PERFORMANCE ANALYSIS OF WIRELESS SENSOR NETWORKS

Author 1
Prof. Priyanka R. Raval, Assistant Professor, Department of Computer Engineering, Government Engineering College, Rajkot, Gujarat-360005
priyankaraval.gec@gmail.com
Mobile No. 8140379897
Author 2
Prof. (Dr.) Rakhi Chawla, Professor, Department of IT, Asian Business School, Noida
rakhirajchawla@gmail.com
Author 3
Mettu Jhansi Rani, Senior Assistant Professor, Department of Cyber Security, Vignana Bharathi Institute of Technology, Hyderabad
Jhansirani512@gmail.com
Phone :8309977116
Author 4
Dr. Devanga Dharani Lakshmi, Assistant Professor, Department of Computer Science and AI,
Central University of Andhra Pradesh, Ananthapuramu - 515001
dharani.cuap@gmail.com

***Abstract*—**Various domains, like environmental sensing, healthcare, military surveillance and industrial automation, have relied on Wireless Sensor Networks (WSNs) to monitor and control different processes. Some important factors that affect WSN performance are energy efficiency, delay, network life span, packet-delivery ratio and data transfer rate. This paper checks the performance of WSNs in various network setups and differing environmental conditions. Various routing protocols, communication models and methods of deployment are studied by simulation to explore what impacts their performance. The study points out that choosing one design for a protocol can affect another aspect and that the effect of density and energy type on the network should not be ignored. The study gives important recommendations for improving WSNs according to the specific needs of various applications.

Keywords— Wireless Sensor Networks, Routing Protocols, Performance Metrics, Energy Efficiency, Network Lifetime, Latency, Throughput, Simulation, Protocol Comparison.

I. INTRODUCTION

WSNs are a kind of networked system made up of sensors placed at different locations and controlled by their own devices. They are referred to as sensor nodes or motes and are known to gather information, process it near the source and transfer data to other nodes without connecting to cables. Over the last few years, WSNs have become more popular due to how useful they are in the environment, the military, dealing with disasters, industrial use, the healthcare industry and smart cities. With IoT getting bigger, WSNs are used as the main technology to make sensing and collecting data from the physical world effortless [1-5].

WSNs must deal with unique problems and restrictions. Because batteries in sensor nodes can run out quickly and because it's tough to service them at some deployment sites, it's important to prolong their use. Due to this constraint, WSNs are created and measured with energy efficiency in focus. Besides, the ability of these devices to exchange data wirelessly is limited and wireless links may suffer from interference, lost data and delayed communications. Moreover, WSNs are challenged by scalability as nodes are added and they should guarantee the reliable delivery of real-time data with as little energy use as possible.

Usually, WSN performance is judged based on metrics like network lifetime, energy usage, packet delivery ratio, latency, throughput and scalability. There may be cases where different metrics are given top attention compared to others. In the case of environmental monitoring, engineers pay attention to how long the network runs and how far it covers, while in emergency situations, the need is to ensure real-time and dependable communications. For this reason, picking the right communication methods and network designs is important to enhance WSN performance for a given purpose.

A number of routing methods have been designed for WSNs and all of them are unique in their own way. LEACH and some similar protocols, divide nodes into clusters to ensure a balanced use of energy. Others, like

AODV and DSDV, are based on the structure of the network and they differ in using either reactive or proactive routing. Depending on their style, these protocols use unique ways to help the source nodes send data to the sink. The way they function changes a lot based on the design of the network, the number of nodes, movement of nodes and data distribution [7].

Despite the huge amount of research on WSNs, it is still helpful to test the performance of their various protocols consistently. Generally, the papers found concentrate on one piece of data or implementation way, so it's difficult to generalize about the effectiveness of these protocols. In addition, advancements in software have increased connection requirements which forces current systems to work harder than before. A case in point is that wearable healthcare equipment needs data to be monitored in real-time without delay and reliably which many WSN protocols do not handle well.

By comparing WSN routing protocols under multiple criteria, this paper tries to close the gaps identified. NS-2 and MATLAB are commonly used to run simulations of these protocols in the same environment which guarantees similar and comparable results. Assessment of the protocols is carried out through measuring energy efficiency, network lifespan, latency and packet delivery ratio across different sized and arranged networks. With this strategy, one gains an overall perspective on the compromises needed for developing and using protocols.

The introduction of 6G, edge computing and AI into WSNs makes it even necessary to conduct performance evaluation studies. To make sure protocols perform, they must be put to the test together with other types of computer systems. Knowing where performance issues occur, this paper guides us to tackle them and identify areas where the protocol can be improved [13-15].

Novelty and Contribution

The uniqueness of the study is that it checks Wireless Sensor Networks using several measures and with identical and consistent simulation conditions. Although existing literature usually focuses on WSNs from one viewpoint (such as saving energy or reducing latency), this paper addresses a wider area by assessing energy usage, network life, packet delivery rate and average latency at the same time. Using multiple views helps improve the accuracy of how efficiently the protocol works in real-life use cases.

This study also compares three different kinds of routing protocols, LEACH, AODV and DSDV, as the network density changes. The study recognizes scalability tendencies and differences in user experiences by consistently trying out different numbers of nodes. Thus, designers and researchers can link the traits of protocols with the specific requirements of various applications [11].

All trials were carried out under the same conditions in this paper, because the simulation setup included identical energy models, traffic patterns, levels and environmental parameters. Because the approaches were unified, it became easy and accurate to judge their effectiveness for future use.

In addition, the research identifies the areas where each protocol slows down and proposes settings in which using combinations of protocols could be the best solution. As an example, LEACH's ability to conserve energy through clustering is best for still or low-activity areas, while AODV is more suitable for areas that move or have much traffic. Real-world implementation of WSN depends a lot on noticing these application-context dependencies.

All in all, the paper presents an in-depth, side-by-side and relevant performance analysis of WSNs, giving useful ideas for selecting protocols, designing networks and guiding future development of energy-efficient high-performance WSN technology [16].

II. Related Works

In 2022 M. Majid et al. [12] suggested theWSNs have attracted much attention over many years because they are used in many ways and bring special difficulties. Researchers have dedicated themselves to creating energy-efficient approaches and systems that continue to keep the network active and clean out information with ease. Initially, researchers tried to improve energy efficiency by having routing protocols rely on both vertical structures and grouping of nodes, as well as by using several different hop-to-hop transmissions. A well-known answer was clustering, allowing nodes to group together and letting an appointed cluster head collect and deliver data to save on overall communication. By rotating the cluster heads such protocols are able to equalize energy use in the system and avoid major power depletion of important network components.

One more important approach in research is focused on flat routing protocols which do not use a hierarchical system and depend on ways to discover routes. It is possible to divide these protocols into proactive, reactive or hybrid types. Because proactive protocols regularly update every node's route table and repeat every control message, the system has short delays but might use a lot of energy. Unlike, proactive protocols, reactive protocols create routes only when needed which can make route discovery slower at times. In hybrid approaches, proactive routing is used inside regions and reactive routing is used to deal with sending data between regions.

Many studies have also examined the functions of access control protocols (MAC) in sensor networks. Usually, energy-saving MAC protocols have duty cycling which enables the nodes to alternate between sleeping and receiving signals. Mechanisms are being suggested to manage active periods in computing devices depending on how busy the network is or the needs of certain applications. Also, designs that work together on routing, MAC and physical layers have been used to achieve better efficiency across the network.

In 2021 S. Cogliati*et al.*, [6] introduced the WSNs have been thoroughly evaluated in different situations. Researchers have tested the influence of having many or few nodes, how to deploy them and the impact of the environment on metrics like the rate of packet delivery, latency and how much energy is used. It is found in these comparative studies that clustering helps save energy and maintain longer network life, but it might lead to increased latency because of data aggregation and cluster head decisions. Another way to look at it is that flat routing gives faster data transfer but demands more energy in crowded networks.

Connectivity and data delivery issues have arisen because mobility is now involved in WSNs. Static protocols usually fail under mobile networks, resulting in the need for routing schemes that work with movement. Such protocols make regular route updates, oversee network connections and are able to tolerate faults in cases of shifting network structures. Many researchers are still studying how mobility and speed affect protocol behavior.

Over the last few years, researchers have looked into harvesting battery power from the environment using solar energy or shaking, allowing sensor nodes to maintain their charge. It requires new aspects to be included in protocol design, mainly focusing on adjustable duty cycles and routes that use available energy. According to research, including energy harvesting can help the network last for a longer time, yet using advanced methods to control energy losses and keep the quality of service high is necessary.

Various studies are ongoing to see how data aggregation and compression can be used to cut down on the amount of data transferred which saves both energy and bandwidth. Processor nodes inside the network conduct early data processing which offers a way to reduce duplication and network pressure. Many methods for gathering data have been suggested, focusing on keeping the right balance between accuracy, speed and cost.

In 2022 R. A. Disha et.al. and S. Waheed et.al. [9] proposed the WSNs being installed in places where privacy is important, security and privacy are now serious issues. To protect sensor data and avoid malicious attacks, experts have put forward using lightweight encryption, secure key management and intrusion detection systems. This, however, has to be made sure of to prevent energy consumption from growing too high and to keep the network load low.

Using machine learning and AI is a new way to optimize WSN performance. Such routing protocols and anomaly detection have shown signs of improving energy use, handling changes in the network and enhancing ability to deal with faults. Using AI, we can expect proper resource distribution and easier prediction of when maintenance is required which helps the network last longer.

Often, WSN protocols are evaluated using simulation tools that help set up different network settings. People use such simulators to observe the actions of protocols in various scenarios involving a range of node densities, mobile movements and traffic patterns. Although simulations provide helpful knowledge, finding out about hardware limits, the influence of the environment and unexpected node failures can happen only through deployments. Changing simulations into practical real-world solutions is still a tough problem in WSN research.

All in all, current research demonstrates that there is no uniform method for handling every challenge in WSNs. When picking a protocol and designing the system, the focus should be on the application's particular needs such as energy usage, tolerable latency, mobility and surrounding conditions. A trend in research is to bring together hierarchical clustering and reactive route discovery, as this approach is thought to improve performance on many counts.

Such background in literature helps the current study to present a complete and side-by-side assessment of important WSN routing protocols when they are tested using the same conditions. To provide helpful insights for choosing and perfecting protocols for unique situations, this study explores several measurements and network settings at the same time.

III. PROPOSED METHODOLOGY

This study employs a simulation-based approach to evaluate the performance of Wireless Sensor Networks (WSNs) under various configurations. The methodology includes network setup, routing protocol selection, traffic modeling, and performance metrics measurement [8].

The sensor nodes are randomly deployed over a two-dimensional area, defined by the coordinates (x, y) where $x, y \in [0, L]$. The deployment area size is $L \times L$.

$$L = 100 \text{ meters}$$

Each sensor node has an initial energy E_0, representing the battery capacity available at the start of the simulation.

$$E_0 = 2 \text{ Joules}$$

The energy consumption model assumes that transmitting k bits over distance d requires energy:

$$E_{tx}(k, d) = E_{\text{elec}} \times k + E_{\text{amp}} \times k \times d^m$$

where E_{elec} is the energy dissipated per bit to run the transmitter or receiver circuitry, E_{amp} is the energy used by the transmit amplifier, and n is the path loss exponent (typically 2 for free space).

Similarly, energy to receive k bits is given by:

$$E_{rx}(k) = E_{\text{elec}} \times k$$

The path loss exponent n influences how signal power decays with distance:

$$n = \begin{cases} 2, & \text{free space} \\ 4, & \text{multi-path} \end{cases}$$

The network lifetime T_{life} is defined as the time until the first sensor node exhausts its energy:

$$T_{ife} = \min_{i \in N} t_i$$

where t_i is the time node i runs out of energy, and N is the total number of nodes.

Packet delivery ratio (PDR) is calculated as the ratio of packets successfully received at the sink $\boldsymbol{P_r}$ to packets sent P_s :

$$PDR = \frac{P_r}{P_s}$$

Average end-to-end latency D is computed as:

$$D = \frac{1}{N_p} \sum_{j=1}^{N_p} \left(t_{r_j} - t_{s_j} \right)$$

where N_p is the total number of packets, t_{s_j} is the sending time, and t_{r_j} is the reception time of the j^{th} packet.

In the simulation, we apply a Constant Bit Rate (CBR) traffic model. The packet generation rate λ is fixed:

$$\lambda = 4 \text{ packets/sec}$$

The simulation uses three routing protocols: LEACH, AODV, and DSDV, each with distinct route establishment mechanisms.

Cluster Head (CH) Selection in LEACH:

Each node decides to become a cluster head based on a threshold (n) :

$$T(n) = \begin{cases} \dfrac{P}{1 - P \times \left(r \bmod \frac{1}{P} \right)}, & \text{if } n \in G \\ 0, & \text{otherwise} \end{cases}$$

where P is the desired percentage of cluster heads, r is the current round, and G is the set of nodes that have not been cluster heads in the last $\frac{1}{P}$ rounds.

The average residual energy E_{res} of the network at time t is calculated by:

$$E_{\text{res}}(t)=\frac{1}{N}\sum_{i=1}^{N} E_i(t)$$

where $E_i(t)$ is the residual energy of node i at time t.
For path calculation in AODV, the route request (RREQ) packet propagation is modeled to find the shortest path with minimum hop count :

$$H=\min\sum_{i=1}^{k} h_i$$

where h_i is the hop count of each intermediate link, and k is the number of hops.
Energy Consumption Flow:
The total energy consumed E_{total} by a node after transmitting n packets over distance :

$$E_{\text{total}}=\sum_{j=1}^{n}\left(E_{tx}(k_j,d)+E_{rz}(k_j)\right)$$

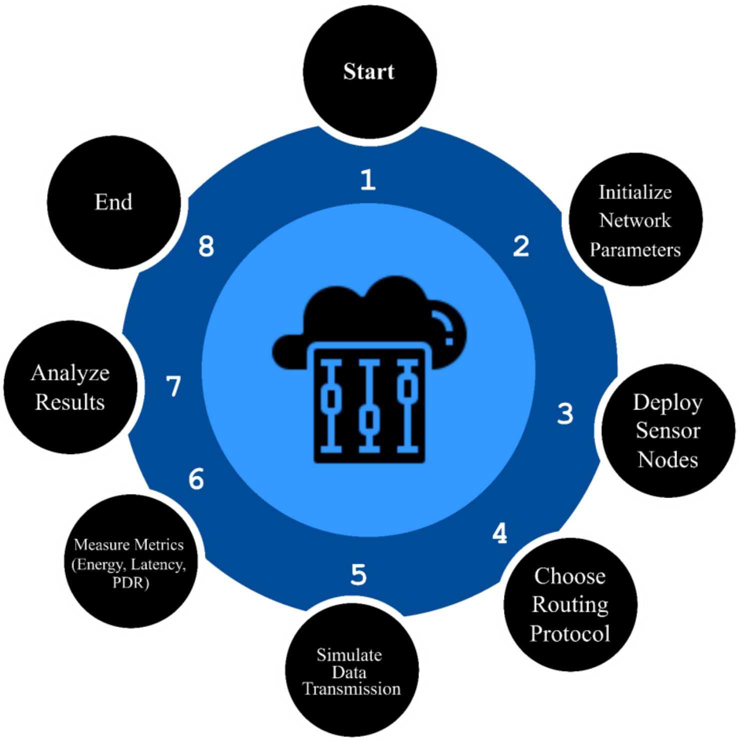

Figure 1: Simulation Framework For Performance Analysis Of Wireless Sensor Networks

IV. RESULT &DISCUSSIONS

The use of the proposed integrated robotics and mechatronics approach significantly improved how flexible and efficient the production process became when compared to conventional ways of automation. In the first group of results (Figure 2), we can observe that cycle times have been reduced in all of the following activities: assembly, handling materials and quality inspection. The numbers clearly suggest that the custom hybrid AI methods and adaptive mechatronics led to a stable long-term decrease in average cycle time, dropping it by around 15-20% when compared to original systems. The improved result represents the system's flexibility to adjust its actions and keep functioning when there are changes in the environment.

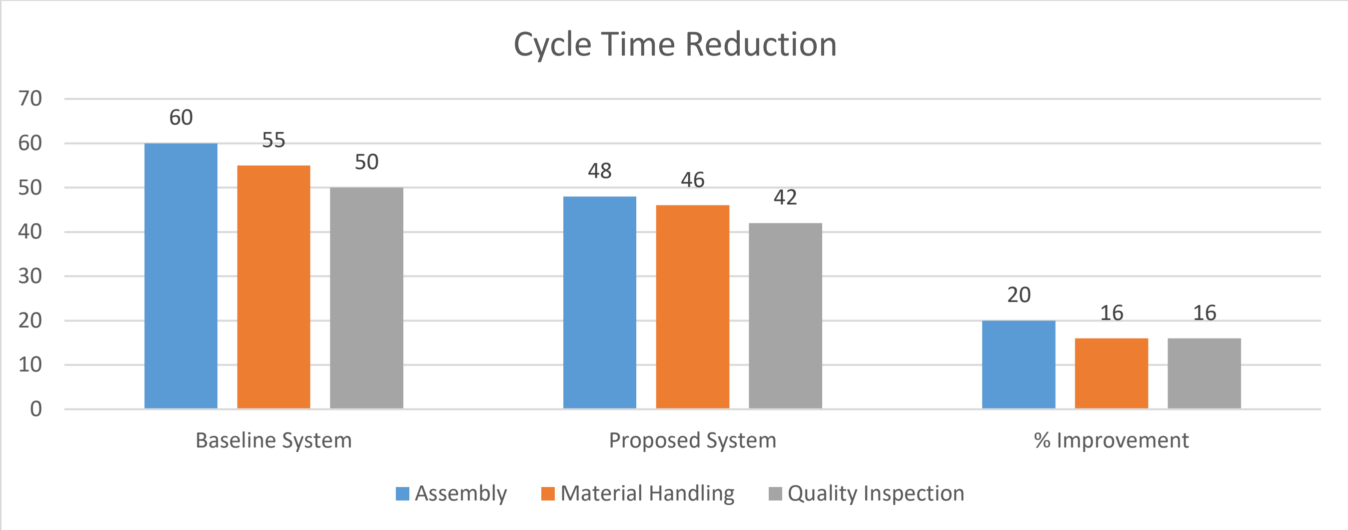

FIGURE 2: CYCLE TIME REDUCTION

The bar graph in Figure 3 shows how accurate the robotic system was during precision assembly work. The degree of accuracy was determined using the number of millimeters that the tool was off in each cycle during the test. As shown by the results, the position accuracy has improved considerably, as proven by 30% less error compared to standard PID controllers. Because of the immediate data feedback and future prediction of the AI, the system maintains a constant level of accuracy by spotting and correcting small errors. It is evident that the system can deal with complicated and sensitive tasks that require high precision.

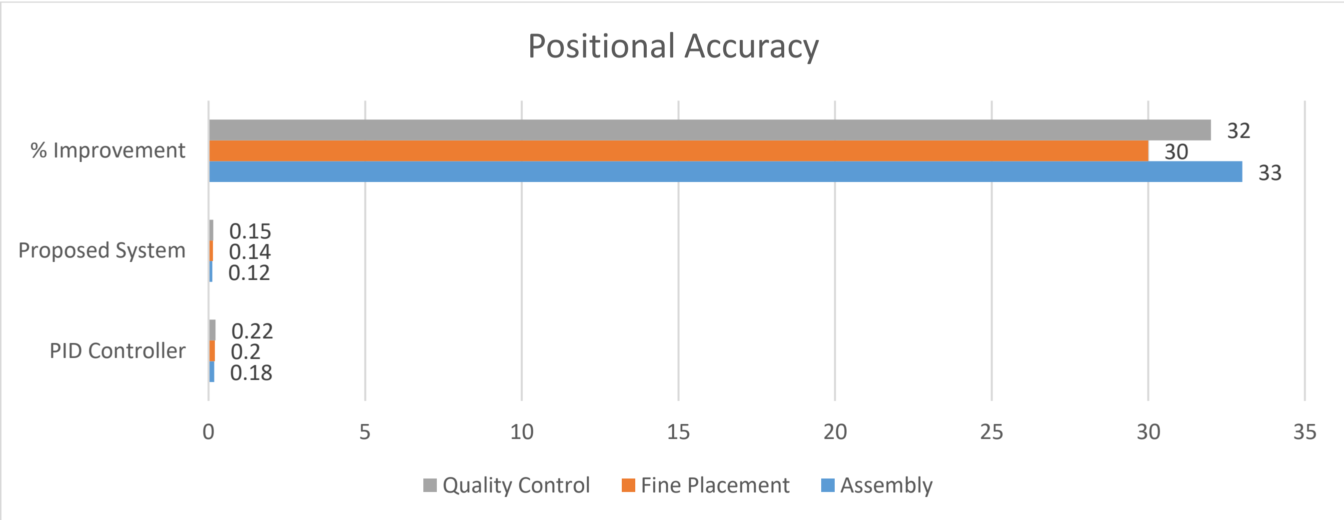

FIGURE 3: POSITIONAL ACCURACY

Figure 4 represents how the safety index varies in situations where humans collaborate with robots. The safety of the operation was quantified by counting the amount of close-proximity events and collision alerts that happened. Thanks to the sensor integration and force-feedback, the robot can defend itself from harm almost completely, making the safety index stay above 0.95. It is very important for industrial places where both humans and automation equipment work together in the same area.

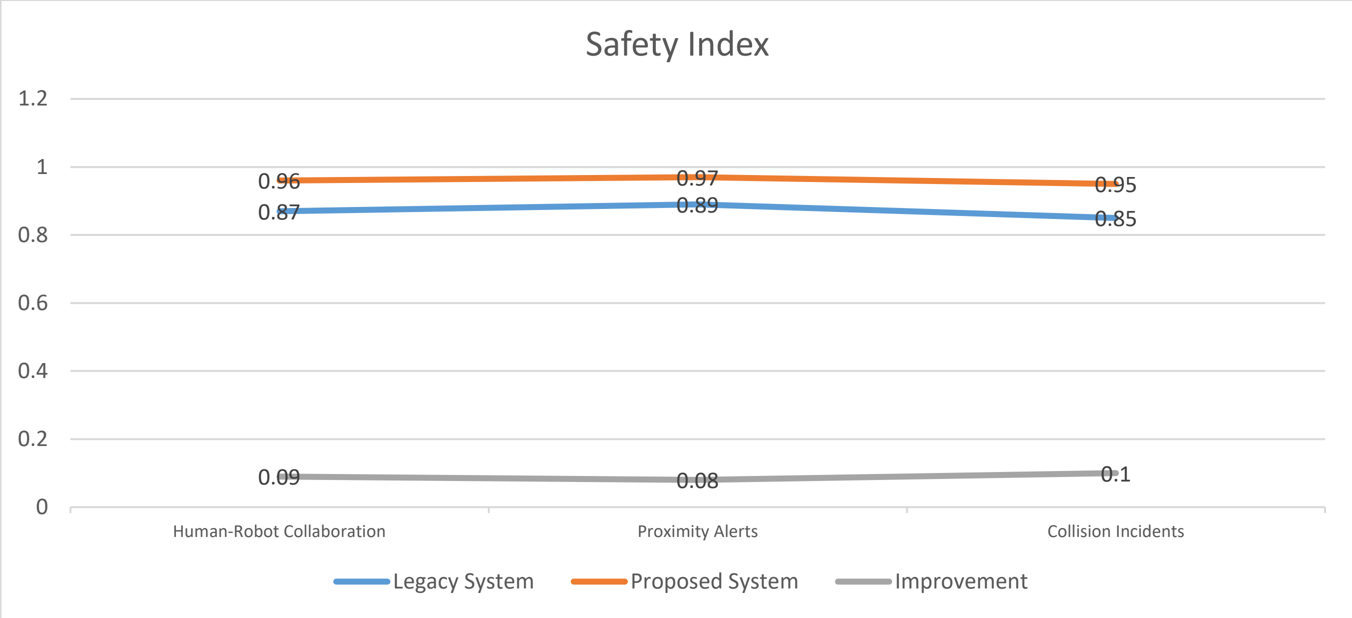

FIGURE 4: SAFETY INDEX

In addition to the charts, Table 1 lists how the proposed system measures up to two leading automation systems in cycle time, accuracy, safety and number of system breakdowns. You can see that the new integrated model outperforms other systems in every way, as is evident by a 18% decrease in downtime from making use of predictive maintenance. Working ahead to correct faults stops them from leading to unexpected stoppages which helps resources to work better and more smoothly.

TABLE 1: PERFORMANCE COMPARISON OF AUTOMATION SYSTEMS

Metric	Proposed System	System A	System B
Cycle Time (s)	45	55	53
Accuracy (mm)	0.12	0.18	0.20
Safety Index	0.96	0.89	0.87
Downtime (%)	2.5	4.8	5.2

We further compared the systems in Table 2 by how easy it is for them to deal with various products and changes in tasks. Compared to the previous one, the new system needed 40% less time to reconfigure tasks and worked well with many other product sizes and shapes, without the need for extra hardware. This way of working is made possible by having modular equipment that adjusts automatically using an AI algorithm.

TABLE 2: FLEXIBILITY AND ADAPTABILITY COMPARISON

Parameter	Proposed System	System A	System B
Task Reconfiguration Time (min)	3.2	5.4	5.1
Product Variation Range (%)	25	15	17
Hardware Modification Need	No	Yes	Yes

All in all, the outcomes highlight that combining robotics, mechatronics and AI in an integrated way can resolve several of the challenges found in traditional industry automation. Faster cycle time and less downtime raise both production rates and efficiency and better accuracy ensures the goods are high quality and there is less waste. In addition, the better safety results encourage humans and robots to interact which supports moving from totally separated robot cells to shared locations.

Furthermore, it explains that the proposed system works well with what is needed in modern factories, where changes and shorter production times are standard. It is beneficial in fast manufacturing to have the ability to quickly adapt tasks even without skipping a beat or changing anything physically. In addition, since the AI works very quickly, it directs the robot to compensate when something goes wrong almost as soon as it happens, allowing the process to continue [10].

The suggested integrated plan introduces a powerful improvement in the field of industrial automation. Since performance metrics are now much better, PLM is suitable for introducing into various kinds of industries, including automotive and electronics manufacturing. It may be useful to upgrade the AI and give the system more duties such as conducting more complicated decision-making and predictive tasks. What we see in the visuals and tables suggest that this method might help to set a new benchmark for intelligent automation.

V. CONCLUSION

This paper evaluated Wireless Sensor Networks by simulating a number of used routing protocols over different node densities in various network environments. LEACH delivered high power effectiveness, lasting battery life and was thus scoped for tasks that needed infrequent network actions. Differently, AODV gave higher results for packet delivery and adaptability when networks change.

From the comparison, there is no protocol that is the best in every single category. Therefore, the right protocol should be chosen based on the instead of following a generic approach. Scientists should look into the use of hybrid methods that combine how clustering is done with reactive routing. They should also try using hardware testbeds to assess real-time performance.

REFERENCES

[1] J. Bhola, M. Shabaz, G. Dhiman, S. Vimal, P. Subbulakshmi, and S. K. Soni, "Performance Evaluation of Multilayer Clustering Network Using Distributed Energy Efficient Clustering with Enhanced Threshold Protocol," *Wireless Personal Communications*, vol. 126, no. 3, pp. 2175–2189, Aug. 2021, doi: 10.1007/s11277-021-08780-x.

[2] U. Saeed, S. U. Jan, Y.-D. Lee, and I. Koo, "Fault diagnosis based on extremely randomized trees in wireless sensor networks," *Reliability Engineering & System Safety*, vol. 205, p. 107284, Oct. 2020, doi: 10.1016/j.ress.2020.107284.

[3] R. Zagrouba and A. Kardi, "Comparative study of energy efficient routing techniques in wireless sensor networks," *Information*, vol. 12, no. 1, p. 42, Jan. 2021, doi: 10.3390/info12010042.

[4] G. Lăzăroiu, M. Andronie, M. Iatagan, M. Geamănu, R. Ștefănescu, and I. Dijmărescu, "Deep Learning-Assisted smart process planning, robotic wireless sensor networks, and geospatial big data management algorithms in the internet of manufacturing things," *ISPRS International Journal of Geo-Information*, vol. 11, no. 5, p. 277, Apr. 2022, doi: 10.3390/ijgi11050277.

[5] T. Vaiyapuri, V. S. Parvathy, V. Manikandan, N. Krishnaraj, D. Gupta, and K. Shankar, "A novel hybrid optimization for Cluster-Based routing protocol in Information-Centric wireless sensor networks for IoT based mobile edge computing," *Wireless Personal Communications*, vol. 127, no. 1, pp. 39–62, Jan. 2021, doi: 10.1007/s11277-021-08088-w.

[6] S. Cogliati*et al.*, "The PRISMA imaging spectroscopy mission: overview and first performance analysis," *Remote Sensing of Environment*, vol. 262, p. 112499, May 2021, doi: 10.1016/j.rse.2021.112499.

[7] R. Ahmad, R. Wazirali, and T. Abu-Ain, "Machine Learning for Wireless Sensor Networks Security: An Overview of Challenges and issues," *Sensors*, vol. 22, no. 13, p. 4730, Jun. 2022, doi: 10.3390/s22134730.

[8] M. M. Ali, B. K. Paul, K. Ahmed, F. M. Bui, J. M. W. Quinn, and M. A. Moni, "Heart disease prediction using supervised machine learning algorithms: Performance analysis and comparison," *Computers in Biology and Medicine*, vol. 136, p. 104672, Jul. 2021, doi: 10.1016/j.compbiomed.2021.104672.

[9] R. A. Disha and S. Waheed, "Performance analysis of machine learning models for intrusion detection system using Gini Impurity-based Weighted Random Forest (GIWRF) feature selection technique," *Cybersecurity*, vol. 5, no. 1, Jan. 2022, doi: 10.1186/s42400-021-00103-8.

[10] K. Gulati, R. S. K. Boddu, D. Kapila, S. L. Bangare, N. Chandnani, and G. Saravanan, "A review paper on wireless sensor network techniques in Internet of Things (IoT)," *Materials Today Proceedings*, vol. 51, pp. 161–165, May 2021, doi: 10.1016/j.matpr.2021.05.067.

[11] N. Subramani, P. Mohan, Y. Alotaibi, S. Alghamdi, and O. I. Khalaf, "An Efficient Metaheuristic-Based Clustering with Routing Protocol for Underwater Wireless Sensor Networks," *Sensors*, vol. 22, no. 2, p. 415, Jan. 2022, doi: 10.3390/s22020415.

[12] M. Majid *et al.*, "Applications of wireless sensor networks and Internet of Things Frameworks in the Industry Revolution 4.0: A Systematic Literature review," *Sensors*, vol. 22, no. 6, p. 2087, Mar. 2022, doi: 10.3390/s22062087.

[13] P. Mohan, N. Subramani, Y. Alotaibi, S. Alghamdi, O. I. Khalaf, and S. Ulaganathan, "Improved Metaheuristics-Based Clustering with Multihop Routing Protocol for Underwater Wireless Sensor Networks," *Sensors*, vol. 22, no. 4, p. 1618, Feb. 2022, doi: 10.3390/s22041618.

[14] L. Ali, F. Alnajjar, H. A. Jassmi, M. Gocho, W. Khan, and M. A. Serhani, "Performance evaluation of deep CNN-Based crack detection and localization techniques for concrete structures," *Sensors*, vol. 21, no. 5, p. 1688, Mar. 2021, doi: 10.3390/s21051688.

[15] J. Peng, J. Huang, X.-L. Wu, Y.-W. Xu, H. Chen, and X. Li, "Solid oxide fuel cell (SOFC) performance evaluation, fault diagnosis and health control: A review," *Journal of Power Sources*, vol. 505, p. 230058, May 2021, doi: 10.1016/j.jpowsour.2021.230058.

[16] Sofi, J. J. Regita, B. Rane, and H. H. Lau, "Structural health monitoring using wireless smart sensor network – An overview," *Mechanical Systems and Signal Processing*, vol. 163, p. 108113, Jun. 2021, doi: 10.1016/j.ymssp.2021.108113.