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Sustainable Communication in 5G/6G Wireless Sensor Networks: A Survey on Energy-Efficient Collaborative Routing

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Abstract: Wireless sensor networks (WSNs) play an important role in modern communication systems with the advances in 5G/6G technologies. These networks have a wide range of applications, from smart cities to industrial automation, from environmental monitoring systems to healthcare applications. However, since sensor nodes have limited energy resources, energy efficiency remains a critical issue for the sustainability of these networks. Low-power routing protocols are needed to ensure the long lifespan and efficient operation of sensor nodes. This study comprehensively studies cooperative energy-efficient routing protocols designed to achieve sustainability in WSNs. First of all, the basic principles of cooperative routing methods are discussed and approaches to optimize data transmission between nodes are reviewed. Then, different energy-efficient routing protocols are compared and the pros and cons of hierarchical, planar and location-based protocols are analyzed. It is shown that by integrating artificial intelligence (AI) and machine learning (ML) techniques into routing protocols, it is possible to dynamically optimize node selection processes and extend the network lifetime. This survey summarizes the current status of energy-efficient routing protocols, discusses the challenges encountered and suggests potential directions for future research.

Keywords: Wireless sensor networks, energy efficiency, routing protocols, 5G/6G, artificial intelligence.

5G/6G Kablosuz Sensör Ağlarında Sürdürülebilir Haberleşme: Enerji Verimli İşbirliğine Dayalı Rotalama Üzerine Literatür Taraması

Özet: Kablosuz sensör ağları (KSA'lar), 5G/6G teknolojilerindeki gelişmelerle birlikte yeni iletişim sistemlerinde önemli bir rol oynamaktadır. Bu ağlar, akıllı şehirlerden endüstriyel otomasyona, çevre izleme sistemlerinden sağlık uygulamalarına kadar geniş bir uygulama yelpazesine sahiptir. Ancak, sensör düğümlerinin sınırlı enerji kaynaklarına sahip olması nedeniyle, enerji verimliliği bu ağların sürdürülebilirliği için kritik bir konu olmaya devam etmektedir. Sensör düğümlerinin uzun ömürlü ve verimli çalışmasını sağlamak için düşük güçlü yönlendirme protokollerine ihtiyaç vardır. Bu çalışma, KSA'larda sürdürülebilirliği sağlamak için tasarlanmış işbirlikçi enerji verimli yönlendirme protokollerini incelemektedir. Her şeyden önce, işbirlikçi yönlendirme yöntemlerinin temel prensipleri tartışılmakta ve düğümler arasında veri iletimini optimize etme yaklaşımları incelenmektedir. Ardından, farklı enerji verimli yönlendirme protokolleri karşılaştırılmakta ve hiyerarşik, düzlemsel ve konum tabanlı protokollerin artıları ve eksileri analiz edilmektedir. Yapay zeka ve makine öğrenimi tekniklerinin yönlendirme protokollerine entegre edilmesiyle, düğüm seçim süreçlerinin dinamik olarak optimize edilmesinin ve ağ ömrünün uzatılmasının mümkün olduğu gösterilmektedir. Bu literatür taraması, enerji açısından verimli yönlendirme protokollerinin mevcut durumu özetlenmiş, karşılaşılan zorluklar tartışılmış ve gelecekteki araştırmalar için olası yönler önermiştir.

Anahtar Kelimeler: Kablosuz sensör ağları, enerji verimliliği, yönlendirme protokolleri, 5G/6G, yapay zeka.

REVIEW PAPER

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1 INTRODUCTION

WSNs have become an essential element in modern communication systems, especially in applications such as environmental monitoring, healthcare, smart cities, and industrial automation. With the advances in 5G and 6G networks, WSNs can do more by offering very reliable communication, low latency, and fast data transfer rates. However, energy efficiency remains one of the key challenges in ensuring the sustainability of WSNs, especially considering the limited resources and energy resources of sensor nodes and their typical deployment in inaccessible locations. Efficient utilization of energy is important to extend the network lifetime, but is also essential to maintain the reliability of the communication infrastructure. Thus, the study of energy efficiency and sustainability has been a major challenge for WSNs. Routing protocols have received considerable attention in recent research [1], [2]. The introduction of collaborative tracking of targets and connections in modern networks exacerbates the energy efficiency problem in WSNs.

Walid Demiga and others [3] have highlighted the importance of collaborative target tracking to reduce redundant probes and optimize communication between nodes to minimize energy consumption. In this context, cooperation between sensor nodes ensure that only the necessary information is available to all nodes participating in the probe and communication process, significantly increasing the network lifetime. Similarly, energy-efficient communication methods, e.g., as discussed by Igor Stanoev et al. [4], the impact of teamwork on improving reliability and reducing energy consumption while communicating, such as the optimized Hybrid Automatic Repeat Request (HARQ) protocol. Efforts towards building collaborative intelligent environments provide a significant positive impact on the sustainable design of WSNs. By leveraging the outcomes of the Internet of Things (IoT) and artificial intelligence (AI), these environments are developing systems that save energy, reduce costs and improve user comfort and safety. According to the work in [5], the interconnected intelligent devices of a Collaborative Smart Environment (CSE) manage their energy consumption more efficiently. This approach, combining different technologies, leads to integrated energy management solutions to improve everyday life.

To improve the energy efficiency of WSNs, many energy-efficient routing protocols have been proposed. T.M. Behera et al. [6] provide a review of various hierarchical clustering protocols, such as the Low Energy Adaptive Clustering Hierarchy (LEACH), and their variations for optimizing energy usage in WSNs. The LEACH protocol, which organizes the sensor nodes into clusters with cluster heads, reduces direct communication to the base station (BS). Different modifications of LEACH, such as LEACHC (LEACH Central) and LEACH-DCS (Deterministic Cluster Selection), have been developed to further optimize the selection of cluster heads based on residual energy and leads to more balanced clusters and networks with increased lifetimes [7]. Other approaches discussed in [8], focus on reducing energy waste through traffic distribution techniques to ensure optimized energy consumption across the network. C. Nakas et al. [9] provides a review of energy-efficient routing protocols for wireless sensor networks and classify them into hierarchical and location-based categories. Each type has its own advantages and disadvantages in terms of energy-efficient savings. Hierarchical routing is notable for reducing duplicate data transmissions and increasing network lifetime by collecting data at the cluster head before transmitting it to the BS. H. L. Gururaj et al. [10] proposed an energy-efficient routing protocol for 5G/6G WSNs that uses RL to improve cluster head selection and the data routing. RL-based methods select nodes with more remaining energy and adjust the routing path based on the current state. This brings sustainable communication in WSNs.

The literature offers a fascinating perspective on the use of autonomous robots for data collection in terrestrial WSNs. By lowering the energy consumption of cluster heads and UAV robots, several research suggested mobile sinks for gathering data from clustered networks [11]–[15]. The work in [16] considers a similar data collection problem by considering underwater communication challenges via an autonomous underwater vehicle (AUV). The underwater system is more costly than terrestrial wireless sensors, although autonomous robots help decrease the energy cost of sensor equipment. The papers [17]–[19] tackle scheduling problem for data collection in single-hop energy harvesting WSN by considering throughput and fairness.

The work [20] suggested a cluster head selection approach for energy-sensitive routing issues in UASNs and examined the impact of predicted available energy on cluster head selection while considering stochastic energy harvesting methods of individual sensors. The paper addresses the same problem and suggests a new reinforcement learning-based approach to identify cluster heads (CHs) that takes into account estimated collected energy as well as the locations and remaining energy of the sensor nodes [1]. Energy harvesting awareness makes underwater sensors last longer. This is shown by numerical results that show our proposed method greatly increases the amount of energy collected, which in turn extends the network's useful life.

Mobility and heterogeneous networks (HetNets) brings extra problems to energy-efficient routing. When you mix macro and small cells in HetNets, you get more handoffs, more signaling overhead, and different types of nodes need more energy. Gures et al. [21] describes mobility handling problems in 5G HetNets, including frequent handover failures, the ping-pong effect, and increased energy usage due to redundant signaling. Addressing these issues requires advanced mobility management techniques such as beam-level mobility, dual connectivity, and mobility resilience optimization (MRO). These approaches helps WSNs to maintain reliable communication without wasting energy. The study of Wang in [22] shows that how mobility affects coverage and energy consumption in WSNs.

AI techniques can improve energy efficiency of WSNs. AI-driven approaches introduced by Parag Biswas et al. [23] include reinforcement learning, genetic algorithms, and neural networks to decrease power consumption for sustainable communication and enables dynamic decision-making that adapts routing and energy management strategies according to real-time network conditions. Pasqualetto in [24] have demonstrated the value of multi-agent systems (MAS) in building smart energy management systems that can process big amount of data from various sensors and devices, optimizing energy usage in the network and the role of MAS and big data is also discussed.

While energy efficiency is considered for WSNs, security should also be considered for sensors. Sensor nodes, often deployed in open environments and susceptible to attacks, make security a critical factor in WSNs. However, traditional security methods such as encryption spends a lot of energy, which poses a problem considering the limited resources of WSNs. M. Mahamat et al. [25] review recent energy-aware security approaches that balance strong protection with low energy consumption. For example, context-aware security avoids unnecessary energy consumption by adjusting protection levels according to the current environment and threat level. M. Biradar and B. Mathapathi [20] describe a trust-based routing protocol that increases security while keeping energy consumption low. These protocols creates link between nodes and saves energy. New research looks into how metaheuristic and biologically inspired algorithms can be used to make routing in wireless sensor networks more energy-efficient. R. Priyadarshi [26] reviews techniques such as particle swarm optimization (PSO), artificial bee colony (ABC) and artificial bee colony optimization (ACO). Natural behaviors, like the flight of bees or foraging ants, inspire these algorithms to determine energy-efficient routes. An approach combining PSO and ACO shows the potential to increase the strengths of algorithms to improve data collection and extend network lifetime.

In conclusion, making 5G and 6G WSNs more energy efficient requires a mix of collaborative routing, mobility management, AI-assisted optimization, and security issues that are aware of energy use. This paper looks at previous research that has been done on energy-efficient routing protocols, collaborative techniques to lower energy use, the effects of mobility and heterogeneous networks, optimizing AI/ML techniques for energy use, and systems that are limited by energy. Covering these areas summarizes current achievements.

1.1 Main Contributions of the Paper

The main contributions of this paper is summarized below:

- This paper provides an overview of collaborative energy-efficient routing protocols designed for 5G/6G WSNs. It categorizes different routing approaches, including hierarchical, planar, and location-based protocols, and compares their advantages and disadvantages.
- We discuss the impact of mobility management and heterogeneous network structures on energy efficiency, focusing on beam-level mobility and handover optimization.
- The study includes how AI algorithms like reinforcement learning, genetic algorithms, and neural networks, can be integrated into routing protocols to optimize node selection and extend the overall lifetime of the network.
- The paper highlights the security concerns in low-power WSNs, evaluating lightweight encryption, trust-based routing and AI-based approaches to ensure secure and efficient communication.
- This survey brings potential future research directions, emphasizing AI-based routing, mobility management, and sustainable communication solutions for 5G/6G WSNs.
- Instead of diving too deep into details, this survey gives a general idea about the problem and fundamental concepts to deal with it, thus providing a basis for further advancements and new solutions.

1.2 Organization of the Paper

We organize the rest of the paper as follows. Section 2 presents energy-efficient protocols in 5G/6G WSNs. Section 3 presents collaborative approaches for energy-efficient routing. Section 4 exhibits impact of mobility and heterogenous networks. Section 5 introduces AI/ML-based techniques in energy-efficient routing. Section 6 provides security challenges in energy-efficient routing. Section 7 concludes the paper.

2 PROTOCOLS FOR ENERGY EFFICIENCY IN 5G/6G WSNS

Energy-saving routing protocols are important for wireless sensor networks, especially for advanced systems such as 5G and 6G. WSN nodes have limited battery power, so using energy wisely ensures that the network operates efficiently for a long time. Figure 1 presents an example model of a clustered WSN. This section focuses on the various protocols developed to conserve energy, how they work, and how they can be adapted to the needs of 5G/6G networks. Misra et al. shows that multimedia streaming in WSNs introduces unique challenges in terms of energy-efficient data transmission and real-time communication [27].

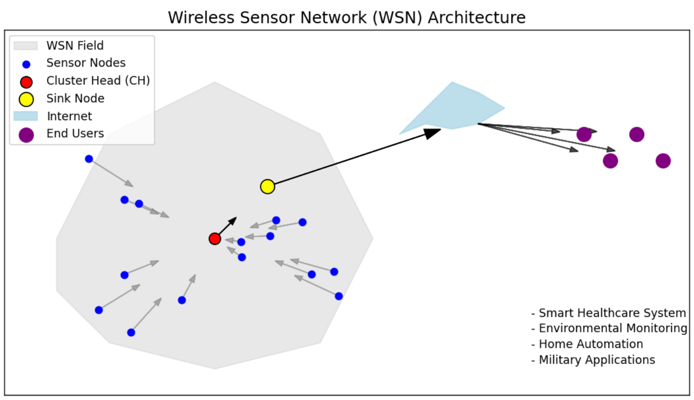

Fig. 1 WSN architecture showing sensor nodes, cluster head, sink node, and data flow to end users for various applications.

Behera et al. [6] also discussed the LEACH protocol in WSNs. LEACH divides sensor nodes into clusters, and cluster heads (CHs) manage the communication within these clusters. This arrangement reduces the number of nodes that transmit data directly to the master station, thus saving energy. However, LEACH's method of randomly selecting CHs are not that efficient. Selecting a low-energy node as a CH quickly exhausts it, leading to a short network lifetime. To solve this problem, LEACH-C (Central LEACH) is used. LEACH-C selects CHs by a centralized system depending on the remaining energy of the nodes. This creates a more balanced cluster and increases the network lifetime, but requires additional infrastructure such as GPS, which increases energy consumption [8], [28]. The another paper deeply reviews clustering protocols in WSNs, analyzing existing classifications, problems encountered and future research directions [29]. Hosseinzadeh et al. propose cluster based trusted routing method in WSNs using Fire Hawk Optimizer (FHO) for better security and efficiency [30]. They show this method improves network performance by optimizing energy in sensor nodes. Also, the study by Hegde et al. shows that the Improved Grey Wolf Optimization (IGWO)-based LEACH protocol significantly enhances network lifetime in Wireless Sensor Networks (WSNs) compared to traditional LEACH and GWO-based methods. Their findings indicate that IGWO optimizes cluster head selection by considering factors such as energy balance and intra-cluster distance and helps to substantially improve the number of operational rounds and energy efficiency in both small- and large-scale WSN deployments [31].

Behera and his team also mention another variation called LEACH-DCS (Deterministic Cluster Selection). This method optimizes the CH selection process by considering whether the node was a CH before and its current energy level. Therefore, high energy sensors are selected as CHs, resulting in a more balanced energy distribution. The authors also consider a distributed LEACH method with solar power. This method uses solar-powered nodes as CHs, thereby reducing the energy consumption of battery-powered nodes.

This approach has been successful in extending the network lifetime, especially in outdoor areas with sufficient sunlight. However, it depends on the environmental conditions [6]. They also highlight the use of multi-hop LEACH. In this method, CHs do not send data directly to the BS, but through intermediate nodes. This method is especially important for large-scale WSNs, as it extends the network lifetime by reducing the energy load in long-distance transmissions [6].

Schurgers and Srivastava [8] focus on local methods and traffic distribution techniques to save energy usage in WSNs. The paper propose to combine data from closer sensor nodes before sending it to the master station. This reduces the amount of data transmitted and saving energy amount. Instead of using fixed cluster heads, they use Data Convergence Units (DCEs) for processing the data locally. If there is a failure, these DCEs quickly adapt, making the system more reliable and energy efficient. They also propose to prevent a single node from running out of power by distributing traffic across the network. Methods such as Gradient-Based Routing (GBR) send data through the path with the largest gradient difference for balancing energy usage and extend the lifetime of the network [8].

Another method focuses on choosing nodes with more energy for routing, which avoids putting too much work on weaker nodes and helps save energy [8], [32]. Nakas, Kandris, and Visvardis [9] provide a detailed review of energy-efficient routing protocols in WSNs, dividing them into four categories: Flat, Hierarchical, Location-Based, and QoS-Based protocols. They emphasize the importance of hierarchical protocols like LEACH and its improved versions for saving energy. These protocols group nodes into clusters, with one node acting as the cluster head (CH) to collect and send data. Upgraded versions like LEACH-C and LEACH-M improve CH selection by considering how much energy each node has left, helping to spread energy use more evenly across the network. The survey also looks at location-based protocols, such as Geographic Adaptive Fidelity (GAF) and Greedy Perimeter Stateless Routing (GPSR), which use location data for better routing. For example, GAF divides the network into grids and activates only one node in each grid to save energy while keeping good coverage. QoS-based protocols, like Sequential Assignment Routing (SAR), are designed to balance energy saving with network performance. SAR chooses paths based on QoS needs, such as delay limits and packet loss rates, making it useful for critical tasks where reliability is important [9]. Table 1 presents a brief comparison of location-based topology protocols in terms of their advantages, disadvantages, scalability, mobility, routing, robustness.

Gururaj et al. [10] have a new idea for how to send data in 5G and 6G sensor networks. They call it CEERP (Collaborative Energy-Efficient Routing Protocol). It uses a type of machine learning, reinforcement learning, to make groups of sensors, or clusters, change as needed. A key part is how it picks the leaders of these groups, the cluster heads. It looks at how much power each sensor has left. This helps spread out the work and keeps any one sensor from running out of power too soon. This makes the whole network last longer. They also use something called MOISA (Multi-Objective Improved Seagull Algorithm). This helps make the network even better by saving energy, sending data faster, and just making the whole process more efficient. By considering multiple objectives simultaneously, MOISA ensures efficient energy management in complex 5G/6G scenarios where high data rates and reduced latency are essential. The authors demonstrate that CEERP significantly outperforms traditional protocols in terms of energy consumption, throughput, and network longevity, with a 50% reduction in energy consumption compared to conventional methods. This collaborative and adaptive approach makes CEERP particularly suitable for 5G/6G WSNs, which require scalable and energy-efficient solutions for sustainable communication [10].

Eriş et al. [47], [48] introduce a new medium access policy for underwater sensor networks that uses reinforcement learning (RL) within the Time Division Multiple Access (TDMA) system to improve energy efficiency. They focus on solving the energy challenges in underwater environments, where high energy use is caused by acoustic communication and environmental noise. Their proposed method uses a cooperative multi-agent RL algorithm that allows nodes to assign TDMA time slots on their own based on energy harvesting opportunities. The work in [49], [50] also considers a similar problem and proposed a novel reinforcement learning based routing algorithm for energy management in networks.

This reduces wasted energy and helps the network last longer. The method also uses multi-armed bandit modeling to help nodes learn the best times to transmitdata, making better use of the energy they collect. Simulations show big improvements in metrics like half node dead (HND) and last node dead (LND), meaning the nodes stay active much longer than with older scheduling methods. Additionally, piezoelectric energy harvesting is used to capture mechanical energy from water flow, providing a sustainable energy source and making the network more resilient to underwater challenges. The study concludes that combining energy harvesting with RL-based TDMA scheduling is a promising way to boost energy efficiency and communication reliability in underwater sensor networks [48]. Yari et al. studies the energy-efficient routing algorithm using sensors to increase longevity by adjusting sensor positions dynamically and optimizing data paths to reduce energy consumption in WSNs [51].

5G networks are expected to achieve significant efficiency improvements, with a goal of improving spectrum efficiency by 90/100 compared to 4G, while future 6G systems are designed to operate at lower power consumption while supporting land, air, and sea connections. A key aspect of this transition is the integration of AI/ML algorithms for intelligent resource management, enabling dynamic adjustments to transmission power, network topology, and service configuration. AI-based technologies such as adaptive beamforming and deep reinforcement learning will enable BS and radio access networks (RAN) for optimized power allocation based on real-time traffic demand, then reducing unnecessary energy consumption [52].

Energy harvesting is another key for achieving energy efficiency in 6G networks. Unlike 5G, which focuses on optimizing power management, 6G aims to integrate renewable energy sources, such as solar and ambient RF energy harvesting into powering the network. This will reduce reliance on traditional carbon-based power grids and align with global sustainable development goals. In addition, ultra-low power communication strategies such as device-to-device (D2D) networks and non-orthogonal multiple access (NOMA) are expected to minimize energy consumption at the user end by enabling localized data exchange and spectrum reuse rather than relying on centralized, power-hungry infrastructure [52].

In addition, 3GPP has defined a set of key performance indicators (KPIs) for mobile network energy efficiency, focusing on reducing the power consumption of core network components while maintaining better high data rates and low latency. These include database sleep mode optimization, adaptive bandwidth allocation, and intelligent scheduling mechanisms that allow mobile devices and network nodes to enter low-power states during inactivity. 6G is expected to be 10 times more energy efficient than 5G while providing higher spectral efficiency, lower power consumption per bit, and sustainable network operation [52].

Mobile Ad Hoc Networks (MANETs) are dynamic, infrastructure-less wireless networks in which nodes function as both hosts and routers, necessitating efficient routing protocols to manage communication and variations in network topology. Roy et al. conducted a performance comparison of leading MANET routing protocols, specifically AODV (Ad Hoc On-Demand Distance Vector), DSR (Dynamic Source Routing), and DSDV (Destination-Sequenced Distance Vector), based on three key perfor-

Table 1 A Synopsis of Location-Based Topology Protocols

Protocol	Advantages	Disadvantages	Scalability	Mobility	Routing	Robustness
GEAR [33]	It balances energy ingestion and extends network lifetime.	The periodic table exchanges increase overhead.	Good	Limited	The best route is selected.	Good
GEM [34]	It efficiently routes messages and offers void and obstacle tolerance.	It overloads low-level nodes.	Good	Limited	The shortest route is selected.	Low
IGF [35]	It has fault tolerance and reduced end-to-end latency.	It depends on the up-to-date local neighbor table.	Good	Limited	The best route is used.	Good
SELAR [36]	It has uniform energy dissipation.	It does not work well with nodes with holes.	Good	Limited	The highest residual power route.	Good
GDSTR [37]	It is easy to apply and offers lower path and hop stretch.	It suffers from the local dead-end problem.	Good	Limited	The shortest route is used.	Low
MERR [38]	It has uniformity of energy consumption.	It wastes energy when nodes are close.	Limited	Limited	The minimum energy ingestion route is used.	Low
OCF [39]	It offers superior energy saving and handles void.	It depends on the up-to-date local neighbor tables.	Good	Limited	The best route is used.	Good
PAGER-M [40]	It manages low overhead of routing.	It is stateless location-based.	Good	Limited	The shortest route using the greedy algorithm is used.	Low
HGR [41]	It has reduced end-to-end delay.	The reduced delay is not guaranteed.	Good	Limited	The minimum energy ingestion route is used.	Good
MECN [42]	Fault tolerance is established.	The link maintenance consumes energy.	Good	Limited	The optimal route in a sparse graph is used.	Good
SMECN [43]	Both link maintenance cost and number of hops are reduced.	High amount of edges increases overhead.	Low	Limited	The optimal route in a sparse graph is used.	Good
GAF [44]	Network lifetime is extended.	Nodes neither aggregate nor merge data.	Low	Limited	The least cost route within the virtual grid is used.	Low
PASC ACO [45]	Redundant data are reduced.	Energy holes are more evident.	Good	Limited	The highest residual energy route.	Good
PASC-AR [46]	It avoids the energy hole problem and extends network lifetime.	GPS increases energy consumption.	None	Limited	The optimal path by using ACO is used.	Low

mance metrics: average end-to-end delay (EED), packet delivery fraction (PDR), and throughput. Their findings revealed that AODV is better than DSR and DSDV regarding end-to-end delay, as AODV employs a hop-by-hop mechanism that reduces buffering delays. Consequently, DSDV demonstrated the highest packet delivery fraction (PDR) due to its proactive routing characteristics, making it more reliable in stable environments. Although DSR is effective under controlled network conditions, it exhibited fluctuations in throughput due to route caching mechanisms that occasionally led to stale routes, impacting performance. The study underscored that reactive protocols (AODV, DSR) are more suitable for dynamic network environments, whereas proactive protocols (DSDV) provide improved packet delivery in static scenarios. The authors concluded that no single routing protocol is optimal for all network conditions, and future research should explore hybrid and AI-enhanced routing strategies to enhance efficiency across various network scenarios [53].

In conclusion, the protocols discussed in this section investigate the importance of energy-efficient routing in WSNs, particularly for advanced 5G/6G environments. LEACH and its variants, reinforcement learning-based approaches like CEERP, and localized strategies such as GBR and TDMA with RL all contribute to enhancing energy efficiency and extending the operational lifetime of sensor networks. These protocols emphasize the need for adaptive, scalable, and sustainable solutions to meet the growing demands of next-generation communication systems, where energy efficiency remains a critical concern.

3 COLLABORATIVE APPROACHES FOR ENERGY EFFICIENCY ROUTING

Energy-efficient routing allows nodes in WSNs to cooperate and reduce energy consumption. This cooperation is especially important in 5G/6G systems to ensure that the network operates longer and more efficiently. Research has shown how nodes can perform better sensing and communication with less energy consumption. Thanks to these methods, the network's lifetime is increased and its efficiency is improved.

Demigha et al. [3] studied cooperative target-tracking techniques used to improve the energy efficiency of WSNs. Researchers classify these techniques into two main groups: perception-related methods and communication-related methods. These methods reduce unnecessary operations and allow the network to operate for a longer period of time. A representative cooperative method is the predictive model. In this method, nodes predict the future position of the target and activate only the necessary nodes. Thus, unnecessary data collection and data transfer are prevented, resulting in energy savings. Also, the sensor selection problem (SSP), which is part of this method, focuses on determining which nodes will work to obtain the best tracking results with the least energy consumption. This technique is an effective way to save energy in WSNs by maintaining tracking accuracy while reducing energy usage. Sabakrou et al. proposes that intelligent distributed sensor activation algorithms optimize the energy usage while maintaning high tracking accuracy in WSNs [54]. Zhang et al. investigated sensor collaboration for parameter tracking using energy harvesting sensors [55]. They show optimal collaboration improve tracking accuracy and energy efficiency in wireless sensor networks.

Demigha et al. [3] state that self-organizing systems are also important for energy saving. There are two common methods: cluster-based and tree-based. In cluster-based methods, the sensors are divided into groups, and each group has a cluster head. The cluster head organizes the groups in real-time based on the target location and activates only the nodes that is required [56]. The other nodes go into sleep mode for saving energy. In tree-based methods, nodes form a hierarchical structure and only the nodes that are best suited to track the target are activated while the others remain in sleep mode. Figure 2 exhibits target tracking process in a WSN, showing active nodes, detecting nodes, estimated target positions, and the predicted path [3].

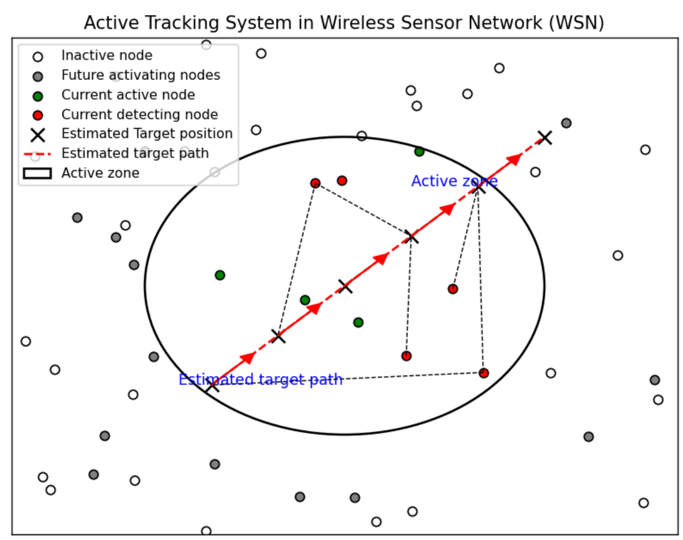

Fig. 2 Target tracking process in a sensor network, showing active nodes, detecting nodes, estimated target positions, and the predicted path [3].

In addition, interoperability of sensing and communication systems is very important for energy saving. Instead of sending raw data from all nodes, the system combines data from the nodes and sends only the processed and important information. This method reduces communication, prevents unnecessary energy consumption, and makes the network work more efficiently. These teamwork methods allow the system to save a lot of energy while still tracking targets effectively. In Javapdour et al., it is stated that integrating MAC layer techniques with active nodes can increase the target tracking accuracy and energy effiency in WSNs [3], [57].

The work by Stanojev et al. [4] extends the discussion on collaborative energy-saving techniques by exploring the use of Hybrid Automatic Repeat reQuest (HARQ) protocols. The study compares the energy efficiency of non-collaborative and collaborative HARQ versions. The authors evaluate three types of HARQ protocols—HARQ Type I (HARQ-TI), Chase Combining (HARQ-CC), and Incremental Redundancy (HARQ-IR)—and analyze the impact of using a relay for retransmissions. In collaborative HARQ settings, energy consumption is reduced by involving a relay, which improves communication reliability while balancing the energy load across the network. The relay helps retransmit data, thereby decreasing the number of retransmissions needed by the source and destination nodes, which directly impacts the energy used in communication. However, the authors note that while collaborative HARQ can save energy over long distances, it is not always advantageous in scenarios where circuitry energy dominates the total energy budge. This is particularly evident in cases where transmission distances are short, and the energy cost of activating additional circuitry (such as relays) outweighs the benefits of reduced transmission power. This highlights the need for a balanced approach when choosing collaborative techniques for energy efficiency, ensuring that the energy costs of both transmission and circuitry are considered. It is stated that energy-harvesting sensors enable optimal sensor collaboration for tracking parameters and extending network lifetime while ensuring data reliability [4], [55], [58].

Felicetti et al. [5] propose a collaborative model that extends the idea of energy efficiency to residential environments through Collaborative Smart Environments (CSEs). The authors introduce a Home Energy Management System (HEMS) as a central control unit to manage energy consumption by smart devices within a household. The proposed model leverages recent advances in the Internet of Things (IoT) and Information and Communication Technologies (ICT) to enable effective communication between different smart devices within a home. The centralized control unit (CCU) collects data from sensors, smart plugs, and other devices, ensuring that energy use is optimized through real-time monitoring and control. By managing energy supply, demand, and appliance use collaboratively, the system can reduce energy consumption while maintaining user comfort and cost efficiency. The smart plugs and smart boxes in the CSE architecture allow existing appliances to become part of the energy management system, providing additional intelligence and connectivity that enable these appliances to adapt to real-time energy demand and supply conditions [48], [59].

The paper talks about how important it is for smart devices to work well together in smart environments. One big problem in making a Collaborative Smart Environment (CSE) is making sure all devices can connect and work without issues. The system suggested in the paper uses smart plugs and a ”smart box” to help regular home appliances talk to a central control unit (CCU). This setup helps the system control energy better, like using stored energy or shared energy systems. It also changes energy use in real time to match what users need and how much energy is available, making the system more efficient.

Felicetti et al. [5] talk about how predicting energy use can help save power. They explain a method that looks at past energy usage to find patterns and predict future needs. This helps the system decide the best time to run appliances or charge local energy storage. With tools like machine learning and simple math models, the central control unit (CCU) can guess how much energy is needed and control devices to use power better. This way, energy is saved while still keeping everything running smoothly and making sure users are comfortable [5].

To sum up, prediction-based schemes, self-organization, collaborative HARQ protocols, and home energy management are some collaborative energy-efficient techniques that show a lot of promise for lowering energy use in WSNs and smart environments. These methods focus on intelligent coordination between network nodes and devices to conserve energy while meeting performance requirements. Prediction based schemes and adaptive clustering help in optimizing the activation of nodes, thereby conserving energy in target tracking.

Collaborative HARQ protocols enhance communication reliability while managing energy costs effectively. Home energy management systems in smart environments use advances in ICT and IoT to dynamically manage energy consumption and optimize household energy use.Together,these techniques represent a promising approach to tackling the challenge of energy efficiency in next-generation communication networks and smart systems.

4 IMPACT OF MOBILITY AND HETEROGENEOUS NETWORKS

Understanding the effects of mobility and heterogeneous networks is key to developing future communication systems that are both energy-efficient and reliable, especially for advanced WSNs and 5G/6G networks.

As more heterogeneous network designs are introduced, combining macro and small cells, new challenges arise in managing mobility while maintaining good performance. This section reviews how mobility and heterogeneity affect network performance, focusing on the difficulties of mobility management, energy use, and maintaining reliable handovers. The study by Gures et al. [21] provides an extensive analysis of mobility management in 5G heterogeneous networks (HetNets), emphasizing the complexity brought on by the deployment of a large number of small cells alongside macro cells. These HetNets offer higher capacity and enhanced coverage, but at the cost of frequent handovers (HOs), leading to issues like HO failures (HOFs), ping-pong HOs, and increased energy consumption. These challenges have a significant impact on user experience, with frequent HOs leading to increased power consumption and reduced battery life for user equipment (UE). To address these challenges, 5G mobility management includes mechanisms such as beam-level mobility and beam management, which allow for more stable connections between UE and BS. Beam-level mobility enables dynamic routing of transmission to maintain connectivity with moving devices, especially in 5G/6G WSNs. Beam-level management helps reduce unnecessary HOs by maintaining directional links to the UE, even as it moves between cells [21].

Gures et al. talk about network slicing as an important part of handling mobility in networks. Network slicing enables a physical network to be divided into virtual network slices with different services, each of which is provided with customized resources and services. It lets many virtual networks run on the same physical system, giving different services based on what is needed. For example, IoT devices and machine-to-machine (M2M) systems can have their own slices with mobility settings that match their needs. IoT devices, which can handle short breaks in connection, are treated differently than services like IP telephony, which need a stable connection all the time. The paper also explains handover methods like XN-based and N2-based handovers, which help reduce connection breaks and keep communication smooth. These methods are very important in crowded HetNet setups where handovers happen often. By avoiding interruptions, they make sure users have a good experience [21].

Managing mobility in HetNets comes with challenges in paging and registration processes, which need to balance saving power and keeping delays low. The 5G Radio Resource Control (RRC) Inactive state is a helpful solution to this problem. This state works as a middle ground between the RRC Idle and Connected states, lowering both delay and energy use by keeping the user equipment (UE) context. This means the device can reactivate quickly without needing a full reconfiguration. This improvement makes handling frequent handovers more efficient, reducing signaling and saving energy, which helps optimize mobility management in HetNets [21].

In their study, Wang et al. [22] explore the impact of mobility and heterogeneity on coverage and energy consumption in WSNs, providing insights into how these factors influence network performance. The authors analyze different sensor deployment schemes, such as uniform deployment and Poisson deployment, to understand their effects on coverage and energy use. In uniform deployment, sensors are placed randomly and uniformly across the operational area, while Poisson deployment uses a 2-dimensional Poisson point process to model sensor placement. The authors focus on blanket coverage (full coverage of an area) and k-coverage (where each point is covered by at least k sensors), both of which are essential for ensuring network reliability in applications such as environmental monitoring and surveillance [22].

A significant concept introduced by Wang et al. is the equivalent sensing radius (ESR), which is used to assess coverage performance in heterogeneous WSNs, where nodes have different sensing capabilities. The study finds that ESR is a critical factor in determining whether full coverage can be achieved, especially under different mobility models, including i.i.d. mobility (independent and identically distributed) and 1-dimensional random walk mobility. The authors show that mobility can significantly enhance coverage by repositioning sensors to improve overall area coverage, which highlights the positive impact of controlled node movement on network performance [22], [60].

The study also addresses the effects of sensor heterogeneity on coverage and energy consumption. Heterogeneous WSNs consist of sensors with varying capabilities, such as different sensing radii or power levels. The authors demonstrate that while heterogeneity can lead to slightly increased energy consumption under certain mobility models, it can also result in better coverage without proportional increases in energy use. For example, under the 1-dimensional random walk mobility model, sensor heterogeneity slightly increases sensing energy, but it also reduces overall network costs by making efficient use of sensors with different capabilities. This trade-off suggests that, under appropriate mobility settings, heterogeneity can enhance coverage without significantly impacting energy consumption, making it a valuable approach for large-scale deployments [22].

The survey by Tashan et al. [61] focuses on Mobility Robustness Optimization (MRO) in future HetNets, emphasizing the importance of optimizing mobility to maintain stable communication in high-mobility environments. The paper highlights the challenges of managing handover (HO) in HetNets, especially due to the deployment of numerous small base stations (SBSs) alongside macro cells. While these SBSs enhance network capacity and coverage, theyalso increase the frequency of HOs, which can lead to handover pingpong and radio link failures (RLFs). These issues degrade user QoE and require effective handover control parameters (HCPs), such as Time-To-Trigger (TTT) and Handover Margin (HOM), to be optimized for better performance. The authors discuss several MRO algorithms that dynamically adjust HCPs based on network conditions to minimize unnecessary HOs and maintain optimal connectivity, especially in ultra-dense networks [61].

Tashan et al. also explore the use of machine learning (ML) in MRO to enhance adaptability. Techniques like fuzzy logic controllers (FLC) and Q-learning are used to dynam ically adjust handover parameters based on real-time data such as received signal strength (RSS), user speed, and cell load. These ML-based approaches help address the challenges posed by heterogeneous cell sizes and different radio access technologies (RATs) in HetNets, making handover decisions more efficient and reducing unnecessary HOs. For instance, fuzzy Q-learning combines reinforcement learning with fuzzy logic to provide adaptive solutions that optimize HCPs with minimal computational overhead. This use of ML highlights the importance of intelligent handover management in main taining stable connectivity and improving user QoE in HetNets [61], [62].

Figure 3 shows the concept of resource management in HetNets under four main categories. These are power allocation, user assignment, mode selection, and spectrum allocation. While power allocation is evaluated in terms of efficiency, energy saving, and spectrum suage, user assignment is considered based on SINR (signal-to-noise ratio) and data rate. Mode selection is divided into static and dynamic, while spectrum allocation is performed over conventional bands, millimeter wave (mmWave) and terahertz (THz). This structure provides a core for efficient resource utilization and performance optimization in 5G/6G WSN networks. [63]

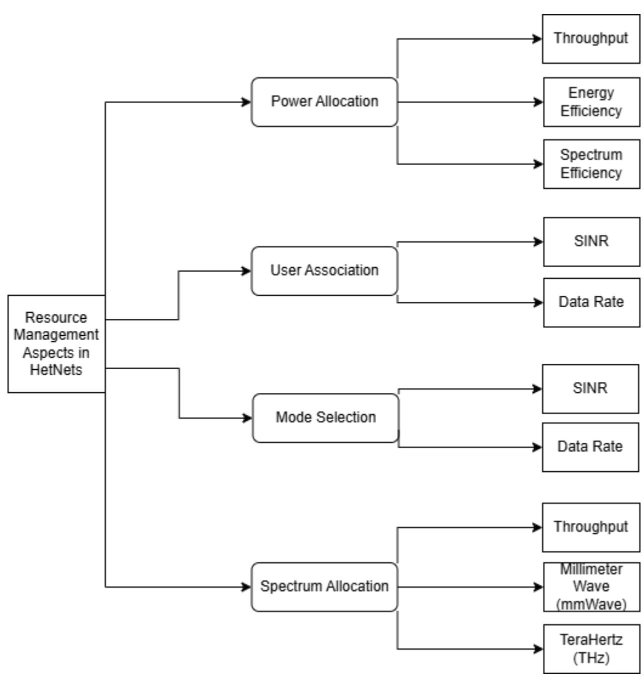

Fig. 3 Key resource management aspects in HetNets [63].

In conclusion, the impact of mobility and heterogeneity on WSNs and HetNets is multifaceted, involving challenges related to frequent handovers, coverage, and energy efficiency. Mobility management in HetNets, as highlighted in [21], requires advanced solutions like beam-level mobility and network slicing to handle frequent HOs and provide tailored services for different types of devices. The work [22] emphasize the positive effects of mobility on coverage and the role of sensor heterogeneity in optimizing energy use in WSNs. Lastly, Tashan et al. [61] underline the importance of robust mobility optimization through self-optimizing algorithms and machine learning techniques to manage HOs in future HetNets effectively. These studies show that two main things are important for better wireless networks, especially with 5G and 6G. First, how devices move around. Second, how different devices are used together. In Yang et al. it is also emphasized that tracking mobile targets in WSNs requires specialized protocols that efficiently manage node coordination and communication overhead [64]. Doing them well can help networks cover more area, use less power, and keep working even when things go wrong.

5 AI/ML TECHNIQUES IN ENERGY-EFFICIENT ROUTING

Lots of people are now looking at using AI and machine learning to help WSNs save power. These networks often work in tough places where it's really important to not waste energy. AI and machine learning can assist by intelligently managing the network's resource usage and making more informed decisions about data transmission. This helps the networks work for way longer. Here, we'll dive into how researchers are using AI and machine learning to make data travel through the network using less power. We'll look at the latest studies on this. Biswas et al. [23] provide a detailed review of how AI is used to optimize power consumption, showing its impact on saving energy in various areas, including WSNs. The authors highlight that AI not only helps achieve sustainability goals but also lowers operational costs. The authors delve into various AI techniques, such as Reinforcement Learning (RL), Genetic Algorithms (GA), and Neural Networks (NN), that enable real-time energy management. For instance, they apply Reinforcement Learning (RL) to manage changing energy demands in HVAC systems, enabling real-time adjustments that save energy while maintaining user comfort. Fuzzy Logic Control (FLC) is another technique they mention, known for managing nonlinear power systems, such as air conditioners, where it achieved up to 25% energy savings. These AI-driven methods show great potential for improving energy efficiency and ensuring a stable energy supply [23]. The another paper presents an approach to optimize the power consumption of wireless sensor nodes by developing a novel power control technique, to improve energy efficiency and extending the network lifetime [65].

Pasqualetto et al. [24] look into how AI can make energy management in smart buildings more efficient and help with global sustainability efforts. They focus on Multi-Agent Systems (MAS), which use decentralized decision-making to create smart environments. MAS is based on the "Belief-Desire Intention" (BDI) model, where different agents work together to optimize energy use. Each agent manages specific tasks like temperature control or HVAC systems, making the building more energy-efficient overall. The paper also highlights the role of Big Data in improving AI models. Data collected from sensors and devices in smart buildings is essential for understanding energy usage, predicting future needs, and managing resources in real-time. The authors discuss Artificial Neural Networks (ANNs) and Genetic Algorithms (GA) as useful tools. ANNs help predict how much energy will be needed, while GAs optimize energy usage based on changing prices. These AI methods offer practical ways to manage energy better, meet user needs, and support sustainability[24].

The survey by Samara et al. [66] focuses on energy efficient routing algorithms in WSNs, emphasizing the need for effective routing to minimize energy consumption in sensor nodes. The authors discuss several well-known algorithms, such as LEACH (Low Energy Adaptive Clustering Hierarchy), TEEN (Threshold Sensitive Energy Efficient Sensor Network Protocol), and APTEEN (Adaptive Periodic Threshold Sensitive Energy Efficient Sensor Network Protocol). These algorithms use clustering strategies to minimize data transmissions, thereby reducing energy consumption. LEACH, for example, organizes nodes into clusters, with Cluster Heads (CHs) responsible for aggregating and forwarding data to the BS. However, the random selection of CHs can sometimes result in inefficient energy usage, especially when selecting nodes with low residual energy. TEEN and APTEEN improve upon LEACH by introducing threshold-based mechanisms to minimize unnecessary data transmissions, especially in event driven scenarios, thus extending the network lifetime. The authors also explore AI-based approaches, such as genetic algorithms and neural networks, to optimize CH selection and routing paths, highlighting their ability to dynamically adapt to changing network conditions and energy levels, which significantly enhances energy efficiency in WSNs [66], [67]. Figure 4 provides a general architecture of data aggregation approach from [66].

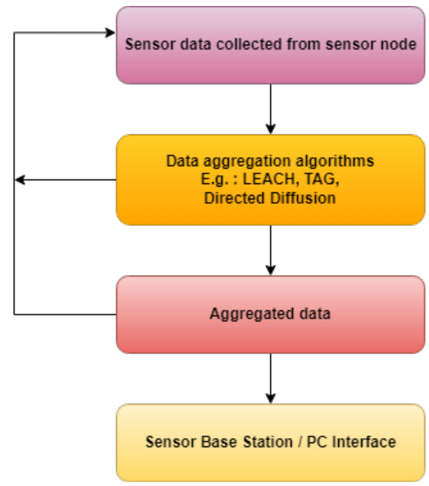

Fig. 4 The general architecture of data aggregation approaches.

Priyadarshi [26] provides an in-depth review of meta-heuristic and AI-based algorithms for energy-efficient routing in WSNs. Some of the optimization algorithms talked about in the paper are Particle Swarm Optimization (PSO), ABC, Ant Colony Optimization (ACO), Genetic Algorithm (GA), Firefly Algorithm (FA), and Bacterial Foraging Optimization (BFO). These bio-inspired algorithms are based on how animals act naturally, like how bees use swarm intelligence or how ants use pheromones to find the best routes. WSNs use these algorithms to solve challenging routing problems. PSO, for instance, helps nodes find the best transmission paths by mimicking the social behavior of birds, while ACO uses pheromone trails to determine the most energy efficient routes. The author also explores hybrid optimization techniques, such as combining PSO with ACO, to enhance data collection and prolong network longevity [68]. Combining different algorithms can make things even better, especially when it comes to saving energy and keeping the network running for a long time. Priyadarshi's work also suggests that AI and certain smart search methods are really useful for tackling power issues in these sensor networks. This makes them more reliable and able to adapt to different uses, like keeping an eye on the environment, running factory equipment, and building smart cities [26], [69], [70].

The study from Rovira-Sugranes et al. concludes that AI-based routing protocols bring significant advantages over traditional routing mechanisms, especially in dynamic and resource-constrained networks. Traditional protocols such as AODV, DSR, and OLSR rely on predefined routing tables and periodic updates, also this can lead to high operational costs and slow convergence in rapidly changing environments. In contrast, AI-driven approaches, such as Q-learning and reinforcement learning (RL)-based protocols, reduce latency and improve packet delivery rates by adapting to changes in network topology in real time. AI-based methods also integrate predictive analytics, enabling proactive route adjustments and better handling of connection failures. However, these intelligent routing solutions often require more computational resources and extensive training data to perform optimally. While traditional routing protocols provide stability and low computational cost, they lack scalability and adaptability in highly mobile networks. In contrast, AI-powered protocols offer superior performance in terms of throughput, reduced latency, and energy efficiency, making them ideal for unmanned aerial vehicles and next-generation wireless networks [71].

AI-driven routing has come with smart ways to manage network traffic, predict congestion, and fix problems automatically. For example, RL models such as Deep Q Networks (DQN) and Proximal Policy Optimization (PPO) help networks choose the best path in real time applications. On the other hand, supervised learning is mainly used to detect unusual network activity and classify traffic. Deep learning methods, such as Recurrent Neural Networks (RNNs) and Transformer-based models, improve predictions but need a lot of computing power. Since studies do not compare these AI techniques properly, it is difficult to know which one works best for different network conditions. Without a clear evaluation system, it is unclear whether AI-based routing is better for quick decision-making, security, or managing traffic over time. This lack of clarity makes it harder to use AI-driven routing effectively in SDN (Software-Defined Networking), cloud systems, and 5G/6G WSN networks [72].

Despite WSNs' advantages, they face significant real-world challenges, including hardware limitations, environmental constraints, and deployment issues. One of the primary constraints is energy consumption, as sensor nodes rely on battery power, making efficient energy utilization a key concern. Furthermore, harsh environmental conditions such as extreme temperatures, humidity, and electromagnetic interference can severely impact the reliability of WSNs. The scalability issues arises when large-scale deployments increase network congestion and brings all problems in data routing and synchronization. To address these concerns, researchers emphasize the need for energy-efficient protocols, adaptive deployment strategies, and AI-driven optimizations to make the robustness better and the longevity of WSN applications [73].

In summary, AI and ML are useful tools for better energy-efficient routing in WSNs. Methods like reinforcement learning, genetic algorithms, fuzzy logic control, and using groups of intelligent agents has also been a good way to make these networks better and last longer. These "multi-agent systems" offer adaptable and smart ways to handle energy problems, so the networks can run for longer and more reliably. Combining different optimization methods, especially ones inspired by nature, also looks promising. These can simplify data gathering, spread out the work evenly, and save power. Basically, using AI and machine learning for energy-efficient routing makes these sensor networks more sustainable and prepares them for all sorts of future uses in smart homes, cities, and other places.

6 SECURITY CHALLENGES IN ENERGY-EFFICIENT ROUTING

Keeping data safe is a big deal when designing ways for devices in the IoT and WSNs to send information while saving power. These networks often don't have much energy to spare, so adding security is tricky. We need to protect the data and make sure it's reliable and private, all while trying to use as little power as possible. This section looks at recent research on the tough problem of designing both secure and energy-efficient routing algorithms, particularly for networks with limited resources [74].

For example, Mahamat et al. [25] talk about how difficult it is to have both good security and low energy use in IoT networks. Due to the frequent placement of these devices in vulnerable areas and their limited power, maintaining a balance becomes crucial. They say that many current security methods use up too much energy, which means the network won't last as long.

We need fresh ideas for security that don't drain the battery. This paper suggests using AI and software-defined networking (SDN) to build flexible security. AI and SDN can tweak security settings instantly based on what's happening around the devices, which saves power and keeps things secure. Think of it like this: simple security rules made for the limited brains of IoT devices are key to protecting data without killing the battery [25].

Mahamat et al. also stress the need for "smart" security, where the level of protection changes based on the actual threat. By constantly checking what's going on, IoT devices can adjust their security. When things are dangerous, they can ramp up the protection. When things are calm, they can dial it back and save power. This not only helps the devices last longer but also finds a good middle ground between strong security and efficient energy use. AI can make this kind of adaptable security possible, which could be a big step forward for making IoT networks both secure and sustainable in ever-changing situations [25]. Figure 5 provides elements needed to provide a security solution balancing the provided security level and energy consumption [25].

Biradar and Mathapathi [20] looked at the tricky job of designing ways for WSNs to send data securely, reliably, and without wasting power. They sorted these data-sending methods into three groups: proactive, reactive, and hybrid. Then, they checked how each group handles energy use and security. Their main point is that it's really tough to build systems that both save power and keep data safe, particularly for important jobs like watching the environment or military operations. Reactive methods are more energy-efficient than proactive ones, as they establish data routes only when necessary. Proactive methods, on the other hand, use up extra energy constantly updating their route maps, even when they're not sending data [20]. They also explore different ways to make these routing methods both secure and energy-efficient. They mention that grouping sensors into clusters, like with LEACH method, can help save power because the cluster leaders can gather and process data more efficiently. They also states that it's vital to have trust-based routing and secure location tracking to keep data safe and stop unauthorized access. Simple encryption methods are also key for adding security to these power-limited networks. Finally, they suggest that machine learning could be promising to boost security with much less energy, so that's the future work [20].

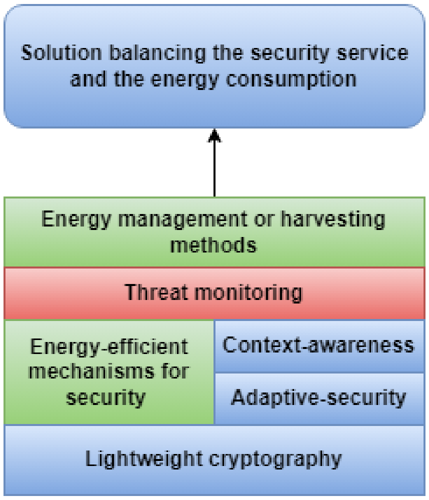

Fig. 5 Elements needed to provide a security solution balancing the provided security level and energy consumption [25].

Both Mahamat et al. and Biradar and Mathapathi highlight the constant struggle to balance saving energy and keeping things secure in IoT and WSNs. Strong security is a must to protect data and keep these networks running reliably. But, because IoT devices and sensor nodes have limited battery power, security measures have to be really energy-efficient. AI-powered, context-aware solutions and lightweight encryption seem like good ways to tackle this problem. These methods make sure that security adjusts to what's happening in network right now, so you can save power while still keeping your data reasonably safe [75].

To wrap things up, building routing methods for IoT and WSNs that both save energy and solve security problems is a tough but essential job. Smart security systems that use AI, software-defined networking, and simple encryption can help keep data safe without draining the battery. By creating systems that adapt to their surroundings and using clever optimization techniques, researchers can make these networks more robust, reliable, and sustainable. This will be crucial for important applications where both security and energy efficiency are paramount [20], [25].

7 CONCLUSION

This study investigates energy-efficient routing protocols for 5G/6G WSNs. Cooperative routing techniques, hierarchical clustering methods, AI, and machine learning (ML) applications reduces unnecessary energy consumption and extend the network lifetime. Protocols such as LEACH and its derivatives (LEACH-C, LEACH-DCS) save energy by selecting more balanced nodes, and AI techniques such as reinforcement learning and genetic algorithms make routing dynamic to have sustainable communication. In mobility and heterogeneous networks, frequent handovers and excessive signaling traffic increases the energy consumption. Solutions such as beam-level mobility and mobility role optimization (MRO) have been proposed to minimize these issues. This review provides an organized comparison of the energy-efficient routing protocols and highlights developing trends that contribute to the sustainable development of 5G/6G WSNs.

Energy-efficient security solutions use lightweight encryption, trust-based routing, and context-aware security mechanisms to secure the network while reducing energy consumption [76]. However, large and rapidly changing networks require scalable and low-power solutions. Future research should focus on AI-assisted routing, advanced mobility management, and the integration of renewable energy sources. These developments will contribute to the widespread adoption of reliable and energy-efficient communication systems in many areas, including smart cities, environmental monitoring, and industrial automation.

Additionally, studies in the future should explore the scalability of AI-driven routing algorithms for very large-scale WSN deployments. They need to optimize the energy consumption without compromising performance. The integration of energy-harvesting techniques, such as solar-powered sensor nodes, brings an exciting research direction for sustainable WSNs. Furthermore, interdisciplinary collaborations between network engineers, AI researchers, and experts can lead to innovative solutions. Practical validation methods, including real-world testbeds and large-scale simulations, will be important for evaluating the feasibility and effectiveness of these proposed solutions.

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