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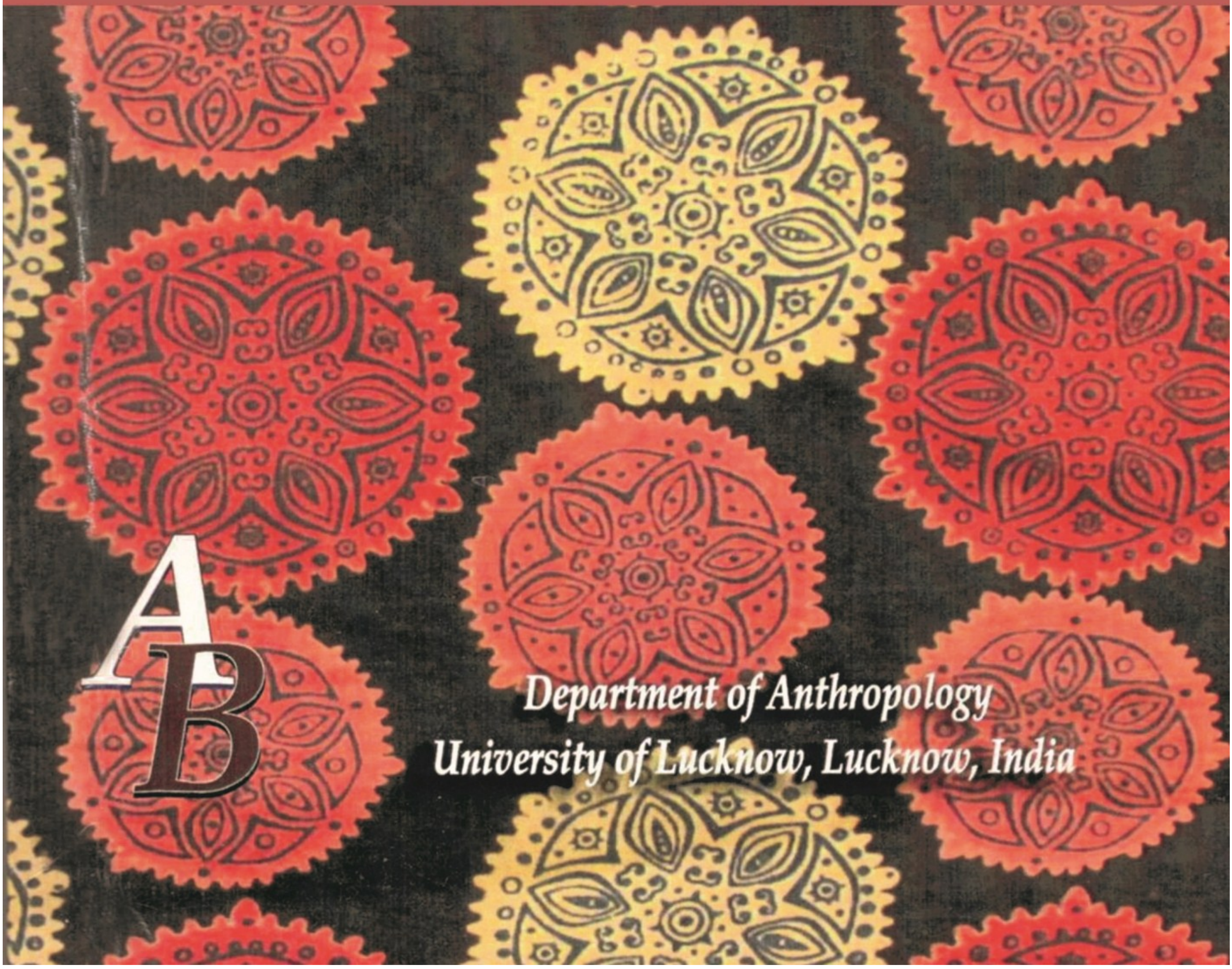

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Routing Protocols in Mobile Ad-Hoc Wireless Sensor Networks: A Systematic Review

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ABSTRACT

Mobile Ad hoc Wireless Sensor networks consist of many tiny autonomous mobile sensor nodes. Each node has processing capability, memory, a transceiver, power source, and sensors and actuators. The nodes are deployed in an ad hoc fashion and allowed to communicate wirelessly without relying on a fixed pre-established infrastructure. This study carries out a systematic literature review for evaluating the comparative performance, structural trade-offs, and operational limitations of the three dominant routing paradigms in MWSNs: Flat, Hierarchical, and location-based routing protocols under variable mobility configurations. This paper delivers a valuable resource for researchers and developers trying to further improve routing protocols for Mobile Ad hoc Wireless Sensor networks.

Keywords: Routing protocols, Sink, Flat, Hierarchical, location-based routing

1. Introduction

Mobile Ad hoc Wireless Sensor Networks represent a significant change in the paradigm of wireless communication and sensing. These networks are composed of many small, autonomous sensor nodes that communicate with each other without relying on a preestablished infrastructure. Each sensor node is equipped with sensors for data collection, processing capabilities, and wireless communication interfaces. After deployment in an ad hoc manner, the nodes self-organize and establish communication links to form a functional network (Stankovic, 2006). Nodes are equipped with mobilizers or wheels to achieve mobility. Such networks are termed as Mobile Ad hoc Wireless Sensor networks. These nodes can be attached to transporters like vehicle, animals, robots etc. Sometimes these nodes have to move due to the environment where they are deployed. When two nodes are not within direct communication range, connectivity is maintained through multi-hop communication via intermediate nodes. Conversely, if two nodes are within each other's transmission range, y can communicate directly in a peer-to-peer manner (Gowrishankar S.

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and Basavaraju, 2010). They are designed to work collaboratively in dynamically changing environments. These networks exhibit the capacity to autonomously adapt to changing conditions and recover from disruptions, making them highly versatile and suited to a wide range of applications.

Although numerous routing protocols have been proposed, their evaluation is challenging due to inconsistent simulation variables, distinct mobility models (Khan, A. R. et. al., 2010) (such as Random Waypoint versus Gauss-Markov Mobility) (Sandeep Kaur et. al 2012), and varied performance metrics across current literature. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology is adopted to fill these research gaps. This study provides a structured and reproducible comparative analysis of different routing protocols, focusing on their ability to withstand conflicting challenges of node mobility and energy consumption.

2. Methodology

This systematic review followed the PRISMA guidelines to reduce selection bias, ensure structural transparency, and facilitate fully reproducible extraction workflow. The scope of my study expands from 1994 to 1019, focusing on reviewing research work carried out in this area. The main aim of this study was to thoroughly explore the dynamic field of Mobile WSNs, routing protocols, and innovative developments, considering both foundational and recent research.

2.1 Search Strategy and Information Sources

In this study, digital libraries like IEEE Xplore, ScienceDirect, Springer, Scopus, ACM, Web of Science and Google Scholar are systematically explored. Systematic searches were carried across digital libraries like IEEE Xplore, ScienceDirect, Springer, Scopus, ACM Digital Library, Web of Sciences and Google Scholar. The search strings were formed by combining Boolean operators with concept-specific keywords to isolate research, explicitly analysing routing paradigms under mobile sensor conditions and ensure comprehensive retrieval of relevant literature, i.e. ("Mobile Ad hoc Wireless Sensor Network" OR "MAWSN" OR "Ad Hoc Sensor Network") AND ("Routing Protocol" OR "Flat Routing" OR "Hierarchical Routing" OR "Location-based Routing") AND ("Comparative Analysis" OR "Mobility Model" OR "Energy Efficiency" OR "Performance Metric"). The scope was targeted to capture both seminal protocol frameworks and highly cited modern iterations, assessed across major performance parameters.

2.2 Inclusion and Exclusion Criteria

Specific operational criteria were strictly used during evaluation and filtering process for assessing the accuracy and appropriateness of the selected data to exclude irrelevant or invalid literature.

Inclusion Criteria:

- Publications in peer-reviewed journals or conference proceedings providing full information about routing protocols for mobile ad hoc wireless sensor environments.
- Studies presenting a clear comparative performance framework.
- Publications presenting measurable outcomes on energy consumption per packet, packet delivery ratio, or scalability.
- Studies lined up with my research questions.

Exclusion Criteria:

- Informal literature, editorials, whitepapers, patents, or general extended abstracts.
- Literature emphasizing exclusively on purely static WSNs or traditional mobile ad-hoc networks MANETs with no sensor-specific constraints.

- Papers that present isolated security encryption or hardware antenna design without providing network-layer routing metrics.
- Manuscripts offering no innovative ideas or contributions to the existing literature on routing protocols for mobile wireless sensor networks.

2.3 Screening and Selection Framework

The study selection process focuses on evaluating whether the retrieved literature directly aligns with your study's core objectives. Initial searches to the database generated a broad set of records, from which duplicate or redundant information is removed. Screening of titles and abstracts were conducted according to the scope of the study and eligibility criteria, followed by a full paper assessment. Table 1. shows total number of research papers selected after this systematic selection procedure.

Table 1. The steps of systematic study selection procedure

Steps	Selection Guidelines	Number of Research Papers
1	Records identified through initial database search	140
2	Removed based on title/abstracts and conclusions	97
3	Selected for main studies	43

Data extraction was independently managed to capture protocol sub-types, baseline network lifetime metrics, performance under congestion, and deployment scale assumptions.

3. Structural and operational taxonomy of routing protocols

A routing protocol is a crucial procedure for the selection of an optimal path to facilitate data transmission from its source to the intended destination. The complexity of this selection process is contingent upon factors such as the network type, channel characteristics, and performance metrics.

Routing protocols play a pivotal role in dictating the communication patterns among nodes and the dissemination of information within a network.

Routing mechanisms in MWSNs are categorized based on two factors as shown in Figure 1:

- How routes are discovered and maintained
- Their structural network layout (how nodes are organized).

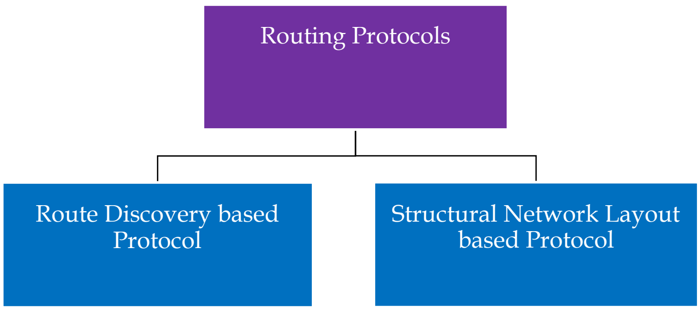

Figure1. Classification of Routing Protocols for MWSN

3.1 Route Discovery based Protocol

3.1.1 Proactive (Table-Driven) Routing

Proactive protocols maintain routing tables for the entire network. They disseminate network information from node to node, and routes are defined in advance, even in the absence of traffic flow. They rely on background control packets sent periodically to announce topological changes. Optimized Link State Routing (T. Clausen and J. Jacquet, 2003) and Destination-Sequenced Distance-Vector (C. E. Perkins and P. Bhagwat, 1994) are proactive routing protocols that utilize a table-driven approach.

Optimized Link State Routing (OLSR) is known for its significant overhead. To mitigate this overhead, it employs Multipoint Relays (MPRs). Each node designates three neighboring nodes as MPRs for data transmission. This approach minimizes the need for consistent control information, as each node takes turns sending it.

In Destination-Sequenced Distance-Vector routing protocol destination sequence number is added with every routing entry in the routing table maintained by each node. A node will include the new update in the table only if the entry consists of the new updated route to the destination with higher sequence number.

High node velocity in MWSNs compels frequent update broadcasts, producing control packet overhead that can deplete node batteries even when payload data is not being transmitted (S.R. Medidi and Y. Zhou, 2012). Since routes are pre-defined, initial packet latency is minimized in proactive routing (D. G. Reina et. at., 2013).

3.1.2 Reactive (On-Demand) Routing

Reactive routing protocols are activated on-demand when a node needs to send data to another node rather than maintaining the entire network structure. Routes are established on an as-needed basis, typically when queries are initiated.

Ad hoc On-Demand Distance Vector Routing (AODV) (C. E. Perkins and E. M. Royer, 1999) is a reactive on-demand routing protocol designed for infrastructure-less networks mobility. It employs an on-demand routing mechanism to build routes between nodes within the network area. A path is created only when the source node intends to transmit data packets, and the route is maintained till the source node requires it. The protocol enables mobile nodes to relay data packets to the desired destination node through neighboring nodes that cannot directly connect to the destination. Routing table information is periodically exchanged among neighbor nodes, allowing for rapid updates. AODV selects the smallest and loop-free path from the routing table to send packets. If errors or changes occur in the selected path, it is capable of establishing a new route for ongoing communication.

Dynamic Source Routing (DSR) (D. B. Johnson and D. A. Maltz, 1996) is a reactive routing protocol for wireless sensor networks. Instead of routing tables it exploits source routing. There are two phases of routing in DSR: path determination and its maintenance.

The source node initiates a path determination phase, which comprises route request and route reply messages. In DSR, only the destination node replies with a route reply message to the source node, unlike AODV, where every intermediate node would reply with route reply messages. The path maintenance phase serves to prevent the overflow of route reply messages and is exploited to shorten the number of nodes between the source and sink.

In reactive model, if a mobile node moves out of range and breaks a link, localized Route Error packets are used to trigger dynamic path repairs (S. Mueller et.al., 2007). This approach introduces initial path setup delays, but it saves considerable idle energy compared to proactive models (S. J. Lee et.al., 1999)

3.1.3 Hybrid Routing Protocol

Hybrid routing protocols integrate the advantages of both proactive and reactive routing approaches, providing quick route accessibility while reducing the routing overhead associated with maintaining network paths.

Zone Routing Protocol (ZRP) (Z. J. Haas, et, al., 2002) is a hybrid routing protocol. It is an enhanced adaptation of the Ad hoc On-Demand Distance Vector (AODV) routing protocol, specifically designed for zone-based network architectures. In this framework, sensor nodes deployed within a monitored area immediately report events whenever activity is detected in their respective areas. The pattern of data transmission varies according to the application requirements and can generally be categorized into three scenarios: static nodes, partially mobile nodes, and fully mobile nodes, as commonly observed in target-tracking applications. Since ZBR imposes no restrictions on node mobility, it effectively supports both highly dynamic and densely populated network environments.

Regardless of the mobility scenario, member nodes communicate their sensed data to the corresponding zone head, which remains a one-hop neighbour to all nodes within the zone. The zone head is responsible for aggregating data based on the application's requirements and forwarding either the aggregated information or individual data packets to the base station. Additionally, the zone head manages critical routing functions, including route discovery, route maintenance, and ensuring continuous route availability to facilitate reliable data transmission throughout the network.

3.2 Structural Network Layout based Protocol

Routing protocols are categorized based on the structural network layout in mobile ad hoc wireless sensor networks (Al-Karaki, et.al., 2004).

3.2.1 Flat Routing Protocols (Topology-Based)

In a flat network architecture, all sensor nodes are assigned identical configuration profiles, processing capabilities, and routing responsibilities. Nodes cooperate globally to forward data to the Sink across multiple hops. Several routing protocols belong to this category.

Gradient-Based Routing (GBR) (Powell et al. 2005) is an energy efficient, distributed, and reactive routing approach that establishes routes using gradient values. In this routing the network nodes calculate a gradient, based on factors like distance to the sink, energy levels, or other relevant parameters, specifying the direction towards a desired destination. This gradient is exploited to find the route for data packets to follow, by moving in the direction of the steepest descent or ascent on the gradient. It is robust to network failures and changes in connectivity.

Cougar routing (Yao and Gehrke 2002) is a database-oriented approach that introduces a query layer between the application and network layers of the sensor nodes. Each sensor node is related to a query proxy, while gateway nodes process user queries. The protocol uses in-network processing to mitigate communication overhead, conserve energy, and increase the life span of the network.

Rumor Routing (RR) (Braginsky et. al., 2002.) is an event-driven routing protocol that propagates event information through special packets known as agents. When a node detects an event, it generates an agent that disseminates event information across the network. These agents accumulate information about newly encountered events and maintain records of recently visited nodes to minimize routing loops and improve query efficiency.

Greedy Perimeter Stateless Routing (GPSR) (Karp, B., and Kung, H. T., 2000) functions using two modes: greedy forwarding and perimeter forwarding. In the first mode, each packet is forwarded to the neighbour that is geographically closest to the destination. When no suitable neighbour is available, the protocol transitions to perimeter mode, where packets are routed around network voids until normal greedy forwarding can be resumed. GPSR scales efficiently and requires less routing state than traditional shortest-path protocols.

3.2.2 Hierarchical Routing Protocols

Hierarchical protocols partition the mobile network into localized subsets called clusters to limit the scope of long-range transmissions and coordinate channel access, with each cluster having a designated cluster head and standard nodes that function as member nodes (O. Younis and S. Fahmy, 2004). Member nodes transmit their sensed data exclusively over short distances to their respective cluster heads. The cluster head, after aggregating data received from all the nodes in the cluster, routes the data to the sink. (W. B. Heinzelman et. al., 2002). This Hierarchical approach is more energy-efficient and easier to manage.

Low Energy Adaptive Clustering Hierarchy (LEACH) (Heinzelman, W. et. al., 2000) is the pioneering hierarchical routing protocol based on data fusion. To distribute energy load evenly across the network, a cluster head is selected randomly that reduces energy consumption and prolongs network lifetime. LEACH operates in iterative rounds having two phases in each round, a setup phase for cluster formation and cluster head election, and a steady-state phase during which member nodes transmit data to their respective cluster heads using TDMA schedules. The cluster heads then aggregate the collected data and forward it to the sink node either directly or through cluster heads along the defined path to the sink.

Power-Efficient Gathering in Sensor Information Systems (PEGASIS) (Lindsey and Raghavendra, 2002) enhances LEACH protocol by organizing nodes to form communication chain rather than directly forming clusters. To build a chain, a greedy algorithm is used, and the process starts with the furthest node from the sink. Each node communicates only with its nearest neighbour on the chain, while a designated node transmits aggregated data to the sink. When a node expires, the chain is constructed by using the same greedy mechanism by ignoring the dead nodes. Only one node in the chain is responsible to transmit data to the sink rather than multiple nodes. This protocol mitigates communication overhead and improves energy efficiency.

Threshold Sensitive Energy-Efficient Sensor Network Protocol (TEEN) (Manjeshwar A, Agrawal D.T., 2001) is a clustering and responsive approach suitable for time-critical applications. It employs two threshold values broadcasted by cluster head-

- Hard Threshold (HT), which represents the minimum value of a sensed attribute that triggers data transmission. When the sensed value exceeds this threshold, the sensor node activates its transmitter and reports the data to the cluster head.
- Soft Threshold (ST), which determines the minimum change in the sensed attribute required to initiate subsequent transmissions.

After the first transmission caused by exceeding the Hard Threshold, the sensed value is stored as a reference. Thereafter, a node transmits data only when the current sensed value remains above the Hard Threshold and the difference between the current and previously reported values is greater than or equal to the Soft Threshold. Now, the newly sensed value becomes the updated reference value. This threshold-based approach reduces unnecessary data transmissions and improves energy efficiency

The Adaptive Threshold Sensitive Energy-Efficient Sensor Network protocol (APTEEN) (Manjeshwar and Agrawal 2002) is an extension of TEEN that serves the dual purpose of transmitting periodic data and responding to time-critical event. In APTEEN, the parameters issued by the cluster head are adjusted that can lead to alteration of related parameters based on the user needs or the type of use. It combines the energy efficiency of TEEN with the periodic monitoring capabilities of LEACH, making it suitable for applications requiring regular updates and sudden event detection.

Hybrid Energy-Efficient Distributed Clustering (HEED) (Younis and S. Fahmy 2004) presents a multi-hop clustering algorithm designed for Wireless Sensor Networks (WSNs) with a strong focus on energy efficiency**. This approach** selects cluster heads mainly based on residual energy of nodes, with communication cost considered as a secondary selection criterion. The protocol achieves balanced energy consumption and longer network lifetime while maintaining efficient cluster formation. Its limitation is that the cluster head selection process is complex, and it is meant for only static networks.

Hybrid Energy-Efficient Distributed Clustering for Mobile nodes (HEED-M) implement link-stability metrics (F. Bajaber and I. Awan, 2011). These protocols determine cluster membership by analysing a node's velocity and direction, in relation to potential cluster heads, thereby enhancing data stream stability in dynamic network environments (S. Deng, J. Li, and L. Shen, 2014).

LEACH-Mobile (D. S. Kim and Y. J. Chung, 2006) is an improvement over LEACH protocol that supports node mobility in wireless sensor networks. As mobile sensor nodes move within the network, they dynamically update their cluster memberships. This protocol verifies whether a node can successfully communicate with its designated cluster head during the assigned TDMA time slot. LEACH-Mobile approach significantly improves data delivery performance in mobile sensor networks by effectively managing changes in node location and maintaining cluster connectivity. It achieves a higher data transmission success rate than the LEACH protocol, particularly as the mobility of sensor nodes increases.

LEACH-ME (LEACH-Mobile Extended) (G. S. Kumar et. al., 2008) is an enhanced version of the LEACH protocol designed to support the mobility of both cluster heads and member nodes. The protocol considers a fixed sink node, homogeneous sensor nodes, and the availability of GPS-based location information for all nodes. Unlike the original LEACH protocol, LEACH-ME selects cluster heads based on node mobility and signal attenuation characteristics. Nodes with lower mobility and lower attenuation are likely to be cluster heads to improve network stability and communication efficiency. Once selected, cluster heads broadcast their status throughout the network, and sensor nodes choose their respective cluster heads based on the received signal strength indicator (RSSI). To accommodate node mobility, LEACH-ME incorporates a handover mechanism. During the steady-state phase, if a member node gets out of the communication range of its current cluster head, it sends a **DISJOIN** request to the existing cluster head and a **JOIN** request to a new cluster head. Following the addition and removal of member nodes, cluster heads generate updated TDMA schedules to maintain efficient communication within the cluster.

LEACH-ME is particularly suitable for large-scale networks where the sink node is positioned far from the sensing field, as it supports multi-hop data transmission. However, the protocol requires all mobile nodes to be equipped with GPS devices, which increases deployment costs. Additionally, frequent handovers and cluster reconfigurations introduce extra communication overhead, affecting overall network efficiency.

The Distributed Weight-based Energy-efficient Hierarchical Clustering protocol (DWEHC) (Ding et al. 2005), is a distributed clustering algorithm akin to HEED. It forms stable clusters, and every node first finds its neighbors, then computes its weight which is based on distance to its neighbors and its remaining energy. The node with maximum weight in a neighborhood is capable of becoming a cluster head. This protocol efficiently manages energy consumption by considering node weights and a hierarchical structure. DWEHC intends to boost up the lifetime of overall network by optimizing energy consumption via clustering.

Virtual Grid Architecture Routing (VGA) (Al-Rahayfeh, Almi'ani, and Abuzneid 2010) is an energy efficient routing protocol. In VGA, network region is divided into virtual grid zones consisting of sensor nodes. Each zone elects a local aggregator responsible for data collection and aggregation. The master aggregator gathers information from local aggregators and communicates with the sink. This approach aims at increasing the network lifetime by data aggregation and in-network processing.

3.2.3 Location-Based Routing Protocols

Location-based routing completely removes the need for global routing tables, periodic updates, and end-to-end path discovery. Instead, it relies on physical coordinate data (M. Mauve et. al., 2001). Nodes track their own location via GPS or localized relative localization algorithms, and learn their immediate neighbours' coordinates through brief, localized beacon exchanges (Y. Cao and Z. Yao, 2017) to improve routing efficiency and support location-aware applications.

Greedy Forwarding and Perimeter Traversal (GPSR) (B. Karp and H. T. Kung, 2000) is a standard protocol in which, a node uses a greedy method to forward data packets, passing them to whichever immediate neighbour is physically closest to the destination Sink's coordinates. As this local hop-by-hop approach does not rely on permanent end-to-end paths it makes the protocol highly resilient to topology shifts (H. Frey and S. Stojmenovic, 2006).

If a packet reaches a local dead-end that is a "routing hole" where no neighbour is closer to the destination than the current node, the protocol shifts to a perimeter face-routing mode (K. Seada, et.al., 2004,). This mode guides the packet along the boundaries of the obstacle using the right-hand rule until it passes the dead-end and can resume greedy forwarding (C. Lochert, et.al 2005).

Geographic and Energy-Aware Routing (GEAR) ((Yu, Govindan, and Estrin 2001)) uses geographic information and residual energy to forward packets toward a target region. Within the destination area, recursive forwarding or restricted flooding mechanisms are employed to efficiently disseminate information while minimizing energy consumption.

Stateless Protocol for Real-Time Communication in Sensor Networks (SPEED) (Tian He et al, 2003) is a QoS-oriented protocol that provides soft real-time communication guarantees. It maintains a desired packet delivery speed through geographic forwarding, delay estimation, neighbourhood feedback mechanisms, and traffic re-routing. SPEED achieves low end-to-end delay and focuses on energy efficient routing.

SPAN: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks (Chen et. al., 2001) conserves energy by creating a dynamic forwarding backbone composed of coordinator nodes. Nodes independently decide whether to participate in routing or enter sleep mode based on local connectivity and energy conditions, thereby maintaining network connectivity with reduced power consumption.

Geographical Adaptive Fidelity (GAF) (W. B. Heinzelman et. al., 2002) is a location-based routing protocol that utilizes the geographic positions of sensor nodes to improve energy efficiency. This approach partitions the sensing area into virtual grid cells, each containing multiple sensor nodes. Since nodes within the same grid are considered equivalent from a routing perspective, only one node remains active while others enter sleep mode to conserve energy. By reducing the number of active nodes without affecting network connectivity, GAF significantly lowers energy consumption and extends the overall network lifetime **(Roychowdhury and Patra 2010).**

Position-Based Aggregator Node Election (PANEL) (Buttyán and Schaffer 2010)) is a location-aware clustering protocol that selects aggregator nodes based on their geographic positions. The protocol supports efficient intra-cluster and inter-cluster communication while ensuring balanced aggregator selection and effective data aggregation.

Two-Tier Data Dissemination (TTDD) (Luo, H., Ye, F., Cheng, J. et al. 2005) (D. Xu, J. Gao, 2011) is a routing protocol for environments with multiple data sources and mobile sink nodes. When an event is detected by several sensor nodes, one node is designated as the source node to initiate data dissemination. The source node establishes a virtual grid structure by designating itself as a grid intersection point. Using a greedy forwarding mechanism, it identifies and selects the nearest nodes to serve as adjacent grid intersections, progressively extending the grid until the network boundary is reached or the process terminates. Each grid intersection stores information about the event and the source node.

For data retrieval, a sink node broadcasts a query to the nearest grid intersection. The query is then propagated through the grid infrastructure until it reaches the source node. Upon receiving the request, the source transmits the corresponding data back to the sink. The protocol supports sink mobility, allowing sink nodes to move while awaiting data delivery, and employs agent-based mechanisms to ensure reliable communication.

TTDD improves network lifetime compared with diffusion-based routing approaches by utilizing efficient data dissemination paths. However, its implementation requires nodes to be location-aware and assumes a relatively high node density. Additionally, the protocol involves complex grid construction and maintenance procedures, leading to increased computational and management overhead.

Scalable Energy-Efficient Asynchronous Dissemination (SEAD) (Hyung Seok Kim et. al., 2003) addresses the trade-off between forwarding delay and energy efficiency. It constructs dissemination tree rooted at each sensor node and enables mobile sinks to receive data without frequently updating their locations. The protocol relies on geographic information and operates as an overlay on location-aware routing schemes.

Robust Ad-hoc Sensor Routing (RASeR) (T. Hayes and F. Ali. 2016) and **Location Aware Sensor Routing (LASeR)** (T. Hayes and F. Ali. 2016) protocols are specifically designed for high-speed mobile ad hoc wireless sensor networks. They perform multipath routing by using blind forwarding method which permits the node to broadcast a data packet to its neighbours. Further, the receiving nodes are responsible to make the decision of either forwarding the packet or dropping it, utilizing a network-wide gradient metric to compare the values of the sender and receiver nodes to find which node is closer to the destination. But they maintain their gradient metrics in different ways - RASeR exploits the regular transmission of short message packets, in which nodes broadcast their current gradient, and LASeR depends on geographical location information of the mobile sensor node.

Mobility-Aware Routing (MAR) (Shahzad Ali, et. al., 2014) is a location-based and hierarchical routing protocol in which the sensing area is partitioned into geographical grids. The mobility factor of sensor nodes is used to select cluster heads, which indicates how frequently a node transitions between different zones. The primary goal of this approach is to choose nodes with the lowest mobility as cluster heads, thereby improving cluster stability and maintaining reliable connectivity with member nodes.

By favouring fewer mobile nodes during cluster head selection, MAR enhances communication efficiency within clusters. However, the protocol does not consider the residual energy of nodes when electing cluster heads, making it unsuitable as an energy-aware routing solution. In addition, MAR does not fully exploit the available location information of sensor nodes, which can lead to increased packet loss. The protocol also faces communication challenges during inter-cluster transmissions, as mobile cluster heads may move out of each other's transmission range, leading to further loss of packets and reduced routing performance.

Distributed Efficient Clustering Approach (DECA) (J.H. Li, et.al., 2005) assigns a weight to each sensor node based on its residual energy, connectivity, and node identifier. A key benefit of DECA is that each node sends only a single clustering message, eliminating the need for multiple rounds of probabilistic message exchanges as required in protocols such as LEACH and HEED. Since communication consumes significantly more energy than sensing and computation, reducing the number of control messages during cluster formation improves the overall energy efficiency of the network.

To support cluster formation, a neighbour table is maintained by each node which is periodically updated through Hello messages. On getting clustering information, the node determines whether to join an existing cluster head or elect itself as a cluster head based on its computed weight. Simulation studies have demonstrated that DECA achieves better performance than several traditional clustering protocols, including HEED (Yu, M., Li, J. H., and Levy, R. 2006).

DECA also has some limitations together with its advantages. For the maintaining neighbour table Hello beacons are periodically transmitted which results in additional energy consumption and processing overhead. In mobile or highly dynamic environments, the frequency of these beacons must increase to maintain accurate neighbour information, making the protocol less suitable for such scenarios. Furthermore, mobility may cause neighbouring cluster heads to move beyond each other’s communication range, leading to packet losses during inter-cluster data transmission and reducing overall network reliability.

4. Comparative evaluation framework

Analysis of the data gathered during the systematic literature review reveals real-world trade-offs across all architectural designs when subjected to node mobility and energy constraints. The protocols must be evaluated across several main performance metrics.

4.1. Performance Metrics Defined

- **Energy Efficiency** Wireless sensor networks rely on battery power, and energy scarcity is a significant concern, particularly in demanding environments. Sensor node performance is severely impacted when their batteries fall below a predefined threshold. Energy conservation represents a primary challenge for network designers, given the large number of nodes within a wireless sensor network, each with restricted energy resources. Energy efficiency deals with how well the protocol minimizes energy consumption during route formation, maintenance, and transmission of data.
- **Scalability** is the capability of the routing protocol to accommodate hundreds or even thousands of sensors in the network with ease and sustain satisfactory performance.
- **Packet Delivery Ratio** denotes the number of data packets successfully received at the sink out of the total number of packets sent by the source nodes.
- **End-to-End Delay** represents the time taken for a packet or data envelope to traverse the network from its source to the sink.
- **Routing Overhead** is the total number of control and management packets (e.g., RREQs, messages, clustering setup frames) sent relative to actual payload data packets.

4.2. Comparison Matrix

Table 2 represents the operational characteristics and performance trade-offs of the main routing protocols for mobile ad hoc wireless sensor networks.

Table 2. Comparison of Routing Protocols

Performance Parameter	**Flat Proactive (e.g., OLSR)**	**Flat Reactive (e.g., AODV)**	**Hierarchical Mobile (e.g., LEACH-M)**	**Location-based (e.g., GPSR)**
Mobility Tolerance	Low; high velocity causes table de-synchronization (C. E. Perkins and P. Bhagwat, 1994)	Moderate to High; reactive loops repair paths dynamically (M. K. Marina and S. R. Das, 2006).	Low to Moderate; frequent CH re-elections degrade performance (D. S. Kim and Y. J. Chung, 2006).	**Excellent**; completely resilient to dynamic topological shifts (H. Frey and S. Stojmenovic, 2006).
Energy Efficiency	Low; continuous table updates drain battery power (S. R. Medidi and Y. Zhou,2012)	Moderate; efficient during low traffic but drops under frequent route discovery floods (S. Mueller et.al., 2007)	High within stable clusters; data aggregation minimizes transmission costs (W. B. Heinzelman et. al., 2002).	Optimal; avoids large control packet overhead and routing tables (M. Mauve et. al., 2001).
Scalability	Poor; table sizes and updates grow rapidly with network size (T. Clausen and J. Jacquet, 2003).	Limited; control overhead increases exponentially with network size (S. J. Lee et.al., 1999).	High; clustering isolates local data traffic within explicit boundaries (O. Younis and S. Fahmy, 2004).	Very High; routing decisions depend entirely on immediate neighbors (B. Karp and H. T. Kung, 2000).
End-to-End Latency	**Very Low**; routes are pre-computed and immediately available (D. G. Reina, S. L. Toral, and F. Barrero, 2013).	High;source nodes must pause data streams to wait for path discovries (C. E. Perkins and E. M. Royer, 1999)	Medium; cluster formation and data compression queues introduce delays (S. Deng, J. Li, and L. Shen, 2014).	Low; immediate, localized hop-by-hop forwarding decisions (C. Lochert, et.al 2005).
Data Aggregation	Yes (At intermediate nodes)	Yes (At intermediate nodes)	Yes (At Cluster Heads)	No
Primary System Bottleneck	Constant table update broadcasts drain network bandwidth (S. R. Medidi and Y. Zhou, 2012).	High control-packet overhead during route discovery stages (S. Mueller et.al., 2007).	High energy spikes occur during dynamic cluster head elections and setup phases (D. S. Kim and Y. J. Chung, 2006).	Complete reliance on high-accuracy positioning hardware (like GPS) (Y. Cao and Z. Yao, 2017).

5. Discussion and analytical insights

Analysis and comparison of the performance of routing protocols highlight their advantages and disadvantages which indicates that they cannot be **optimized for every metric at once.** Flat and proactive routing approach has low latency but bears a high energy cost caused by constant table updates that makes it impractical for highly mobile, and energy-constrained sensor environments. Reactive mechanisms like AODV balance network overhead by only establishing routes on-demand, though the packet latency is high and the network can be flooded with control traffic when routes break frequently due to high mobility of the node.

Hierarchical clustering protocols perform data aggregation at the cluster head node and reduce long-distance transmissions to the sink node, which make these protocols more energy efficient. But if the cluster head moves rapidly or runs out of battery power then all member nodes get disconnected with the sink node. The fast movement of nodes sharply increases the cost of constantly reforming the clusters. This re-clustering, route recalculation and broadcasting cluster head status generate huge packet overhead that consumes more energy and neutralizes the energy benefits of data aggregation.

Location-based routing protocols outperform flat and hierarchical routing approaches under high mobility because it depends on local positions of the nodes rather than end-to-end routes which conserves energy drastically. However, its efficiency relies heavily on the belief that nodes are aware of their exact physical coordinates. If GPS system does not exist in the network area (like underground tunnels, dense forests, under water or indoor environments) then nodes have to use local relative localization methods. The computational processing power needed to calculate the locations of the nodes can quickly surpass the communication energy saved by tableless routing.

Conclusion and future directions

This study demonstrates that selection of the optimal routing protocol for mobile ad hoc wireless sensor networks depends upon the specific requirements of the application and trade-off between performance parameters like packet loss, packet delivery ratio, and network lifetime.

- Location-based routing provides superior scalability and mobility tolerance for large-scale, high-velocity outdoor deployments with reliable location data.
- Hierarchical routing provides the best energy conservation for localized, high-density networks with low or predictable mobility patterns.
- Flat and Reactive routing is highly reliable for smaller, sparse networks characterized by sporadic, event-driven data streams.

To mitigate the weaknesses associated with conventional routing protocols, following two future research trends have been identified:

Machine Learning and AI Integration

Explore the integration of machine learning and artificial intelligence techniques for more adaptive and self- learning WASNs. In this approach, mobile sensor nodes function as intelligent agents capable of learning from their operational experiences. By analysing factors such as historical transmission success rates, node mobility patterns, and energy consumption behaviour, these agents can identify and choose optimal routing paths over time. So, the network will become more adaptive, resilient, and capable of responding effectively to changing topology and unpredictable environmental conditions.

Cross-Layer Optimization

Adopt cross-layer optimization techniques that enable the exchange of real-time information among different protocol layers. By considering parameters such as link quality, interference levels, and signal strength from the Physical and Data link layers, along with remaining energy of the sensor nodes, the routing layer can determine in advance the possible link failures and proactively choose more reliable routes for data transmission. This integrated approach can lead to more holistic solutions and improve performance, energy efficiency and reliability of the network.

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