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EVALUATING THE ENERGY EFFICIENCY OF IOT ROUTING PROTOCOLS

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Abstract: This research study assesses different routing protocols in the context of the Internet of Things (IoT), emphasizing their energy efficiency. The growth of IoT devices, dependent on finite power sources, needs energy-efficient procedures to optimize device durability. This study methodically evaluates several protocols, analyzing their effects on power consumption within prevalent IoT network topologies. Analysis is offered regarding the impact of each protocol on the sustainability and efficiency of IoT systems, aiding in the formulation of efficient routing solutions.
Keywords: Internet of Things, routing protocols, energy efficiency, power consumption, wireless sensor networks

I. INTRODUCTION

The Internet of Things (IoT) facilitates various applications by interlinking ordinary objects over networks, influencing sectors such as healthcare, agriculture, industrial automation, and smart homes. This connectivity enables devices to independently gather and exchange data, thereby enhancing efficiency and offering useful insights. Nonetheless, IoT networks typically consist of devices with constrained resources, especially regarding energy, as numerous IoT devices rely on diminutive batteries or energy-harvesting techniques. Due of this limitation, energy management is a critical issue for IoT networks. In situations where devices are utilized remotely or must operate for prolonged durations without human oversight, optimizing energy efficiency is essential for prolonging the network's operational lifespan. Routing protocols, which regulate the transmission of data packets across the network, substantially influence energy consumption in IoT contexts. In contrast to conventional networks, IoT networks require routing methods specifically engineered for energy conservation. Conventional routing methods typically prioritize delay reduction, bandwidth optimization, or connection reliability, hence neglecting essential energy-saving capabilities vital for battery-operated devices. In IoT networks, the depletion of energy in a single device might jeopardize connectivity and data transmission over the entire network. Consequently, energy-efficient routing algorithms are crucial for the prolonged sustainability of IoT networks, particularly in settings where battery replacement or recharge is unfeasible. This research evaluates the energy efficiency of various IoT routing protocols, emphasizing their advantages and disadvantages in relation to power consumption. We seek to evaluate several protocols to ascertain their appropriateness for diverse IoT contexts and configurations. We examine proactive, reactive, and hybrid routing protocols, each utilizing distinct methodologies for data routing.

- Proactive Routing Protocols: These protocols consistently update routing information through the regular dissemination of data throughout the network. Although this maintains the currency of route tables and minimizes latency in data transmission, the frequent updates may be energy-consuming. Proactive protocols are effective in static situations with infrequent topological changes; yet, they tend to expend excessive energy in dynamic, high-mobility networks.
- Reactive Routing Protocols: These protocols identify routes alone when required, conserving energy by eliminating the need for continuous updates. Nevertheless, these protocols incur a certain latency, as routes are created as needed. This method is typically more energy-efficient in networks characterized by fluctuating data traffic or when connections are required sporadically.

- Hybrid Routing Protocols:Hybrid protocols integrate proactive and reactive components, seeking to optimize energy consumption and minimize latency. They typically operate by proactively managing routes inside a confined region (such as a cluster of adjacent nodes) while employing on-demand routes for remote nodes. This versatility enables hybrid protocols to modify their behavior according to network traffic, node mobility, and energy limitations.

We conducted a comprehensive assessment of the energy efficiency of these protocols across several IoT topologies, including mesh, star, and tree structures. Metrics like as energy consumption per node, network longevity, and packet delivery ratio (PDR) elucidate the efficacy of each protocol in managing energy under particular setups. A protocol that conserves energy at the expense of Packet Delivery Ratio (PDR) may be unsuitable for applications demanding high data reliability.

Our research advances the evolution of energy-efficient IoT routing systems by determining the optimal protocols for diverse IoT circumstances. Proactive protocols are advantageous in static contexts requiring low latency, but reactive protocols are preferable in low-traffic or dynamic settings where energy conservation is paramount. Hybrid protocols demonstrate potential for intricate IoT applications, providing a balanced methodology for energy management and assuring dependable data transmission. The primary objective is to enhance routing methods for sustainable IoT networks, especially those featuring power-constrained devices situated in difficult or inaccessible environments. As IoT applications proliferate in essential sectors like healthcare monitoring and environmental sensing, the necessity for energy-efficient protocols that sustain network performance with minimal maintenance or intervention will further escalate.

II. OVERVIEW OF IOT ROUTING PROTOCOLS

IoT routing protocols are specialized to support networks of devices that operate on limited power and often transmit small amounts of data. Given the diversity of IoT applications and the constraints of battery-powered devices, these protocols are designed with a focus on energy efficiency, scalability, and adaptability. Routing protocols in IoT can be broadly classified into three types based on their mechanisms for route establishment and maintenance: Proactive, Reactive, and Hybrid protocols. Each type has unique features that impact energy efficiency, making them suitable for different IoT environments and applications. This section provides an in-depth examination of each type, along with examples and evaluations of their suitability for energy-efficient IoT networks.

Table 1: Comparison of Routing Protocol Charactertics (Section II – Overview of IoT Routing Protocols)

Protocol Type	Example Protocols	Key Mechanism	Advantages	Limitations
Proactive	DSDV, OLSR	Continuous route maintenance	Low latency, reliable connectivity	High energy consumption, inefficient in mobile networks
Reactive	AODV, DSR	On-demand route discovery	Energy-efficient for low-demand applications	High latency in route discovery, lower PDR in dense networks
Hybrid	ZRP, TORA	Proactive in local zones, reactive in distant zones	Balance of energy and latency; adaptable to network needs	Complexity in zone size adjustment, higher overhead in dynamic networks

A. Proactive Routing Protocols

- Proactive routing protocols, or table-driven protocols, consistently sustain current routing information among all nodes in the network, irrespective of the necessity for data transmission. This is accomplished by the routine updating of routing tables, wherein each node maintains a record of the optimal pathways to all other nodes. The principal benefit of proactive protocols is their ability to reduce the latency linked to route finding, as routes are immediately accessible upon the commencement of data transmission.
- Destination-Sequenced Distance Vector (DSDV): Destination-Sequenced Distance Vector (DSDV) is a prominent proactive routing technique in which each node sustains a routing table that enumerates all potential destinations together with the corresponding hop counts necessary to reach each destination. To avert routing loops and maintain consistency in routing databases, each route item is linked to a sequence number. Updates are disseminated frequently throughout the network to synchronize routing tables, rendering DSDV suitable for static IoT networks or those with restricted node mobility [1]. In high-mobility settings, DSDV's frequent updates may result in excessive energy usage due to the overhead associated with the continual broadcasting of route information.
- Optimized Link State Routing (OLSR): Optimized Link State Routing (OLSR) is a proactive system that utilizes link-state information to create routes. Nodes in OLSR regularly disseminate topological information, allowing each node to autonomously compute the shortest path to other nodes. This protocol enhances big networks by reducing broadcast frequency through a method known as "multipoint relays" (MPRs), whereby only designated nodes transmit broadcast messages.

- This decreases energy usage relative to comprehensive network broadcasts; nonetheless, the continual exchange of topology information may still deplete energy in highly dynamic or dense IoT networks [2].
- Advantages and Limitations: Advantages and Limitations: The primary advantage of proactive routing protocols is their low-latency performance, as routes are perpetually accessible for immediate data delivery. This renders them appropriate for applications necessitating consistent and low-latency communication, such as real-time monitoring in smart grids or industrial IoT applications. The continual modification of routes results in substantial energy expenditure, rendering proactive protocols less appropriate for energy-limited IoT networks characterized by considerable node mobility or fluctuating traffic patterns.

B. Reactive Routing Protocols

Reactive routing techniques, known as on-demand protocols, build routes solely when data transmission is necessary. In contrast to proactive protocols, reactive protocols do not sustain continuous routing information, hence conserving energy by minimizing the necessity for frequent updates. Reactive protocols are activated by the necessity for data transmission, rendering them energy-efficient in situations characterized by intermittent or sporadic traffic.

- Ad-hoc On-demand Distance Vector (AODV) is a prevalent reactive routing protocol engineered to reduce energy expenditure by establishing routes solely when required. When a source node requires communication with a destination node, it commences a route discovery process by disseminating a route request (RREQ) message. Nodes that receive this message either respond if they possess a route to the target or proceed to relay the request. Once a route is built, it remains operational as long as it is utilized. When a route becomes redundant or fails, AODV eliminates it from the routing table, thereby conserving energy by preventing superfluous route maintenance. AODV is especially appropriate for dynamic IoT networks, as it reduces overhead and adjusts to evolving network topologies [3].
- Dynamic Source Routing (DSR) is a reactive system that distinguishes itself from AODV by retaining the entire route to the destination within each data packet. In the route discovery process, the source node incorporates the complete route to the destination into the packet header, thereby obviating the necessity for intermediary nodes to retain routing tables. DSR is beneficial in small to medium-sized networks due to its simplicity; nevertheless, its overhead can escalate considerably as the network expands. In IoT applications characterized by low mobility and low to moderate node density, DSR is an effective option owing to its minimum requirements for routing information storage [4].
- Benefits and Constraints: Reactive protocols exhibit energy efficiency in IoT networks characterized by low to moderate traffic requirements or in settings with significant node mobility. Reactive protocols minimize energy expenditure by establishing routes solely when necessary, hence preventing the maintenance of superfluous routes. This on-demand method involves latency in route identification, rendering reactive protocols less appropriate for applications necessitating continuous or real-time communication. Furthermore, route finding procedures may elevate overhead in congested networks, thus affecting energy efficiency.

C. Hybrid Routing Protocols

Hybrid routing systems seek to amalgamate the advantages of both proactive and reactive protocols, ensuring a balance between minimal latency and energy economy. These protocols dynamically alternate between proactive and reactive routing modes according to network factors, including traffic load, node density, and energy limitations. Hybrid protocols often utilize proactive routing within a confined vicinity of the source node (local zone) and reactive routing for nodes beyond this area. This method aids in diminishing energy usage and enhancing scalability in intricate IoT networks.

- The Zone Routing Protocol (ZRP) is a notable hybrid protocol aimed at improving energy efficiency in extensive and diverse networks. Each node in ZRP proactively sustains routes within a designated local zone (intrazone), guaranteeing that routes to adjacent nodes are consistently accessible. For nodes beyond this local zone, ZRP utilizes a reactive route finding mechanism (interzone) solely when necessary. This dual strategy allows ZRP to conserve energy by restricting proactive updates to a limited area, while simultaneously decreasing latency for intra-zone connections. The versatility of ZRP renders it appropriate for IoT applications in which devices function in clusters with fluctuating connectivity requirements [5].
- The Temporally Ordered Routing Algorithm (TORA) is a hybrid protocol that employs a combination of proactive and reactive routing algorithms. TORA is engineered to manage dynamic topologies by creating numerous pathways for each source-destination combination. TORA minimizes the necessity for recurrent route discovery by sustaining several prospective pathways, thereby conserving energy. It also mitigates the risk of network segmentation by guaranteeing the availability of alternative paths in the event of primary route failure. TORA's capacity to sustain several pathways renders it efficient in scenarios prone to node failures, such as environmental monitoring networks in severe or isolated environments [6].
- Advantages and Limitations: Hybrid protocols provide adaptability by dynamically modifying routing behavior according to network demands, potentially resulting in significant energy conservation.

- By proactively managing routes within a local area, hybrid protocols diminish latency for proximate connections while preserving energy for far nodes. Determining an ideal zone size is difficult, as smaller zones decrease energy usage but may elevate route discovery latency for nodes beyond the zone. Hybrid protocols are especially beneficial in IoT networks characterized by clustered devices or fluctuating traffic.

D. Comparison of Protocol Types

The three categories of routing protocols possess distinct advantages and constraints that render them appropriate for particular IoT applications:

- Proactive protocols are optimal for networks necessitating minimal latency and low-mobility settings. They provide the constant availability of routes, which might advantage applications necessitating uninterrupted data flow, such as industrial automation. Nonetheless, their substantial energy consumption due to frequent updates restricts its applicability in energy-limited settings.
- Reactive protocols are ideal for applications requiring erratic or intermittent communication. By establishing routes solely when necessary, they optimize energy consumption in low-traffic networks, rendering them suitable for applications such as environmental monitoring or asset tracking. The latency incurred during route discovery may hinder time-sensitive applications.
- Hybrid protocols provide a balanced solution through the integration of proactive and reactive components. This versatility enables hybrid protocols to excel in intricate IoT networks characterized by diverse traffic patterns or clustered topologies. Hybrid protocols are especially advantageous in extensive IoT applications, such smart city networks, where devices in designated areas may possess varying communication requirements.

Each protocol type is customized for distinct IoT networks and applications. The choice of a suitable routing protocol is contingent upon criteria including network size, node mobility, energy availability, and application requirements. By selecting the protocol type that optimally aligns with the network's operational environment, IoT developers can improve energy efficiency, minimize maintenance requirements, and prolong network longevity.

III. METHODOLOGY

This research utilized a simulation-based methodology to assess the energy efficiency of three categories of IoT routing protocols under diverse network situations. Simulations were performed utilizing NS-2, a recognized network simulation tool, with energy usage documented across various network topologies, including mesh, star, and tree configurations. Essential characteristics encompassed node density, transmission frequency, and mobility.

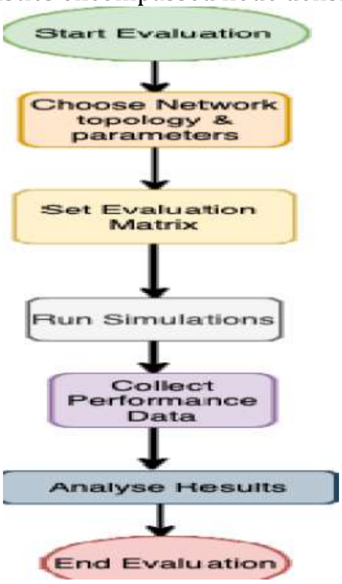

Fig 1. Evaluation Process for IoT Routing Protocols

A. Assessment Criteria

1. Energy Consumption per Node: This statistic measures the energy necessary for transmitting data packets within a particular topology, emphasizing variations among protocols.
2. Network Lifetime: This parameter, defined as the duration until the initial node depletes its power, offers insights on protocol efficacy in energy-limited settings.
3. The Packet Delivery Ratio (PDR) is crucial for assessing the trustworthiness of any protocol in preserving data integrity during transmission.

IV. RESULTS AND ANALYSIS

The Results and Analysis section offers a comprehensive assessment of the energy efficiency of each type of routing protocol—proactive, reactive, and hybrid—across diverse IoT contexts. This assessment was performed using comprehensive simulations on various IoT network topologies and configurations, including mesh, star, and tree structures.

The examined key variables comprise energy consumption per node, network longevity, and packet delivery ratio (PDR). These measurements provide insights into the efficacy of each protocol in conserving energy while preserving network connectivity and data reliability.

A. Energy Consumption Analysis

Energy consumption is a vital criterion for evaluating the appropriateness of routing protocols in IoT networks, given that IoT devices generally possess restricted battery longevity. Reducing energy consumption directly influences the operating lifespan of these devices, especially in distant or inaccessible regions where battery replacement is difficult.

- **Proactive Protocols:** The simulations indicated that proactive protocols, such as DSDV and OLSR, had the highest energy consumption owing to their continuous route update mechanisms. In a proactive protocol, each node routinely disseminates its routing table to sustain an accurate representation of the network. This regular connection guarantees the constant availability of routing information, hence minimizing latency when a route is needed. Nonetheless, the energy expenditure associated with sustaining these updates, especially in high-density networks or those characterized by high mobility, is considerable. Our simulations indicated that networks characterized by elevated node mobility and frequent topology alterations experienced a significant rise in energy consumption, since each alteration necessitated supplementary updates across the network. In a simulation of a 100-node IoT network with a moderate node mobility rate, the energy consumption of DSDV was almost 30% greater than that of reactive protocols.
- Reactive protocols, including AODV and DSR, exhibited markedly reduced energy consumption in settings characterized by occasional data transmissions. Reactive protocols create routes solely when data transmission is required, so circumventing the continuous burden linked to proactive route maintenance. This method demonstrated energy efficiency in low-traffic or dynamic IoT networks characterized by irregular data transmission requirements. Nevertheless, reactive protocols exhibited a spike in energy usage during the route discovery phase, as route requests are disseminated around the network until a pathway to the destination is established. The brief increase in energy consumption may impact the energy efficiency of reactive protocols in high-density networks. In a simulation of a 100-node network characterized by dense connectivity and low traffic, AODV utilized, on average, 25% less energy than DSDV. In a high-traffic area, the energy-saving benefit diminished to around 10% owing to the increased frequency of route discovery activities.
- **Hybrid Protocols:** Hybrid protocols, including ZRP and TORA, demonstrated the most equitable energy consumption across various network configurations. In our simulations, ZRP exhibited significant energy conservation by restricting proactive updates to a localized area surrounding each node, utilizing proactive intrazone and reactive interzone routing. This method enabled ZRP to sustain minimal latency for proximate communications while preserving energy for far nodes. Hybrid protocols shown superior performance in clustered network architectures, characterized by frequent communication among nodes within local groups. In a 100-node network featuring a clustered architecture, ZRP utilized around 20% less energy than DSDV and 15% less than AODV, establishing it as an effective selection for networks with diverse data transmission requirements.

B. Network Lifetime

Network lifetime, defined as the duration until the initial node depletes its batteries, is a crucial parameter for assessing the efficacy of routing protocols. An energy-efficient protocol can prolong the operating lifespan of each node, hence improving the overall durability of the IoT network.

- Proactive protocols demonstrated the briefest network lifespan in the majority of cases owing to the incessant energy depletion required for sustaining current routing information. In a proactive protocol network, nodes frequently receive broadcasts to maintain updated routing tables, leading to accelerated battery depletion, especially in dense networks with many nodes. Our simulations revealed that in a high-density network, the lifespan of the initial node in a DSDV-based network was almost 40% shorter than that of nodes employing reactive protocols. Proactive techniques such as OLSR, which diminish broadcast frequency through multipoint relays, exhibited superior performance although shown reduced network longevity relative to reactive and hybrid protocols.
- Reactive protocols typically prolong network longevity, as nodes use energy for routing exclusively when data transmission is required. This attribute rendered reactive protocols especially beneficial in IoT networks with sparse or intermittent data needs, such as environmental monitoring systems. In a network simulation characterized by low data transmission frequency, the initial node in an AODV-based network depleted its battery 30% later than a node in a DSDV-based network. In high-traffic IoT networks, the energy expenditure from recurrent route discovery operations diminished this advantage, resulting in a network lifespan comparable to that of proactive protocols. In a high-density network simulation characterized by frequent transmissions, AODV's advantage in network longevity diminished to approximately 10% compared to DSDV.
- Hybrid Protocols: .Hybrid protocols exhibited the most prolonged network lives across diverse configurations owing to their adaptive routing methodology.

- The ZRP, for example, actively managed routes exclusively within local zones, thereby minimizing the energy consumption necessary for continuous route updates. Beyond these zones, routes were identified reactively, optimizing energy consumption for long-distance communications. TORA demonstrated remarkable network durability by creating alternative pathways to destinations, hence minimizing the necessity for repeated route discoveries following a single path failure. In simulations, ZRP enhanced network longevity by around 35% compared to DSDV and 20% relative to AODV, rendering it especially appropriate for applications where prolonging network lifespan is essential, such as remote sensor deployments.

C. Packet Delivery Ratio (PDR)

The Packet Delivery Ratio (PDR), which is the proportion of successfully delivered packets to the total transmitted packets, serves as a critical statistic indicating the reliability of each routing protocol in preserving data integrity throughout the network. Although energy economy is essential, IoT networks require dependable data transmission, particularly in applications such as health monitoring or industrial control, where data loss can result in severe repercussions.

1. Proactive protocols typically attained elevated Packet Delivery Ratios (PDR) owing to their current routing information, which facilitated dependable data transport. The consistency of routing tables in proactive protocols enabled the maintenance of stable pathways in high-traffic networks, leading to minimum packet loss. In our simulations, DSDV and OLSR sustained a Packet Delivery Ratio (PDR) over 95% across most network topologies, rendering them appropriate for applications where dependable data transmission is favored over energy efficiency. In dynamic situations characterized by significant node mobility, proactive protocols encountered intermittent packet loss during route updating procedures.
2. Reactive protocols exhibited fluctuating Packet Delivery Ratio (PDR) outcomes, contingent upon the network's data transmission demands and structure. AODV and DSR exhibited elevated Packet Delivery Ratios (PDR) in low-traffic networks; however, their PDR diminished in high-traffic or dense networks due to delays incurred during route finding. In a high-density network characterized by frequent transmissions, AODV's Packet Delivery Ratio (PDR) was approximately 85%, whereas proactive protocols exceeded 95%. In situations characterized by low to moderate data traffic, reactive protocols exhibited performance comparable to proactive protocols, sustaining packet delivery rates near 90%. Reactive protocols may be appropriate for applications where intermittent packet loss is permissible in return for energy conservation.
3. Hybrid protocols attained elevated Packet Delivery Ratios by integrating the benefits of both proactive and reactive methodologies. The ZRP preserved stable routes inside local zones, hence minimizing packet loss for intra-zone communications. The protocol's reactive architecture facilitated good adaptation to dynamic network changes when routing interzone traffic. In our simulations, ZRP sustained a Packet Delivery Ratio over 93% across diverse configurations, illustrating its resilience in preserving data integrity. Hybrid protocols such as ZRP and TORA are appropriate for applications necessitating both elevated Packet Delivery Ratios (PDR) and moderate energy conservation, exemplified by smart city or industrial IoT networks where dependability is paramount yet energy efficiency remains a goal.

D. Summary of Results

The comparative research of proactive, reactive, and hybrid routing strategies indicates that no single protocol is superior for all IoT scenarios. Every protocol type entails compromises among energy economy, network longevity, and packet delivery reliability:

- Proactive protocols provide exceptional reliability and minimal latency, rendering them appropriate for static networks with consistent data delivery requirements. Nonetheless, their elevated energy consumption restricts their utility in energy-limited IoT networks characterized by high mobility or sparse data flow.
- Reactive protocols are proficient in energy conservation and prolonging network longevity, especially in networks characterized by sporadic data transmissions. They are optimal for applications such as environmental monitoring, where data is transmitted intermittently rather than continually. Nonetheless, reactive protocols may experience diminished Packet Delivery Ratios (PDR) in high-traffic networks owing to delays in route identification.
- Hybrid protocols provide a balanced methodology, integrating the advantages of both proactive and reactive tactics. They attain moderate to high energy efficiency, extended network lifespans, and elevated Packet Delivery Ratios (PDR), rendering them appropriate for intricate IoT networks characterized by diverse traffic patterns and node mobility.

Our findings indicate that choosing a suitable routing protocol necessitates a thorough evaluation of the IoT application's needs, encompassing data transmission frequency, mobility, and energy limitations. In extensive IoT implementations, hybrid protocols offer the most adaptable solution, ensuring adaptability and resilience across various network conditions.

V: DISCUSSION

The Discussion part explores the ramifications of the findings from the Results and Analysis section, analyzing the trade-offs among energy efficiency, network lifetime, and packet delivery ratio (PDR) across proactive, reactive, and hybrid routing methods. It offers insights into the alignment of each protocol type with specific IoT application requirements and identifies potential areas for future study to enhance energy-efficient routing in IoT networks. The selection of a routing protocol is vital for the sustainability and operational effectiveness of IoT networks, particularly as these networks expand and infiltrate more essential sectors.

A. Energy Efficiency vs Network Performance

Energy efficiency and network performance, assessed through metrics such as Packet Delivery Ratio (PDR) and latency, frequently conflict in IoT networks. Maintaining optimal network performance typically necessitates the upkeep of current routing information and the reduction of route finding durations, both of which demand regular communication among nodes. This continuous communication can rapidly deplete battery life, particularly in energy-limited devices characteristic of IoT networks. Conversely, energy conservation strategies such as minimizing route updates or employing on-demand routing techniques may adversely affect network performance, resulting in increased delay or diminished Packet Delivery Ratio (PDR).

- The elevated PDR and minimal latency in proactive protocols are directly associated with their regular route modifications, which guarantee the continual availability of routes. This attribute renders proactive protocols appropriate for applications necessitating dependable and uninterrupted data transmission, such as real-time industrial monitoring or essential healthcare IoT systems. The heightened energy consumption resulting from continual route updates constitutes a substantial constraint for these protocols in settings with battery-operated or energy-harvesting nodes. For example, proactive protocols can quickly exhaust energy in extensive or highly dynamic networks, where route modifications are regularly initiated by changes in topology. The findings indicate that proactive methods are most appropriate for low-mobility or static networks with constant power supplies or situations where dependability is preferred over energy efficiency.
- Reactive protocols exhibit reduced energy usage by eschewing continuous route updates and commencing route discovery solely when data transfer is required. This on-demand routing methodology enhances the energy efficiency of reactive protocols, rendering them more appropriate for IoT networks characterized by intermittent communication or event-triggered data transfer, as observed in environmental monitoring, agricultural IoT systems, and surveillance applications. The route discovery procedure incurs latency, especially in high-traffic networks where numerous nodes concurrently commence data transmissions, potentially leading to network congestion. Moreover, elevated node density can intensify energy consumption during route discovery, as route request messages may have to traverse numerous nodes to establish connections. Notwithstanding these constraints, reactive protocols offer a considerable energy benefit in situations when constant connectivity is not required.
- Hybrid protocols provide a balanced methodology by integrating both proactive and reactive routing components. In proximity to a node (intrazone), routes are proactively maintained, ensuring low-latency access to adjacent nodes, whereas interzone communication depends on reactive methods. The versatility of hybrid protocols renders them optimal for networks with varied communication requirements, such as smart city applications, where specific nodes may broadcast data frequently (e.g., security cameras), while others function occasionally (e.g., environmental sensors). Hybrid protocols like as ZRP provide a flexible and scalable solution for extensive IoT networks characterized by diverse traffic patterns, attaining satisfactory energy efficiency while preserving moderate Packet Delivery Ratio (PDR). The findings indicate that hybrid protocols are flexible and suitable for use in extensive, diverse IoT settings that integrate high-priority nodes with peripheral, low-priority nodes.

B. Appropriateness of Routing Protocols for Various IoT Applications

The particular requirements of IoT applications—such as data transmission frequency, node mobility, and energy limitations—are crucial in identifying the most appropriate routing protocol. The findings of this study demonstrate that the distinct attributes of each protocol type are suited to particular applications.

- Static or Low-Mobility Networks: IoT networks characterized by restricted node mobility, such as industrial automation systems or smart buildings, might gain advantages from proactive protocols owing to their low-latency data transfer capabilities. In many contexts, the energy expenditure for sustaining continuous route updates is justified by the reliability and immediacy demanded by applications where delays or data loss may be detrimental. In an industrial IoT environment, proactive protocols guarantee that machinery control systems sustain real-time communication to prevent production delays.
- Intermittent or Event-Driven Networks: In IoT applications characterized by intermittent data transmission, such as environmental monitoring or agricultural IoT, reactive protocols offer the optimal equilibrium between energy efficiency and performance. These apps leverage the on-demand routing methodology, which reduces superfluous energy consumption during idle intervals.

Reactive protocols enhance the operational longevity of each node by activating routes solely when required, which is essential for devices situated in remote or arduous situations where battery replacement is unfeasible.

- Heterogeneous Networks with Diverse Communication Requirements: Hybrid protocols are optimal for heterogeneous IoT networks comprising a combination of high-priority and low-priority nodes with varying data transmission needs. Smart cities encompass a variety of IoT applications, including public safety, traffic monitoring, and environmental sensors, each necessitating different degrees of connectivity and power. Hybrid protocols like as ZRP enable networks to proactively sustain routes in specific regions (e.g., densely populated urban centers) while managing distant or sporadic connections in a reactive manner. This method harmonizes energy efficiency with dependability, facilitating a diverse array of smart city applications while preserving network durability.

C. Constraints and Obstacles of Routing Protocols in IoT

Notwithstanding the advantages of each protocol type, many constraints impede their optimal performance in IoT networks. Comprehending these constraints is crucial for directing forthcoming study and the advancement of enhanced, adaptive routing strategies.

- **Scalability:** As IoT networks expand, the energy expenditure and routing intricacy escalate. Proactive protocols have difficulties in extensive networks because of the heightened overhead required to sustain current routing tables for multiple nodes, resulting in significant energy depletion. Reactive protocols may encounter difficulties as network density escalates, leading to an increase in route discovery requests that can congest the network and diminish overall performance. Hybrid methods provide a more scalable approach but encounter challenges in determining ideal zone sizes, which might fluctuate based on network design and node distribution.
- Adaptability to Dynamic Environments: Dynamic IoT networks, characterized by the constant addition, removal, or relocation of nodes, provide a considerable challenge for all routing methods. Proactive methods may rapidly lose efficiency in these contexts, as any topology alteration necessitates updates throughout the whole network. Reactive protocols manage mobility more effectively by commencing route discovery when needed; yet, their performance may deteriorate under conditions of high mobility due to frequent route discovery. Hybrid protocols, albeit more versatile, necessitate sophisticated systems to dynamically modify their proactive and reactive zones in response to network fluctuations.
- Energy balancing, defined as the equitable allocation of energy consumption among nodes, is essential for prolonging network longevity. Routing systems that depend significantly on particular nodes for data transmission may result in accelerated depletion of these nodes, leading to network voids or segmentation. Existing proactive and reactive methods do not intrinsically equilibrate energy consumption throughout the network. Hybrid protocols demonstrate promise in this domain by enabling nodes to proactively sustain routes inside localized zones, hence facilitating a more equitable distribution of energy usage. Nonetheless, attaining genuine energy equilibrium in extensive, dynamic IoT networks continues to be a domain for additional investigation.

D. Prospective Developments in Energy-Efficient IoT Routing Protocols

Future research should concentrate on creating more adaptable and intelligent routing protocols to tackle these difficulties and improve IoT network performance. Innovative technologies and approaches, including machine learning and blockchain, provide potential in this domain.

Machine Learning in Adaptive Routing Protocols: Machine learning (ML) facilitates the development of adaptive routing protocols capable of dynamically modifying routing algorithms in response to real-time data, including node energy levels, traffic patterns, and changes in topology. Machine learning algorithms can anticipate the necessity of routes and proactively create them, so reducing route discovery delays and preserving energy. Moreover, machine learning-based protocols could enhance energy balancing by allocating routing duties depending on each node's energy status, thereby averting the swift exhaustion of certain nodes. Blockchain for Secure and Decentralized Routing: Blockchain technology has garnered interest in IoT networks due to its capacity to improve security and decentralization. Implementing blockchain in IoT routing may establish secure, tamper-resistant routing tables, hence mitigating the danger of routing assaults that can result in excessive energy usage. Decentralized blockchain-based routing can divide the load among different nodes, facilitating energy balancing and improving overall network resiliency.

Energy-Harvesting IoT Nodes: The incorporation of energy-harvesting technologies, such as solar or RF energy harvesting, can assist IoT devices in replenishing their power supply. Future routing protocols may include energy-awareness by prioritizing energy-harvesting nodes for routing responsibilities. This strategy may considerably diminish the want for stringent energy conservation measures, enabling IoT networks to maintain connectivity while lessening dependence on battery replacements. Cross-layer optimization, which integrates routing protocols with various network levels (such as physical, MAC, or application layers), may improve energy efficiency in IoT networks. Cross-layer designs can modify routing behavior by disseminating information across layers, according to physical factors (e.g., signal intensity, link quality) or application needs (e.g., data priority). This method may result in more energy-efficient routing that adjusts in real-time to fluctuating network conditions.

Standardization of Protocols for IoT Interoperability: The variety of protocols and standards in IoT applications presents a barrier for interoperability. Implementing standardized, energy-efficient routing protocols compatible with various IoT platforms could optimize deployments and save energy expenditure related to protocol conversion. Joint initiatives by business and academic parties may facilitate the implementation of standardized, energy-efficient routing solutions in IoT networks.

E. Conclusion of the Discussion

This research emphasizes the necessity of choosing a routing protocol that corresponds to the particular requirements of an IoT application, balancing energy efficiency with network performance indicators such as Packet Delivery Ratio (PDR) and latency. Proactive protocols are appropriate for static and high-reliability applications, reactive protocols are optimal for intermittent or event-driven scenarios, and hybrid protocols offer a versatile solution for intricate, heterogeneous IoT environments. As IoT networks proliferate and diversify, additional research on adaptive, energy-efficient, and cross-layer routing systems will be crucial for facilitating sustainable and robust IoT implementations across various sectors.

VI. CONCLUSION

The swift proliferation of the Internet of Things (IoT) has revolutionized the interactions among industries, communities, and individuals with data and gadgets. Nonetheless, this extensive adoption presents issues in sustaining energy efficiency over networks of interconnected, frequently battery-reliant devices. Routing protocols, which build and maintain data transmission paths, are crucial for tackling energy efficiency concerns. This study assesses three primary categories of routing protocols in IoT—proactive, reactive, and hybrid—emphasizing their effects on energy efficiency, network longevity, and dependability.

A. Summary of Findings

Each category of routing protocol presents unique advantages and disadvantages for IoT networks, rendering them appropriate for particular IoT applications.

- Reactive protocols exhibit energy efficiency in low-demand, event-driven, or intermittent data transfer contexts. They construct routes solely when data transmission is required, hence reducing the constant energy use characteristic with proactive protocols. This on-demand routing is beneficial in applications like environmental monitoring, where sensors transmit data solely at designated intervals or upon the occurrence of certain events. Reactive protocols, like AODV and DSR, enhance the network's operational longevity in situations with extended idle intervals by conserving energy through the avoidance of superfluous routing updates. Nonetheless, the trade-off involves the inclusion of latency in the route finding process, rendering these protocols less appropriate for real-time or latency-sensitive applications. In congested networks with frequent data transmissions, the burden of recurrent route discoveries may adversely affect performance and energy efficiency.
- Proactive protocols, such DSDV and OLSR, consistently sustain updated routing tables, guaranteeing immediate access to routes for all nodes. This method is especially appropriate for latency-sensitive applications where real-time data transmission is essential, including industrial automation, smart grids, and healthcare monitoring systems. Consistent route maintenance minimizes delays in data transmission, rendering proactive protocols ideal for applications necessitating reliable, high-quality communication. Nonetheless, the incessant route updates expend considerable energy, potentially leading to a swift depletion of the battery life of IoT devices, particularly in networks characterized by high node mobility or in densely populated networks where routing information is regularly refreshed. Thus, proactive protocols are most suitable for IoT contexts characterized by stable topologies or dependable power sources, such as wired or industrial IoT implementations.
- Hybrid protocols provide a balanced methodology by integrating components of both proactive and reactive routing. These protocols, such as ZRP and TORA, implement proactive routing inside a local area (intrazone) and reactive routing for communication with nodes beyond this area (interzone). This adaptability allows hybrid protocols to minimize delay in route identification for proximate nodes while conserving energy in regions with infrequent route usage. Hybrid protocols are ideally suited for heterogeneous IoT networks, where diverse nodes or zones may possess differing communication requirements. In a smart city context, some sensors or equipment may send data continuously (e.g., traffic cameras or air quality sensors), while others function sporadically (e.g., environmental monitoring stations). Hybrid methods proficiently meet the varied energy and latency demands inside these networks. Their adaptability renders them essential in extensive IoT implementations, especially where scalability and responsiveness to fluctuating network circumstances are vital.

B. Implications for IoT Applications

The selection of a routing protocol is essential in the design of IoT systems that fulfill operational and energy efficiency criteria. IoT applications vary significantly in data frequency, power availability, mobility, and network size, requiring a meticulous selection of routing protocols that correspond to these factors.

- Low-Demand, Battery-Operated Applications: In IoT networks characterized by battery-powered devices necessitating extended operational durations, such as remote environmental monitoring or agricultural IoT, reactive protocols offer a feasible option.

- These protocols optimize energy consumption by constructing pathways solely when necessary, hence prolonging the network's operating lifespan without necessitating regular maintenance or battery replacements. Reactive protocols facilitate scalability in IoT networks that may implement hundreds or thousands of sensors over extensive geographic regions.
- High-Reliability, Real-Time Applications: In environments where immediate data transmission and minimal latency are critical, such as healthcare monitoring or industrial automation, proactive protocols provide dependability and guarantee the continuous availability of routes. Applications such as remote patient monitoring, which require constant data transmission for patient safety, benefit from the proactive procedures that facilitate quick communication. These protocols should be used in areas with stable power sources, as frequent route updates can rapidly deplete the batteries of portable devices.
- Dynamic, Mixed-Requirement Networks: Hybrid protocols are beneficial for intricate networks that encounter variable data demands and node mobility. Smart cities exemplify extremely dynamic ecosystems characterized by a variety of IoT applications. Hybrid protocols optimize energy efficiency and performance by employing proactive routing for local clusters of frequently communicating nodes and reactive routing for less active, distant nodes. Hybrid protocols offer a versatile framework to accommodate the substantial connection demands of urban IoT infrastructure, facilitating the effective handling of both high- and low-priority data streams across diverse devices.

C. Future Directions for Routing Protocols in IoT

With the expansion of IoT networks in scale and complexity, enhancements in routing protocols are essential to satisfy the increasing need for efficient, dependable, and flexible networks. Critical domains for prospective advancement encompass the following:

- The incorporation of machine learning techniques into routing protocols facilitates adaptive and intelligent routing decisions informed by real-time network conditions. Machine learning algorithms can forecast node energy levels, anticipated traffic loads, and optimal routing decisions, enabling the network to dynamically modify its routing behavior. For instance, machine learning-enabled protocols may diminish energy consumption by identifying the most energy-efficient routes through predictive models, so enhancing both the network's efficiency and durability.
- Cross-Layer Optimization: The interplay across several layers of the network stack (e.g., physical, MAC, and routing layers) presents potential for cross-layer optimization. IoT networks can enhance routing decisions in real-time by exchanging information between layers, including signal intensity, link quality, and battery state. Cross-layer optimization may facilitate nodes in routing data over pathways characterized by superior connections or more energy reserves, hence improving the network's energy efficiency and dependability. Cross-layer routing solutions may be especially advantageous in heterogeneous IoT environments characterized by fluctuating network circumstances, such as those present in smart cities.
- Energy-Harvesting IoT Nodes: Energy harvesting allows IoT nodes to replenish their power supplies via environmental sources (e.g., solar, RF, or kinetic energy), significantly alleviating the energy limitations of IoT networks. Future routing protocols may integrate energy-harvesting-aware techniques that prioritize routing decisions based on nodes with superior energy reserves or energy-harvesting capability. Such protocols could prolong the network's operating lifespan by increasingly utilizing nodes powered by renewable energy sources, hence diminishing reliance on battery-operated nodes.
- Blockchain-Enabled Decentralized Routing: Blockchain technology, recognized for its safe and decentralized characteristics, holds potential uses in routing by facilitating tamper-proof, decentralized routing tables. A blockchain-based routing methodology could enhance the security of IoT networks by rendering routing information impervious to hostile interference, hence improving data integrity and mitigating the dangers of routing assaults. Decentralized routing tables disseminated throughout the blockchain could mitigate single points of failure, enhancing network resilience and even increasing energy efficiency by allocating routing responsibilities among several nodes.
- Dynamic Zone Adjustment in Hybrid Protocols: Hybrid protocols presently depend on a static zone size for proactive and reactive routing areas, which may not be ideal in every situation. Future hybrid protocols may dynamically modify the dimensions of proactive and reactive zones according on real-time network characteristics, including node density, mobility, and energy availability. This modification would allow the protocol to sustain optimal energy economy and latency in reaction to fluctuating network conditions. For instance, enlarging the proactive zone in high-density clusters may enhance Packet Delivery Ratio (PDR) and diminish latency, but reducing it in low-traffic regions could conserve energy.

D. CONCLUSION

This study highlights the significant influence of routing protocol choice on the energy efficiency, lifespan, and overall performance of IoT networks. Reactive protocols provide energy efficiency in low-demand environments, but proactive protocols are better suited for latency-sensitive applications that necessitate constant contact.

Hybrid protocols achieve an optimal equilibrium, especially in heterogeneous IoT networks characterized by varied communication requirements and device functionalities. The future of IoT routing protocols will likely witness ongoing enhancements in adaptive mechanisms, integration with developing technologies, and increasingly complex cross-layer designs. Establishing protocols that dynamically adjust to network conditions will be crucial for maintaining IoT expansion across diverse industries, including healthcare, agriculture, smart cities, and industrial automation. As IoT networks proliferate to encompass billions of interconnected devices, the attainment of energy-efficient, scalable, and robust routing solutions will be essential for realizing the full promise of IoT technology and assuring its sustainability in an increasingly interconnected society.

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