

Article

Energy-Efficient Network Protocols and Resilient Data Transmission Schemes for Wireless Sensor Networks—An Experimental Survey

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Abstract: Wireless sensor networks (WSNs) are considerably used for various environmental sensing applications. The architecture and internal specifications of WSNs have been chosen based on the requirements of particular applications. On this basis, WSNs consist of resource (energy and memory)-limited wireless sensor nodes. WSNs initiate data communication from source to destination via physical layer management principles, channel slot scheduling principles (time division multiple access), wireless medium access control (WMAC) protocols, wireless routing protocols and application protocols. In this environment, the development of WMAC principles, routing protocols and channel allotment schemes play crucial roles in network communication phases. Consequently, these layering functions consume more energy at each sensor node, which leads to minimal network lifetime. Even though the channel management schemes, medium control protocols and routing protocols are functionally suitable, the excessive energy consumption affects the overall network performance. In this situation, energy optimization algorithms are advised to minimize the resource wastage of WSNs during regular operations (medium control and routing process). Many research works struggle to identify the optimal energy-efficient load balancing strategies to improve WSN functions. With this in mind, the proposed article has conducted a detailed literature review and notable experimental comparisons on energy-efficient MAC protocols, channel scheduling policies and energy-efficient routing protocols. To an extent, the detailed analysis over these wireless network operations helps to understand the benefits and limitations of recent research works. In the experimental section of this article, eight existing techniques are evaluated under energy optimization strategies (WMAC, channel allocation, sleep/wake protocols, integrated routing and WMAC policies, balanced routing and cooperative routing). The proposed review and the classified technical observations collected from notable recent works have been recognized as crucial contributions. The results infer the suggestions for feasible WSN communication strategies with optimal channel management policies and routing policies. Notably, the simulation results show that cross-layer or multi-layer energy optimization policies perform better than homogeneous energy optimization models.

Keywords: wireless sensor network; energy optimization; MAC; routing; review and data communication

1. Introduction

WSNs consist of tiny sensor nodes made for data sensing, data computation, data transmission and data reception tasks. Unlike wired network scenarios, wireless sensor nodes transmit the sequence of environmental data from one location to another location via open multi-hop channels. In this case, each sensor node is intended to broadcast beacon messages to recognized neighbor sensor nodes in order to establish multi-hop channels. At the same time, each sensor node must hear the requests coming from other sensor nodes. Thus, the sensor nodes crucially spend significant amounts of energy in listening states. As the sensor nodes are vulnerable to resource limitations in real-time conditions, wireless network protocols and communication frameworks are expected with energy consideration functions.

Generally, WSNs manage various services in their protocol stack, such as mobility management, security management, power management, event management and quality management. The application-specific WSN architectures are deployed in order to provide various levels of network services. Wireless physical layer functions, WMAC functions and wireless routing protocols are the major considerations for achieving superior data transmission in WSNs. In this regard, configured physical layer parameters and nodes' effective attributes initiate network operations. To an extent, wireless channel allotment policies (scheduled or random) are decided by WMAC procedures. Similarly, identifying optimal routes for multi-hop data communication along the channel from source node to destination node must be configured with the help of suitable wireless routing protocols. According to the deployment strategies of WSNs, the routing protocols are chosen to enable a multi-path routing process or a uni-path routing process.

Along the execution of layering functions in the network, each sensor node receives irregular energy distribution, computation load and memory utilization. Under the conventional or standard network functions, the lifetime of the WSN is unacceptably undersized. The lifetime of the WSN or sensor nodes can be increased through proper energy utilization policies and load distribution policies. These policies are expected in MAC and route management tasks. Initiating crucial experimental analysis over various WSN-based energy optimization techniques and load optimization techniques provides a new motivation for future research works. In this concern, the individual energy optimization rules established for WMAC and routing function in each node ensure the entire network's lifetime and link availability. The importance of energy-sensitive communication protocols is seriously considered for research under WMAC and routing layer functions. As WMAC and routing jobs are more closely related to channel liveliness than other layers, the need for controlling energy wastage along the respective channel is a critical task. In the same manner, multi-path routing protocols are noted as better solutions than uni-path routing mechanisms against security threats. Apart from physical architectures, the sensor nodes require logical neighbor association rules to build usable network channels. Logical network configuration and successful data communication are confirmed through effective WMAC principles and resilient routing protocols, respectively. On the other hand, energy-efficient WMAC procedures and routing protocols are widely expected in each wireless sensor node to save the individual node's energy. With this in mind, this experimental survey has been initiated from the study of the WSN's characteristics, types, future-generation policies and real-time network problems. Accordingly, the major problems and solutions are described, as given in Table 1.

Table 1. WSN studies and categories of works.

WSN Studies	Respective Categories of Studies
[1–4]	Energy optimization, mobility, applications, general overview and security.
[5–11]	Channel rate allocation (lifetime management), reliable data collection, energy optimization, channel eavesdropping, network coverage, localization and mobility prediction.
[12–16]	Reliability and energy considerations, energy problems in IoT, channel scheduling, medical sensors and performance optimization in IoT.

As given in Table 1, the general aspects and WSN characteristics are discussed. In addition, other research works [17–27] discuss various resource allocation issues, routing protocols, smart sensor characteristics and energy problems of WSNs. The baseline understandings of WSNs and their application inspires researchers to focus on suitable WMAC and wireless routing strategies in real time. In the same manner, the articles used for experimental survey are categorized under WMAC and wireless routing protocols. Particularly, the related research works are classified under energy optimization policies, energy balancing policies, channel scheduling policies and machine learning techniques [28–88].

The detailed literature discussions and relative observations mainly target the optimized WSN functions. Notably, energy-optimized solutions on the relative functions between WMAC and routing protocols of WSNs (channel allocation and route identification) are vastly explained in this article. Moreover, the experimental section of this article details a crucial set of energy optimization policies and load balancing policies in order to suggest better WSN strategies on the basis of WMAC and wireless routing protocols. As many research works propose resource-constrained communication protocols (channel control and route control), the need for classified results is mandatory to obtain crucial aspects through appropriate experimental conditions.

In the same manner, research problems are widely noted under energy-efficient channel management policies, medium utilization quality, energy-aware WMAC routines, node liveliness, node connectivity and optimized neighbor discovery processes. As the battery-powered wireless sensor nodes are vulnerable to unplanned energy depletions, the overall functions of the entire WSN cannot be expected as static and stable in real-time conditions. In this regard, the proposed article analyzes and compares recent works conducted regarding the issues mentioned. In addition, this article mainly finds the technical benefits, limitations and scientific facts of crucial research works accompanied by the energy-efficient WMAC principles, optimal medium utilization and energy sensitive wireless routing protocols of WSNs.

The study contributions of the article are listed, and details are given in the respective sections.

- Discussing the types of WSNs, configuration details, resource management, channel rate allocation and future requirements.
- Taking a comparative study and experiments on WMAC principles, channel allocation strategies and energy optimization issues.
- Discouraging the functions, limitations and properties of various wireless routing protocols.
- Energy optimization issues in wireless routing environment and protocol support.
- Experimenting a detailed energy optimization scenario between different cases of WMAC functions and wireless routing protocol functions.

Many literature survey works are proposed under energy optimization policies for enabling feasible network communication between wireless sensor nodes. At any rate, the implications of multi-layer energy conservation policies (WMAC energy solutions, WMAC channel management, routing problems and load balancing problems) provide an integrated problem analysis and solution-making platform for future researchers. Crucially, the existing study articles consider mostly uniform energy-efficient solutions on a particular layer. The energy optimization solutions discussed on single-layer functions limits the

relative energy-based interpretations between WMAC (channel allocation) functions and routing protocol functions. On the whole, the novelty and contributions of the proposed literature survey give diversified technical details on multi-layer network functions and energy considerations. On this basis, the research findings are taken in order to solve the energy optimization issues regarding wireless channel allotment schemes, WMAC protocol functions and wireless routing protocols.

The proposed review article has been classified under different sections. Section 2 of the article consists of the technical discussions on WSN architectures, network problems, energy-sensitive WMAC strategies and energy-efficient routing protocols. Section 3 includes practical investigations and performance comparisons between notable literatures. Section 4 of this article provides a detailed conclusion on the review findings and future scopes.

2. Materials and Methods

2.1. Technical Discussions on Related Works

As discussed earlier, the importance of WMAC and wireless routing protocols is seriously considered in many recent research works. Predominantly, the research initiatives focused on medium control, channel allotment, routing efficiency and energy constraints to ensure fault-protective sensor nodes during independent data transmissions. Additionally, the guarantee to increase network stability and lifespan is the most essential quality for well-organized WSNs. Among the unexpected environmental conditions and network uncertainties, the assurance of successful data communication can be attained through a deep technical survey and a newly created solution. The following sections of this proposed review article discuss the details of WMAC concerns and routing concerns to achieve energy-controlled lifetime enhancement routines.

On the whole, the MAC protocol basically has two variants, such as the carrier sense multiple access with collision detection approach (CSMA/CD) and the carrier sense multiple access with collision avoidance approach (CSMA/CA), used on wired networks and wireless networks, respectively. Under the CSMA/CD approach, the network interface card (NIC) of any node supervises the availability of the other node's activity on the wired channel (collision) to start data transmission. The detection of collision at the NIC delays the data transmission of a particular node. On the other hand, the CSMA/CA approach monitors the wireless channel for a random duration to prevent collision during data transmission. In addition to MAC layer functions, logical link control (LLC) functions are operated in a data link layer for multiplexing, de-multiplexing and network layer interfacing services. In any event, the WMAC (CSMA/CA), LLC and wireless routing functions consume much more energy in WSNs.

In this case, routing protocols execute neighbor discovery functions (route requests and route replies), routing table organizations, link establishment functions and data routing functions continuously. Particularly, neighbor discovery jobs consume crucial amounts of energy in the idle listening state. From these discussions, this article finds energy optimization challenges through multi-layer network protocols to assure the lifetime of the WSN.

2.1.1. Wireless Sensor Networks and Challenges

WSNs are vastly used for establishing autonomous communication environments, Internet of Things (IoT) platforms and other distributed networks. As a collection of tiny sensor nodes is responsible for multi-path distributed communication, the effective utilization of medium, channel slot management and routing processes executed are expected to be optimized under limited energy-consumption practices. Generally, WSNs are categorized as static WSNs, mobile WSNs, deterministic WSNs, uncertain WSNs, single base station (BS) WSNs, multiple BS WSNs, direct-hop WSNs, multi-hop WSNs, homogeneous WSNs and heterogeneous WSNs (IoT), etc. The environment of various

types of WSNs consists of crucial network properties such as energy optimization, network scalability, node responsiveness, communication reliability and node mobility.

A wireless sensor node deployed in the field has internal components such as sensor units, data processing units, data communication units and optional software modules (operating system or system software). The sensor nodes used in WSNs are identified as generic, special purpose, gateway and other higher models. In this regard, Cardei et al. [1] proposed an energy-efficient data communication strategy for organizing the sensing, processing and data transmission tasks in each sensor node. The novel contribution of this work was identifying and managing disjoint connected dominating sets around the WSN. At the same moment, the nodes that were not participating in the communication were considered as disjoint entities. The connected dominating sets managed a logical association between various disjoint nodes in the network. The logical construction of connected dominating sets provided the optimal energy wastage spent from inactive sensor nodes. On the other hand, this work had not provided a crucial cross-sectional energy optimization model at different layers.

Ekici et al. [2], Zhang et al. [3] and Yick et al. [4] discussed various types of WSNs, wireless data communication and applications. Among these works, Ekici et al. explained the scenarios and practical difficulties of mobile sensor networks where the nodes are allowed to move around the geographical region. As discussed, each type of WSN architecture is important for appropriate field applications. Notably, mobile WSNs have the most flexible yet unstable network architectures against the uncertainties of wireless medium and network failures.

In this situation, the responsibilities of channel allocation strategies, WMAC transactions and routing protocols are crucial compared to other types of standard WSNs. On behalf of these wireless network environments, Zhang et al. and Yick et al. discussed the common functions of WSNs and the applications. These works deliver the recent needs of wireless communication technology and sensor platforms. The growth of WSNs is placed around the fields of agriculture, health monitoring systems, home automation systems, industrial automation systems, military security systems, ocean monitoring systems, wild animal tracking systems, underground sensor systems and other object surveillance systems.

Each type of application-specific system needs a suitable set of wireless sensor nodes with various configurations. According to that, the processor model, memory model, signal transmitter, signal receiver, signal converters, sensor standards and the type of power source are selectively considered for managing overall network functions. On that note, this work provided the details of data collection techniques, coverage properties and other communication strategies. Figure 1 gives the internal components of a generic wireless sensor node.

Hou et al. [5] analyzed the problems of distributed sensor data collection and accumulation throughput rate. This work had taken the idea of implementing lexicography-based minimum–maximum rate allocation principles, linear rate evaluation programming models and data parametric analysis models to stabilize the overall network lifetime. As the irregular data allocation and data accumulation strategies severely affect each node's performance and lifetime, the entire WSN has been disturbed in its functionality and liveliness. The problem of flexible rate allocation and lifetime stability assurance are considered as the most important issues in WSNs. With this in mind, this work observed the close relationship between individual data rate of each sensor node and the node's lifetime issues during data transmission.

The determinations of this existing work had crucial results, yet the need for power stability and channel properties were not considered seriously through MAC and routing cautions. Similarly, Wei et al. [6] prescribed the problems and reliable technical supports for collecting data through underwater sensor networks (wireless channel). As compared to other communication bands such as microwave frequencies and radio frequencies, underwater sensor networks require acoustic signal transmission for data dissemination. The water medium is not free to transmit signals as easily as possible using generic signal

bands. Data dissemination through a water medium has many problems relevant to data rate sustainability, packet drops, route breakages, channel reliability and data collisions.

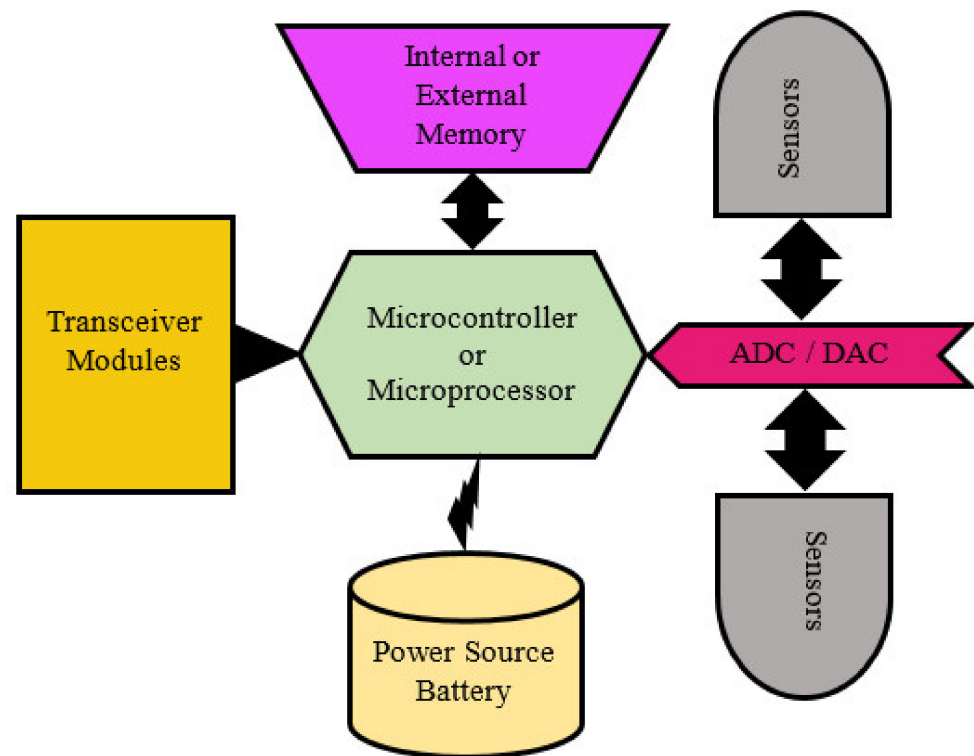


Figure 1. Internal components of sensor node.

The acoustic signals used for multi-hop communication through water become scattered, diverted and attenuated before reaching the destination node. In these situations, the energy spent by each sensor node is not useful. Thus, the need for underwater medium allocation and energy-controlling mechanisms are highly recommended against unequal channel distortions. Particularly, the applications of underwater sensor networks are useful in military-based underwater vehicles and submarine systems.

Optimizing the sensor node's resources ensures a long-time data communication through the wireless medium. Especially, the resources of sensor nodes are plunged by both the medium and the malicious activities injected around the network. Boubiche et al. [7] and Bashar et al. [8] expressed the importance of cyber threats and physical layer (channel) threats executed in WSNs. The cyber threats or attacks massively acquire energy resources through unauthorized activities. Particularly, active attacks such as denial of service (DoS) create a major problem for resource availability in WSNs. In contrast, passive attacks such as eavesdropping and wormhole attacks silently gather data dissemination efforts. With this in view, solutions have to be met to ensure stable energy-saving practices against cyber threats. At the same time, counter algorithms to stand against the attacks are expected with energy optimization techniques.

Cao et al. [9] and Kotiyal et al. [10] proposed innovative solutions on node coverage and connectivity problems. Among the above contributions, the earlier work developed a unique social spider optimization for improving the sensor node's coverage capability in heterogeneous sensor networks. Each sensor node can transmit the data based on the coverage probability, neighbor availability and neighbor discovery ability. However, the quality of coverage probability and neighbor discovery processes of each node was completely raised based on residual energy level. Generally, various types of technical contributions are motivated to improve the functionalities of the sensor node to attain quality communication. The disparity and the research problems with those works were consistent with inadequate energy optimization views. The second work focused on

managing node localization procedures using a cuckoo search algorithm in WSNs. Likewise, a few other research works find solutions against node localization issues [11].

Energy-focused research is driven towards WSNs in order to extend network lifetime and node availability. Reliable energy considerations and energy-optimized computing frameworks are deeply analyzed with body sensor networks and IoT systems, respectively [12,13]. IoT architectures and software-defined networks depend highly on minimal energy consumptions under WSN pitches. Nweye et al. [14] provided the necessity of heat, ventilation and air conditioning (HVAC)-based communication schedules for saving the node's energy in wireless local area networks (WLANs). The technical diversity provided in the energy optimization field was mandatory for specific wireless communication technologies. The application of WSNs decides the required level of energy savings during data communication. With this in mind, Chandra et al. [15] proposed intelligent energy optimization techniques for cardio sensor networks.

In this work, Chandra et al. identified the use of sensor data compression possibilities against energy wastage. In the same way, many research works have been conducted to produce green computing application using WSNs [16,17]. The need for green computing technologies and energy optimization principles are mandatory for the innovative applications of WSNs such as IoT, smart city systems, intelligent farming systems, fault-tolerant energy models, edge computing systems and smart learning systems [18–22]. The well-defined energy optimization technique must focus on both WMAC policies and routing policies to save the node's energy. Specifically, the energy wastage of every sensor node happens during active listening, passive listening, data transmitting and data receiving activities.

Under these unavoidable circumstances, an efficient solution has a huge impact on each sensor node to save energy. In this manner, Nayak et al. [23] proposed machine learning (ML) techniques for enabling intelligent routing processes to reduce overhead and energy consumption rates. This work found the benefits and limitations under ML-based routing solutions. The benefits were noted, with this technique providing the optimal routing process with minimal latency. At the same time, the limitations were considered as how to develop lightweight ML algorithms in order to reduce the computation overhead and energy consumption rate. The detailed comparisons are illustrated in Table 2. The increasing demand of sensors and WSNs through military equipment, drone applications, IoT environments and secure sensor environments must be addressed with energy optimization models and load management models [24–27]. The detailed review about WSNs, deployment issues, MAC policies, channel assignment policies and routing schemes identifies the following research problems and future scopes:

- Energy-efficient WMAC principles are required for application-specific sensor nodes.
- Energy optimization and green computing models are expected for increasing the lifetime and availability of WSNs.
- Reactive energy-saving routing protocols and on-demand channel establishment strategies are estimated.
- Channel quality determination and reactive scheduling mechanisms are required to build green computing platforms for future WSN architectures.

Table 2. WSNs and recognized challenges.

Related Articles	Strategies	Problems Considered
Cardei et al. [1]	Energy optimization using disjoint and connected dominating sets	Energy optimization and live connectivity identification
Ekici et al. [2]	Understanding mobility issues and solutions	Connectivity, lifetime and mobility
Hou et al. [5]	Lexicographical order of channel rate Allocation and lifetime management (Linear programming and serial channel parametric analysis)	Optimal data rate allocation and network lifetime

Table 2. Cont.

Related Articles	Strategies	Problems Considered
Boubiche et al. [7]	Cyber security solutions and challenges using light weight methodologies	Network security and energy-efficient cyber security
Bashar et al. [8]	Physical layer interception probability model	Physical layer and channel-trapping attacks
Cao et al. [9]	Heterogeneous social spider energy optimization and coverage scheme	Energy optimization, network coverage and neighbor identification
Kotiyal et al. [10]	Optimized cuckoo search and locality management	Node localization error and neighbor identification
Nain et al. [11]	Propagation latency and delay prediction with energy optimization	Acoustic signaling and underwater energy wastage
Mishra et al. [13]	Nature-inspired algorithms (grey wolf Optimization, PSO and balanced clustering)	Energy optimization for IoT systems
Nweye et al. [14]	HVAC scheduling and energy plans (Wi-Fi)	Energy optimization for Wi-Fi systems
Chandra et al. [15]	Data compression and channel modelling systems	Energy optimization for body sensor networks (cardio health care systems)
Dhaya et al. [18]	Multi-modal resource allocation and load balancing systems	Energy optimization for agriculture IoT sensors
Humayun et al. [20]	Smart energy plans for fifth-generation IoT systems	Network lifetime and energy plans
Zhu et al. [21]	Artificial-IoT systems with energy-efficient scheduling frameworks	Energy optimization and channel timelines
Vashisht et al. [22]	A review on ML-based smart sensor platforms	Current and future challenges in WSNs
Nayak et al. [23]	A review on routing protocols, energy problems, lifetime and localization	Routing and neighbor monitoring challenges
Bhargava et al. [24]	Low-cost link establishment using cuckoo neural network System	Network lifetime and nonlinear network modelling
Haseeb et al. [25]	Multi-attribute learning and secure sensor modelling system	Wireless security, uncertainty and mobility models
Geetha et al. [26]	Green energy modelling, future load forecasting and energy balancing system	Load balancing, energy optimization, delay computing and distance management
Ren et al. [27]	Edge computing and energy modelling for smart city	Green energy and edge models

As mentioned above, the basic identifications and expectations of WSNs and their recognized challenges should be the motive for any researcher. This article has extended its deep dive into the current technologies of WMAC, wireless routing protocols and energy-saving limitations of wireless infrastructures around the world.

2.1.2. WMAC Strategies with Energy Optimization Techniques

Wireless communication techniques, medium access principles and channel modelling strategies are common in research aspects. At the same time, finding suitable techniques and proposing novel techniques with reliability are challenging tasks. Richert et al. [28] implemented the variances of MAC protocols such as carrier sense multiple access/collision avoidance (CSMA/CA), the sensor MAC (S-MAC) protocol, weak channel or signal detection policies, the timeout MAC (T-MAC) protocol and other variances. This experimental view of MAC policies extracts the functions of each MAC model including delay-sensitive MAC (DS-MAC), energy-sensitive time division multiple access (TDMA) policies and tree MAC policies. According to the details given in this work, MAC models can be expressed as shown in Table 3. In this case, collision models such as collision detection (CD), collision notification (CN) and weak signal detection (WSD) are experimented. Similarly, reduced TDMA (TDMA-R), schedule exchange protocol (SEP), adaptive neighbor election algorithm (AEA) and neighbor discovery protocol (NDP) are evaluated.

Table 3. Collision models and MAC models [28].

Collision Models	MAC Models	Channel Allocation
CSMA/CD	MAC	TDMA
CSMA/CA	WMAC	TDMA-R
CSMA/CN	S-MAC	SEP
CSMA/WSD	DS-MAC	AEA
	T-MAC	NDP

However, this experiment limits the assumptions in MAC policies only for energy wastage in WSNs. This assumption shall be extended into routing policies with the considerations of various technical glitches of wireless routing protocols. Jain et al. [29] discovered a novel energy-efficient network architecture with cluster head coordination principles and hot-spot analysis procedures. In this scheme, cluster heads are selected with the help of the Harris hawk optimization protocol and dynamic clustering protocol. In addition, this technique has been extended with the dynamic routing protocol to reduce the sensor node's energy depletion rate.

The implementation section of this work has provided performance metrics such as network energy depletion rate, lifespan of sensor nodes, packet transmission rate, network coverage factor, etc. At any rate, this contribution is limited to node selection procedures rather than channel organizing policies. Energy-efficient MAC models widely apply sleep and wakeup mechanisms to increase the lifespan of nodes in WSNs. The sleep and wakeup protocols work based on reactively initiated transmission schedules for multi-path channels. Chawra et al. [30] and Alzahrani et al. [31] proposed energy-efficient sleep and wakeup scheduling techniques in each sensor node to save energy. Particularly, the former work uses memetic techniques for organizing WMAC by determining the qualities of energy consumption rates of sensor node, coverage factor, neighbor connectivity rate and optimal wakeup duration for each channel. Accordingly, this technique ensures the benefit of energy control and liveliness of sensor nodes in WSNs.

The latter work analyzes the architectures of ad hoc sensor networks and establishes quorum-assistive sleep and wakeup protocols for organizing WMAC policies. In this case, the quorum properties of each sensor node are validated and slots are activated to minimize energy expenditure. However, both works are limited with WMAC perspectives. The efforts in producing sleep and wake models, duty-sensitive scheduling procedures and adaptive channel utilization with WMAC continue for various types of WSNs [32–34]. Moreover, the standpoint of energy-optimized WMAC establishment is a required aspect for all researchers.

Ranjan et al. [35] discussed impacts on energy diffusion rate and the network disturbances. According to this model, the network irregularities and traffic turbulences happened due to the excessive diffusion of energy in each node. At the time, the underprivileged deliberations of MAC management rules and irregular load distribution among sensor nodes were creating energy losses in each node. Hence, the entire WSN met communication problems. This work provided the experimental analysis cases for different types of WSNs such as cluster-based environments and random environments around different sizes of geographical regions. Under this testbed, this experiment revealed issues with the lifespan of each sensor node and the downtime of each node. This experiment helped to study the stability of the overall network during continuous energy drops.

In the same way, a few other research works tried energy-efficient MAC models in static WSNs [36]. Alablani et al. [37] recommended a novel energy-controlled MAC and routing protocol for underwater sensor networks. Generally, underwater sensor networks use acoustic signal propagation models and resource-constrained sensor nodes. Unlike other sensor networks, underwater sensor nodes are not feasible to be charged regularly through any modes (electricity or solar power). The hostile nature of underwater sensor networks requires more efficient energy-saving mechanisms for both MAC protocols and routing protocols. This scheme used network properties such as finite energy limits, a

multi-hop communication session, narrow transmission possibilities, sleep mode executions and a uniform energy utilization factor. The observations of this work revealed the better utilization of channels and routing sessions to improve the quality of energy optimization principles.

In the same manner, Samal et al. [38] established MAC models for energy-sensitive body sensor networks. Compared to other types of WSNs, body sensor networks are extremely tiny and simple components. The diffusion of energy from each node severely affects the performance of each body sensor in its health monitoring functions. This leads to improper determinations of health recordings. With this in mind, this work proposes multi-channel scheduling techniques and sleep mode supports for biosensor units. Sakib et al. [39] implemented a new MAC policy for WSNs using quality of service (QoS) parameters (delay, throughput, jitter, bandwidth, packet loss rate, etc.) and data priority models. According to this method, multi-priority values are computed for each data packet for each session. The multi-hop data transmission was initiated based on priority values and priority-assistive MAC principles. On the other hand, the determinations of optimal QoS quantities for each node were taken for energy-controlled data communication sessions. Both techniques are better in terms of multi-property considerations to achieve energy-efficient MAC solutions.

In this concern, Darabkh et al. [40] proposed uncertainty-aware transmission scheduling models for clustered IoT systems through TDMA and spread spectrum-based MAC techniques. In this work, cluster heads were selected based on locality information, residual energy rate and balanced workload distribution models. In another way, this scheme contributed to observing the presence of uncertainties, interference, delay, power distortion and other channel problems. The focus on multiple channel properties supports allocating TDMA slots for wireless data transmission in IoT systems. In the same vein, Subramanyam et al. [41] and Gowda et al. [42] illustrated the possible ways of building on-demand duty cycle establishment principles and hybrid MAC policies, respectively, for energy-controlled wireless transmission. Most of the works executed under energy-efficient MAC policies were conventional in terms of limited hardware assumptions and resource considerations for various types of WSNs.

The contribution of Ajmi et al. [43] varied from other MAC policies under the attentions of logical modelling procedures. This scheme found an idea of configuring inter-cluster and intra-cluster MAC policies with cross-layered communication principles. Notably, the establishment of inter-cluster and intra-cluster MAC solutions provides independent handling of energy wastage in the IoT environment. The establishment of energy optimization techniques for MAC policies for wireless health monitoring systems are widely required around the world. In this case, mobility management protocols, static channel policies and energy harvesting models are created for autonomous health monitoring systems [44–46].

Udoh et al. [47] justified the relationship between MAC layer functions and radio signaling models with regards to energy consumption. Relating to other existing MAC solutions, this work validated malicious events related to energy wastage in each sensor node. Under this scenario, this work compared S-MAC and T-MAC policies based on duty slot allocation procedures. According to the establishment of active and idle slots, T-MAC and S-MAC principles managed the radio signal propagations. Against these signal propagation models, special-type attacks are generated such as denial of ideal/sleep attack and active channel attack. These attacks mainly target channel availability and energy-saving slots (sleep mode) of WSNs. Consequently, the residual energy in each node automatically reduces to the inactive state. This scheme provided security frameworks against attacks to minimize the impact of energy wastage. At any rate, the need for lightweight security models against channel attacks are ignored in this contribution.

In a similar fashion, Sadeq et al. [48] and Lakshmi et al. [49] created theoretical MAC models and heterogeneous MAC models for WSNs, respectively. These works found the maximization of packet delivery rate through energy optimization models. Sah et al. [50] intended an energy-efficient sensor management architecture for industrial applications. Conspicuously, industrial IoT systems are completely distributed and heterogeneous in

nature. Hence, the provision of energy optimization procedures is complicated for different types of sensor nodes. Additionally, this technique implemented load balancing rules and MAC scheduling procedures to optimize the sensor node's energy in the distributed IoT platform to organize the industrial components. In this case, Yang et al. [51] concentrated on node clustering techniques, multi-hop routing principles and bearable energy solutions for underwater sensor networks. The contributions of the above works mainly found MAC-based and channel-based energy leakages due to various circumstances. At the same time, the future findings regarding green-MAC (G-MAC) computing models and reactive scheduling models are expected as follows:

- Adaptations of various WMAC principles are expected to save energy under tiny autonomous WSNs.
- Distributed and heterogeneous WMAC principles are highly anticipated for IoT-based WSNs.
- Multi-channel reactive scheduling models and control management principles are required for WSNs.
- Routing and medium coordination solutions are needed to minimize the energy with a cross-layered design.

Hence, the exhaustive literature search and contribution analysis provided future technical needs in order to improve the energy-efficient solutions for WMAC functions. To a certain extent, knowing the impacts of routing layer functions with energy-saving models is essential for confirming a better lifespan of WSNs.

2.1.3. Energy-Efficient Wireless Routing Strategies and Protocols

The significance of integrated WMAC principles and wireless routing protocols are identified around the research community arena. Most of the research works focused on the energy-saving plans of WSNs having determinations with WMAC policies only. However, route discovery, route management and data routing protocols heavily control the energy release rate in each sensor node. As a result, the inventions on individual energy-efficient WMAC protocols, energy-efficient routing protocols and hybrid interface energy management principles are inescapably required.

Zagrouba et al. [52] described various wireless routing solutions such as cluster-based routing protocols, hierarchical routing protocols, random (flat) routing protocols, node-centric routing protocols, data-centric routing protocols, static routing protocols, mobility-support routing protocols, time-sensitive routing protocols and other geography-aware routing protocols. In addition to these protocols, wireless networks and WSNs focus on application-specific routing protocols, medium-specific routing protocols and energy-efficient routing protocols. Each routing protocol has many variances, such as low-energy adaptive clustered hierarchy (LEACH), dynamic source routing (DSR), ad hoc on-demand distance vector routing (AODV), temporary ordered routing algorithm (TORA), the real-time routing protocol (RTRP), geographic and location-based routing protocol (GLRP), QoS-based routing protocol (QRP) and other protocols. Among these protocols, the strategy of data communication and route management policies are initiated in a proactive manner or reactive manner.

Figure 2 relates the energy-efficient rules required at each layer. As illustrated in Figure 2, the top-down communication (network layer to MAC layer) and upward communication (MAC layer to network layer) are expected to attain the energy controlling principles to increase the lifetime of WSNs. The routing protocols used for WSNs are anticipated to perform successful data communication with optimal energy-saving rules compared to other types of wireless networks. Since the internal resources of sensor nodes are more limited than other network nodes, the effective governance of suitable energy-saving mechanisms are highly needed at routing layer functions.

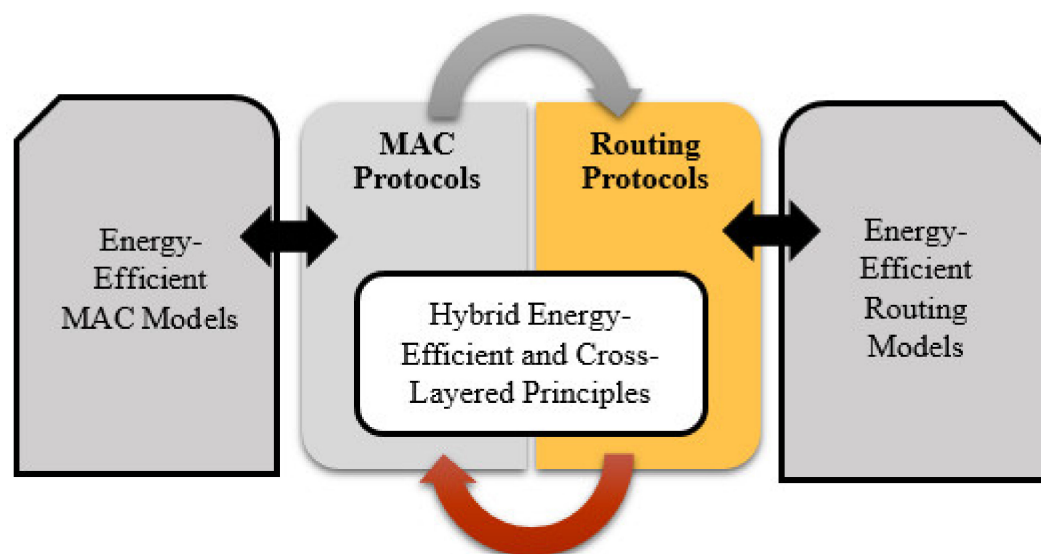


Figure 2. Cross-layered model.

The requirements of future-generation networks, IoT systems, are progressively specified by different researchers. In this manner, Dogra et al. [53] identified the importance of energy-efficient future-generation networks and fifth-generation IoT systems and wireless technologies. The reliability, scalability and lifespan of future-generation IoT systems are sorely needed to manage multiple-input and multiple-output channels. This work mainly focuses on the development of fifth-generation routing principles with energy optimization techniques to handle multi-channel data transmission practices. Notably, the distributed load balancing mechanisms, energy sharing principle and heterogeneous channel allocations are considered major technical problems in this domain. In another way, the assumptions of this proposed model lead to clustered IoT-based WSNs. Similarly, the prospects of flat IoT models, coverage liability and appropriate energy-saving routing models cannot be ignored around the domain of wireless technologies [54,55].

Kumar et al. [56] proposed an optimized zonal energy-balancing technique and adaptive Dijkstra's technique for improving routing principles. This method evaluates the node's transmission distance and residual energy in the network. In this manner, the entire wireless network (personal network) has been divided into various local zones to ensure the even distribution of the communication load. At the same time, optimized shortest-path routing algorithms are applied to manage the energy consumptions of each sensor node in a balanced manner. This scheme justifies that the proposed technique has a confirmed packet transmission ratio, energy wastage and routing delay.

In the same vein, Navarro et al. [57] and Hajipour et al. [58] developed energy-balanced routing protocols for WSNs. Angurala et al. [59] identified the solar energy production and consumption models for sensor networks. Using this platform, this scheme proposes a modified solar-constrained AODV protocol for enriching the energy plans of each sensor node. Compared to other sensor platforms, the establishment of solar sources admits periodical recharging panels and energy-utilization principles. In this concern, the modified AODV has been trained to coordinate the events of each sensor node in terms of data production, data collection, load balancing and recharging plans. In any event, the technical benefits of solar initiative AODV have not been justified against natural disturbances.

Equally, Singla et al. [60] and Asqui et al. [61] developed multi-path energy optimization possibilities for constructing flat routing protocols in small scale WSNs. Yun et al. [62] proposed a deep-learning model for improving the routing quality to reduce the energy depletion rate.

Particularly, reinforcement learning (RL) networks are trained with Q-matrix computations for observing the practices of routing protocols in order to reduce the energy consumption rate. In this case, the observation reveals that the energy of each sensor node

has been spent excessively during irregular data aggregation and transmission periods. Accordingly, the Q-learning model computes event-based Q-values or weights for classifying the sensor node's issues.

In association with previous routing protocols, this method initiates data aggregation and routing processes based on the computed Q-values. On the other hand, the limitations of deep-learning procedures in tiny sensor nodes are not significantly explored in this effort.

Sharma et al. [63] implemented energy optimization techniques for achieving efficient routing policies in order to operate agricultural sensor networks. Agricultural sensor networks are widely used for automating irrigation systems, plant monitoring systems, surveillance systems and soil monitoring systems. In this field, various types of sensor nodes are used according to the sensing role. This can be considered as a heterogeneous sensor network where the nodes are oddly deployed and configured. Simultaneously, these nodes are completely different in terms of internal components and other communication tools attached with sensor nodes. This field-based sensor network has serious vulnerabilities against uniform energy plans. Under this circumstance, this work proposes LEACH principles, deterministic energy clustering principles, sensor information collection modules and stable node selection models in a hierarchical fashion. The network assumptions are made with clustered sensor communities, base stations and gateway points.

The contribution of this work is commendable, yet the computation complexity of proposed techniques is ignored for contemplation. In the same way, a related set of techniques are contributed for energy optimization problems and clustered communities in WSNs [64–66]. The considerations of energy limitations and optimization parameters in WSNs are extensively noted with regard to WMAC and routing policies. From the vast analysis, the clarifications are derived on the basis of the contributions and limitations of current technologies [67–69]. In this sense, several existing techniques only consider WMAC irregularities as the causes for the fastest downtime of sensor nodes and energy wastage. On the other hand, a few notable research works consider the energy problems against routing functions and data aggregation functions [70–73]. The perspectives of each research work vary with respect to the authors' own research motivations.

The research contributions are extended for different types of networks, such as generic sensor networks, body sensor networks, personal sensor networks, health sensor networks, surveillance sensor networks, agricultural sensor networks and IoT-based sensor networks [74]. Each existing technique is specifically formed with static assumptions under WMAC and routing policies [76–78]. More insights into energy-aware routing in WSN, MIMO systems, 4G and 5G networks are also briefly discussed in [79–83]. However, the need to integrate irregular cross-layer functions in order to monitor individual energy consumptions is a more important quality.

These cross-layer solutions and integrated energy plans are not effectively taken into consideration for research practices. With this in mind, the proposed experimental survey has been executed for justifying the solutions against energy issues. The reason for continuous energy depletion is related to listening (active and passive) activities, data transmission policies, data aggregation policies, network deployment strategies, routing policies, WMAC practices and physical problems in WSNs.

3. Experiments, Comparative Investigations and Results

Experimenting the notable technical contributions is a challenging yet useful practice to observe the practical abilities and limitations of the developed frameworks. As illustrated in Table 4, the related articles are taken under considerations such as energy-efficient WMAC policies and routing strategies [84–86]. The successful development of the earlier research frameworks leads to noteworthy benefits for energy-saving plans in WSNs [87,88].

Table 4. Related contributions on energy-efficient WMAC and routing protocols.

No.	Existing Techniques	Energy Optimization Solutions			
		WMAC Energy Optimizer/Balancer	WMAC Scheduler and Time Divider	Energy-Efficient Wireless Routing Protocol	Energy Balancer/ML-Based Routing Protocol
1	Richert et al. [28]	✓	✓	✗	✗
2	Chawra et al. [30]	✗	✓	✗	✗
3	Alzahrani et al. [31]	✗	✓	✗	✗
4	Alablani et al. [37]	✓	✗	✓	✗
5	Samal et al. [38]	✗	✓	✗	✗
6	Sakib et al. [39]	✓	✗	✓	✗
7	Darabkh et al. [40]	✗	✓	✗	✗
8	Gowda et al. [42]	✓	✗	✗	✗
9	Ajmi et al. [43]	✓	✗	✓	✗
10	Sah et al. [50]	✓	✓	✗	✗
11	Yang et al. [51]	✗	✗	✓	✗
12	Dogra et al. [53]	✗	✗	✓	✗
13	Hao et al. [54]	✗	✗	✓	✗
14	Kumar et al. [56]	✗	✗	✓	✓
15	Navarro et al. [57]	✗	✗	✓	✓
16	Sharma et al. [63]	✗	✗	✓	✗
17	Huamei et al. [65]	✗	✗	✓	✓
18	Almalki et al. [66]	✗	✗	✓	✓
19	Goswami et al. [69]	✗	✗	✓	✓
20	Mohan et al. [72]	✗	✗	✓	✗
21	Yao et al. [73]	✗	✗	✓	✗
22	Gayathri et al. [75]	✗	✗	✓	✓
23	Han et al. [79]	✗	✗	✓	✗
24	Senthil et al. [80]	✗	✗	✓	✓
25	Mir et al. [81]	✗	✗	✓	✓

✓—Techniques Implemented, ✗—Techniques Not Implemented.

At any rate, this article was motivated by the intention to conduct an experimental comparison between crucial existing works developed based on energy-efficient WMAC policies, energy-efficient routing policies and multi-layer optimization policies (WMAC and wireless routing protocols), as shown in Table 5.

Table 5. Related experiments.

No.	Existing Techniques	Energy Optimization Strategies
1	Richert et al. [28]: E1	Modified WMAC and channel allocation
2	Chawra et al. [30]: E2	Memetic-based sleep and wakeup scheduling
3	Alablani et al. [37]: E3	Integrated WMAC and routing policies using timeline management
4	Sakib et al. [39]: E4	Data priority computation and QoS modelling
5	Sah et al. [50]: E5	Load balancing and aggressive WMAC scheduling
6	Navarro et al. [57]: E6	Balanced routing for low-powered WSNs
7	Gayathri et al. [75]: E7	Cooperative authentic routing protocol and feedback system
8	Han et al. [79]: E8	Adaptive and hierarchical routing models

Based on the illustration of Table 5, the technical cohesions between each work deliver the implementation details and findings. In this experimental section, E1 [28] is denoted for modified MAC protocols for managing energy distributions in the critical WSN environment. Notably, this work analyzed weak signal detection through CSMA/CA principles (CSMA/WSD). In this regard, this work found the variants of MAC models and the MiXiM-OMNet++ environment. On this basis, the proposed CSMA/WSD was implemented to

classify weak signals and channel collisions. Under this mechanism, each packet loss event was evaluated, as given in Figure 3.

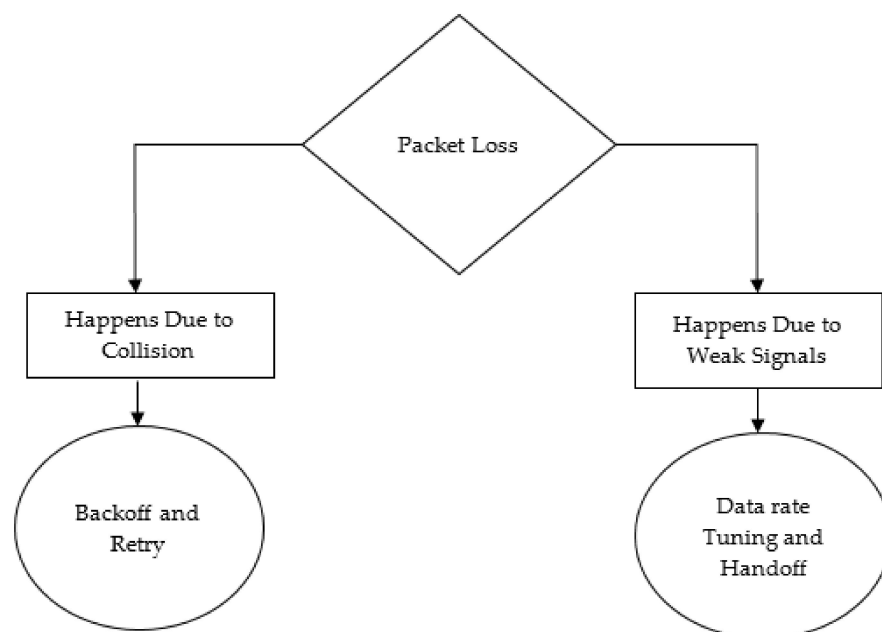


Figure 3. E1-carrier sense and weak channel detection.

In this process, the random determination of packet loss under collision state is evaluated for weak signal conditions. On successful detection of weak signals, the proposed CSMA/WSD helps to re-tune the data rate and finds handoff possibilities. Thus, the systems reduce the number of collision-based retransmissions and save the sensor node's energy. In the same manner, E2 [30] implemented a memetic algorithm–meta-heuristic suit for improving the ability of MAC-based sleep and wake operations. The proposed memetic algorithm implemented five steps to identify the possible number of active nodes in sensor networks to avoid the failure rate of data transmissions. The optimal selection of an active node on the wireless channel minimizes excessive consumption of energy.

According to the model, the active sensor node selection process is illustrated in Figure 4. Notably, the determination of this memetic approach considers the sensor node's coverage quality and connectivity factors, the remaining energy in the sensor node and the duration of sleep–wake periods.

Figure 4 shows the modified genetic algorithm-based memetic node selection approach through population vectors and solution vector computations. In this case, population vectors are computed based on successful sensor node identification marks. To an extent, the solution vectors are computed on the basis of available nodes around consecutive neighbors. In this solution vector, each node's neighbors are updated as child entries to create possible active channels. Under this MAC-based memetic approach, coverage costs, connectivity costs and energy costs are identified with maximum quantity to wake up the nodes from sleep mode. In this connection, each sensor node has been identified with possible solution vector entries (covering sleep nodes), coverage crossover points and sleep–wake mode factors. With this in mind, sensor nodes are searched to enable active node communication channels regularly. This work stated that the modified memetic approach reduces channel allocation time and energy consumption rate for channel allotment.

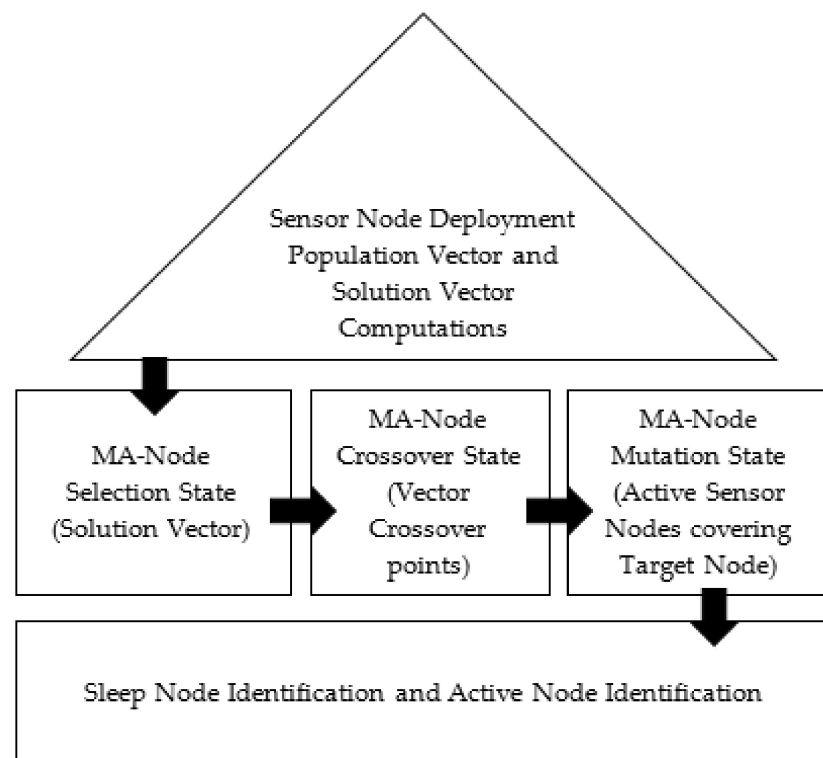


Figure 4. E2-heuristic.

Comparing E1 and E2, both works minimize the cost of packet retransmission through the proper handling of collision cases and node availability issues, respectively. In the same manner, E3 [37] provided the integrated channel management and routing solutions using energy-optimized underwater sensor networks. Compared to other types of WSNs (radio frequency), underwater WSNs use acoustic communication models. Acoustic signaling models are vulnerable to significant data loss, maximum propagation delay, restricted bandwidth, limited energy provisions and channel distortions. In comparison with E1 and E2, E3 takes critical channel (water medium) characteristics to establish energy optimization solutions. In the implementation phases, E3 found depth modelling procedures for numerous acoustic sensor nodes. In this work, the AUVNet simulator toll was used to observe the benefit of energy-efficient underwater MAC and routing protocols against other techniques such as the focused-beam routing protocol, distance-aware collision avoidance protocol and cluster-based protocol. In this scheme, multi-path clear-to-send (CTS) and request-to-send (RTS) packets are shared among the acoustic sensor nodes. On the basis of acoustic sensor placement, the score of any node was computed with respect to node distances (D) and energy levels (E). The score values are calculated based on Equation (1).

$$C = D_r + E_r \quad (1)$$

$$D_r \rightarrow \frac{\text{Distance between node and sink}}{\text{maximum distance}}$$

$$E_r \rightarrow \frac{\text{Available Energy in node}}{\text{maximum energy.}}$$

To a certain extent, the appropriate node-level computations are useful for finding multi-path channels to route the packets. In the multi-layer network protocol tuning process, E4 [39] developed quality of service (QoS)-MAC assisted multi-path routing protocols and data priority computation schemes. This work produced cross-layered packet analysis procedures, priority evaluation procedures, channel listening activities and flexible routing principles according to channel quality metrics. On this basis, this scheme used AODV

protocol and QoS-MAC principles under a single point of concern. According to the system design, this work embedded a packet priority field in WMAC frames. This field was pointed with four priority levels, as shown in Figure 5.

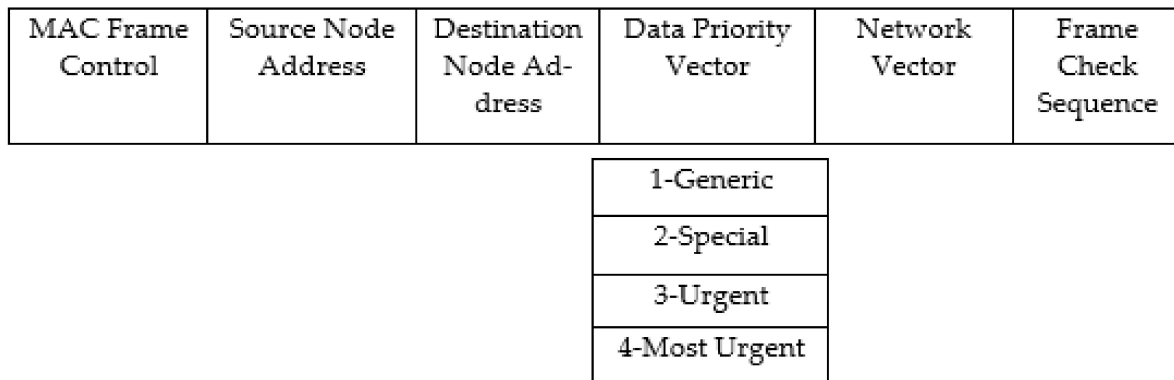


Figure 5. E4-QoS and MAC and data priority analysis.

In this concern, E5 [50] and E6 [57] proposed load balanced sequence scheduling and a routing protocol, respectively, for reducing the sensor node's energy consumptions. In E5, each sensor node adaptively used the internal buffer to process the data on demand. In multi-hop communication, each sensor node is activated through aggressive scheduling-based MAC models to hold the time division multiple access (TDMA) slots. The even distribution of load among sensor nodes shall forward the channel data using minimal requirement margins. At the same time, these TDMA slots were occupied by multiple sensor data streams. Similarly, E5 proposed an energy-efficient collection tree protocol for low-powered WSNs. The protocol functions executed in each sensor node collected and distributed the data streams based on energy-sensitive tree-like paths. In particular, WSNs are categorized under a low-powered wireless personal area network standard due to their resource-limited environment. In this regard, both works suggested restricted channel allocation policies and low-powered routing mechanisms in WSNs. Notably, E6 compared energy-efficient collection tree protocol with lossy routing protocols and conventional routing protocols. Figure 6 illustrates the functions of E5.

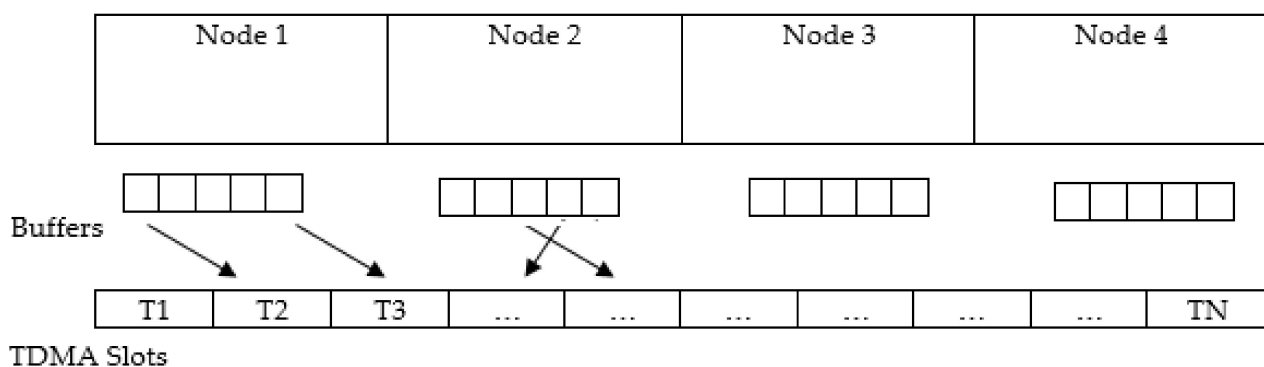


Figure 6. E5-Aggressive TDMA scheduling and buffer management.

In addition, E7 [75] and E8 [79] produced notable solutions on energy-aware wireless routing protocols. Particularly, E7 generated trust value computation techniques using an average packet delivery ratio, route reply ratio, residual energy rate and number of retransmissions on the channel. In this scheme, local trust cost and global trust cost were computed for each sensor node. Local trust values of the sensor nodes were computed in the node itself. At the same time, global trust values were computed at border router points to optimize the data transmission rate. Under this trust evaluation scheme, each trusted

sensor node formed a channel to avoid any discrepancies during the data transmission period. This practice reduced the number of retransmissions and packet drops on the channel. Thus, the cooperative routing methodology manages all active sensor nodes under trusted communities (Figure 7). At the end, E8 discussed the particulars of routing protocol issues, connectivity problems and energy control mechanisms in detail. In the experimental sections, this work compared the AODV routing protocol and stateless real-time routing protocol for ensuring energy optimization qualities.

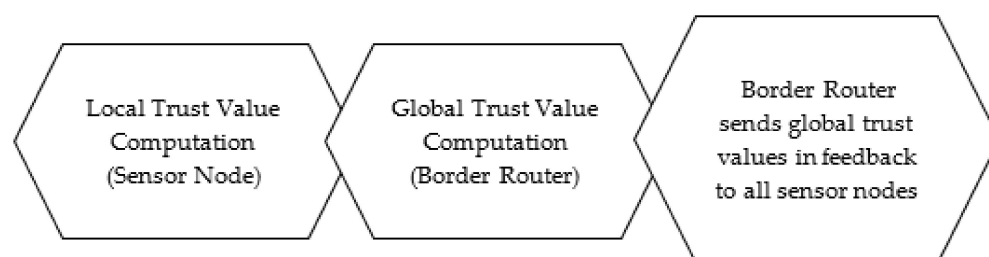


Figure 7. E7-Cooperative feedback trust values for energy-efficient routing principles.

According to the technical observations, WMAC customization and channel allocation strategies [28], sleep and wake strategies [30], cross-layered implementations [37], priority-based channel allocation [39], balanced WMAC/routing solutions [50,57] and adaptive routing models [75,79] are observed for effective comparison practices. The diversified nature of the restricted choices from existing energy-saving policies provides the best understandings under experimental testbed conditions. On the execution of experimental study practices, this work was implemented using tools such as Network Simulator (NS-3.35) and the tool command platform.

The scenario of the WSN is created with a maximum of 300 sensor nodes around the geographical area (1000 m × 1000 m). Generally, NS-3.0 supports deploying more than 300 sensor nodes. At any rate, this experimental survey sets an assumption of 300 sensor nodes around a 1000 m² area, which is significant in terms of network population. Additionally, the network configuration sets a mobility model for the sensor nodes in the prescribed region. The real-time deployment for this type of sensor network (300 sensor nodes with mobility features around a 1000 m² area) provides enough challenges for data transmissions, energy harvesting schemes, channel management and route establishment tasks. NS-3.0 is a network scenario creator with simulated configurations of WSNs.

The network scenario has been assumed with the heterogeneous nature of sensor nodes where the internal components of nodes vary in terms of energy, transmission range and mobility constraints. In this regard, node characteristics such as initial energy (joules), transmission energy (joules), receiving energy (joules) and node coverage abilities (meters) are differently configured for each sensor node in the network (Table 6).

Table 6 illustrates the implementation details of WSNs in the NS-3.0 environment. Consequently, the supportive packages of Python and C++ were used to implement the existing techniques. The performance metrics for evaluating the exiting techniques illustrated in Table 4 (E1, E2, E3, E4, E5, E6, E7 and E8) are average energy consumption rate (joules), liveliness rate, successful data delivery rate, number of retransmissions (count), computational overhead (%), routing delay (milliseconds), scheduling time (milliseconds), packet drops due to downtime (count) and energy optimization rate. The definition of each performance metric is given as follows:

- Average energy consumption rate (AECR): The average amount of joules spent by a sensor node throughout data transmission, collection and idle listening modes.
- Liveliness rate: The availability rate of active appearance (data transmission, collection and idle listening) made by each sensor node against expected lifetime.
- Successful data delivery rate (SDDR): The ratio between the quantity of packets delivered successfully by a sensor node against the packets dropped by the node.

- Number of retransmissions: Total number of packets retransmitted by a sensor node during a simulation cycle.
- Computational overhead: The excessive amount of packets (control messages, retransmitted data and other recovery messages) processed against the average number of network packets processed.
- Routing delay: The time taken by the routing protocol to find the optimal route and deliver the data to the destination.
- Scheduling time: Time taken by WMAC scheduler to make the unique channel period for sending the data through the multiple access medium.
- Packet drops due to downtime (PDD): Number of packets dropped by an inactive node due to failure.
- Energy optimization rate (EOR): The ratio between the amount of joules spent using the energy optimization policies and the amount of joules spent without using optimization policies.

Table 6. The environment of WSN.

No.	Configuration Parameters	Magnitudes
1	Initial energy (joules(J))	2.56–2.67 (variable)
2	Transmission energy (J)	1.06–1.16 (variable)
3	Receiving energy (J)	0.87–0.99 (variable)
4	Number of sensor nodes	100, 200, 300 (variable)
5	Antenna type	Omnidirectional
6	Channel and propagation	Wireless (air/water), two-ray
7	Throughput level (Kbps)	200–250 (variable)
8	Node's coverage ability (meters (m))	30, 40, 50, 60 (variable)
9	Routing protocol	AODV and AODV-LS
10	Signaling modes	Electromagnetic and acoustic
11	Mobility ranges (meters/second (m/s))	15, 25, 35, 45 (variable)
12	Simulation cycle time	100 s
13	WMAC	IEEE 802.11-CSMA-CA

The existing works are investigated under variable constraints as given in Table 5. According to that base, the routing protocols are chosen as AODV and AODV-link-state (LS) models. Similarly, the traffic characteristics, mobility, coverage and energy levels of sensor nodes are configured as variable at different sensor nodes. In addition, the signaling models configured in this experiment are built with the functionalities of both electromagnetic and acoustic nature (underwater/underground).

The experiment starts with the performance validations of the existing techniques (Table 4) using the metric AECR of each sensor node. In this experiment, the cross-layered techniques (WMAC and routing) consume minimal AECR compared with other single-layered solutions. In this concern, the observation has been conducted with the minimal AECR of E3, E4 and E5. The existing works E3, E4 and E5 consider the impactful factors of medium, power limitations and equilibrium in load distribution. As these works are developed to consider multi-layered network functions (MAC and routing issues) with evenly distributed load management policies, they produce optimal AECR between 1.75 J and 1.85 J. At the same time, the AECR of E2, E6 and E7 fall closely under E1. The reason behind this observation is that the specified approaches consider energy optimization as the main problem. In this regard, E2 used heuristic MAC management strategies to effectively organize the data transmission slots (sleep and wake up node selection). In contrast, E6 and E7 focused on balanced load management on routing procedures to reduce the AECR.

In this observation, each existing technique initiated various energy optimization solutions regarding MAC principles or routing protocols. At any rate, the successful engagement of MAC and routing protocol principles of E3 assures minimal AECR. At the same time, other techniques experience a slight hike in AECR where the number of sensor nodes is 300. The variations among the techniques are not huge in AECR, yet the range

between 1.57 J and 1.95 J shows significant impacts in resource-limited sensor nodes and network lifespan reduction (Figure 8).

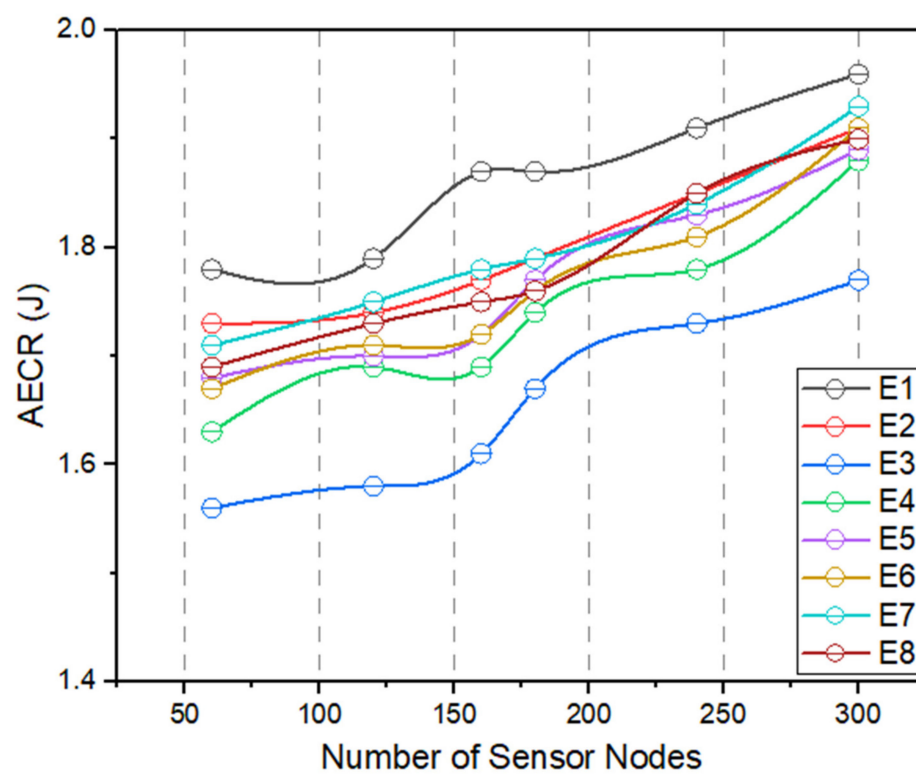


Figure 8. AECR and number of sensor nodes.

Figure 9 describes the average liveliness (active) rate of sensor nodes around the WSN. As the network population is increased in the prescribed geographical area (1000 m × 1000 m) due to the increasing number of nodes, the frequency of a node's activity increases to manage the neighbor discovery process, data transmission, data collection, route updating process and idle listening process. Hence, each sensor node consumes more energy to accomplish the requested tasks and gradually falls at the critical stage of residual energy.

At this point, the need for energy optimization techniques is essential to keep the node live to handle the data transmissions in a dense network field. The illustration given in Figure 9 implicates the fall of the average active conditions of sensor nodes in the network. The proven performance of cross-layered techniques (E3, E4 and E5) shows a better liveliness rate from 0.93 to 0.85 as the number of sensor nodes increases from 50 to 300.

In this experiment, E3, E4 and E5 diversely manage their MAC principles by considering channel quality metrics and network dynamics. Significantly, E3 managed both timeline-based channel allocation and route consistencies throughout the increasing number of sensor nodes. In the same way, E5 developed the load distribution and aggressive scheduling procedures. Based on these reasons, E3 and E5 compactly maintained the overall node liveliness rate better than other works. In the next level, E4 achieved an even better liveliness rate (0.83) under a highly populated WSN (300 sensor nodes). In this experiment, other techniques found active node selection procedures (E2-0.81 and E6-0.82) and load-optimized energy control procedures, respectively. This kind of practice improves network lifetime and the active state of nodes (liveliness rate). By contrast, other existing techniques such as E1, E7 and E8 hold the sensor nodes in an active condition for a more limited period of time than the expected case (20 to 25% of limited downtime). These existing techniques mainly concentrate on the WMAC-based energy efficiency than the node's overall behaviors (routing, advertising, discovery and listening).

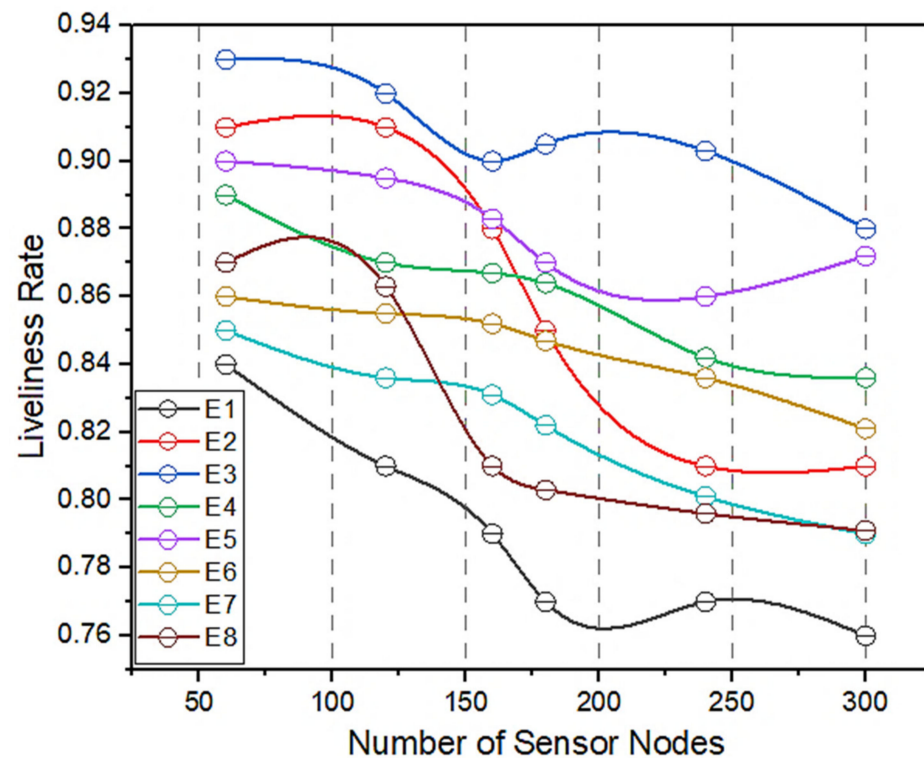


Figure 9. Average liveliness rate of sensor nodes.

From the observations, this article classifies the cross-layered energy-efficient strategies from other techniques, as given in Figure 10. The performance of each cross-layered technique is evaluated using SDDR for multiple data sessions. As denoted, the data communication sessions are populated (20 to 220) and executed for multiple test cycles. Let us assume the number of sessions increase as the number of sensor nodes increases to handle the increasing rate of throughput. In this comparison, the integrated principles of WMAC, routing assistance and scheduler policies of E3 ensure a better SDDR than other works. In any event, E4 manages the SDDR at a higher rate than E3 (94.7%) during initial sessions. The priority calculation and QoS management tasks of E4 give optimal results in SDDR around the network. In contrast, the stability in data delivery needs proper organization of routing strategies at any cost. Accordingly, E3 attains optimal SDDR during the moments of more populated sessions than other works.

During this moment, the performance of E5 starts at the lowest SDDR (94.4%) during initial sessions and manages with the average performance between E3 and E4 as it is modelling both balanced power assumptions and balanced scheduling possibilities. Finally, E5 achieves the SDDR of 93.5% against densely populated sessions. Consequently, the changes in the number of retransmissions are crucially noted for the existing techniques such as E3, E4 and E5. The number of retransmissions is closely connected with SDDR and the node's liveliness rate. The SDDR is indirectly proportional to the retransmission rate and directly proportional to the liveliness rate. According to that, E3 produces the minimal number of data retransmissions from 45 to 95 (number of packets) as the increasing number of sessions at each test cycle. In the same manner, the retransmission rate of E4 reaches a higher point for the maximum number of sessions (116). Similarly, E5 produces a moderate load in data retransmission compared to other works (between 55 and 105). The implications of data retransmission for varying number of transmission sessions are given in Figure 11. In the same manner, E6 shows notable contributions in both routing and WMAC policies. E6 achieves balanced routing and medium management policies in WSN. In this case, the observations of E6 performance using AECR, liveliness rate and SDDR are

denoted in Figures 8 and 9. The effort of E6 on these metrics is crucial after the implications of E3, E4 and E5.

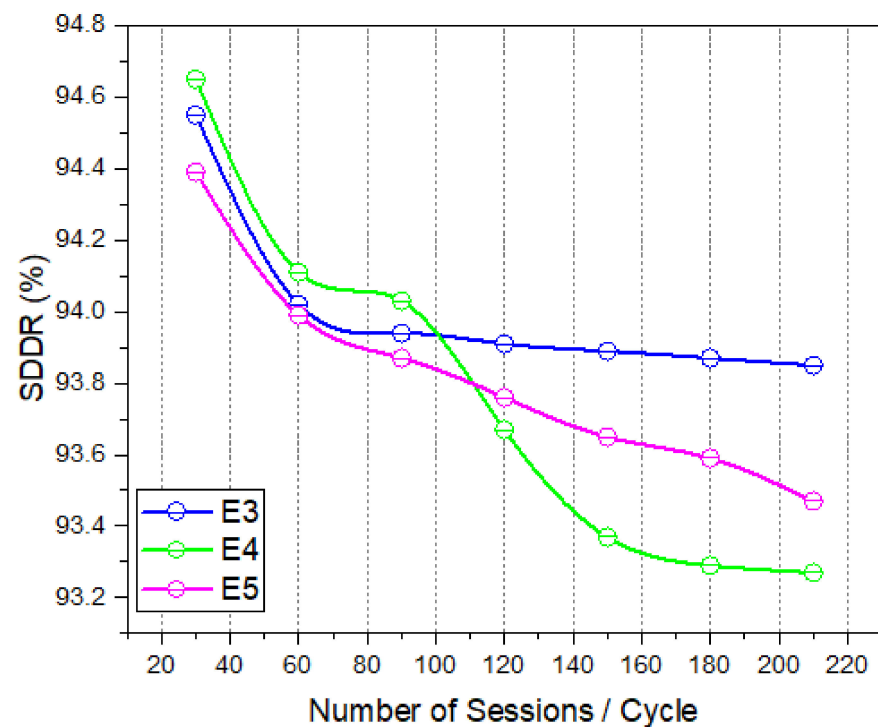


Figure 10. SDDR during the sessions.

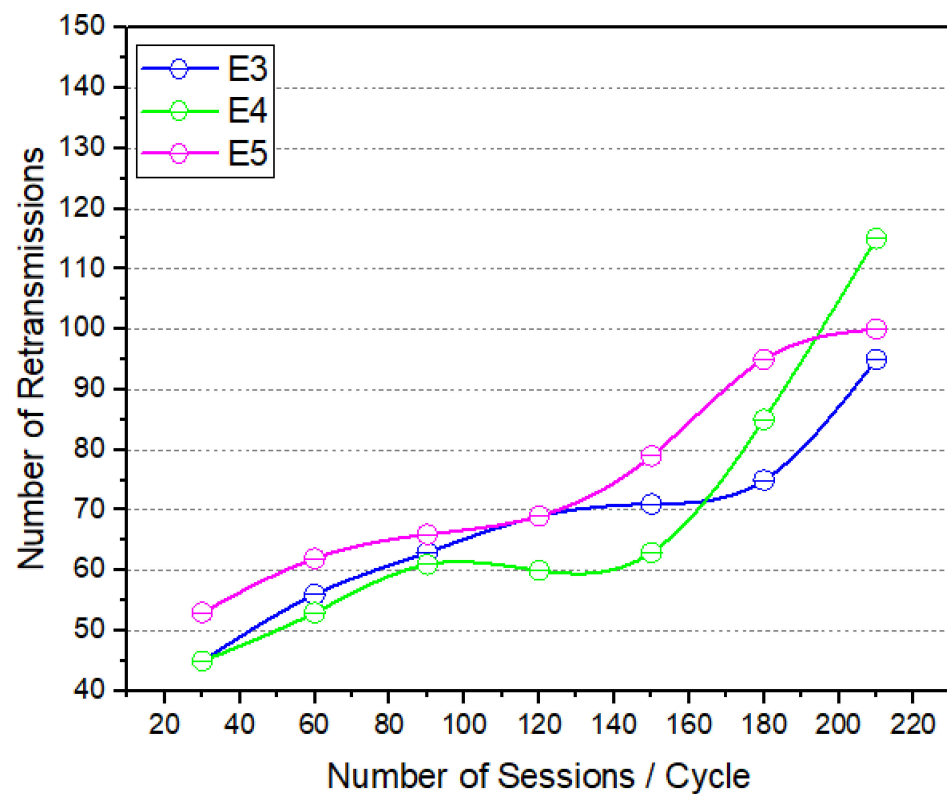


Figure 11. Total number of retransmissions.

With this in mind, Figure 12 shows the comparative cases of E3, E6, E7 and E8 with respect to computation overhead. In this association, the assumption on the computation

overhead of the existing techniques E1, E2, E4 and E5 are directly mapped with the number of retransmissions taken for each session. In any event, the comparison given in Figure 12 relates the existing techniques E3, E6, E7 and E8 in terms of routing behaviors. These techniques commonly achieve energy-optimized routing solutions in WSNs. The efficient and energy-optimized routing models need to produce minimal computation overhead irrespective of the node's location. Additionally, the processes involved in each sensor node vary depends upon the mobility of sensor node.

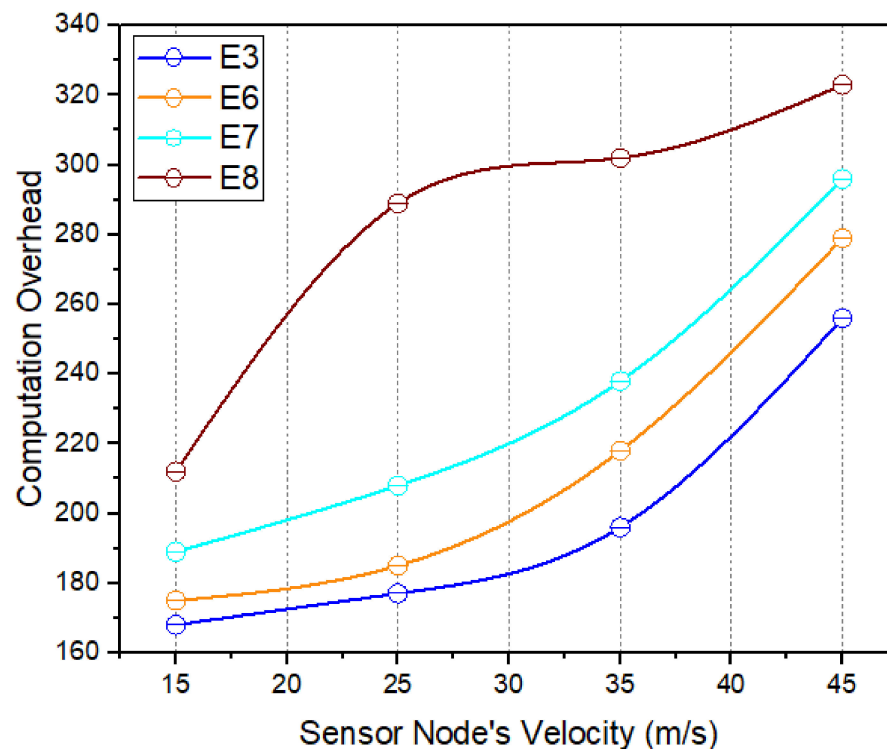


Figure 12. Overall computation overhead.

The challenges taken under mobile sensor nodes lead us to solve new problems such as link breaks, node failures, data retransmission, frequent route updates and energy loss. In this preference, the computation overhead of related routing principles are denoted in Figure 12 against the changing velocity of sensor nodes. As the sensor nodes' velocity changes from 15 m/s to 45 m/s, the excessive load initiated in the sensor node's processor slowly increases and it increases energy AECD definitively. The comparison with energy-optimized routing practices is noted in terms of the excessive number of processes raised in the distributed environment. As discussed, the additional processes in each sensor node are created as a result of managing real-time issues such as node failures, link breaks, excessive route updates, etc.

At this point, the computation overhead of E8 varies from 210 packets to 321 packets over the changing velocity of sensor nodes. Similarly, other techniques such as E7 have 290 packets as the computation load in the front end for a maximum velocity of 45 m/s. On the other hand, E6 produces a rate between 175 and 270 of overhead. Among these techniques, E8 was developed for the hierarchical routing model and it is not flexible with random networks. Hence, an excessive load in E8 is observed. In this case, E6 and E7 target load balance and cooperative routing procedures, respectively. The comparison between E6 and E7 shows the better contribution of the cooperative routing technique (E7) in computation reduction. As E7 uses an authentic and distributed cooperative model for computing twin-trust costs (local trust value and global trust value), the elimination of irregular nodes is easy in the network. In addition, the excessive packet transmission to unethical nodes

or inefficient nodes is ignored in the network. At any rate, the performance of E6 directly deals with low-powered computation procedures in order to limit transmissions.

In this manner, the technical pitches and purposes used for establishing these existing techniques make notable performance variations. In this comparison, E3 falls in both channel and efficient routing practices in order to reduce the overloaded tasks at different layers. Accordingly, the production of computation overhead in E3 is maintained between 170 and 250 which is the minimum compared to other techniques. The experimental contributions of this article are extended to analyze the practical betterment of routing delay (routing protocol) and scheduling time (channel allotment). The motive of understanding the routing-based research techniques and channel slot management techniques leads to separate comparative observations.

Hence, the implications are noted as given in Tables 7 and 8, respectively. Table 7 shows the performance of energy-efficient routing strategies (E3, E6, E7 and E8). As discussed, E3, E6, E7 and E8 mainly focus on the implementation of energy-efficient routing protocols, and routing delay calculation is an important task. With this in mind, the successful elimination of overhead and retransmission leads to minimal routing delay (milliseconds (msec)). Thus, the performance of E3 is optimal in terms of routing delay production (maximum 553 msec) during the change in the node's velocity. In this experiment, this article takes the node's velocity as changing parameter to validate the routing delay. Since the dynamic velocity rate (meter/seconds, m/s) increases the possibilities of node failures and link breaks continuously in the network, the routing delay produced from each protocol varies rapidly. In this case, E6 produces a moderate routing delay compared to other techniques such as E7 and E8. The existing techniques E7 and E8 deal with secure and hierarchical routing models; therefore, the production of routing delay is higher than E6 (load balanced and low-powered scheme).

Table 7. Routing delay.

Sensor Node's Velocity	E3	E6	E7	E8
15	458	472	499	523
25	499	518	539	557
35	514	544	569	589
45	553	573	592	603

Table 8. Scheduler time.

Sensor Node's Velocity	E1	E2	E3	E5
15	101	101	104	102
25	122	117	128	126
35	130	134	148	129
45	139	145	155	142

Similarly, Table 8 gives the identifications of channel scheduling strategies (E1, E2, E3 and E5) and their performance. As E3 is noted, it is a cross-layered solution for energy optimization in WSN, and it is not effective in scheduling processes. At the same time, the development of E1, E2 and E5 are channel allocation and timeline scheduling tasks to reduce frame allocation time on the channel. In this regard, E1 and E2 effectively process the timeline slot for scheduling through modified MAC policies and memetic-heuristic scheduling policies, respectively. These techniques perform better than aggressive scheduling policies in dynamic WSNs (E5).

Table 9 illustrates the routing benefits of using a standard AODV protocol and hybrid AODV protocol with link-state features. This work identifies the limitations of standard AODV as frequent updates and overhead during network changes. Generally, an AODV protocol performs optimally for reactive updates yet takes maximum overhead for a more dynamic network. At the same time, AODV takes maximum time to update the route

information for the whole network regularly. The implementation of both link-state routing models and distance vector models gives fast route updates and reactive route updates, respectively. Especially, the varying velocity of sensor nodes affects the established wireless links frequently. In this case, the uni-protocol system struggles to initiate either global updates or frequent neighbor updates. However, the idea behind AODV-LS supports both reactive and proactive updates (global updates and frequent neighbor updates).

Table 9. Routing strategies.

Sensor Node's Velocity	R1 [AODV]	R2 [AODV-LS]
15	169	125
25	190	144
35	215	151
45	246	179

Figure 13 compares the efforts of all existing techniques using the metric as the number of packets dropped due to energy shortage (downtime) at a sensor node. This is an important evaluation that relates the amount of residual energy maintained by the node and the active participation of that node itself in data communication. Apart from the continuous oscillations in packet drops produced by each technique, the optimal results are observed for E1, E3, E4 and E5 under various test cycles. As noted in Figure 13, the existing techniques E3 and E4 attain the drops between 35 and 60 as optimal compared to other techniques. At the end, the EOR was taken for performance analysis of all experimented techniques. According to this observation, the higher rates of E2, E3 and E4 show the suitable nature of energy optimization in WSN. On the scope of energy-efficient routing methodologies, many recent works are developed in the research arena [89,90].

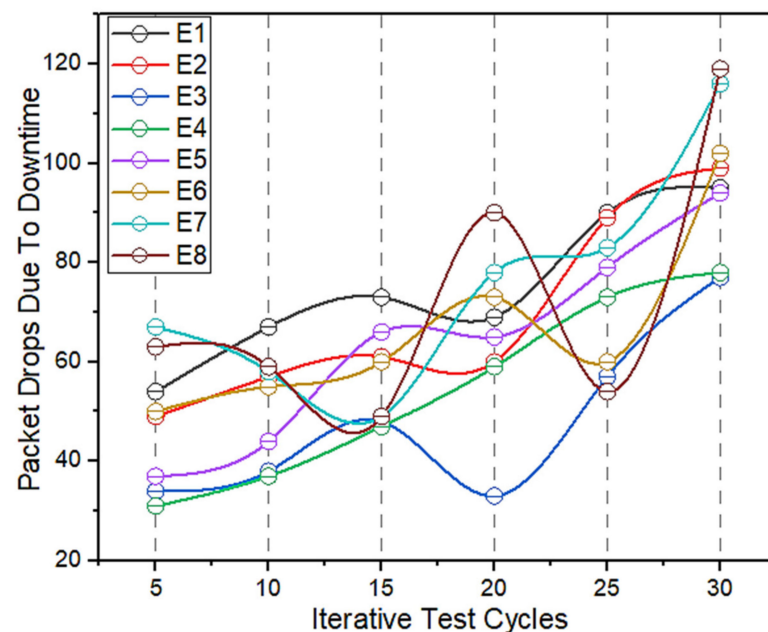


Figure 13. Total number of packets dropped due to sensor node's downtime.

Finally, the practical evaluations are crucially mounting on the considerations of packet drops due to the node's downtime and EOR (Table 10). EOR is the definite attainment of each work towards an energy optimization goal. In this experiment, better energy harvesting (saving) solutions are produced from E3, E4 and E5. Particularly, the effective reduction in computation overhead and retransmission rate gives optimal attainment in EOR. Thus, the EOR of E3 varies between 0.365 and 0.467 during various iterative simulations. In the same manner, E4 attains an EOR from 0.321 to 0.563 as it is using a

channel adaptive quality evaluation procedure to initiate data transmission compared to E3. On the next level, E5 attains a better EOR (0.443) due to its load balancing principles compared to other works. In addition, the practical comparison between more recent energy-efficient routing protocols gives diversified solutions to the research community. In this regard, this proposed review article extends the evaluation of E9 [51], E10 [54], E11 [55] and E12 [56] under the considerations of energy optimization and multi-hop routing principles in WSNs.

Table 10. EOR.

Iterative Test Cycles	E1	E2	E3	E4	E5	E6	E7	E8
5	0.278	0.361	0.385	0.563	0.443	0.359	0.333	0.309
10	0.299	0.318	0.365	0.478	0.389	0.303	0.301	0.328
15	0.372	0.404	0.467	0.321	0.435	0.388	0.361	0.371
20	0.396	0.412	0.434	0.367	0.366	0.401	0.408	0.401
25	0.354	0.399	0.411	0.401	0.301	0.382	0.357	0.366
30	0.267	0.358	0.397	0.387	0.318	0.298	0.284	0.299

The most recent ideologies on novel energy-optimized routing protocol development and relevant discussions lead to future-generation WSN energy models [91,92]. In this concern, E9 developed swarm-intelligence-based chimp optimization solutions and hunger game searching principles to find energy-efficient multi-hop routing paths. This work followed the natural habits of chimps to optimize path-finding problems with minimal overhead. Particularly, the first phase of the chimp optimization algorithm initiated the network formation under a hierarchical structure (base station and clusters). The clusters were formed as driving nodes, chaser nodes, barrier nodes and attacker nodes using chaotic cost computations. In the same manner, the second phase of this work provided a hunger search-based path selection approach for initiating an energy-efficient multi-hop routing process in underwater sensor networks.

E10 proposed energy classification and channel assessment techniques using a greedy approach for minimizing the overload of the node's energy resources. According to the strategies, each sensor node's energy levels are monitored with adaptive internal buffer management policies on the reception of data packets. Similarly, the routing protocol used for this mechanism found the greedy-based route selection with sufficient node resources to avoid packet losses. In this connection, E11 and E12 considered coverage problems and locality problems, respectively. Particularly, E11 proposed link stability evaluation protocols and grid-level stimulated network models to achieve coverage optimization in WSNs. In this concern, Figure 14 illustrates the functions of link stability evaluation and coverage problem analysis models (holes or inactive nodes).

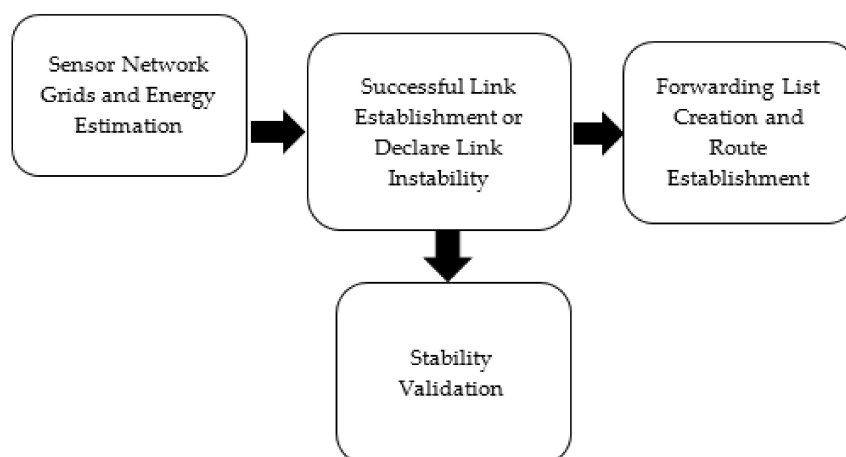


Figure 14. E11-Link stability management and routing.

Finally, E12 proposed zone-based routing protocols and energy optimization policies throughout the WSNs. In this concern, each sensor node was constructed under various zonal locations with allotted energy resources to be associated with other zonal sensor nodes. The proposed routing protocol running in each sensor node evaluated residual energies to proceed data routing into other zones. Thus, various recent routing protocols were proposed under energy consideration platforms. These works are compared as illustrates below.

Figure 15 depicts the performance comparison between E9, E10, E11 and E12 in terms of AECR against changing number of sensor nodes. In this experiment, four different types of energy-efficient routing protocols are compared. E9 has been experimented for underwater sensor networks. Compared to other sensor networks, underwater sensor networks use acoustic sensors with minimal energy resources. In this concern, E9 developed hierarchical energy optimization solutions and chimp optimization policies in order to search active nodes to enable flawless communication. In this case, the network clustering process and node searching processes consume significant energy (1.93 J). On the other hand, protocol implemented in E12 consumes maximum energy as it is related to zonal computational policies. At any rate, E10 and E11 are optimally designed for improving the quality of energy-saving mechanisms via the greedy approach and link stability validation approach.

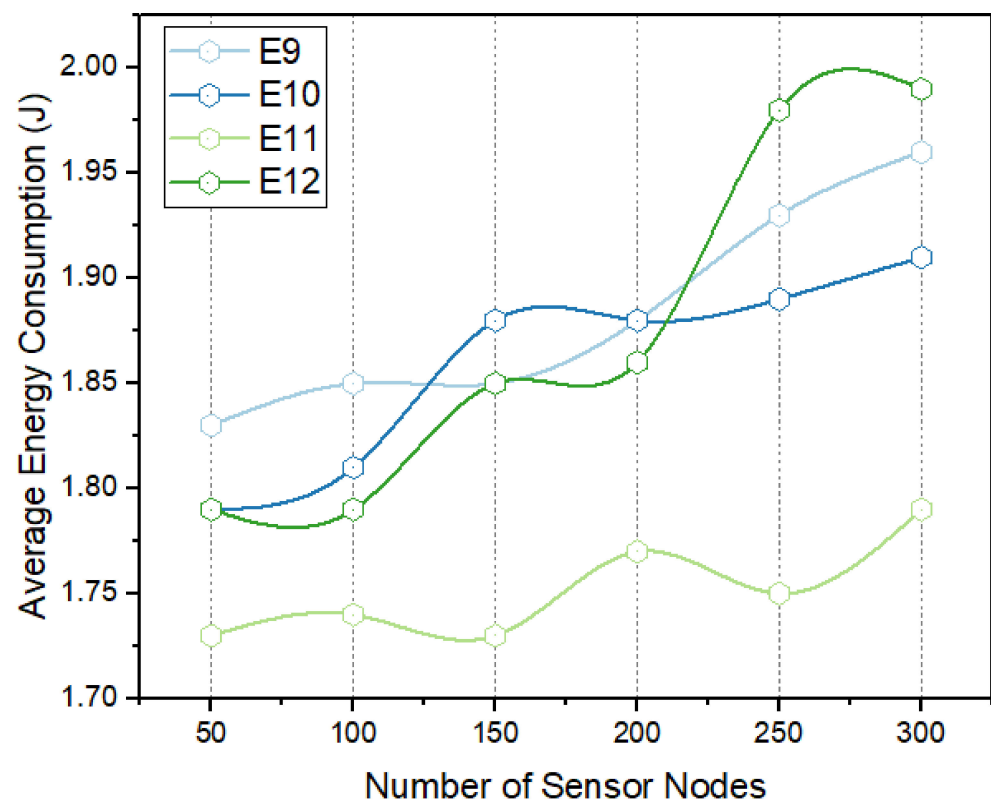


Figure 15. Energy-efficient routing schemes and AECR.

In this comparison, E11 ensures network coverage optimality and link stability concerns to operate successful data transmission from source to destination. In this analysis, E11 provides more stable and optimized channel circumstance to reduce packet drops and retransmissions. Thus, the AECR of E11 attains a minimal value (1.77 J). At the same time, E10 secures 1.88 J which is better than other works such as E9 and E12. Similarly, Figure 16 shows the calculation of the average routing delay in milliseconds.

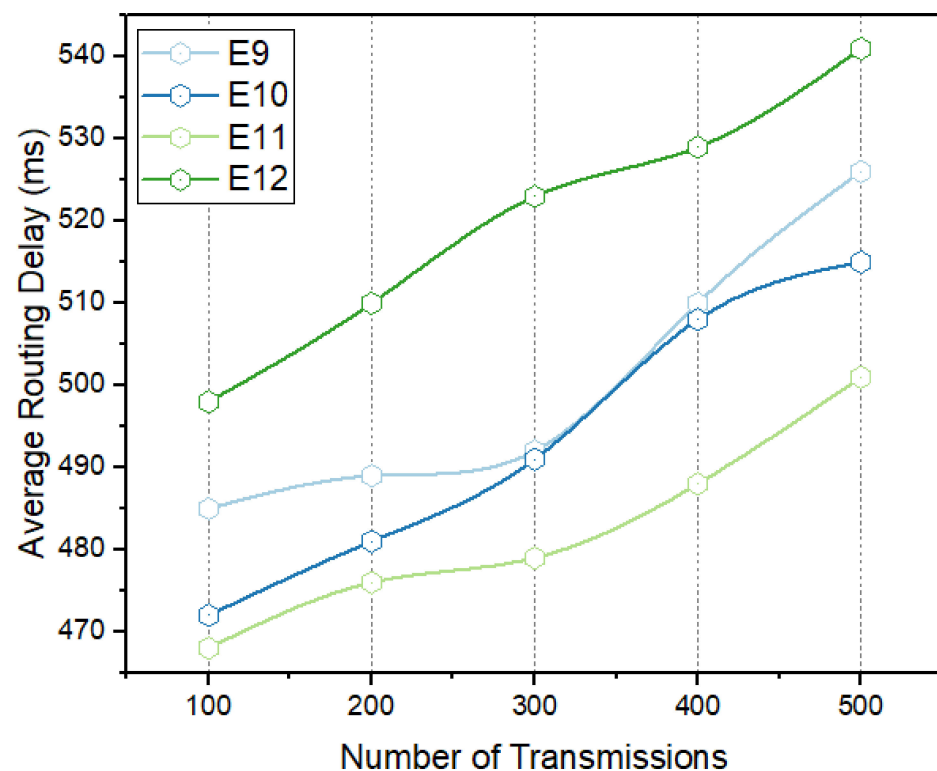


Figure 16. Energy-efficient routing schemes and Delay.

The routing delay of E10 and E11 are minimal compared to E9 and E12. The category of E9 and E12 fall under clustered or zonal network architecture. Under these network management policies, the route construction to deliver the data from source to destination has to follow clustered or zonal rules. This makes the routing delay a little higher than flat network architectures (E10 and E11). In this regard, E11 strongly builds stable links and coverage assurance in the WSN for data transmission. Once this process has been successfully developed, it reduces the routing delay during data transmission. Thus, it minimizes the delay (495 ms). In the same manner, E10 produces 510 ms of routing delay, which is still better than E9 and E12. Figure 17 illustrates the computation overhead of E9, E10, E11 and E12. As discussed, E9 and E12 produce more computation overhead (additional packet transmission) than E10 and E11. The observed results of E9 (145) and E12 (170) are closely related to AECR produced by each technique.

In contrast, E10 and E11 managed the computation overhead with minimal rates compared to E9 and E12. The reason for the optimized overhead of E10 and E11 is the energy stability and link stability in the network. In this manner, E10 produces 140 additional transmissions and E12 produces 110 additional transmissions in order to stabilize network communications. The observations are gathered against the number of actively participating sensor nodes for each iteration. Finally, Figure 18 illustrates the average packet delivery ratio (PDR) attained by each work. In this experiment, E10 and E11 obtained 0.93 to 0.94 of average PDR for a maximally populated network (300 sensor nodes). On the other hand, E9 and E12 sent packets at the PDR of 0.9. In general, the difference in PDR produced by each system is not crucial, yet the delay and energy consumptions significantly vary due to network changes. Hence, the comprehensive experimental analysis and technical discussion described in this article clarify the crucial efforts of energy-efficient WMAC policies and routing strategies to extend the lifetime of sensor nodes.

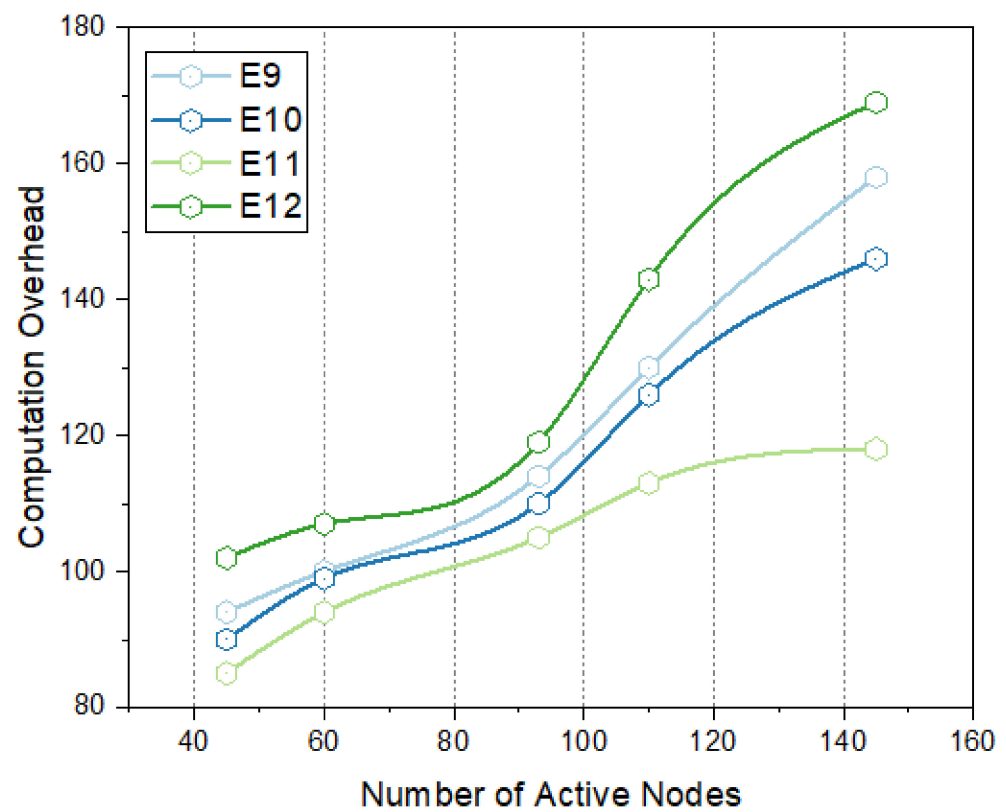


Figure 17. Energy-efficient routing schemes and Overhead.

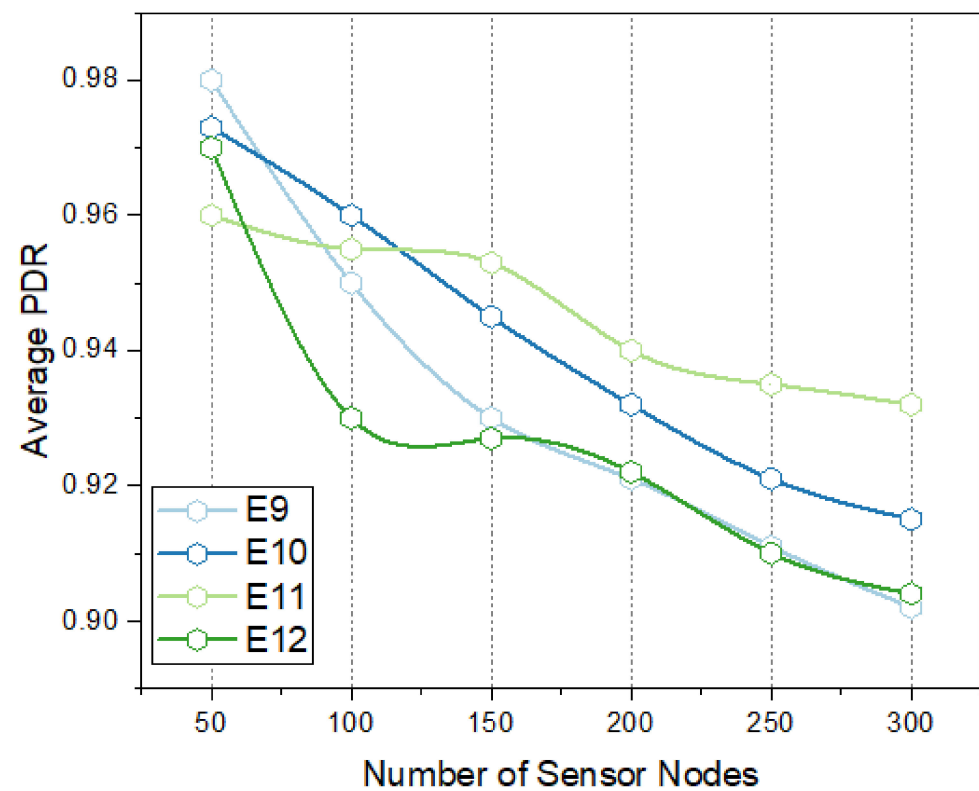


Figure 18. Energy-efficient routing schemes and Average PDR.

4. Conclusions

Wireless sensor nodes are known for their limited resources such as local memory, processor and other internal components. The deployment strategy of the WSN changes the need for unique energy-saving plans and lifetime saving plans. On this basis, this article has conducted a deep study on WMAC policies, routing protocols and energy optimization solutions. This article found the importance of energy-efficient processes under MAC policies, channel allotment policies and network routing protocols to attain novel growth towards the green computing era. As the applications of WSNs and IoT environments are widely growing around the world, energy consumption and feasible data communication practices are surely expected. Accordingly, this article technically and practically compared the recent contributions of various articles to ensure optimal energy consumption plans in WSNs. This article reviewed various energy-optimized routing protocols, load balancing approaches, variants of the WMAC protocol and data scheduling algorithms under an experimental testbed. The experimental evaluation of the existing energy optimization solutions and load balancing solutions (E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E11 and E12) against network dynamics (number of nodes, mobility, session, etc.) clarified the contributions of each work. Notably, this experimental survey found a better performance of multi-layer energy optimization policies (MAC and routing protocol) and routing policies than single-layer optimization solutions. From this experimental survey, the research community can understand the practical limitations and benefits of the mentioned techniques. In addition, the future world is in need of tiny yet efficient network participants (nodes) with the hope of safe energy plans. In particular, this article gives a future direction for researchers to build energy-optimized sensor nodes.

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