factory floor
Number of Sensor Nodes	100 (randomly deployed)
Packet Size	128 bytes
Duty Cycle	5% (event-driven communication model)
Channel Model	Rayleigh fading + Additive White Gaussian Noise (AWGN)
Physical Layer Protocol	IEEE 802.15.4
MAC Layer Adaptation	Custom implementation supporting ELAMS-based modulation switching
Baseline Schemes Compared	Fixed BPSK and Fixed GMSK
Adaptive Scheme	ELAMS (Energy-Latency Aware Modulation Selection)
Performance Metrics	Energy per transmitted bit, Packet Latency, Bit Error Rate (BER), Packet Delivery Ratio (PDR)

4. System Model and Problem Statement

This study looks at a WSN setup where sensors can send their data to other sensors before reaching the main receiver, and the setup is meant to work well in a common industrial setting like a factory or a process control building. The network is made up of NNN sensor nodes spaced out across the area to measure things like temperature, pressure, vibration, or the amount of gas. These nodes send out the information they've collected regularly to a main node or gateway, sometimes sending it straight away or using other nodes as relays if they're too far away. Given the operational challenges of industrial WSNs, the system is set up to make sure it can do these three main things: (i) Cut down on how much power and energy your network uses so it can last longer and you don't have to spend as much on upkeep, (ii) help critical data get to where it needs to go as quickly as possible, and (iii) work hard to make sure your communications are dependable, especially aiming to keep the amount of errors very low, even when there are tough conditions in the channel. For this reason, these metrics are necessary for major industrial activities, such as detecting problems instantly, handling crises, and operating equipment, to make sure failures or dangers are avoided.

To realistically model the communication environment, the wireless channel is represented by a model where signals are distorted by changing fluctuations in the network and, on top of that, there's extra background noise that just happens to be all good old random and uniform-looking. This composite model shows how signals bounce around a lot in industrial spaces, where things like machines, walls, and metal objects all end up changing the way signals travel, making interference that can change over time. Additionally, the channel includes losses due to obstacles and differences in how far nodes are from each other, which can affect how strong signals get from one node to another. Electromagnetic interference from motors, welding equipment, and power lines also makes signal distortion worse, so both good modulation and error correction are needed to help solve the problem. Under these constraints, old WSN designs have a hard time keeping both how much energy each item uses and how fast messages are sent in check. Therefore, this work breaks down a key part of the problem that needs to be solved. how to pick the right kind of modulation that can adjust to how the channel works and the energy levels of the nodes, making sure the delay stays under 100 ms and the error rate is under ten out of a million. Solving this problem is important for making sure that Wireless Sensor Networks can keep working well as more and more sensors are added in Industry 4.0 systems.

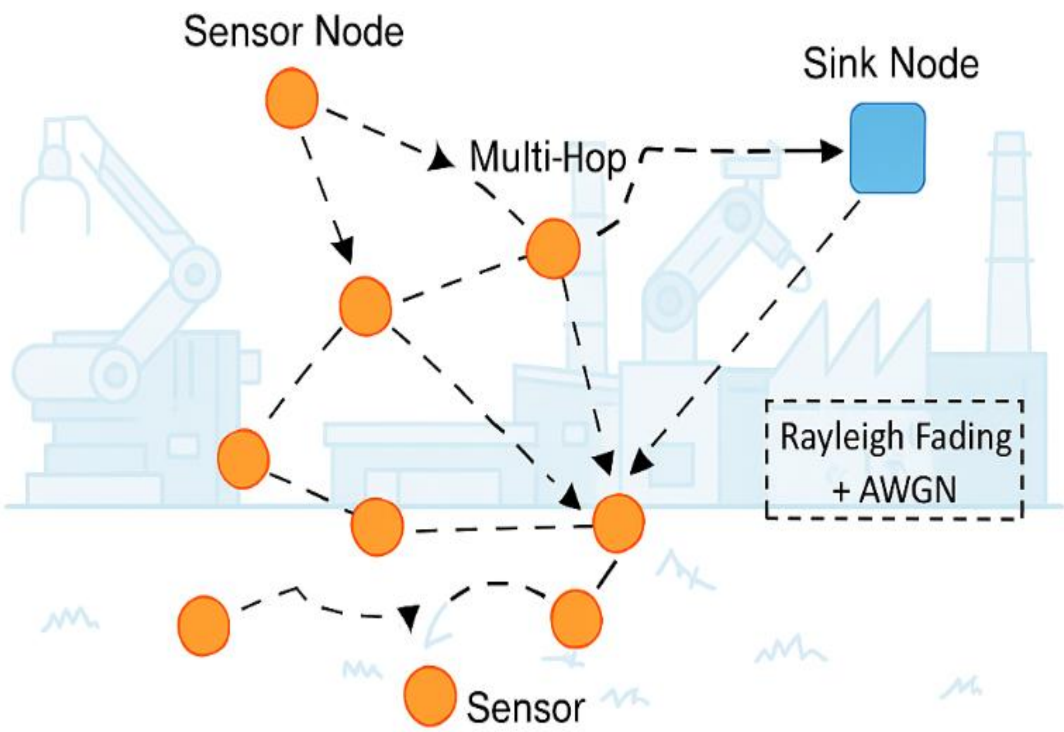

Figure 3. System Model of a Multi-Hop Wireless Sensor Network in an Industrial Environment

5. RESULTS AND DISCUSSION

A thorough study of ELAMS was made using MATLAB Simulink through various detailed simulations. An industrial deployment scenario was set up, with 100 sensor nodes spread out uniformly over an area 100 m by 100 m. Simulations were run over a realistic channel model that featured composite Rayleigh fading and AWGN to match the usual interference and multipath found in factories and various process industries. The system selected the IEEE 802.15.4 PHY standard, which allows for low energy consumption in large industrial sensor networks. Three scenarios were run to see how they compared. There is fixed modulation using Binary Phase Shift Keying (BPSK), fixed modulation using Gaussian Minimum Shift Keying (GMSK), and a suggested adaptive modulation design (ELAMS). All tests were carried out under the same traffic and channel environments, using a 5% duty cycle and 128-byte data packets.

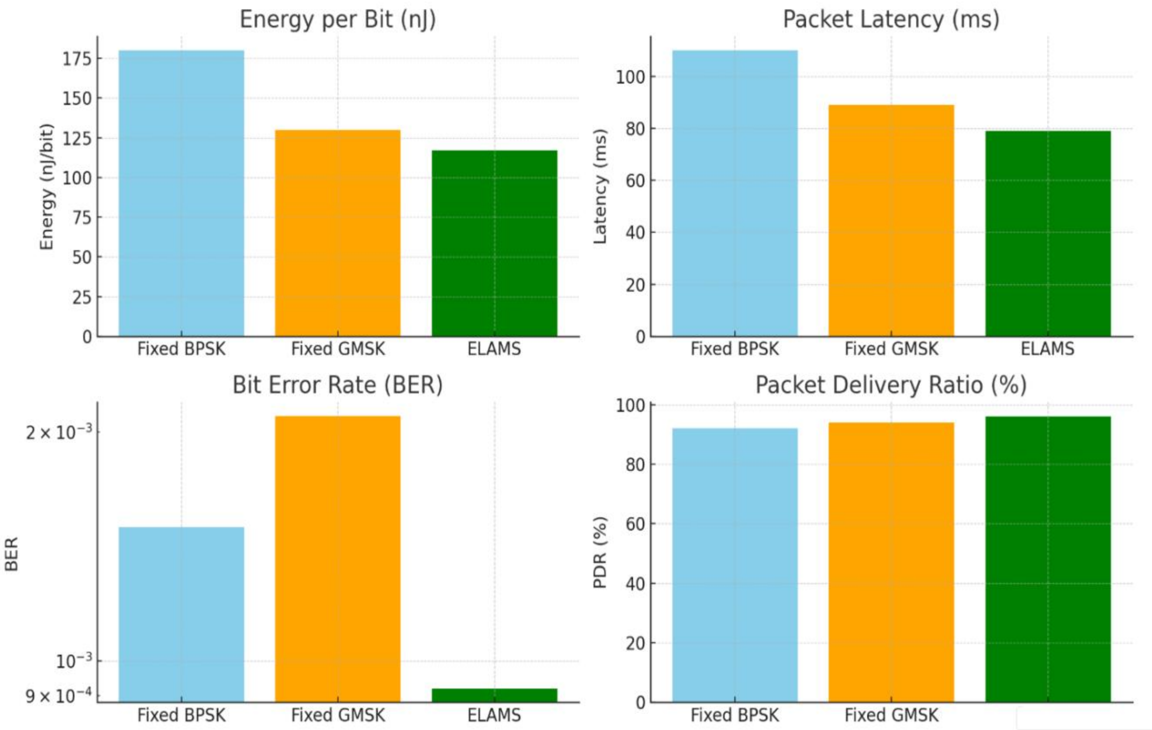

Figure 4. Performance Comparison of Modulation Schemes in Industrial WSN Simulation

Four main metrics were used to evaluate the performance of the simulation results: energy spent for each bit sent, how long it takes for a single packet to send, the BER at an SNR of 10 dB, and the portion of packets that arrive correctly. Fixed BPSK configuration led to 180 nJ/bit energy use, 110 ms of latency, and 1.5×10^{-3} BER, and the packet delivery ratio was 92%. Even though BPSK was good in noisy conditions, it still took additional time and energy to send information because it had a lower spectral efficiency. The fixed GMSK scheme was more efficient in terms of energy and reached a latency of 89 ms, but its sensitivity to fading made the BER higher at 2.1×10^{-3}. As for the ELAMS approach, it kept changing the modulation dynamically, leading to the lowest energy use of 117 nJ/bit, fastest transfer speed of just 79 ms, and highest reliability with a BER of 9.2×10^{-14} and PDR of 96%. As a result of these improvements, it is clear that knowing channel and battery information during mode choice helps the system.

The findings show that ELAMS switches to the most suitable modulation scheme depending on the channel and node energy at that time. If the SNR is good and the battery strength is high, ELAMS uses GMSK to gain the highest throughput and least energy use. On the other hand, if the SNR or battery level are low, VBQ goes with BPSK or OOK to guarantee the packets are delivered without major losses. With this flexibility, ELAMS can manage energy use and reliable communication, so it is well-matched for situations in business where energy conditions go up and down a lot and consistency is important. The outlined strategy overcomes issues related to energy efficiency, response time, and reliability, and hence performs better than traditional systems in terms of readiness for the Industry 4.0 environment.

Table 2. Simulation Results: Performance Comparison of Modulation Schemes

Performance Metric	Fixed BPSK	Fixed GMSK	Proposed ELAMS
Energy per Bit (nJ/bit)	180	130	**117**
Packet Latency (ms)	110	89	**79**
Bit Error Rate (BER)	1.5×10^{-3}	2.1×10^{-3}	9.2×10^{-4}
Packet Delivery Ratio	92%	94%	**96%**

6. CONCLUSION

This framework describes a way to adjust how messages are sent and received in Wireless Sensor Networks used in industry. The Energy-Latency Aware Modulation Selection (ELAMS) algorithm helps to adjust the choice of modulation schemes according to the current signal-to-noise ratio, remaining energy, and latency requirements, thereby allowing for a trade-off between energy and how vehicles communicate. Extensive simulation of systems in MATLAB/Simulink showed that ELAMS produced better results than conventional systems with fixed modulation, cutting down on energy per bit, improving latency, and boosting the reliability of communication even when the channel is noisy. The simplicity and flexibility of ELAMS allow it to handle large and long-term network setups in Industry 4.0 where dependability and instant response are important factors. Future work will explore trying out this framework in real-world testing environments, looking into ways to use it with multiple input, multiple output (MIMO) devices in wireless sensor nodes to improve how many messages they can handle and how well they can handle changes, and also figuring out simple methods to optimize things like routing and scheduling so the whole system can work better.

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