

A Taxonomy-Based Survey of Energy Efficiency, Security and Scalability Challenges in Wireless Body Area Network Routing Protocols

C.G Kokane Pawar¹, S B.Vanjale², M.S.Vanjale³

¹ Dept.of Computer Engineering, BV(DU) College of Engineering, Pune.
Email: chirag.kokane@gmail.com

² Dept.of Computer Engineering, BV(DU) College of Engineering, Pune.

³Dept. of E&TC Engineering AISSMS Institute of Information Technology, Pune.

Abstract: Wireless Body Area Networks (WBANs) is growing up technologies that enable continuous health monitoring by using wearable and implantable sensor nodes. Routing process in this network is challenging due to factors such as energy limitation of sensor nodes, the need to frequently transmit data, motion of human body and security constraints. Well-developed routing implementing above factors plays an important role in ensuring reliable communication, extended operation of the network, less delay and security in health care settings.

The current survey provides a thorough review of routing protocols in WBANs with major focusing on performance metrics parameters like energy efficiency, scalability and security. Many research articles from 2015 to 2025 are reviewed critically and differentiated based on techniques used for routing mechanism such as flat routing, hierarchical routing, cross layer routing, thermal aware routing, QoS aware routing and trust-based routing. Evaluation of the protocols is done based on parameters such as network lifetime, packet delivery ratio, end-to-end delay, throughput and energy consumption.

comparative analysis done shows that hierarchical routing techniques can substantially increase the lifetime of the network whereas any other security measures generally require energy expenditure. However, it has been observed that currently available technologies have shown low scalability and degrade performance when there is some level of mobility and dynamism of the traffic. As per research gaps identified it is required to emphasize the necessity of using adaptive routing protocols, energy efficient security techniques and efficient methods for temperature regulation. The future directions of the research include the implementation of routing with the help of efficient inter-wban communication supporting federated learning, energy harvesting, and cryptography technologies.

Key words: Wireless Body Area Networks, Safe Routing Protocols, Network Scalability, Thermal-Aware Routing, Energy-Efficient Routing,

1. Introduction

Wearable and stationary sensors enable continuous health monitoring via Wireless Body Area Networks [1]. Heart rate, blood pressure, oxygen capacity, ECG, glucose level, and illness are all measured by these networks [2]. They are used for remote patient nursing in clinics. They are used to support ageing in home-based care systems [3]. In recent years, the global market for wearable medical devices has surpassed 30 billion USD and is still growing [4][5]. The need for reliable and secure data transmission is increased by this development.

Small batteries, usually between 100 and 500 mAh, are used by WBAN nodes [6]. Data is transmitted by numerous sensors every one to five seconds. Energy is swiftly piped by regular transmission. It is difficult and expensive to replace or renew implanted devices [7]. Network lifetime is directly impacted by routing results. Due to frequent retransmissions and inadequate link collection, studies show that ineffective routing can reduce node lifetime by 30 to 40 percent [8][9]. Human body movement makes active topology deviations [10]. Posture changes, walking, and arm motion alter link excellence [11].

Packet loss rises during mobility. Increased packet loss causes surges in delay and energy consumption [12]. In medical nursing, delay can be detrimental to patient care. For example, in arrhythmia detection, the end-to-end delay must be less than 250 milliseconds for timely detection [13]. Routing protocols must support dependability in the presence of flexibility [14] [15].



Security has always been a major concern [16]. WBANs deal with complex medical information. Intruder attacks such as snooping, rerun, sinkhole, or denial of services are possible in WBANs [17]. The presence of a single faulty node in the network can disrupt the entire network. Adding lightweight coding results in 5-15 percent energy overhead [18]. The creator has to make a trade-off between the strength of the security and the energy supply. The following figure1 illustrates the challenges in Wireless Body Area Network [19][20].

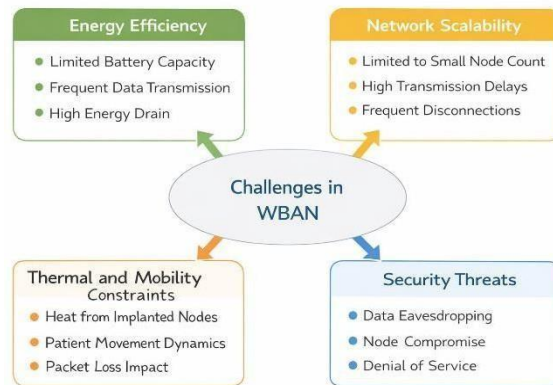


Fig. 1. Challenges in WBAN

Most routing protocols today are geared towards one factor [21]. Some routing protocols are geared towards setting up energy efficiency. Some are geared towards the quality of service or the level of security [22]. Few routing protocols are geared towards energy efficiency, scalability, and security at the same time. Most routing protocols are geared towards networks with less than 15 nodes [23]. When the concept of multimodal nursing is considered, real routing protocols with more than 25 sensors per patient are found in reintegration centers and smart hospitals. Scalability kills the underexplored [24].

Things that are thermal make things even harder. The things that are implanted generate heat. The implanted sensors generate heat by sending it [25]. The temperature of the flesh has to be kept within certain limits. The routing of things that is thermal-aware makes things less hot. However, it could make things longer. The creators of things have to make things safer and more effective [26].

The latest developments in WSNs show that cluster-based routing; cross-layer optimization, trust-based approaches, and AI-based techniques are used for selecting the paths in WSNs [27].

In reproduction studies, cluster-based routing has been used, and it has been observed that network lifetime can be increased up to 35% compared to flat routing approaches [28]. However, there are many studies that are carried out in static environments, and there is a lack of studies that validate the protocols using actual patient flexibility indicators [29][30].

In light of security, scalability, and energy efficiency, this review aims to review routing protocols for Wireless Body Area Networks. The review aims to categorize these routing protocols based on their protection mechanisms, optimization objectives, and network structures. The review also aims to assess these routing protocols based on their assessable criteria, including network lifetime, packet delivery ratio, throughput, delay, and energy per bit. The review also aims to identify gaps in mobility support, frivolous cryptanalysis, adaptive routing, and thermal management. The review aims to identify research directions for future healthcare applications, including edge computing-assisted protected routing, federated learning optimization, and energy harvesting.

2. Literature Review

A. Review Methodology

Systematic analysis of Wireless Body Area Network routing protocols was performed. The search was conducted using Web of Science, IEEE Xplore, and Scopus. Journals and conferences of high impact factor for wireless communication and healthcare systems are listed. The examination string used was: WBAN (wireless

body area network), routing, energy efficiency, security, QoS, and thermal awareness.

The search was limited to journal articles and conference proceedings published between 2015 and 2025. This range was chosen to capture new developments in lightweight safety and low-power design.

The early search returned 6,347 archives. We detached duplicates and partitioned titles and abstracts. We omitted papers that did not focus on WBAN routing, did not report presentation metrics, or lacked investigational validation. We omitted survey papers unless used for background framework.

After showing, 150 full-text articles were measured. We used presence criteria: focus on WBAN routing, calculation using simulation or hardware, and reporting of at least one metric such as energy ingesting, packet delivery ratio, delay, or network period. Finally, 60 studies met all standards and were included in the qualitative mixture.

Figure 2 shows the PRISMA flow diagram. The process recovers transparency and decreases selection bias.

The figure outlines the literature selection workflow adopted in this survey. Following database searches, duplicate removal and eligibility assessment certain high-quality studies were shortlisted for comprehensive analysis. Routing Protocols identified in above process are categorized in 4 types like priority ,cross layer etc..some measurement parameters mentioned in the given literatures for concern protocols where noted to be used in analysis process.

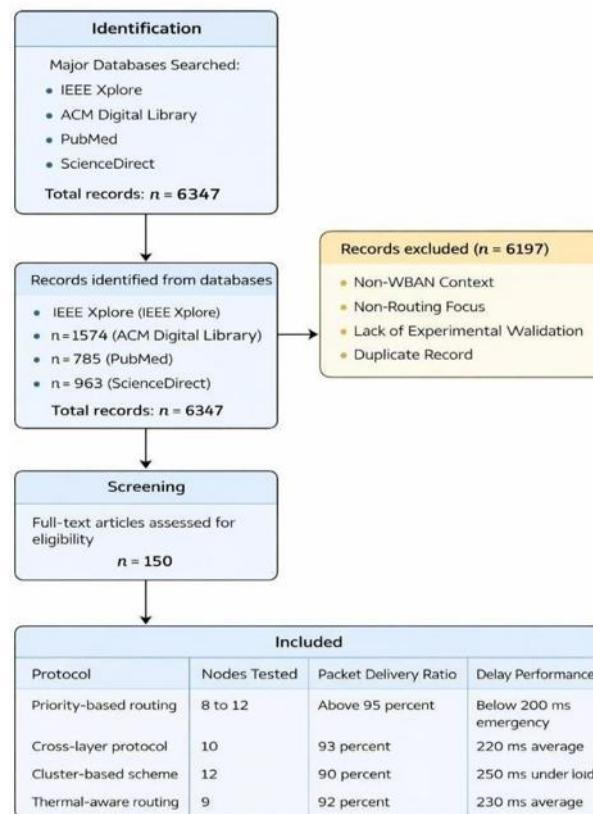


Fig. 2. PRISMA flowchart for WBAN studies

B. Background and Theoretical Context

A Wireless Body Area Network contains of wearable or implantable sensors located on or inside the human body [34]. Nodes measure physiological signs such as ECG, temperature, and blood pressure [35]. A manager node forwards data to a gateway. Energy efficacy is perilous. Typical sensor nodes work with batteries below 500 mAh. Radio transmission consumes up to 70 percent of node energy [36].

Quality of Service describes delay, dependability, and throughput requirements [37]. Backup data requires delay below 250 ms. A reliability standard that is frequently applied is a packet delivery ratio greater than 95%. Tissue damage is prevented by thermal consciousness. Human tissue can be harmed by temperature increases greater than one degree Celsius. Routing protocols have to avoid identified hotspots. Trust groups, encryption, and verification are examples of security mechanisms. AES-128 and other inconsequential cryptography are frequently used because of insufficient processing power [38, 39].

Thematic Literature Analysis

Energy Efficiency

Investigators use cost-based, cluster-based, and cross-layer routing [40]. Outstanding energy is used by cost-based systems to choose the subsequent hops [41]. According to several studies, lifetime development is 15–30% higher than with straight gearbox. Cluster-based protocols minimize long-distance transmissions and switch up the cluster heads [42]. In 10-node networks, some simulations demonstrate energy savings of up to 40%. MATLAB or NS-2 simulations are used in the majority of evaluations [43].

Strength: assessable liveliness decrease.

Limitation: minor network size and static body carriage assumptions.

Table I shows Energy-Efficient Routing Protocols in WBANs.

TABLE I. ENERGY-EFFICIENT ROUTING PROTOCOLS IN WBANS

Ref	Protocol	Routing Type	Technique	Reported Outcome
[44]	SIMPLE	Cost-based	Residual energy metric	20 percent lifetime gain
[45]	M-ATTEMPT	Thermal-aware	Hotspot avoidance	50 percent hotspot reduction
[46]	LEACH-BAN	Cluster-based	Rotating cluster head	30 percent energy saving
[47]	PEGASIS-BAN	Chain-based	Sequential data fusion	25 percent lower transmission cost

Security Mechanisms

Trust models, ECC-based schemes, and symmetric encryption are used in many studies. Low computational overhead is added by AES-128 [48]. Although ECC enhances key management, controlled nodes experience a 10–20% increase in latency. Although trust-based routing can identify malicious nodes, it suffers from erroneous trust estimation when there is mobility [49].

Strength: improved flexibility against selective forwarding antinodes.

Limitation: limited real attack application on hardware testbeds.

QoS Support

Priority-based routing is classified into usual and emergency traffic. Emergency packets obtain delays of below 200 ms in 8 to 12 node imitations [50]. Cross-layer protocols regulate the transmission power as well as responsibility cycles. Packet delivery ratios of above 93 percent are shared under usual load [51].

Strength: enhanced dependability for critical data.

Limitation: performance drips under burst traffic and mobility.

QoS and Scalability Evaluation is shown into the table II.

TABLE II: QoS and Scalability Evaluation

Ref	Protocol	Nodes Tested	Packet Delivery Ratio	Delay Performance
[52]	Priority-based routing	8 to 12	Above 95 percent	Below 200 ms emergency

[53]	Cross-layer protocol	10	93 percent	220 ms Average
[54]	Cluster-based scheme	12	90 percent	250 ms under load
[55]	Thermal-aware routing	9	92 percent	230 ms Average

Scalability

Most researches test fewer than 15 nodes. Few reflect multi-patient clinic scenarios. Scalability analysis often overlooks interference from nearby WBANs.

Strength: full evaluation in small networks.

Limitation: lack of solid placement authentication.

Thermal Awareness

Thermal-aware routing evades enflamed nodes. Some studies report 50 percent decrease in hotspot formation [56]. These protocols monitor node temperature and redirect traffic dynamically [57].

Strength: improved patient safety.

Limitation: extra control overhead and limited experimental authentication

3. Mathematical Modeling of WBAN Routing

This segment shows the common mathematical models used in energy-efficient, scalable, and secure WBAN routing study. These constructions join the optimization methods reported in the works.

Energy Consumption Model

Maximum researches accept the first-order radio energy model.

Transmission energy:

$$E_{t(k)} = k \times E_{elec} + k \times E_{amp} \times d^n \quad (1)$$

Reception energy:

$$E_{r(k)} = k \times E_{elec} \quad (2)$$

Where, k is packet size in bits, d is distance between nodes,

E_{elec} is energy spent by transmitter or receiver electronics,

E_{amp} shows an amplifier energy coefficient,

n is path loss exponent, classically between 2 and 4 Total energy consumed in one round:

$$E_{total} = \sum E_{tx} + \sum E_{rx} \quad (3)$$

Energy-efficient routing reduces E_{total} while maintaining connectivity.

Network Lifetime Model

Network lifetime is usually described as the time until the first node finishes its battery.

For node i:

$$T_i = E_{i_initial} / E_{i_consumed_per_round} \quad (4)$$

Network lifetime:

$$T_{network} = (T_i) \quad (5)$$

Routing objective:

Maximize $T_{network}$

theme to $E_{i_residual} \geq E_{t_res_old}$

Protocols select advancing nodes with higher remaining energy to delay node letdown.

Delay Model

End-to-end delay is expressed as:

$$D_{total} = \Sigma (D_{processing} + D_{queue} + D_{transmission} + D_{propagation})$$

QoS-aware routing constrains delay:

$$D_{total} \leq D_{max}$$

For emergency traffic, D_{max} is often set below 250 ms.

Packet Delivery Ratio Model

Reliability is measured as:

$$PDR = \text{Packets}_{received} / \text{Packets}_{sent}$$

Routing aims to maximize PDR:

Thermal Constraint Model

Thermal-aware routing confines node temperature.

$$Temp_i \leq Temp_{safe}$$

$Temp_{safe}$ is naturally clear as 1-degree Celsius above baseline tissue temperature .If $Temp_i > Temp_{threshold}$, node i is omitted from routing path selection.

Security Overhead Model

Security machines present computational and transmission overhead.

Total energy with security:

$$E_{secure_total} = E_{base} + E_{crypto}$$

Where

$$E_{crypto} = k \times E_{enc_per_bit}$$

Routing must satisfy:

$$E_{secure_total} \leq E_{energy_budget}$$

This formalizes the trade-off between confidentiality and energy consumption.

Scalability Model

Let N represent number of nodes. Control overhead ratio:

$$OH = \text{Control_packets} / \text{Total_packets}$$

A scalable protocol maintains:

$$OH \leq OH_{max} \text{ and } D_{total} \text{ remains stable as } N \text{ increases.}$$

Multi-Objective Optimization Model

Numerous current protocols combine numerous metrics using weighted optimization.

Minimize:

$$F = w1 \times Enorm + w2 \times Dnorm + w3 \times (1 - PDR) + w4 \times Tempnorm \quad (6)$$

Where

E_{norm} shows regularized energy consumption

D_{norm} is regularized delay

PDR_{norm} is regularized packet delivery ratio $Temp_{norm}$ is regularized temperature rise

$w1, w2, w3, w4$ are weighting features

This model seizes energy, QoS, consistency, and thermal limitations in a single framework.

4. CRITICAL ANALYSIS AND DISCUSSION

A. Cross-Theme Analysis

Most routing protocols optimize one aspect, but some of these optimize the following: "Energy-aware routing protocols extend the network lifetime by 20% to 40% in small simulations." "Security-aware routing protocols provide improved resistance to attacks, but also incur an additional 5% to 15% in energy consumption." "QoS-aware routing protocols provide alternative delay less than 200 ms, but also incur increased control overhead. Few routing protocols optimize all three dimensions [59].

Energy efficacy and security are frequently at odds with one another. Encryption and authentication impose calculation and transmission costs. Researches that incorporate AES-128 have exhibited energy overheads. Thermal routing can reduce hotspot formation by as much as

50 percent but may also extend path length and delay. Scalability traces are few and far between across all themes. Most evaluations are done with fewer than fifteen nodes. Realistic hospital scenarios can involve 20 to 30 sensors per patient [60]. Mobility is under-addressed. Human stance changes cause link variations. Studies assume static body models. Packet delivery ratio above 95 % is common in static surroundings. Performance drops under mobility, yet few papers report detailed mobility analysis.

B. Methodological Weaknesses

The present research relies on simulation tools such as MATLAB, NS-2, or NS-3. Real hardware authentication is not common. Channel models often assume perfect or simplified propagation. Surveillance and interference through human bodies are not fully modeled.

Traffic models are not good enough; many experiments employ continuous bit rate traffic. In the real world, medical applications have diverse traffic with bursts during crises. The energy model assumes that the battery has a certain capacity, without taking into account the aging of the battery or the release of energy, which is nonlinear.

Security valuation is hypothetical, i.e., the attacks are simulated without the actual implementation of confrontational nodes. The detection rate is stated, but the false positive and false negative rates are not monitored. Cryptographic overhead is evaluated, not experimentally authenticated.

C. Evaluation Limitations

Most researches have a small Network size. 8 to 12 nodes are used to control the experimental setups. Multi-patient nosiness is seldom tested. Few studies test the coexistence of multiple WBANs within the same hospital ward.

The simulation period is short. The simulation period of many researches is just a few thousand rounds. The energy constancy over long periods of time, such as days or weeks, is not examined. In thermal studies, relative temperature difference is frequently used instead of actual impact on the tissue. Proportional analysis does not offer continuous measures. Various studies use various initial energy levels, area sizes, and radio parameters. It becomes challenging to compare them. Some studies offer percentage development, although the formation of the baseline is unknown.

D. Common Assumptions Across Studies

Most researches agree on one controller, positioned at the center of the body. Most researches agree on gateway connectivity. Packet loss because of external interference is not modeled at all.

Most protocols start with similar nodes with similar energy capabilities. In practice, stationary nodes are more constrained than wearable nodes. Trainings mostly ignore hardware capabilities.

The mobility models are simple, as constant motion patterns are not verified, and walking or sitting postures are adopted as static belongings.

Energy harvesting has been addressed in recent works, but the realistic power levels are not measured.

The security models consider an imperfect attacker with local access, but the advanced attacks, i.e., coordinated attacks across multiple nodes are not commonly addressed.

The above trends clearly indicate that the recent research on WBAN routing protocols is still in the simulation environment, and the tested size needs to be increased, along with the consideration of realistic mobility traces and attack scenarios.

1. OPEN RESEARCH CHALLENGES

Energy efficacy, scalability, and security continue partly solved in WBAN routing. Many protocols report enhancements under controlled simulations. Real deployments present harder restrictions. The following gaps need focused research. Table III presents Open Research Challenges in WBAN Routing.

TABLE III: OPEN RESEARCH CHALLENGES IN WBAN ROUTING

Challenge Area	Current Limitation	Practical Impact
Energy Modeling	No battery aging or nonlinear model	Overestimated network lifetime
Dense Deployment	Tested with fewer than 15 nodes	Uncertain performance in hospitals
Mobility Handling	Static posture assumptions	Packet loss during body movement
Security Validation	Simulated attacks only	Unverified real-world resilience
Thermal Management	Relative temperature metrics only	Safety risk for implantable sensors
Multi-Objective Optimization	Focus on single metric	Imbalanced trade-offs
Standard Evaluation Setup	Non-uniform simulation parameters	Difficult cross-paper comparison

2. FUTURE RESEARCH DIRECTIONS

Table IV reviews research directions for WBAN routing protocols with expected outcome and practical impact.

TABLE IV: FUTURE RESEARCH DIRECTIONS FOR WBAN ROUTING PROTOCOLS

Future Direction	Research Focus	Expected Outcome	Practical Impact
Hardware validation	Test routing protocols on real WBAN devices such as Shimmer, TelosB	Accurate measurement of energy use, delay and packet delivery	Reliable deployment in real healthcare monitoring systems
AI-based	Use machine learning models to select routes based on node energy,	Adaptive routing decisions and improved packet delivery	Longer network lifetime and stable medical data

routing	link quality, and traffic priority	ratio	transmission
Cross-layer optimization	Integrate routing decisions with MAC scheduling and physical layer parameters	Lower communication delay and reduced packet loss	Better Quality of Service for emergency health data

3. CONCLUSION

Wireless Body Area Networks permit continuous health monitoring through wearable and implantable sensors. Efficient routing is serious because sensor nodes operate with imperfect battery power and strict consistency requirements. This paper studied routing protocols that focus on energy efficacy, scalability, and security in WBAN surroundings. The study demonstrates the recovery of energy efficacy using the residual energy metric, clustering, and thermal statement in routing protocols. Various studies have achieved energy savings ranging from 20 percent to 35 percent with packet delivery ratios over 90 percent in small network environments. The review identifies the major gaps in the existing literature. Most of the existing literature lacks hardware validation and real deployment tests. Scalability in multi-patient environments is also incomplete. Energy efficacy, security, and thermal safety are integrated using a routing background in few existing literature. Future research directions involve real hardware tests, AI-based adaptive routing protocols, and cross-layer optimization techniques to improve network lifetime, reliability, and secure data transfer in real-time WBAN healthcare environments.

References

1. Preethichandra, D. M. G., Piyathilaka, L., Izhar, U., Samarasinghe, R., & De Silva, L. C. (2023). Wireless body area networks and their applications—A review. *Ieee Access*, 11, 9202-9220.
2. Javaid, S., Zeadally, S., Fahim, H., & He, B. (2022). Medical sensors and their integration in wireless body area networks for pervasive healthcare delivery: A review. *IEEE Sensors Journal*, 22(5), 3860-3877.
3. Nassra, I., & Capella, J. V. (2025). Smart body area networks. In *Sensor Networks for Smart Hospitals* (pp. 41-75). Elsevier.
4. Mahalakshmi, K., Palanivelu, V. R., & Kirubakaran, D. (2025). Global Market trends in biomedical sensors: Materials, device engineering, and healthcare applications. *Biomedical Materials & Devices*, 1-19.
5. Kale, D. R., Shinde, H. B., Shreshthi, R. R., Jadhav, A. N., Salunkhe, M. J., & Patil, A. R. (2025, March). Quantum-Enhanced Iris Biometrics: Advancing Privacy and Security in Healthcare Systems. In *2025 International Conference on Next Generation Information System Engineering (NGISE)* (Vol. 1, pp. 1-6). IEEE.
6. Preethichandra, D. M. G., Piyathilaka, L., Izhar, U., Samarasinghe, R., & De Silva, L. C. (2023). Wireless body area networks and their applications—A review. *Ieee Access*, 11, 9202-9220.
7. Gherairi, S. (2022). Healthcare: A priority-based energy harvesting scheme for managing sensor nodes in WBANs. *Ad Hoc Networks*, 133, 102876.
8. Wase, M. A., & Siddaiah, P. (2024). Enhanced Sensor node lifetime Based Routing Protocol in Mobile Wireless Sensor Networks. *Journal of Electrical Systems*, 20.
9. Kale, D. R., Mane, T. S., Buchade, A., Patel, P. B., Wadhwa, L. K., & Pawar, R. G. (2024, October). Federated learning for privacy-preserving data mining. In *2024 international conference on intelligent systems and advanced applications (ICISAA)* (pp. 1-6). IEEE.
10. Shankar, S., Souslov, A., Bowick, M. J., Marchetti, M. C., & Vitelli, V. (2022). Topological active matter. *Nature Reviews Physics*, 4(6), 380-398.
11. Zhou, C., Xu, X., Huang, T., & Kaner, J. (2024). Effect of different postures and loads on joint motion and muscle activity in older adults during overhead retrieval. *Frontiers in Physiology*, 14, 1303577.
12. Bortolani, S., Brusa, C., Rolle, E., Monforte, M., De Arcangelis, V., Ricci, E., ... & Tasca, G. (2022). Technology outcome measures in neuromuscular disorders: A systematic review. *European Journal of Neurology*, 29(4), 1266-1278.
13. Coston, I., Plotnizky, E., & Nojournian, M. (2025). Comprehensive study of iot vulnerabilities and countermeasures. *Applied Sciences*, 15(6), 3036.
14. Reusch, N., Craciunas, S. S., & Pop, P. (2022). Dependability-aware routing and scheduling for Time-Sensitive Networking. *IET Cyber-Physical Systems: Theory & Applications*, 7(3), 124-146.
15. Kale, D. R., Buchade, A., Nalavade, J., Sapate, S. G., & Umbarkar, A.
16. J. (2023, October). Detecting violations of conditional functional dependencies in distributed database. In *2023 IEEE International Conference on Blockchain and Distributed Systems Security (ICBDS)* (pp. 1-4). IEEE.
17. Nalavade, J. E., Sachdeo, R., Kale, D. R., Buchade, A., Subhedar, M., & Shinde, S. K. (2024, December). Enhancing Road Safety: An Intelligent Drowsiness Detection System Based on Deep Neural Networks. In *2024 IEEE Pune Section International Conference (PuneCon)* (pp. 1-6). IEEE.
18. Singh, A. K., & Kumar, S. (Eds.). (2024). *Security, Privacy, and Trust in WBANs and E-Healthcare*. CRC Press.
19. Pabitha, B., Sanshi, S., & Karthik, N. (2024). A Comprehensive Security Framework for WBANs in the Healthcare Environment. In *Security, Privacy, and Trust in WBANs and E-Healthcare* (pp. 186-205). CRC Press.

20. Soni, M., & Singh, D. K. (2023). New directions for security attacks, privacy, and malware detection in WBAN. *Evolutionary Intelligence*, 16(6), 1917-1934.
21. Abirami, R., & Malathy, C. (2024). Security requirements and challenges in WBANs and E-Health systems. In *Security, Privacy, and Trust in WBANs and E-Healthcare* (pp. 3-22). CRC Press.
22. Abuashour, A., & Kadoch, M. (2017). Performance improvement of cluster-based routing protocol in VANET. *Ieee access*, 5, 15354- 15371.
23. Kale, D. R., Dixit, C., Patil, N., & Kaulwar, B. (2025, October). Detection Systems for Robust IoT Security. In *Integration of Artificial Intelligence in IoT: Opportunities and Challenges: Proceedings of 9th International Conference on Internet of Things and Connected Technologies (ICIoTCT 2024)* (p. 123). Springer Nature.
24. Siamantas, G., Rountos, D., & Kandris, D. (2025). Energy saving in wireless sensor networks via LEACH-based, energy-efficient routing protocols. *Journal of Low Power Electronics and Applications*, 15(2), 19.
25. Nguyen, T. A. (Ed.). (2025). *Blockchain and Digital Twin for Smart Hospitals*. Elsevier.
26. Bahru, R., Hamzah, A. A., & Mohamed, M. A. (2021). Thermal management of wearable and implantable electronic healthcare devices: Perspective and measurement approach. *International Journal of Energy Research*, 45(2), 1517-1534.
27. Veletic, M., Apu, E. H., Simic, M., Bergsland, J., Balasingham, I., Contag, C. H., & Ashammakhi, N. (2022). Implants with sensing capabilities. *Chemical Reviews*, 122(21), 16329-16363.
28. Behura, A., Kumar, A., & Jain, P. K. (2025). A comparative performance analysis of vehicular routing protocols in intelligent transportation systems. *Telecommunication Systems*, 88(1), 26.
29. Rajput, M., & Yadav, R. N. (2025). Machine and deep learning driven energy efficient clustering in IoT-WSNs: A Review. *IEEE Sensors Journal*.
30. Abujassar, R. S. (2025). Intelligent IoT-driven optimization of large-scale healthcare networks: the INRWLF algorithm for adaptive efficiency. *Discover Computing*, 28(1), 93.
31. Kale, D. R., Jain, P., Deshpande, T., Mujawar, S. A., Sapate, S. G., & Hirve, S. A. (2025, October). Design and Evaluation of a Quantum-Enabled Explainable AI System for Disease Risk Prediction in Healthcare. In *2025 IEEE International Conference on Blockchain and Distributed Systems Security (ICBDS)* (pp. 1-6). IEEE.
32. Sharma, V., Beniwal, R., & Kumar, V. (2024). Multi-level trust-based secure and optimal IoT-WSN routing for environmental monitoring applications. *The Journal of Supercomputing*, 80(8), 11338-11381.
33. Morin, E., Maman, M., Guizzetti, R., & Duda, A. (2017). Comparison of the device lifetime in wireless networks for the internet of things. *IEEE Access*, 5, 7097-7114.
34. Sani, M. S., Iranmanesh, S., Raad, R., & Tubbal, F. (2026). Energy-efficient routing protocol in vehicular opportunistic networks: A dynamic cluster-based routing using deep reinforcement learning. *IEEE Transactions on Intelligent Transportation Systems*.
35. Al Majdoubah, R., & Eljaafreh, Y. (2025). Review of implantable-based wireless body area network metrics issues. *International Journal of Electrical & Computer Engineering* (2088-8708), 15(4).
36. Kale, D. R., & Mulla, J. M. S. (2024). AI in healthcare: Enhancing patient outcomes through predictive analytics. *Industrial Engineering Journal*, 53(5), 73-79.
37. De La Fuente, R., Radrihan, L., & Morales, A. S. (2025). Enhancing predictive maintenance in mining mobile machinery through a hierarchical inference network. *IEEE Access*.
38. Dixit, C., Shirke-Deshmukh, S., Sonkamble, R. G., Thepade, S. D., & Kale, D. R. (2025, November). Blockchain-Driven Framework for Secure and Transparent Customer Relationship Management. In *2025 International Conference on Future Technologies (ICFT)* (pp. 1-6). IEEE.
39. Sarangi, D. (2025). A comparative study of AES encryption modes and hashing for blockchain applications (Doctoral dissertation, Dublin, National College of Ireland).
40. Hemantlal, R. A. (2025). Enhancing Security Against Power Analysis Attacks Using Internal Re-Keying Based Modified AES (Doctoral dissertation, Gujarat Technological University). Raj, V. P., & Duraipandian, M. (2024). An energy-efficient cross-layer-based opportunistic routing protocol and partially informed sparse autoencoder for data transfer in wireless sensor network. *Journal of Engineering Research*, 12(1), 122-132.
41. Saif, S., & Saha, R. (2025). M-EEMH: an energy-efficient mobility aware multi-hop protocol for QoS-driven WBAN applications. *Cluster Computing*, 28(10), 670.
42. Zhang, S., Liu, X., & Trik, M. (2025). Energy efficient multi hop clustering using Artificial Bee Colony metaheuristic in WSN. *Scientific Reports*, 15(1), 26803.
43. Sha, K., Striegel, A., & Song, M. (Eds.). (2022). *Advances in Computer Communications and Networks From Green, Mobile, Pervasive Networking to Big Data Computing*. CRC Press.
44. Kneifel, J., Kneifel, J., & Webb, D. (2022). *Life cycle costing manual for the Federal Energy Management Program*. US Department of Commerce, National Institute of Standards and Technology.
45. Yaqoob, M. M., Fatima, K., Shamshirband, S., Mosavi, A., & Khurshid, W. (2025). AMHRP: Adaptive Multi-Hop Routing Protocol to Improve Network Lifetime for Multi-Hop Wireless Body Area Network. *arXiv preprint arXiv:2510.12698*.
46. Bharathi, R., Kannadhasan, S., Padminidevi, B., Maharajan, M. S., Nagarajan, R., & Tonmoy, M. M. (2022). Predictive model techniques with energy efficiency for IOT-based data transmission in wireless sensor networks. *Journal of sensors*, 2022(1), 3434646.
47. Raj, V. P., & Duraipandian, M. (2024). An energy-efficient cross-layer-based opportunistic routing protocol and partially informed sparse autoencoder for data transfer in wireless sensor network. *Journal of Engineering*

- Research, 12(1), 122-132.
48. Shah, A. M., & Gor, A. (2025). Comprehensive Survey of Symmetric and Public-Key Cryptographic Algorithms: Foundations, Attacks, and Applications. *International Journal Of Informative and Futuristic Research*, 12(10), 20-38.
 49. Sangeetha, K., & Arulanandam, K. (2025). Adaptive trust-based secure routing protocol with reinforced anomaly detection for IoT networks. *International Journal on Smart Sensing and Intelligent Systems*, 18(1).
 50. Yaseen, F. A., Alkhalidi, N. A., & Al-Raweshidy, H. S. (2022). She networks: Security, health, and emergency networks traffic priority management based on ml and sdn. *IEEE Access*, 10, 92249-92258.
 51. Mustafa, R., Sarkar, N. I., Mohaghegh, M., Pervez, S., & Vohra, O. (2025). Cross-layer analysis of machine learning models for secure and energy-efficient IoT networks. *Sensors*, 25(12), 3720.
 52. Hao, Z., Wang, Y., & Yang, X. (2024). Every second counts: A comprehensive review of route optimization and priority control for urban emergency vehicles. *Sustainability*, 16(7), 2917.
 53. Mustafa, R., Sarkar, N. I., Mohaghegh, M., Pervez, S., & Vohra, O. (2025). Cross-layer analysis of machine learning models for secure and energy-efficient IoT networks. *Sensors*, 25(12), 3720.
 54. Khajavi, K., & Wang, T. (2025). Lightening the Load: A Cluster-Based Framework for A Lower-Overhead, Provable Website Fingerprinting Defense. *arXiv preprint arXiv:2509.01046*.
 55. Abdullah, A. M. (2025). Energy-efficient and thermal-aware routing protocol for wireless body area networks based on ant colony optimization. *Computing*, 107(5), 119.
 56. Rahimi, A., Jafari Shahbazzadeh, M., & Khatibi, A. (2025). An adaptive intelligent thermal-aware routing protocol for wireless body area networks. *Journal of Cloud Computing*, 14(1), 26.
 57. Das, S., Das, A., & Karfa, C. (2025). Developing Deadlock-Free Routing Algorithms in Torus NoC: A Formal Approach. *ACM Transactions on Embedded Computing Systems*, 24(5s), 1-26.
 58. Khan, I., Rauf, M., & Jamil, A. (2025). A Hybrid CT-DEWCA Based Energy-Efficient Routing Protocol for Data and Storage Nodes in Underwater Acoustic Sensor Networks. *IEEE Access*.
 59. Khan, N. R., Ahmad, G. F., Barskar, R., & Shukla, P. K. (2025). Mobile Adhoc Networks: Protocols and Its Challenges. *IETE Journal of Research*, 1-31.
 60. Adewoyin, M. A., Onyeke, F. O., Digitemie, W. N., & Dienagha, I. N. (2025). Holistic offshore engineering strategies: Resolving stakeholder conflicts and accelerating project timelines for complex energy projects. *Int. J. Multidiscip. Res. Growth Eval*, 6(1), 92-98.

About the Author



Mr. Chirag Gajanan Kokane Pawar received B.E Degree in Computer Science & Engineering from DKTE ,Ichalkaranji in 2008 and M.Tech degree in Computer Science & Engineering from GIT , Belgaum in 2014 .He is currently working towards Ph.D Degree at Department of Computer Engineering ,Bharati Vidyapeeth (Deemed to be University) College of Engineering, Pune India



Dr. S. B. Vanjale is currently serving as a Professor in the Department of Computer Engineering at Bharati Vidyapeeth (Deemed to be University) College of Engineering, Pune, India. He has over two decades of academic and research experience. His areas of expertise include wireless networks, networks security, cyber security , cloud computing.

He has authored and co-authored numerous research papers in reputed international journals and conferences. He has also guided several postgraduate and doctoral research scholars. He is an active member of professional bodies such as IEEE and ISTE. His current research interests focus on Wireless Body Area Networks (WBAN) and energy-efficient routing algorithms for healthcare applications