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Research Article

"A Comprehensive Survey of Routing Protocols for Wireless Sensor Networks"

Sonali Prashant Bhoite[1], Dr. Ganapati A. Patil[2]
1Ph.D Scholar, Department of Computer Science and Engineering, JSPM University Pune, Assistant Professor, Department of Information Technology, VIIT , Pune
2Professor, Department of Computer Science and Engineering, JSPM University Pune

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ABSTRACT

Usually small sensors tracking environmental conditions and sending data to a base station, a Wireless Sensor Network (WSN) is made of networked embedded devices. Given that these sensor nodes run on batteries, their lifetime is limited. Energy consumption mostly relates to sensing and communication, which finally causes node failure when the battery runs empty. Furthermore, the non-rechargeable and difficult-to- replace character of these batteries emphasizes the need of energy economy in extending the lifetime of networks. By means of routing protocols, effective energy management is possible. Based on important performance criteria like network lifespan, delay, distance, throughput, cluster head selection, energy efficiency, and general network stability, this work offers a thorough assessment of several WSN routing techniques.

Keywords: Heterogeneous wireless sensor network, energy efficiency, wireless network lifetime, cluster head selection.

1. INTRODUCTION

An heterogeneous WSN (HWSN) is a wireless sensor network composed of several kinds of sensors. Sensible utilization of heterogeneous nodes in WSN can raise application capability and extend lifetime. Military, medical, environmental, industrial, and commercial environments find application for the diverse WSNs. Since it has a long-lasting energy resource, it does not need regular replacement; so, heterogeneous node in a heterogeneous WSN can satisfy challenging communication demands. Furthermore more capable of processing data and transmitting than standard nodes are heterogeneous nodes.

1.1. Problems with system architecture and design

Depending on the application, several sensor network topologies and design limits have been taken into account. This part tries to portray architectural challenges and emphasize their consequences since the performance of the architectural model and the routing protocol is closely entwined.

1.1.1. Dynamics of networks

Three main components make up a sensor network: actions under observation, sink, sensor nodes. Except for a relatively small number of configurations that make use of mobility sensors, most WSN designs take immobile sensor nodes into consideration [11]. Still, occasionally it is necessary to enable the movement of sink or cluster-heads [12]. Routing messages from or to the moveable nodes becomes more challenging since route stability becomes a major determinant.

1.1.2. Deployment of nodes

One more consideration is the topology of the network among the nodes. The performance of the routing protocol relies on the application. Either deterministic or self-organizing deployment is possible. Manually orienting the sensors and routing the data along pre-defined paths define deterministic scenarios. By contrast, in self-organizing systems the sensor nodes are scattered at random and create an infrastructure on demand [2,14–16]. Performance

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and energy economy depend much on the position of the cluster-head or sink in that infrastructure. Ineffective clustering and network operations follow from non-uniform distribution of the sensor nodes.

1.1.3. Energy-related factors

The way the paths are developed during the infrastructure building process is heavily influenced by energy issues. Because a wireless radio's transmission power is linked to distance squared or even higher order when there are obstacles, multi-hop routing uses less energy than a single hop connection. For topology management and medium access control, however, multi-hop routing burdens greatly. Direct routing might work sufficiently if nodes were close to the sink [14]. Generally though, sensors are scattered randomly over areas of interest, so multi-hop routing is unavoidable.

1.1.4. Data delivery models

The sink's data supply approach might be hybrid, [13] continuous, event-triggered, query-driven, or constant. Under the continuous delivery notion, every sensor regularly produces data. In both event-triggered, query-activated approach, the data flow begins on occurrence of any event or the query driven by the sink. Certain networks integrate all three data delivery methods using a hybrid technique. Particularly in regard to route stability and energy consumption reduction, data delivery mechanism greatly affects the routing protocol. For instance, it was found in [17] that particular applications using a hierarchical routing system must constantly transmit the data to the sink.

1.1.5. Node capabilities

WSN assigns different purposes for its sensor nodes. Previous investigations [5,18,19] find all sensor nodes to be homogeneous with identical computing, communication, and power capacity. Depending on the application, a node may be committed to a certain special function—relaying, sensing, or aggregation—but executing all three functions concurrently on a node may quickly run out of its energy. Some of the hierarchical systems proposed in the literature define a cluster-head unique from the conventional sensors. Some networks choose cluster-heads from the installed sensors [14,20,21; in some applications a cluster-head is more potent than sensor nodes in terms of energy, bandwidth, and memory [11,15]. Many technological issues related to data routing surface when one incorporates a diverse collection of sensors [22]. For tracking moving objects in photos or videos, for motion detection utilizing acoustic signals, and for environmental temperature, pressure, and humidity monitoring, some applications may demand a wide spectrum of sensors.

1.1.6. Data aggregation/fusion

Because sensor nodes may generate significant redundant data, similar data packets from several nodes are merged to cut the number of transmissions. Data aggregation [23] is the combination of data from many sources utilizing averages, min, max, and suppression—removing duplicates. Some of these activities can be completed totally or in part by each sensor node by allowing sensor nodes to undertake in-network data reduction [18, 20, 24]. Given that processing consumes less energy than communication [14], data aggregation can produce notable energy savings. Many routing systems have used this method to maximize traffic and attain energy economy [18, 20, 24–27].

2. CLASSIFICATION OF ROUTING PROTOCOL

The figure 1 shows the several routing techniques examined in this article. Their classification depends on the method and strategy applied in the protocols.

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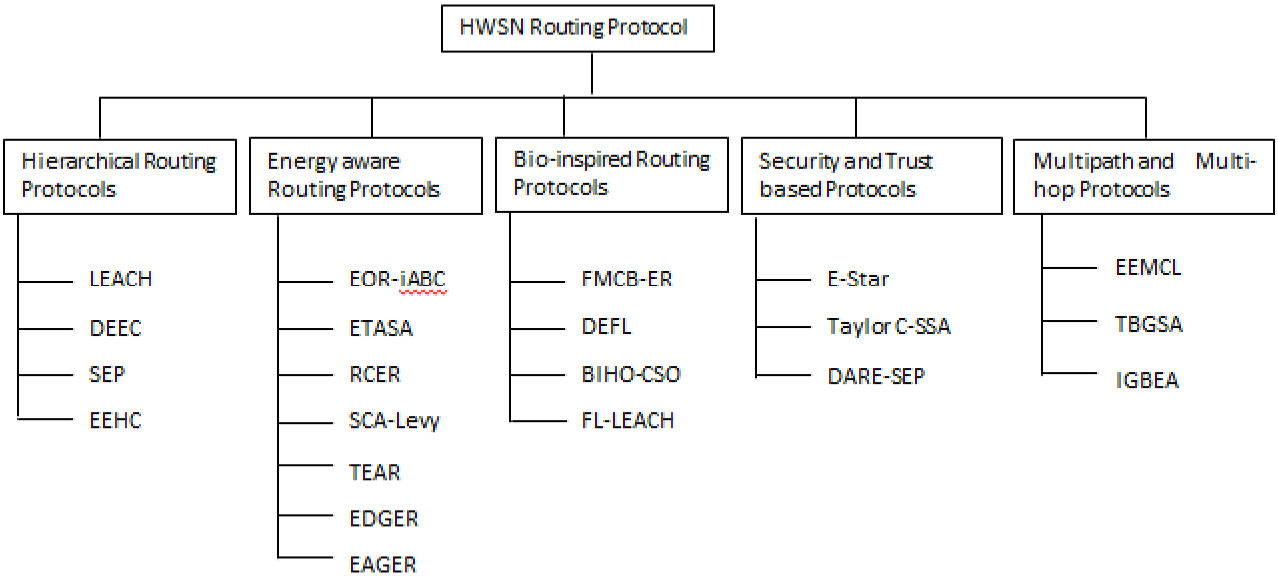

Fig 1– classification of routing protocol

3. LITERATURE SURVEY

This section presents a review of the literature on various existing techniques used for routing in WSN.

3.1 Hierarchical Routing Protocols

Low-energy adaptive clustering hierarchy, LEACH, is a technique meant to improve energy economy. LEACH arranges nodes into clusters under the direction of cluster-heads handling the base station for communication. Roles with cluster heads rotate among nodes to balance energy use. This method consists in two phases: in set-up phase, nodes self-organize into clusters, elect cluster-heads, and generate schedules. Data is driven from sensors to the sink and then to the base station in steady-state phase. Combining several signals at cluster-heads helps to minimize energy consumption by so lowering the volume of delivered data. LEACH lowers energy dissipation by a factor of 8, according to simulation studies, when compared to conventional techniques. It delays the death of the first node by eight times and the death of the last node by three times relative to alternatives. Maximum energy efficiency is obtained with optimal cluster-head selection—5% of nodes. In terms of energy efficiency and system lifetime LEACH beats systems like minimum-transmission-energy (MTE) routing and static clustering. Energy efficiency has been presented by LEACH since it drastically lowers energy usage when compared to direct transmission or multi-hop routing. By means of consistent energy consumption among all nodes, it doubles the usable life of the network. LEACH is fit for large-scale networks because of its localized coordination and dynamic clustering. Furthermore lessening the impact of individual node failures is the randomized cluster-head selection. But then Management and generation of clusters could call for more processing time and setup time. Plus Compression at the cluster-heads could cause partial data loss, hence lowering signal integrity. 22 [22]

Yahya Kord Tamandani Mohammad Ubaidullah, etal.[15] have presented the present stable election protocol (SEP) paired with the fuzzy logic-based mechanism to simplify the CH selection process as well as increase the lifetime of the network. Here there three input purposes: Distance, battery level, and node density help to convert the clear inputs into fuzzy sets. Before the probability is computed via a fuzzy rule, each sensor's power level, density, and distance to the base are computed. Every node has a computed and stored individually threshold value. Two separate probabilities derived from the fuzzy system and threshold equations are taken into account while choosing the best applicants for the post of cluster head. By 73.2% compared to SEP and SEP-E protocols, respectively, simulation reveals that SEPFL increases the WSN longevity when compared to the SEP-E protocols. By 68.54% and 33.5% respectively, the protocol also increases network throughput by comparison to SEP and SEP-E protocols.

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For Wireless Sensor Networks (WSNs), Mei Wu et al. [5] presented an energy-efficient routing method termed DCK-LEACH. This method emphasizes on lowering energy consumption, hence extending the lifetime of the network by fairly dispersing the burden throughout it. Along with a dual cluster-head approach to light the load on a single cluster-head, the algorithm combines the Canopy optimization approach with the K-means clustering method. While the secondary cluster-head is selected using the node's remaining energy and distance to the base station, the selection of the main cluster-head is based on the node's residual energy and closeness to the cluster center. The method also has a mechanism to control the re-clustering frequency, therefore preventing needless energy loss. Results of simulation show that DCK-LEACH increases general network durability over standard protocols and efficiently spans the lifetime of energy-critical nodes. The method also lowers energy usage, boosts network throughput, and generates superior clustering effects. Nevertheless, this method has few restrictions since the algorithm ignores security issues, which are absolutely important in WSNs. The method also presumptions that nodes are stationary, which might not be the case in actual environments.

For application in heterogeneous wireless sensor networks (WSNs), Suniti Dutt et al [12] provide a new routing protocol called Cluster-Head Restricted Energy Efficient Protocol (CREEP). By changing the selection criteria for cluster heads (CHs) and restricting their count, this protocol is meant to improve the longevity and performance of the network. In situations including both stationary and moveable nodes, the paper also assesses CREEP's performance against other well-known protocols including LEACH, DEEC, SEP, TDEEC, ETSSEP, and ECHATSEP. The simulation findings show that CREEP achieves network lifetime and throughput higher than these standards. higher precisely, CREEP increases the network lifetime by 24.3% and 30.1% higher than ECHATSEP and ITDEEC correspondingly in stationary node environments, with 10% of the nodes alive as CHs. In movable node conditions, CREEP performs somewhat similarly. CREEP also boasts more throughput than the ECHATSEP, TDEEC, and ITDEEC protocols. Although limiting the number of CHs to 10% of living nodes produces the best lifetime, this may adversely affect the throughput. In both stationary and mobile node environments, CREEP performs admistically. The protocol does, however, assume a limited network region and might not be scalable across more expansive locations.

Wenbo Zhang, et al. have proposed a better version of IPv6 Routing Protocol for Low Power and Lossy Networks (RPL) since load balancing and power consumption of the former version suffer. 14] This version determines the optimal number of cluster heads by means of an effective topology control model of the loop domain. The WSN is split into equal-sized concentric rings, and it is indicated that communication and data transfer would be ideal from here. Here, a clustering probability model is used to divide the network into several clusters by means of the residual energy and relative position of the sensor nodes. The heterogeneous cluster working together balances the energy consumption with the cluster head. The simulation considers a WSN with 100 nodes; so, the average lifetime of the network is increased by about 25%. IRPL balances node energy usage and lowers network energy consumption generally. In particular at high bandwidth, it also achieves a lower packet loss rate than RPL.

Table 1 – summary of Hierarchical Routing Protocols

Name of Author	Name of Journal	Algorithm/ Methodology / Technic proposed	Observations	Advantages	Limitations
Wendi Rabiner Heinzelman, et al	IEEE - Hawaii International Conference	LEACH (Low-Energy Adaptiv	- LEACH reduces energy dissipation by up to 8x. - Extends system lifetime: First node death occurs 8x	- Significant energy savings - Doubles	- Assumes static base station and homogeneous nodes,

	on System Sciences - 2000	e Clustering Hierarchy)	later, and last node death 3x later. - Optimal cluster-head percentage (5%) achieves maximum energy efficiency. - Balances energy usage among nodes, enabling consistent network monitoring over time.	network lifetime - Scalable and robust - Effectively manages fault tolerance	limiting real-world applicability. - Requires additional processing for cluster setup and management. - Performance might degrade in highly dynamic or heterogeneous networks.
Mei Wu, Zhengliang Li , et al	Journal of Sensors 2022 Volume 22 Issue 24	DCK-LEACH	Prolonged network lifetime, reduced energy consumption	Balanced network load, better throughput	Does not consider security, assumes static nodes
Dutt S, Agrawal S, Vig R	Wireless Personal Communications peer-reviewed journal (Springer)	CREEP	Improved network lifetime and throughput	Performance in both stationary and mobile settings	May not scale well in larger networks
Wenbo Zhanga Et al	Journal of Systems Architecture: the EUROMICRO Journal (ACM digital library)	IRPL	Extended network lifetime by 25%, lower packet loss rate	Balanced energy consumption	Limited scalability, complexity in real-world dynamic conditions
Smaragdakis , Georgios et al	The Journal of Mobile Communication, Computation and Information	SEPFL	Improved network lifetime by 73.2%, throughput by 68.54%	Enhanced CH selection, extended network lifetime	Does not consider mobility

Protocols Summary –

Hierarchical protocols split the WSN into clusters, in which each cluster has a Cluster Head (CH) who compiles and forward gathered data to the sink. This increases network lifetime and helps to slow down energy depletion. Apart from this, it has minimal restrictions; for example, CH choice could result in unequal energy usage if not maximized. It makes assumptions about stationary nodes, so restricting practicality. Compression at cluster-heads could cause partial data loss.

3.2 Energy aware Routing Protocols

The paper "Energy optimization routing for hierarchical cluster based WSN using artificial bee colony" presents a routing strategy aiming at optimizing energy consumption in large-scale cluster-based Wireless Sensor Networks

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(WSNs) by using an enhanced Artificial Bee Colony (ABC) algorithm. Using fitness probability parameters that affect the choice of a node as a cluster head, the ABC method is applied to choose ideal cluster heads. Unique search algorithms such the Cauchy operator and the Grenade Explosion Method (GEM) enable dynamic extension of search operations over several areas within a large-scale sensor network. Global optimization techniques are included to balance and improve network energy in order to stop regular cluster head selection. Evaluated against current methods including OCABC and IABCOCT, the new method, EOR-iABC, shows better performance in energy efficiency, packet delivery, and delay. Over OCABC, simulation results show EOR-iABC improves energy efficiency by 27%; over IABCOCT, it does so by 16%. Furthermore emphasized in the work by G. Santhosh a, et al [3] are the higher number of active nodes and the higher packet delivery ratio, which help to lower delay relative to OCABC and IABCOCT.

Aiming at increasing energy efficiency and load distribution in heterogeneous Wireless Sensor Networks (WSNs), Nura Modi Shagari et al [8] have presented a hybrid solution called as the Energy and Traffic Aware Sleep-Awake (ETASA) mechanism. This approach is used to a WSN distinguished by densely positioned sensor nodes varying in energy levels and data rates. Two or more nearby sensor nodes with the same application are combined for data sensing and transmission under the ETASA mechanism using a pairing technique. Depending on their energy levels and traffic rates, these paired nodes alternate between sleep and active modes to avoid the early failure of nodes experiencing high traffic. To guarantee balanced energy usage, the method also includes a modified cluster head selection mechanism that selects nodes with high energy, low traffic, and many pairs. Focusing on network lifetime, residual energy, and throughput, the performance of the ETASA mechanism is evaluated against two currently in use protocols: Traffic and Energy Aware Routing (TEAR) and Sleep-Awake Energy Efficient Distributed (SEED). Results of simulations show that the ETASA mechanism surpasses the current techniques in improving network's life, remaining energy, and throughput. In particular, ETASA improves lifetime by 16% and by 15% respectively compared to TEAR and SEED. It also shows somewhat better throughput and more leftover energy than both TEAR and SEED. On network performance, the ETASA method does not, however, consider the consequences of packet loss and retransmission. Based on a specific network scenario, the simulation outcomes might not be relevant in other situations.

Khalid Raseebi Using node energy heterogeneity and in two steps, Naveed Abbas et al [9] devised RCER technique; Second; the use of an optimal route detection mechanism considering hop count, the weighted value of the trip duration, and residual energy improves the next-hop selection; the network field is divided into several geographical clusters to make use of less energy. Only elected high-energy CHs are responsible for employing a multi-hop path to transmit the obtained information to the sink since RCER promotes the heterogeneity of nodes. The results show better performance and longevity increases of 11.5%, 12.2%, 14.7% and 23%, respectively when compared to ETSSEP, TBC, LCM, and Partition-based LEACH methods.

In their research paper, Xiaoling Guo and associates [2] provide a novel routing algorithm for Wireless Sensor Networks (WSNs) combining the Sine Cosine Algorithm (SCA) with Lévy Mutation. This method, called SCA-Lévy, is meant to improve WSN network lifetime and energy economy. The work presents a thorough analysis of the algorithm together with information on its structure, methods, and simulated results. Data is transported from cluster heads to the base station (BS) through a routing procedure. Should the distance be more than d0, a relay node may be found to transport data within the area; should the distance be less than d0, data can be routed straight to the BS. < Regarding energy usage, network lifetime, and throughput, the simulation findings show that SCA-Lévy outperforms current methods. The results show that SCA-Lévy can improve throughput by up to 20%, increase the network lifetime by up to 50%, and cut energy consumption by up to 30% relative to present techniques.

Deepak Sharma et al. [11] offer TEAR (Traffic and Energy Aware Routing) to increase the stability period in heterogeneous WSNs. This method takes traffic of a node into account together with its initial and residual energy. More suited for genuine WSN conditions, TEAR takes traffic and energy heterogeneities into account in the routing process. TEAR exceeded several present methods in the multi-homogeneous situation about stability period. In terms of stability period under multi-homogeneity scenarios, the simulation findings demonstrate TEAR beats current methods (LEACH, SEP, and DEEC). Under a scenario with αth = 4 and αeh = 1 TEAR exhibits an

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improvement in stability period of 33.6% and 8.3% compared to LEACH and DEEC, respectively; under a scenario with αth = 2 and αeh = 1, TEAR shows an improvement in stability period of 17.9% and 8.3%. Under circumstances with αth = 4 and αeh = 1, TEAR's stability period is 379 and 614 rounds respectively; αth = 2 and αeh = 1 in the other cases. This approach is computationally challenging even if it exhibited good performance in the face of traffic heterogeneity. The proposed method yields 80 live nodes, an equivalent of Simulations show that full energy is depleted by round 786. The suggested method supposes homogeneous energy drainage in every round, which could not be the situation in practical environments. Furthermore, the simulation results depend on a small-scale network (100 nodes), hence TEAR performance in bigger systems is not assessed. To lower the degree of energy consumption and postpone the organization lifetime, Yuan-Po Chi Hsung-Pin Chang, et al.[13] offers the Energy-aware Grid-based Routing Scheme (EAGER). EAGER divides the region to be monitored into numerous simulated grid cells, where each grid is identified by a unique grid number (GID), therefore offering the solution for problems with mobile sinks at start-up. Every node existing in the same grid shares this GID. In every grid cell, the coordinator—known as the Grid Head (GH)—is chosen by all members, in charge of overseeing all members and distributing data. Periodically turning off their sensing, grid members rely just on their active sensing channels until the target stimulates them. Should the sink require additional data, it sends a query management packet to GH only to lower the consumption of other grid members. GH answers the question and forward it to intended grid members just. EAGER's performance is assessed by means of three criteria—total energy usage, rerouting frequency, and average packet ratio—against Energy-Aware Data Aggregation (EADA). Simulation reveals that, for a maximum 25m/s sink speed, EAGER consumes 600w, compared to about 800w for the same sink speed.

For Compressive Sensing in Multi-Hop Heterogeneous Wireless Sensor Networks (HWSN), Bejjam Komuraiah and Dr. M.S. Anuradha [18] presented an Efficient Data Gathering Model with Energy-Based Routing (EDGER). The suggested solution solves the main problems with limited sensor lifespan, power efficiency, energy consumption, and routing failures. It seeks to lower energy usage, boost throughput, and raise dependability of communication. K-means clustering is the method of clusterering. Distance, energy, and buffer capacity all factor in the CH choosing process. Higher residual energy and greater proximity to the network center sensors rank highest as CHs. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is the routing technique that guarantees flawless communication and helps to avoid packet collisions. Network Simulator 2 (NS2) was used for evaluation of the proposed EDGER-HWSN model. Five current models—CDAS-WSN, EEPC-WSN, TCCS-WSN, MTODS-WSN, and LPICR-WSN—were then compared with the results. For EDGER-HWSN, routing overhead results in 125 packets—much less than CDAS-WSN (525 packets). With EDGER-HWSN's 865.17 kbps, far greater than CDAS-WSN's (399.28 kbps) and LPICR-WSN's (798.33 kbps), is throughput. While that of CDAS-WSN is 253.25J, EDGER-HWSN's energy efficiency is 686.17J. Effective routing, lower retransmissions, and best CH and parent node selection account for this improvement in energy efficiency, hence extending the sensor lifespan generally. The EDGER-HWSN paradigm has some restrictions including computational complexity, limited scalability and fault detection overhead notwithstanding its enhanced performance.

Malicious detection	12% to 38% increase.
Communication cost	15 bits to 140 bits lower.
Success rate	3% to 28% higher data success rate
Data loss ratio	2% to 38% lower data loss ratio.
Delay	10 ms to 200 ms lower end-to-end delay.
Routing overhead.	20 packets to 300 packets lower routing overhead.
Throughput	80 kbps to 450 kbps higher throughput.
Energy efficiency	60J to 400J higher energy efficiency

Poornachander Vadicherla and Dhanalakshmi Vadlakonda[26] suggest a possible approach for energy-efficient transmission in autonomous WSNs based on opportunistic routing. Under this method, every cluster head has a set of surrounding nodes. Along with the coordinates of the source node and cluster heads (CHs), each node is

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aware of the energy levels of its neighbors. Based on average CH energy consumption in the previous round, the algorithm projects energy consumption in the upcoming round. CHs are selected from nodes whose predicted residual energy exceeds others. Based on their energy levels, weighted probabilities help to choose nodes as CHs (type 0 and type 1 nodes with varying energy levels). Based on simulations, the study evaluates, in five routing protocols (EDFCM, MCR, EEPCA, LEACH, and LEACH+) their efficiency. The results demonstrate that the quantity of packets the sink gathers and the round the first node dies in reduces with increasing sensing field size. This is so because declining density of nodes results in larger gaps between them and higher data transmission energy usage. Aiming to guarantee transmission inside the minimum energy path, opportunistic routing is Dynamic data relay enhances network throughput and transmission dependability.

Table 2 – summary of Energy aware Routing Protocols

Name of Author	Name of Journal	Algorithm / Methodology/ Technic proposed	Observations	Advantages	Limitations
G. Santhosh a,b , K.V. Prasad	Measurement: Journal of International Measurement Confederation (IMEKO) ELSEVIER	EOR-iABC	27% improvement in energy efficiency, higher packet delivery ratio, lower delay	Energy efficiency, enhanced network performance	Computational complexity
NURA MODI et al	IEEE Access VOLUME 8, 2020.	ETASA	Improved network lifetime by 16%, higher remaining energy	Balanced energy consumption, improved throughput	Does not consider packet loss and retransmission
Haseeb K, Abbas N, Et al	Plos One open Access (Q1 Scopus)	RCER	Lifetime improvement by up to 23% over various protocols	Energy efficiency, better route optimization	Assumes static nodes
XIAOLING GUO, et al	IEEE access	SCA-Lévy	Reduced energy consumption by 30%, prolonged network lifetime by 50%, improved throughput by 20%	Energy efficiency, network lifetime, throughput improvement	Complexity of algorithm implementation
Sharma D, Bhondekar AP	IEEE COMMUNICATIONS LETTERS, VOL. 22, NO. 8,	TEAR	Stability period improved by up to 33.6%	Effective under traffic heterogeneity	Computationally complex, limited evaluation in small-scale networks

	AUGUST 2018				
BEJJAM KOMURAIAH et al	Journal of Theoretical and Applied Information Technology Vol.102. No. 14 2024	EDGER	Higher throughput, lower energy consumption, improved sensor lifespan	Energy efficiency, reduced routing overhead	Computational complexity, limited fault detection
Poornachander Vadicherla, Dhanalakshmi Vadlakonda.	Elsevier - Materials Today: Proceedings	Opportunistic routing		Opportunistic routing ensures transmission within the minimum energy path.	Forwarder node selection may lead to longer transmission paths beyond intermediate nodes.

Protocols Summary –

Through choosing energy-efficient paths and balancing the energy load across nodes, these systems maximize energy consumption. They reduce pointless transmission and extend network longevity. Some methods, meanwhile, bring great computing complexity and presume stationary nodes—which might not be reflective of actual installations. Furthermore neglected are security issues, which make them easily attacked.

3.3 Bio-inspired Routing Protocols

Developed by Yufei Zhang, et al [1], the Bio-inspired Hierarchical Order Chicken Swarm optimization (BIHO-CSO) algorithm is a fresh optimization method showing interesting results in either optimal or near-optimal solutions. Based on studies recorded in the Biomimetric International Journal. The BIHO-CSO technique shows efficient search and exploitation of the search space.

Leaders in transmitting significant messages are roosters, hence their choice and updating are vital. An optimal guided search approach for roosters is presented in this work. This approach chooses multiple individuals with greater fitness values from the population to act as roosters instead of choosing one rooster as in the original CSO algorithm. Concurrent with this is the search directed towards the global optimal individual (xbest). The enhanced roosters solve the poor convergence accuracy issue of the CSO method by fully leveraging the past experience of the population and having more exploitation potential. This approach cut computational complexity as well as energy consumption. Also enables effective use of few resources. Nonetheless, the suggested method has restrictions regarding the restricted resources including processing capacity, memory bandwidth and energy.

A Distributed Energy-conscious Raja Al-Kiyumi et al. [10] developed fuzzy logic-based routing method (DEFL) to concurrently address balance problems and energy efficiency. To find the shortest way, this method transformed appropriate energy measurements—which represented network health—into cost values. Moreover, mapping operations in order to implement human thinking was done using a fuzzy logic method. Since this approach raised the complexity of network communication, network performance was threatened even if it considerably improved energy balancing performance. With a value of 998 seconds, the DEFL approach proposed in this work shown good network life time performance based on simulation findings.

Fuzzy Multi-criteria Clustering and Bio-inspired Energy-efficient Routing (FMCB-ER) has been presented by Deepak Mehta, et al [7] as a hierarchical wireless sensor network (WSN). Employing a fuzzy multi-criteria decision-making approach and a bio-inspired optimization algorithm, the protocol seeks to improve the network lifetime and lower energy usage. Three parts comprise the protocol: grid-based clustering; cluster head selection using adaptive fuzzy multi-criteria decision-making; optimal path finding using Emperor Penguin Optimization

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(EPO). In most of the performance measures, the simulation findings show that FMCB-ER beats current routing systems. With a maximum decrease of 23%, FMCB-ER utilizes less energy than Fuzzy-ACO. With a maximum improvement of 3.79% FMCB-ER reaches higher throughput than Fuzzy-ACO. With a maximum reduction of 22% compared to Fuzzy-ACO, FMCB-ER has lower end-to- end delay than LEACH, Fuzzy-ACO, Fuzzy-Cuckoo, and Fuzzy-PSO. With a maximum reduction of 24% relative to Fuzzy-ACO, FMCB-ER has lower latency than LEACH, Fuzzy-ACO, Fuzzy-Cuckoo, and Fuzzy-PSO. With a maximum improvement of 15% against Fuzzy-ACO, FMCB-ER has longer network lifetime than LEACH, Fuzzy-ACO, Fuzzy-Cuckoo, and Fuzzy-PSO. The findings do, however, also highlight some limits in FMCB-ER. For FMCB-ER, for instance, the energy consumption rises with the number of nodes, which can shorten network lifetime. Furthermore shown by the data is FMCB-ER's higher computational complexity than current routing techniques, which could result in lower network lifetime and higher energy usage.

Marwa Gamal, et al [4] called FLLEACH Technique based on PSO propose a fresh approach for increasing the lifetime of Wireless Sensor Networks (WSNs) based on Fuzzy Logic (FL) and Particle Swarm Optimization (PSO). Its aim is to improve the energy efficiency. The approach uses FL to select the Primary Cluster Head (PCH) and Secondary Cluster Head (SCH) and a hybrid PSO and K-means clustering algorithm to build clusters. Three criteria—res residual energy, distance to cluster center, and distance to BS—help to guide the PCH choice. Two criteria—res residual energy and distance to PCH—help to guide the SCH choice. Other present techniques such FCM clustering and FLS-based CH selection, LEACH-Fuzzy Clustering (LEACH-FC) protocol, and LEACH based on energy consumption equilibrium are compared with the proposed method. With an improvement of over 46% and packet transmissions by 17.6%, the simulation results show that the proposed technique performs better than the other protocols in network lifespan.

Table 3 – summary of Bio-inspired Routing Protocols

Name of Author	Name of Journal	Algorithm / Methodology/ Technic proposed	Observations	Advantages	Limitations
Yufei Zhang Limin et al	Biomimetics international journal published by MDPI	BIHO-CSO (Chicken Swarm Optimization)	Reduced energy consumption, improved resource usage	Low energy consumption, computational efficiency	Limited by processing power, memory bandwidth, and energy
Raja AlKiyumi , Et al	IEEE TRANSACTIONS ON GREEN COMMUNICATIONS AND NETWORKING,2018	DEFL	Improved network lifetime to 998 seconds	Effective energy balancing	Increased communication complexity
Deepak Mehta1 et al	Journal of Multimedia Tools and Applications, 2022 - Springer	FMCB-ER	23% less energy consumption, higher throughput, lower delay	Energy efficiency, improved network lifetime	Increases energy consumption with more nodes, higher computational complexity

MARWA GAMAL , N. E. et al	IEEE access volume 10 2022	FL LEACH PSO	Improved network lifetime by 46%, packet transmission by 17.6%	Enhanced energy efficiency, better cluster head selection	Limited scalability, assumes static nodes

Protocols Summary –

Inspired by natural phenomena including swarm intelligence, evolutionary algorithms, and fuzzy logic, these protocols dynamically adjust to changing network conditions to increase efficiency. They cut energy use by means of adaptive and ideal routing. But they demand great computational capability, which raises processing overhead. For WSNs with limited resources, some protocols may not be feasible and have scalability problems.

3.4 Security and Trust based Protocols

e-stars, Mahmoud, et al. [16] present a safe protocol to get consistent and dependable paths in homogeneous-based homologies. ESTAR bases on an energy-aware and trust-based routing protocol integrates the trust and payment systems. Here the payment mechanism energizes the nodes using the credits or micropayment. The packets are delivered from ESTAR via its nodes, which also reward the relaying packets. Not part of the communication sessions, an offline trusted party (TP) manages the credit accounts of nodes and is therefore essential. The sensor nodes, known as receipts, which are sent to the TP, contain the evidence of packet relay. The payment mechanism simulates selfish nodes to obtain credits to distribute on packets of other nodes. Offering the nodes compensation helps to enforce fairness by means of which additional packets—available at the network's center—can be transmitted. Still, the payment method by itself is insufficient to guarantee the route stability. The payment mechanism generates the reasonable nodes to accumulate credits. Some factors like node failure, hostile attacks or limited resources could cause the routes to be broken. The simulation results validate enhanced route stability and network lifetime as well as high packet delivery ratio. E-STAR, however, calls for a sophisticated trust system and payment mechanism, which could raise protocol overhead and complicate matters also it might not be scalable to big networks because of the complexity of the trust system and payment mechanism.

A. Vinitha, et al. [17] offer a safe and energy-aware multi-hop routing protocol in Wireless Sensor Networks (WSNs) with a Taylor-based hybrid optimization method (TBHO). Through choosing the best cluster head (CH) and multi-hop routing method, the protocol seeks to solve the energy problem in WSNs. The proposed Taylor-based Cat Salp Swarm Algorithm (Taylor C-SSA) and the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol are used in the protocol to choose the optimal multi-hop routing path and the CH respectively. Integrating the Taylor series with the Cat Salp Swarm Algorithm (C-SSA) helps the Taylor C-SSA algorithm to improve convergence and accuracy of the method. To guarantee routing process security, the protocol additionally uses a trust concept. Regarding energy efficiency, delay, throughput, and alive nodes, the simulation findings reveal that the suggested Taylor C-SSA-based routing protocol beats current methods. With an energy value of 0.129—above that of current protocols—the suggested system With a delay value of 0.291, which is less than that of the current protocols, the suggested one With a 0.1 throughput value—above that of the current protocols—the suggested protocol Higher than current protocols, the suggested protocol achieves an alive node value of 42.

For best transmission routing in Wireless Sensor Networks (WSNs), Afia Naeem, et al [6] proposed DARE-SEP (Distance Aware Residual Energy-Efficient Stable Election Protocol), a hybrid approach combining the characteristics of Residual Energy Efficient Stable Election Protocol (REE-SEP) with Direct Transmission (DT) and Distance-Based protocol (DP). Regarding the count of live nodes, DARE-SEp beats LEACH and SEP. DARE-SEp has 40% more alive nodes than LEACH and 20% more alive nodes after 1000 rounds than SEP. Less dead nodes in DARE-SEP than in LEACH and SEP. DARE-SEP has 30% less dead nodes than LEACH and 20% less dead nodes than SEP after 1000 rounds. Stable period of DARE-SEP exceeds LEACH and SEP. DARE-SEP's stable period is 15% longer than SEP and 20% longer than LEACH. Average residual energy of DARE-SEP is more than LEACH and SEP's. DARE-SEp has 10% more average residual energy than SEP and 15% more than LEACH after 1000

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rounds. The method does, however, presume a homogeneous network architecture, which might not be the case in actual situations as nodes could be placed in a diverse surroundings.

Table 4 – summary of Security and Trust based Protocols

Name of Author	Name of Journal	Algorithm/ Methodology/ Technic proposed	Observations	Advantages	Limitations
Mohamed M. E. et al	IEEE TRANSACTIONS ON PARALLEL AND DISTRIBUTED SYSTEMS	E-STAR	High packet delivery ratio, improved route stability	Trust-based routing, energy efficiency	Complex trust and payment system, scalability issues
A. Vinithaa et al	Journal of King Saud University-Computer and Information Sciences	TBHO (Taylor-Based Hybrid Optimization)	Higher energy value (0.129), lower delay (0.291), higher throughput (0.1), and more alive nodes (42)	Improved energy efficiency, reduced delay, increased throughput, enhanced security	Potential complexity in implementation due to hybrid optimization and trust model
Afia Naeem, Abdul Rehman Javed, et al	IEEE TRANSACTIONS ON GREEN COMMUNICATIONS AND NETWORKING, VOL. 5, NO. 2, JUNE 2021	DARE-SEP	40% more alive nodes, 30% fewer dead nodes, longer stable period	Energy efficiency, longer network lifetime	Assumes homogeneous network topology
Yuan-Po Chi · et al	Journal of Telecommun Syst by Springer July 2013	EAGER	Lower energy consumption, higher packet delivery rate	Energy efficiency, lower rerouting frequency	Does not address security threats

Protocols Summary –

To guarantee safe and consistent data flow, these systems include trust models, encryption, and payment-based systems. While improving network security, they lower data tampering and packet dropping threats. They raise computational overhead, though, which might compromise network speed. Certain models depend on centralized trust management, which could not be scalable for big networks.

3.5 Multipath and Multi-hop Protocols

Proposing an Energy-Efficient Multipath Clustering with Load Balancing Routing Protocol (EEMCL), Madyen Mohammad Saleem et'al [24] tackled the energy consumption issues in WMSNs. By means of a cluster-based multipath routing technique, the aim is to increase network lifetime, lower energy dissipation, and so strengthen network stability. The network consists of a sink, Main Cluster Heads (MCHs), and normal nodes split into several clusters. There are twelve clusters within nodes, each with two secondary cluster heads (SCHs), seven normal nodes, and one MCH. Distance and residual energy dictate either single-hop or multi-hop communication. Before sending to MCHs, SCHs compile and compress data. Routing choices rely on residual energy and distance to maximize use of resources.

The proposed system reduces energy usage by means of cluster-based routing using multi-path routing techniques without sacrificing network performance. Two secondary cluster head nodes (SCHs) are picked in every round depending on distance and residual energy to amplify and compress sensed data from regular nodes to MCH. The main cluster head (MCHs) of every cluster has been preselected with more energy compared to normal sensor nodes. Initially scattered randomly into clusters, the sensor nodes of the communication network—that is, the MCH—are also the regular nodes. Finally, an intra-cluster multipath or single path routing is built on distance and residual energy to transfer detecting information from the MCH to the sink and an inter-cluster multipath routing is built on residual energy. MATLAB was used for simulations under varying performance settings including residual energy, first node dead (FND), half node dead (HND), and last node dead (LND). Based on FND, HND, and LND, the EEMCL protocol reported in this work outperformed SEP, SEP-E, and SEPFL protocols. EEMCL offered enhanced node survivability together with the longest network lifetime.

Proposed is an Improved Gateway-Based Energy-Aware Multi-Hop Routing Protocol (IGBEAMR) intended to improve the network lifetime and throughput in heterogeneous wireless sensor networks (HWSNs). Four fields define the network. While nodes near the base station (BS) use direct transmission, nodes in far fields depend on gateways or multi-hop routing to save energy in sending data. Nodes are supposed to remain fixed after deployment; each sensor node incorporates a global positioning system (GPS) to help in node location identification. Although every sensor node has different starting energy, their processing and transmission capacity is same (homogeneous network). Performance of the proposed protocol is evaluated in heterogeneous WSNs with two and three tiers. MATLAB hosts the simulations; the protocol is compared with other methods including HCR (Hierarchical Cluster-Based Routing), ERP (Evolutionary Routing Protocol), DDEEC (Distributed Energy Efficient Clustering), ModLEACH (Modified Low-Energy Adaptive Clustering Hierarchy) and D-MSEP (Distance Modified Stable Election Protocol). The suggested system greatly increases the lifetime of the network. Network lifespan was raised by 130%, 151%, 167%, 171%, and 215% for 2-level heterogeneity accordingly over HCR, ERP, ModLEACH, D-MSEP, and DDEEC. The network lifetime increased by 123%, 150%, 163%, and 218% over HCR, ModLEACH, hetSEP, and hetDEEC protocols correspondingly for 3-level heterogeneity.

Table 5 – comparative result analysis

Metric	HCR	ERP	DDEEC	ModLEACH	D-MSEP	Proposed Protocol
Network Lifetime	Less	Moderate	Moderate	Moderate	High	Very High
Residual Energy	Less	Less	Moderate	Moderate	Moderate	High
Packet Throughput	Less	Less	Moderate	Moderate	Moderate	High
First Node Death	Quick	Moderate	Moderate	Moderate	Moderate	Late
10% Nodes Dead	Quick	Moderate	Moderate	Moderate	Moderate	Late
50% Nodes Dead	Quick	Moderate	Moderate	Moderate	Moderate	Late

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In [23] a new energy-efficient multi-hop routing system for Wireless Sensor Networks (WSNs) employing a Taylor-based Gravitational Search Algorithm (TBGSA) is presented. Maximizing data delivery rates and network longevity and minimizing energy usage is the main goals here. With an artificial bee colony (ABC) algorithm for Cluster Head (CH) selection and the TBGSA for routing, the paper aims to improve energy economy. When CHs are far from the Base Station (BS), the protocol helps multi-hop communication to lower energy consumption compared to single-hop techniques, which can result in too great energy use. Comparatively to current approaches, the suggested TBGSA model showed much reduced energy consumption. With 500 nodes, for example, TBGSA ate just 82 mJ while EBMRS, MOGA, and DMEERP ate 180 mJ, 150 mJ, and 95 mJ correspondingly. With 100 nodes, the TBGSA model attained a higher data delivery rate—99.3%—than either EBMRS or MOGA—97% or 97.5%. As more nodes were added, this kept on as TBGSA regularly exceeded current systems in data delivery. With 500 nodes, TBGSA attained a maximum throughput of 0.79 Mbps, far greater than the other techniques ranging from 0.46 to 0.65 Mbps according to the throughput analysis. Achieving 5300 rounds with 500 nodes, the TBGSA model further increased the network longevity; EBMRS, MOGA, and DMEERP had lifetimes of 3000, 4000, and 4600 correspondingly. The energy-efficient routing technique implies a significant increase in the network's lifetime. Few restrictions apply to the proposed approach, except TBGSA ignores possible security risks such rogue nodes or data interception, which are fundamental in many WSN applications. Furthermore, under dynamic conditions—that is, node migration and different network topologies—the protocol might not function as best-fit. The presumptions used throughout the simulation—that of stationary node positions—may not be valid in real-world situations when nodes can fail or migrate.

Turkki In order to maximize routing in multi-hop wireless sensor networks (WSNs), Ali Alghamdi et'al[19] suggested a hybrid approach to raise the Quality of Service (QoS). This article suggests a method considering four fundamental network parameters: Bandwidth, Distance, Energy and intensity of Traffic. The suggested method gives every one of these criteria equal weight (25%), therefore allowing a more balanced path of optimization. While increase throughput, packet delivery ratio (PDR), and routing efficiency, the main objectives are to lower latency, overhead, and packet loss. According to simulation studies, the suggested method reduced overhead and delay while yet showing a better PDR. Furthermore, if other problems—such as a link failure or node congestion—cause the first ideal channel between end users to be unable to transfer data packets.

The enhanced energy-efficient routing protocol based on zone (IERPZ) for heterogeneous wireless sensor networks (HWSNs) [20] is developed to improve network lifetime and lower energy consumption. The sensing area is split into three different zones (Area 1, Area 2, and Area 3). Normal nodes are found in Area 2; super nodes and advanced nodes are found in Areas 1 and 3. This configuration best uses node energy usage during data transfer. MATLAB is used to replicate the network with 100 randomly positioned nodes across a 100x 100 m² region. Ten percent super nodes, twenty percent advanced nodes, and seventy percent standard nodes comprise the node count. The proposed protocol, the Stable Election Protocol (SEP), and the Threshold-Sensitive Stable Election Protocol (TSEP) are among the subjects of the comparative analysis.

Table 6 – comparative result analysis

Metric	SEP	TSEP	Proposed Protocol
Network Lifetime	Less	Moderate	High
Residual Energy	Less	Moderate	High
Packet Throughput	Less	Moderate	High

This system has few restrictions, including a hotspot problem. Faster depletion of energy in some nodes resulting from the generation of energy hotspots produced by the multihop transmission may cause Data Loss: Complexity of communication may cause packet loss.

[25] investigates the routing design problems in homogeneous-based single-channel devices. The paper underlines how differences in sensor network heterogeneity—that is, in energy resources, communication ranges, and

processing power—can improve network performance, extend network lifetime, and raise data transmission dependability. Among the classification categories of HWSNs the authors investigate are link, energy, computational, sensor, communication, deployment, and sensing heterogeneity; each influences the network performance in different ways. The paper investigates further the benefits of heterogeneity including lower latency in data transportation, improved network longevity, and more dependability of data transmission. Emphasizing data aggregation, security, and coverage, it tells about the effective network services that HWSNs provide. Investigated are routing protocol design issues in HWSNs as well.

Name of Author	Name of Journal	Algorithm / Methodology/ Technic proposed	Observations	Advantages	Limitations
Madyen Mohammad et al	IET Wireless Sensor Systems Volume13 , Issue3 June 2023	EEMCL (Energy-Efficient Multipath Clustering with Load Balancing Routing)	Outperformed SEP, SEP-E, and SEPFL in FND, HND, LND metrics, achieved longest network lifetime	Enhanced network lifetime, reduced energy dissipation, improved stability	May have increased complexity due to multipath and clustering strategies
Abdelkader Benelhou et al	Simulation Modelling Practice and Theory Volume 116, April 2022	IGBEAMR (Improved Gateway-Based Energy-Aware Multi-Hop Routing)	Increased network lifetime by 130%-215% for 2-level heterogeneity and 123%-218% for 3-level heterogeneity compared to other protocols	Enhanced network lifetime, reduced energy consumption, improved throughput	Assumes stationary nodes, relies on GPS for node location
Sivasankari B et'al	Volume 14, Number 3, 2023	TBGSA (Taylor-Based Gravitational Search Algorithm)	Lower energy consumption (82 mJ with 500 nodes), higher data delivery rate (99.3% with 100 nodes), maximum throughput of 0.79 Mbps, extended network lifetime (5300 rounds)	Energy efficiency, improved data delivery rate, higher throughput, extended network lifetime	Does not address security threats, may not perform well under dynamic conditions, assumes static node positions
Turki Ali Alghamdi	Journal of Wireless networks, by Springer Vol 30, 2024	Hybrid Strategy for Multi-Hop WSNs	Hybrid Strategy for Multi-Hop WSNs	Hybrid Strategy for Multi-Hop	Hybrid Strategy for Multi-Hop WSNs

Table 7 – summary of Multipath and Multi-hop Protocols

Protocols Summary –

By means of several pathways or hop-by-hop data forwarding, these protocols increase fault tolerance and network dependability. Large-scale networks would find them appropriate since they balance network traffic and help to lower congestion. Nonetheless, too heavy traffic can cause increased transmission delays and energy depletion in hotspot nodes. Managing several pathways is more difficult with network scale and calls for increased processing capability.

CONCLUSION

We investigated the several terrains of routing protocols for Wireless Sensor Networks (WSNs) in this survey, arranged under hierarchical, Energy aware Routing Protocols, Bio-inspired Routing Protocols, Security and Trust based Protocols, Multipath and Multi-hop Protocols. Every category offers special solutions catered to the important problems of energy efficiency, scalability, fault tolerance, and communication overhead in contexts limited in resources. To satisfy the needs of next-generation WSNs in fields such smart cities, healthcare, and environmental monitoring, future study has to concentrate on improving adaptability, security, and interoperability of routing protocols. Understanding the strengths and constraints of current protocols helps one to create more effective and flexible routing methods to release the full potential of WSNs in practical uses.

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