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A COMPREHENSIVE SURVEY OF DISTRIBUTED ENERGY-HARVESTING AWARE ROUTING ALGORITHMS FOR IOT NETWORKS

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ABSTRACT:

Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs) have emerged as a pivotal solution in addressing the energy challenges of modern Internet of Things (IoT) networks. With the proliferation of IoT devices powered by diverse energy sources, efficient energy management and communication are crucial for network sustainability. DEHARAs leverage the capabilities of energy-harvesting devices, aiming to optimize energy consumption, extend network lifetime, and ensure reliable communication. This paper provides a comprehensive survey of DEHARAs, encompassing their evolution, design principles, evaluation methodologies, and future prospects. We commence by elucidating the context of IoT networks and their energy challenges, paving the way for the necessity of DEHARAs. Emphasizing the importance of energy harvesting technologies, we explore their role in sustainable IoT deployments. Subsequently, we delve into the motivations behind DEHARAs, uncovering their design considerations and the factors driving their development. An exploration of various energy harvesting techniques, including solar, kinetic, and thermal methods, sheds light on the diverse energy sources harnessed by IoT devices.

Our survey encompasses a detailed evaluation of energy-harvesting rates and constraints inherent in IoT devices, providing a foundation for understanding the energy dynamics at play. Traditional routing protocols for IoT networks are dissected, offering insights into their strengths and limitations. Addressing the challenges posed by heterogeneous energy-harvesting capabilities and varying energy demands, we discuss the intricacies of energy-aware routing algorithms and the approaches to tackle these complexities. Key factors to consider in formulating energy-aware routing algorithms are identified, outlining design considerations for DEHARAs. Metrics for evaluating their performance, including network lifetime, energy efficiency, and data transmission delays, are elucidated, enabling a comprehensive assessment of their effectiveness. An in-depth analysis of existing prominent DEHARAs offers insights into their design philosophies and capabilities. A comparative study of these algorithms' strengths and limitations provides a holistic view of their applicability in different scenarios.

The categorization of DEHARAs based on their approaches, be it centralized, distributed, or hybrid, offers a taxonomy for understanding their architectural foundations. An overview of simulation environments employed for assessing DEHARA performance sheds light on the tools and methodologies used in research. Concluding the survey, we summarize the insights gained, highlight the challenges yet to be addressed, and present potential avenues for future research and improvements. In sum, this survey paper aims to provide a comprehensive understanding of the current state and future prospects of DEHARAs in the realm of heterogeneous IoT networks. By exploring their motivations, designs, and evaluations, we contribute to the advancement of energy-efficient and resilient routing solutions, fostering innovation and collaboration across disciplines.

INTRODUCTION:

The rapid proliferation of Internet of Things (IoT) devices has ushered in an era of unprecedented connectivity, enabling diverse applications across industries. However, the energy constraints of IoT devices, especially those powered by energy harvesting sources, pose significant challenges to the sustainable operation of IoT networks. In this context, Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs) have emerged as a pivotal solution, aiming to intelligently manage energy resources, optimize communication, and extend network lifetimes.

DEHARAs represent a groundbreaking advancement in the realm of IoT networking, as they bridge the gap between energy availability and communication demands. Unlike traditional routing protocols, DEHARAs factor in the heterogeneous energy-harvesting capabilities of IoT devices, enabling them to make informed routing decisions based on real-time energy conditions. This approach holds the promise of revolutionizing energy efficiency, reliability, and performance across a wide range of IoT applications.

This survey paper comprehensively examines the landscape of DEHARAs, shedding light on their evolution, design principles, evaluation methodologies, and real-world implications. We explore the current state of DEHARAs, reviewing advancements in algorithm design, simulation-based evaluations, hybrid approaches, and the integration of energy prediction models. Building upon this foundation, we delve into the future prospects of DEHARAs, outlining potential avenues for research and improvement.

The objective of this survey is to provide researchers, practitioners, and IoT stakeholders with a comprehensive understanding of the advancements and challenges in the field of DEHARAs. By critically analyzing the strengths and limitations of existing algorithms, we aim to facilitate the development of innovative routing solutions that effectively address the energy challenges of heterogeneous IoT networks.

The structure of this survey paper is organized to presents an overview of IoT networks and their energy challenges, setting the stage for the need of DEHARAs. It delves into the importance of energy harvesting technologies in sustainable IoT deployments. Paper also provides an in-depth exploration of the motivations behind Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs). Subsequently, discusses various energy harvesting techniques, including solar, kinetic, and thermal methods als evaluates energy-harvesting rates and constraints of IoT devices. Section VII offers a detailed examination of traditional routing protocols for IoT networks.

In subsequent sections, we delve into the challenges posed by heterogeneous energy-harvesting capabilities and varying energy demands, the factors to consider in formulating energy-aware routing algorithms, and the metrics for evaluating DEHARAs' performance. It present an in-depth analysis of existing prominent distributed energy-harvesting-aware routing algorithms and a comparative study of their strengths and limitations.

Moving forward, we categorized existing DEHARAs based on their approaches, such as centralized, distributed, or hybrid also offered an overview of simulation environments used to assess DEHARA performance. Finally, summarizes the survey's key insights and outlines potential avenues for future research and improvements in the domain of DEHARAs.

Through this survey paper, we aim to contribute to the advancement of energy-efficient and resilient routing solutions for heterogeneous IoT networks. By providing a comprehensive overview of DEHARAs, we hope to inspire further interdisciplinary collaboration and innovation in this critical field of study.

1. INTRODUCTION:

1.1. Overview of IoT networks and their energy challenges.

The Internet of Things (IoT) refers to the network of interconnected devices and objects that communicate and exchange data through the internet. These devices, equipped with sensors and actuators, can gather and share information, enabling various applications and services to enhance efficiency, automation, and convenience in various industries.

IoT networks can be classified into several categories based on their communication protocols, range, and power consumption:

1. **Wide Area Networks (WANs)**: These networks cover a large geographical area and provide long-range connectivity. Examples include cellular networks (3G, 4G, 5G) and Low Power Wide Area Networks (LPWANs) like LoRaWAN and Sigfox.
2. **Local Area Networks (LANs)**: These networks cover a smaller area, such as a home or a building. Wi-Fi and Bluetooth are commonly used for local connectivity.
3. **Personal Area Networks (PANs)**: These are even smaller networks that connect devices within a person's immediate vicinity. Bluetooth and Zigbee are common PAN technologies.

Energy challenges in IoT networks:

1. **Limited Battery Life**: Many IoT devices are powered by batteries, which have a finite capacity. Energy-efficient design is crucial to extend the device's operational lifespan without frequent battery replacements.
2. **Energy Harvesting**: To address the battery life issue, energy harvesting techniques are used to capture energy from ambient sources like solar, vibration, or heat. However, the amount of energy harvested may be limited and inconsistent.
3. **Transmission Power and Range**: IoT devices often need to transmit data wirelessly, and the transmission power required for long-range communication can consume a significant amount of energy.
4. **Communication Overhead**: Network communication involves energy-consuming tasks such as establishing connections, maintaining synchronization, and managing data transmission. Efficient communication protocols are necessary to minimize this overhead.
5. **Scalability**: As IoT networks expand, managing a large number of devices efficiently becomes challenging. Energy-efficient protocols and algorithms are needed to ensure that network management doesn't become a significant energy drain.
6. **Dynamic Environments**: IoT devices may operate in dynamic environments where signal strength and quality vary. Adapting to changing conditions while minimizing energy consumption is a challenge.
7. **Security and Encryption**: Implementing security measures like encryption can consume additional energy, impacting battery life. Balancing security needs with energy constraints is important.
8. **Data Processing**: Edge computing, where data is processed locally on IoT devices, can reduce the need to transmit large amounts of data to central servers. However, processing data on resource-constrained devices requires efficient algorithms.
9. **Quality of Service (QoS)**: Ensuring a certain level of service quality while optimizing energy consumption is a complex task. Prioritizing critical tasks and optimizing resource allocation are important aspects.

Efforts are continually being made to address these energy challenges in IoT networks. Researchers and engineers are developing energy-efficient hardware, communication protocols, algorithms, and management strategies to enable the widespread adoption of IoT technologies while mitigating their impact on energy consumption.

1.2. Importance of energy harvesting technologies in sustainable IoT deployments.

Energy harvesting technologies play a crucial role in enabling sustainable Internet of Things (IoT) deployments. These technologies enable IoT devices to draw energy from the environment, such as solar, kinetic, thermal, or electromagnetic sources, reducing or eliminating the need for conventional battery replacements and extending the operational lifespan of devices. Here's a detailed explanation of the importance of energy harvesting technologies in susainable IoT deployments:

1. **Extended Battery Life and Maintenance-Free Operation**: Traditional battery-powered IoT devices often have limited operational lifespans due to the finite capacity of their batteries. Energy harvesting allows devices to continuously recharge or supplement their power sources, resulting in significantly extended lifetimes. This eliminates the need for frequent battery replacements, reducing maintenance costs and environmental impact.
2. **Environmental Impact Reduction**: Conventional batteries used in IoT devices contain hazardous materials that can pose environmental risks if not disposed of properly. Energy harvesting reduces the demand for disposable batteries and thus helps minimize electronic waste and its associated ecological impact.
3. **Remote and Inaccessible Locations**: IoT deployments are increasingly found in remote or hard-to-reach locations, where replacing batteries can be challenging and costly. Energy harvesting technologies enable these devices to operate autonomously for extended periods, reducing the need for regular maintenance trips.
4. **Uninterrupted Operation**: Energy harvesting ensures a more reliable power source for IoT devices. By continuously generating energy from the environment, these devices can maintain uninterrupted operation, critical for applications like environmental monitoring, disaster response, and infrastructure management.
5. **Scalability and Deployment Flexibility**: Sustainable IoT deployments become more feasible when energy-harvesting-powered devices are used, as they reduce the logistical challenges associated with battery management and replacement, especially in large-scale deployments.
6. **Harvesting from Various Sources**: Energy harvesting technologies can utilize a range of ambient sources such as solar radiation, vibrations, temperature gradients, and radiofrequency signals. This diversity allows IoT devices to operate in various environments and adapt to available energy sources.
7. **Reduced Overall Cost**: While the upfront cost of incorporating energy harvesting technologies may be higher compared to traditional battery-powered solutions, the reduced need for battery replacements and maintenance can lead to significant cost savings over the device's lifetime.
8. **Supporting Renewable Energy Initiatives**: The use of energy harvesting aligns with the broader shift towards renewable energy sources. By leveraging naturally available energy sources, IoT

deployments can contribute to reducing the overall carbon footprint and dependence on non-renewable energy.

9. **Flexibility and Customization**: Energy harvesting solutions can be tailored to the specific requirements of IoT devices and their operating environments. Different devices can utilize different types of energy harvesting technologies based on their energy needs and available ambient sources.
10. **Innovation and Research**: The development and integration of energy harvesting technologies encourage innovation in fields such as materials science, electronics, and sensor technology. Research in this area drives advancements that benefit both IoT deployments and broader energy-efficient applications.

In conclusion, energy harvesting technologies are integral to achieving sustainable IoT deployments. They enhance device longevity, minimize maintenance efforts, reduce environmental impact, and align with the growing emphasis on renewable energy sources. As these technologies continue to evolve, they hold the potential to revolutionize the way IoT devices are powered, contributing to a more sustainable and efficient future.

1.3. Motivation for Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs).

Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs) are a class of routing algorithms designed to optimize energy efficiency and performance in wireless communication networks, particularly in the context of Internet of Things (IoT) deployments where energy-constrained devices rely on energy harvesting technologies. These algorithms take into account the dynamic availability of energy from harvesting sources and aim to route data in a way that maximizes the network's overall efficiency and ensures reliable communication. The motivation behind DEHARAs is rooted in addressing several key challenges posed by energy harvesting in wireless networks:

1. **Variable and Unpredictable Energy Availability**: Energy harvesting sources, such as solar panels or ambient vibrations, generate energy that can be highly variable and unpredictable based on environmental conditions. DEHARAs aim to utilize this energy efficiently by dynamically adapting routing decisions to the availability of energy.
2. **Energy-Aware Communication**: Traditional routing algorithms may not consider the energy status of individual devices or nodes. DEHARAs prioritize routes that conserve energy, ensuring that devices with low energy levels are not excessively drained during data transmission.
3. **Prolonging Network Lifetime**: One of the primary goals of DEHARAs is to extend the operational lifetime of IoT networks. By intelligently routing data through energy-abundant paths, energy depletion is balanced across nodes, preventing premature node failures and network partitioning.

4. **Maintaining Data Reliability**: In IoT applications, data reliability is crucial. DEHARAs consider the energy levels of nodes when selecting routes, helping to avoid situations where data transmission is interrupted due to energy depletion in the middle of communication.
5. **Scalability and Network Coverage**: IoT networks can encompass a large number of nodes spread across vast areas. DEHARAs can optimize the routing paths to ensure efficient coverage while minimizing energy consumption and maintaining network connectivity.
6. **Dynamic Network Topology**: IoT networks often operate in dynamic environments, where node connectivity and energy harvesting conditions change frequently. DEHARAs adapt to these changes, selecting routes that remain efficient even as the network topology evolves.
7. **Energy Harvesting Diversity**: DEHARAs can exploit the diversity of energy sources available in the environment. For instance, if a node is experiencing low solar energy but high vibrations, the algorithm can route data through paths where vibrations can contribute to energy harvesting.
8. **Balancing Energy Consumption**: DEHARAs distribute energy consumption more evenly among nodes, reducing the likelihood of certain nodes becoming overburdened and depleting their energy resources faster than others.
9. **Enhancing Quality of Service (QoS)**: DEHARAs aim to ensure a certain level of QoS by considering factors like energy availability, data transmission rate, and latency. These algorithms strike a balance between energy conservation and meeting application-specific requirements.
10. **Efficient Data Aggregation**: DEHARAs can optimize data aggregation and forwarding strategies, reducing redundant transmissions and conserving energy by efficiently consolidating and transmitting aggregated data.

In summary, the motivation behind Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs) is to address the unique challenges posed by energy harvesting technologies in wireless communication networks, especially in IoT scenarios. These algorithms optimize routing decisions to maximize energy efficiency, prolong network lifetime, maintain data reliability, adapt to dynamic conditions, and ultimately support the sustainable and reliable operation of energy-constrained IoT networks.

2. ENERGY-HARVESTING TECHNOLOGIES IN IOT:

2.1. Exploration of various energy harvesting techniques, including solar, kinetic, and thermal.

Energy harvesting techniques harness energy from the surrounding environment to power electronic devices, offering an alternative to traditional battery-powered systems. These techniques have gained significance in applications such as IoT, wearable electronics, and remote sensors where long-lasting, sustainable energy sources are needed. Here's an exploration of various energy harvesting techniques, including solar, kinetic, and thermal:

1. **Solar Energy Harvesting**: Solar energy harvesting involves capturing and converting sunlight into electricity using photovoltaic (PV) cells. This technique is widely recognized and utilized due to the abundance of solar energy available in many environments. Key points to consider:
    - **Photovoltaic Cells**: PV cells are semiconductor devices that directly convert sunlight into electricity through the photovoltaic effect. They are commonly used in solar panels.
    - **Advantages**: Solar energy is abundant, especially in sunny regions. It provides a consistent and reliable energy source for various applications.
    - **Challenges**: Energy production is dependent on sunlight availability. In low-light or nighttime conditions, energy generation is reduced or absent.
2. **Kinetic Energy Harvesting**: Kinetic energy harvesting involves converting mechanical motion or vibrations into electricity using various mechanisms. This technique is suitable for applications where devices experience movement or vibrations. Key points:
    - **Piezoelectric Generators**: Piezoelectric materials generate voltage when subjected to mechanical stress. These materials are often integrated into devices to convert vibrations or motion into electrical energy.
    - **Electromagnetic Induction**: Electromagnetic generators use magnets and coils to convert mechanical motion into electrical energy through electromagnetic induction.
    - **Advantages**: Kinetic energy is available from sources such as human motion, machinery vibrations, or vehicle movement. It can provide a continuous source of energy in certain environments.
    - **Challenges**: Energy generated can be relatively low, and efficiency depends on the amplitude and frequency of the vibrations.
3. **Thermal Energy Harvesting**: Thermal energy harvesting captures temperature differences or gradients to generate electricity using thermoelectric materials. This technique is valuable in applications with temperature variations. Key points:
    - **Thermoelectric Generators**: Thermoelectric materials produce voltage when there is a temperature difference across them. They are used to convert heat into electricity.
    - **Advantages**: Thermal energy is available from temperature differences between surfaces. Waste heat from industrial processes or temperature gradients in the environment can be harnessed.
    - **Challenges**: Efficiency is influenced by the temperature difference and the properties of the thermoelectric materials. Higher temperature differences result in better performance.

4. **Radio Frequency (RF) Energy Harvesting**: RF energy harvesting captures electromagnetic energy from ambient radio frequency signals, including Wi-Fi, cellular, and other wireless transmissions. It's useful for low-power applications. Key points:
    - **Rectification**: RF energy is converted to direct current (DC) voltage using rectifying circuits like diodes or rectifiers.
    - **Advantages**: RF signals are ubiquitous in urban environments, providing a continuous energy source. It's particularly suitable for low-power, long-range applications.
    - **Challenges**: Energy harvested from RF signals is relatively small and requires efficient rectification techniques to be useful.
5. **Hybrid Energy Harvesting**: Many real-world scenarios involve multiple energy sources. Hybrid energy harvesting combines techniques like solar, kinetic, and thermal to achieve more reliable and consistent energy generation.

In conclusion, energy harvesting techniques provide innovative ways to power electronic devices sustainably. The choice of technique depends on factors such as the available energy sources, the application's power requirements, and environmental conditions. As technology advances, the efficiency and feasibility of these techniques continue to improve, making them increasingly valuable for a wide range of applications.

2.2. Evaluation of energy-harvesting rates and constraints of IoT devices.

Evaluating the energy-harvesting rates and constraints of IoT devices involves assessing the amount of energy that can be harvested from various sources and understanding the limitations imposed by these energy-harvesting methods. Here's an evaluation of energy-harvesting rates and constraints for IoT devices:

1. **Solar Energy Harvesting**:
    - **Energy Source**: Solar energy is abundant and renewable, making it a popular choice for energy harvesting.
    - **Harvesting Rate**: The energy harvested from solar panels depends on factors such as the intensity of sunlight, panel efficiency, and the size of the solar panel.
    - **Constraints**: Energy harvesting from solar panels is affected by weather conditions (cloud cover, rain) and variations in daylight hours. It's not suitable for applications in low-light or indoor environments.
2. **Kinetic Energy Harvesting**:
    - **Energy Source**: Kinetic energy can be derived from vibrations, motion, or mechanical impacts.

- **Harvesting Rate**: The energy harvested from kinetic sources depends on the amplitude and frequency of the vibrations or motion.
- **Constraints**: Harvesting rates can be relatively low in environments with minimal mechanical activity. High-frequency vibrations might not generate significant energy due to the limitations of energy conversion technologies.

3. **Thermal Energy Harvesting**:
   - **Energy Source**: Thermal energy harvesting relies on temperature differences or gradients.
   - **Harvesting Rate**: The energy harvested depends on the temperature difference, the size of the heat source, and the efficiency of the thermoelectric materials.
   - **Constraints**: Harvesting rates are influenced by the availability of temperature differences. In certain environments, temperature differences might not be substantial enough for efficient energy conversion.
4. **RF Energy Harvesting**:
   - **Energy Source**: RF energy harvesting captures ambient radio frequency signals.
   - **Harvesting Rate**: Energy harvested from RF signals is typically low due to the low power of many RF sources. However, it's suitable for ultra-low-power applications.
   - **Constraints**: Harvesting rates are constrained by the density of RF sources in the environment. Effective rectification techniques are required to efficiently convert RF energy into usable power.
5. **Hybrid Energy Harvesting**:
   - **Energy Source**: Hybrid energy harvesting combines multiple sources to improve overall energy generation.
   - **Harvesting Rate**: The effectiveness of hybrid harvesting depends on the complementary nature of the combined sources and the efficiency of the integration.
   - **Constraints**: Hybrid systems can be complex to design and implement. Balancing the different energy sources to achieve optimal energy harvesting requires careful consideration.
6. **Constraints Common to Energy Harvesting**:
   - **Energy Variability**: Energy harvesting rates can be variable due to changes in environmental conditions, leading to inconsistent power availability.
   - **Storage and Management**: Efficient energy storage and management systems are essential to store harvested energy and deliver it as needed to the IoT device.
   - **Energy Conversion Efficiency**: The efficiency of energy conversion mechanisms affects the amount of usable energy generated from the available sources.

- **Power Requirements**: Some IoT devices might have higher power requirements than what can be sustained by available energy sources, leading to operational challenges.

In summary, evaluating energy-harvesting rates and constraints for IoT devices involves understanding the potential energy sources, assessing their variability and availability in the deployment environment, and considering the efficiency and limitations of energy conversion technologies. Different sources have varying potential and constraints, and the choice of energy-harvesting method should align with the specific requirements and constraints of the IoT application.

3. ROUTING IN HETEROGENEOUS IOT NETWORKS:

3.1. Discussion of traditional routing protocols for IoT networks.

Traditional routing protocols, originally designed for conventional wireless networks, have been adapted and extended for Internet of Things (IoT) networks to enable efficient communication and data exchange among IoT devices. These protocols play a crucial role in maintaining connectivity, managing data transmission, and optimizing network resources. Here are some in-depth details about traditional routing protocols used in IoT networks:

1. **Ad Hoc On-Demand Distance Vector (AODV)**:
    - **Principle**: AODV is a reactive routing protocol that establishes routes between nodes on-demand. It forms routes when needed and maintains them only as long as they are required.
    - **Operation**: When a node wants to communicate with another node, it sends a route request (RREQ) broadcast. Nodes along the path record the route and send back a route reply (RREP).
    - **Advantages**: AODV reduces overhead by establishing routes only when needed, making it suitable for energy-constrained devices. It adapts well to dynamic network topologies.
    - **Challenges**: Reactive behavior can introduce latency during route establishment. Frequent route discovery may be inefficient in highly mobile or dense networks.
2. **Destination-Sequenced Distance Vector (DSDV)**:
    - **Principle**: DSDV is a proactive routing protocol that maintains a routing table at each node containing routes to all destinations with associated sequence numbers.
    - **Operation**: Periodic updates and route advertisements are used to ensure consistent routing tables. Sequence numbers prevent routing loops and ensure loop-free paths.
    - **Advantages**: Loop-free routes are guaranteed due to the sequence numbers. It's suitable for networks with relatively stable topologies.
    - **Challenges**: Frequent updates and advertisements can lead to overhead, especially in large or highly dynamic networks.

3. **Dynamic Source Routing (DSR)**:
    - **Principle**: DSR is a reactive protocol that relies on source routing. Each data packet carries the complete route to the destination.
    - **Operation**: When a node wants to send data, it includes the entire route in the packet header. Intermediate nodes process the header and forward the packet.
    - **Advantages**: DSR is flexible, adaptable to dynamic topologies, and supports multiple routes to the same destination.
    - **Challenges**: Longer headers increase overhead, and source routing can be impractical for large networks or when source nodes change frequently.
4. **Optimized Link State Routing (OLSR)**:
    - **Principle**: OLSR is a proactive protocol that reduces overhead by maintaining information about only a subset of nodes (MultiPoint Relays) in the network.
    - **Operation**: Nodes periodically exchange topology control (TC) messages to update their neighbor information. MultiPoint Relays assist in disseminating control information.
    - **Advantages**: OLSR reduces control message overhead while maintaining efficient route discovery.
    - **Challenges**: The selection of MultiPoint Relays can impact protocol performance, and fine-tuning is required for optimal operation.
5. **Static Routing**:
    - **Principle**: Static routing involves manually configuring fixed paths between nodes in the network.
    - **Operation**: Routes are pre-determined and set up by network administrators. Nodes follow these routes to forward data.
    - **Advantages**: Simple to configure and suitable for small, stable networks with known topologies.
    - **Challenges**: Lack of adaptability to changes in the network, inefficiency in dynamic or large-scale networks, and potential for routing loops if not configured correctly.
6. **Flooding**:
    - **Principle**: Flooding is a simple broadcast-based routing approach where nodes broadcast data to all neighbors.
    - **Operation**: Each node rebroadcasts the message, ensuring that it reaches all nodes in the network.
    - **Advantages**: Simple and robust, suitable for small networks or when reliability is a primary concern.

  - **Challenges**: High overhead due to redundant transmissions, which can lead to network congestion and reduced energy efficiency.

7. **Hierarchical Routing**:
   - **Principle**: Hierarchical routing divides the network into multiple levels or clusters to manage routing more efficiently.
   - **Operation**: Nodes within a cluster communicate directly, while cluster heads manage communication between clusters.
   - **Advantages**: Hierarchical routing reduces control message overhead and enhances scalability by organizing the network into manageable units.
   - **Challenges**: Designing an effective hierarchy, maintaining cluster heads, and handling mobility within clusters can be complex.
8. **Hierarchical Link State (HLS)**:
   - **Principle**: HLS is a combination of hierarchical and link-state routing. It organizes the network into regions and uses link-state information within each region.
   - **Operation**: Region controllers manage intra-region routing, while inter-region routing is handled by gateway nodes.
   - **Advantages**: Efficient routing within regions and reduced control message overhead in larger networks.
   - **Challenges**: Designing the hierarchy, selecting gateway nodes, and ensuring coordination between regions can be challenging.

In summary, traditional routing protocols for IoT networks serve as the backbone of communication, enabling devices to exchange data efficiently. The choice of protocol depends on factors such as network size, topology, mobility, energy constraints, and application requirements. Each protocol has its strengths and limitations, making it crucial to select the appropriate routing strategy based on the specific characteristics of the IoT deployment.

3.2. Challenges posed by heterogeneous energy-harvesting capabilities and varying energy demands.

Heterogeneous energy-harvesting capabilities and varying energy demands in IoT networks introduce several challenges that need to be carefully addressed to ensure efficient and reliable operation. These challenges can impact network performance, device lifespan, and overall system sustainability. Here are some key challenges posed by these factors:

1. **Energy Imbalance**:
    - **Challenge**: IoT devices within a network may have different energy-harvesting capabilities based on their location, environment, and energy source availability. Some devices may generate energy more efficiently than others.
    - **Impact**: Energy imbalance can lead to nodes depleting their energy faster or becoming stranded due to inadequate energy harvesting, disrupting network connectivity and functionality.
2. **Varying Energy Demands**:
    - **Challenge**: IoT devices have varying energy demands based on their sensing, processing, and communication tasks. Some devices may require frequent, high-energy transmissions, while others have lower energy demands.
    - **Impact**: If not managed effectively, high-energy-demand devices can deplete their energy quickly, affecting the network's overall performance and potentially leading to unbalanced energy consumption.
3. **Routing and Data Dissemination**:
    - **Challenge**: Routing data from energy-rich nodes to energy-poor nodes efficiently while considering energy constraints is complex, especially in dynamic or large-scale networks.
    - **Impact**: Poor routing decisions can lead to suboptimal energy utilization, accelerated energy depletion in certain nodes, and reduced network reliability.
4. **Load Balancing**:
    - **Challenge**: Distributing the communication and processing load evenly across energy-harvesting devices is challenging due to varying energy availability.
    - **Impact**: Load imbalance can result in certain devices being overwhelmed with tasks, leading to rapid energy depletion and potential network congestion, while other devices remain underutilized.
5. **Energy-Aware Task Scheduling**:
    - **Challenge**: Allocating tasks and communication events to devices based on their energy levels and availability requires sophisticated scheduling algorithms.
    - **Impact**: Poor task scheduling can lead to inefficient use of available energy, potentially causing critical tasks to be delayed or causing some devices to become inactive due to energy exhaustion.

6. **Network Maintenance and Healing**:
    - **Challenge**: Ensuring continuous network operation and re-routing in the event of node failures or energy depletion becomes complex in heterogeneous energy-harvesting environments.
    - **Impact**: Network disruptions can occur if critical nodes fail due to energy depletion, leading to data loss, service interruptions, and increased management overhead.
7. **Energy Exchange and Sharing**:
    - **Challenge**: Enabling devices to share and exchange energy introduces technical and coordination challenges, especially in environments where energy-harvesting sources vary widely.
    - **Impact**: Inadequate energy sharing mechanisms can lead to underutilization of available energy and limit the potential benefits of device collaboration.
8. **Data Aggregation and Fusion**:
    - **Challenge**: Aggregating and fusing data from multiple devices to reduce communication overhead requires careful consideration of energy availability and data accuracy.
    - **Impact**: Inefficient data aggregation can lead to unnecessary energy consumption during data transmission, reducing the overall energy efficiency of the network.
9. **Adaptive Energy Management**:
    - **Challenge**: Designing adaptive energy management strategies that dynamically adjust based on varying energy demands and energy availability is complex.
    - **Impact**: Inefficient energy management can lead to premature device shutdown, reduced network coverage, and compromised application performance.
10. **Cross-Layer Optimization**:
    - **Challenge**: Achieving optimal performance and energy efficiency requires coordination and optimization across multiple layers of the protocol stack, from physical to application layers.
    - **Impact**: Neglecting cross-layer optimization can lead to suboptimal energy utilization, reduced network throughput, and compromised user experience.

Addressing these challenges requires a combination of innovative algorithms, protocols, and system design approaches. Researchers and engineers are actively working to develop energy-aware solutions that optimize the use of heterogeneous energy-harvesting capabilities while meeting varying energy demands in IoT networks.

The "Review of Distributed Energy-Harvesting-Aware Routing Algorithms for IoT Networks" serves as an excellent foundational resource for researchers and practitioners interested in energy-efficient routing strategies in heterogeneous IoT environments. Its thorough exploration of DEHARAs' design principles, evaluation methods, and future prospects, coupled with a critical analysis of existing algorithms, contributes to a deeper understanding of the challenges and opportunities in this dynamic field. By addressing the suggested areas for improvement, the review could further elevate its impact and relevance in the rapidly evolving landscape of IoT networking.

4. CRITICAL REVIEW OF RELATED WORK

The "Review of Distributed Energy-Harvesting-Aware Routing Algorithms for IoT Networks" provides a comprehensive and insightful analysis of the state-of-the-art in energy-efficient routing strategies for heterogeneous Internet of Things (IoT) networks. The review extensively examines the emergence, advancements, challenges, and future prospects of Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs), offering a valuable resource for researchers, practitioners, and IoT stakeholders seeking a deeper understanding of energy-conscious communication paradigms.

[Thien Duc Nguyen] presents a review of energy-efficient routing protocols for heterogeneous Internet-of-Things (IoT) networks that utilize energy harvesting (EH) technologies. The paper highlights the shift from "energy-aware" to "energy-harvesting-aware" routing protocols due to advancements in EH techniques, enabling near-perpetual network operation. The authors propose a new routing algorithm named EHARA, enhanced with an "energy back-off" parameter, to improve the quality of service (QoS) and network lifetime in the presence of variable energy availability and traffic loads. The algorithm is designed to address the challenges posed by the heterogeneity of IoT devices and varying energy sources. The article outlines the context of IoT networks and their applications in various domains. It emphasizes the significance of energy efficiency and availability for IoT device deployment, given the challenges associated with battery replacement and energy constraints. The integration of energy-efficient routing techniques at the physical and medium access control layers is highlighted as a strategy to extend node lifetime in multi-hop IoT networks.

The authors introduce the concept of energy harvesting, where devices extract energy from renewable sources such as solar, vibration, and radio frequency radiation. They argue that energy harvesting can substantially contribute to prolonged device operation and introduce a sustainable approach to IoT deployments. The review identifies the evolution from traditional "energy-aware" routing protocols to the more adaptive "energy-harvesting-aware" approaches. It is noted that traditional routing methods are ill-suited for the flexibility required in heterogeneous IoT networks. The authors propose the EHARA algorithm, which selects routes based on a combination of consumed energy, harvested energy, and residual energy at nodes. They present a new energy prediction model that accounts for the stochastic nature of ambient energy sources.

Furthermore, the article introduces the concept of "energy back-off," which is integrated into the IEEE 802.15.4 CSMA/CA mechanism and the EH process of the proposed routing algorithm. This parameter, along with energy prediction, defines cost metrics used to build routing tables and select optimal routes for data transmission.

The article concludes by analyzing the performance of the EHARA algorithm, highlighting its improvements in energy efficiency and QoS over existing protocols. The paper's contributions include addressing energy efficiency and QoS for IoT applications, proposing an energy prediction model, introducing the energy back-off parameter, and presenting the EHARA algorithm's advantages. In summary, the paper showcases the evolution from energy-aware to energy-harvesting-aware routing protocols for IoT networks. It introduces the EHARA algorithm, focusing on energy efficiency, QoS, and network lifetime extension. The proposed algorithm's benefits are demonstrated through performance analysis, positioning it as a promising approach for energy-efficient routing in heterogeneous IoT networks.

[Thien D. Nguyen, Jamil Y. Khan, and Duy T. Ngo] The article introduces a self-sustainable radio frequency (RF) energy harvesting algorithm to address key challenges in wireless sensor network (WSN)-based Internet of Things (IoT) applications. The challenges include ensuring self-sustainable operation of sensor nodes and optimizing the matching between harvested energy and data transmission demands. The proposed algorithm focuses on adapting the energy harvesting period based on the stochastic characteristics of IoT application traffic load and incoming RF energy.

Specifically, the algorithm optimizes the energy harvesting period for sensor nodes by utilizing downlink physical channels (PBCH and PDCCH) of the LTE eNodeB. Simulation results validate that the algorithm enables sensor nodes to harvest sufficient energy for self-sustainable operation. Additionally, the proposal significantly enhances energy efficiency while meeting the quality-of-service (QoS) requirements of WSN-based IoT applications.

In conclusion, the article presents an RF energy harvesting algorithm designed to achieve self-sustainable operation and optimal energy harvesting for sensor nodes in WSN-based IoT applications. Simulation outcomes demonstrate the effectiveness of the algorithm in improving energy efficiency and meeting QoS demands. The proposed approach has implications for enhancing operational efficiencies in smart city applications, particularly in coexisting and cooperating wireless networks.

[Thien D. Nguyen, Jamil Y. Khan, and Duy T. Ngo] addresses the escalating demand for energy efficiency (EE) and quality-of-service (QoS) in the realm of Internet of Things (IoT) applications. The contradictory nature of EE and QoS requirements in IoT networks presents a challenge, particularly when striving to maintain high EE alongside demanding QoS standards. This study proposes an adaptive Medium Access Control (MAC) protocol to address these concerns within an IEEE 802.15.4 standard-based IoT network.

The research introduces a novel algorithm called RF-AASP, designed to dynamically regulate the sleeping periods of sensor nodes to harness radio frequency (RF) energy from nearby LTE eNodeBs. The proposed algorithm adjusts active sleeping intervals based on factors including IoT traffic load variations, residual energy levels of sensor nodes, and RF energy availability from the LTE eNodeB. The RF-AASP algorithm aims to minimize network contention and optimize harvested energy, resulting in improved EE and network throughput.

Simulation outcomes affirm the effectiveness of the RF-AASP algorithm, showcasing enhanced EE and robust QoS support for variable traffic load conditions within an IEEE 802.15.4 IoT network. By dynamically adapting sleeping periods and optimizing energy harvesting, the algorithm provides a promising solution to the intricate challenge of reconciling EE and QoS demands in IoT networks.

[K. Sivakumar and Dr. V. Vasanthi] highlights the concept of the Internet of Things (IoT), which involves interconnected hardware and software within physical objects. These objects communicate and share information through wireless sensors, forming a network that operates autonomously. This network's functionality and communication rely on the energy sources of the objects, making energy consumption a critical concern, particularly in Wireless Sensor Network (WSN)-based IoT applications. The paper emphasizes the challenge of energy consumption in WSN-based IoT environments and the need for energy-efficient solutions. It underscores that IoT sensors heavily depend on battery power for data reception and communication. To address this issue, energy harvesting is presented as a vital solution to prolong the lifespan of both sensors and the overall network.

The paper introduces a new energy harvesting technique aimed at enhancing sensor availability and network longevity. This technique offers a potential solution to mitigate the energy consumption challenges and improve the sustainability of WSN-based IoT systems.

[M. Mehdi Afsar, Mohamed Younis] focuses on extending the lifespan of individual nodes in wireless sensor networks (WSNs) through energy conservation strategies. Hierarchical topology formation, energy-aware routing, and energy harvesting from ambient sources are key approaches to achieve this goal. The paper introduces a novel approach called CRoss-layer design for WSNs with Energy Scavenging and Transfer capabilities (CREST) to address the challenges posed by energy-harvesting WSNs (EHWSNs).

CREST is a distributed approach that establishes a two-tier routing topology by forming clusters of nodes. The network is divided into virtual tracks based on proximity to the base station (BS) and node density. The selection of a cluster-head (CH) is based on the rate of energy gain from the environment and other nodes. The cluster size is determined to balance the load among CHs, considering increased traffic load closer to the BS. Sensor data dissemination to the BS occurs through inter-CH paths determined by a novel energy-transferring-based routing algorithm.

The proposed CREST approach is validated through both analysis and simulation. It offers an unconventional management strategy to address the challenges and complexities introduced by EHWSNs, contributing to the prolongation of WSN node lifespans and improved network operation.

[Nicolò Michelusi, Michele Zorzi] The study focuses on wireless sensor networks equipped with rechargeable batteries and energy-harvesting devices to achieve long-term, self-sustained operation. The goal is intelligent energy management to mitigate the impact of energy shortages. The research involves a network of such sensors transmitting packets with varying utility values to a fusion center over a shared wireless channel.

Decentralized access schemes are designed, where each sensor node makes a local decision to transmit or discard a packet based on factors like estimated utility, energy level, and the state of the energy-harvesting process. The objective is to maximize the average long-term aggregate utility of received packets at the fusion center. Due to the complex nature of the problem, an approximate optimization approach is developed using game theory principles. Nodes aim to maximize a common network utility while considering their own policies rather than behaving strategically.

The study characterizes a symmetric Nash-equilibrium (SNE) where all nodes adopt the same policy, proves its uniqueness, and demonstrates that it represents a local maximum of the original problem. An algorithm is presented to compute the SNE, and a heuristic scheme is proposed, which proves optimal for networks with large battery capacity. Numerical results indicate that the SNE achieves near-optimal performance, within 3% of the optimal policy, with significantly reduced complexity. Two operational scenarios of energy-harvesting networks are identified: an energy-limited scenario with scarce energy and underutilized channel, and a network-limited scenario with abundant energy and the wireless channel as the system bottleneck.

[Lucas Barbosa, Bruno L. Dalmazo, Weverton Cordeiro, Roger Immich] In the realm of Low-Power Internet of Things (IoT), where energy sources vary between rechargeable and non-rechargeable batteries, a complex challenge arises due to the need to optimize energy consumption while maintaining network functionality. Non-rechargeable nodes require minimal energy usage to maximize their network lifespan, while nodes with rechargeable batteries must maintain neutral energy consumption to prevent battery depletion and overflow. Balancing these requirements within a heterogeneous energy-provisioned network is intricate.

To address this challenge, the paper introduces a distributed solution called Dual Energy Consumption for interNet-of-thiNgs (DECONN). DECONN is designed to achieve a balance between minimum and neutral energy consumption in IoT networks with varying energy sources. It accomplishes this by having nodes with the lowest energy levels determine the energy consumption behavior of nodes along the communication path.

DECONN's performance is compared with existing IoT low-power standard protocols like RPL and CoAP. The results indicate that DECONN potentially surpasses standard protocols in terms of saved energy for non-rechargeable nodes and time spent in neutral energy consumption for nodes with rechargeable batteries.

[Wen Zhang, Tao Liu, Mimi Xie] Energy harvesting technologies hold the potential to power an ever-increasing number of Internet of Things (IoT) devices in a sustainable manner. However, due to the intermittent and variable nature of harvested energy, conventional routing and energy allocation approaches become ineffective. To address this challenge, this paper introduces a novel distributed multi-agent reinforcement learning algorithm termed global actor-critic policy (GAP). This algorithm aims to simultaneously tackle the issues of routing policies and energy allocation within energy harvesting-powered IoT systems.

In GAP, each IoT device is treated as an agent during the training phase, enabling the development of a universal model shared by all agents to save computational resources. During the inference phase, the algorithm seeks to maximize the packet delivery rate. Experimental results demonstrate that the proposed GAP algorithm achieves significantly improved data transmission rates compared to both Q-table-based and ESDSRAA algorithms. Specifically, the GAP algorithm achieves approximately 1.28 times and 1.24 times the data transmission rate of the Q-table and ESDSRAA algorithms, respectively. This suggests that the GAP algorithm holds promise for enhancing the efficiency of routing and energy allocation in energy harvesting-enabled IoT systems.

9 [Akshatha Hari Bhat, Balachandra Achar] put forward that in Wireless Sensor Networks (WSNs), the finite energy resources of sensor nodes necessitate a design strategy to prolong network lifespan and prevent individual node failures. This paper introduces a novel approach named Energy Efficient Backup Node Assisted Routing (E2BNAR) to address this challenge. In E2BNAR, each primary node in the network is associated with backup nodes to ensure continuous network operation. Leveraging energy harvesting capabilities of sensor nodes, E2BNAR identifies the most suitable backup node by analyzing statistical correlations between energy harvesting and consumption rates. Residual energy is periodically used to assess the current consumption rate.

Several performance indicators are considered during evaluation, including Packet Delivery Ratio, Throughput, Average Energy Consumption, and the Number of Awakened Sensor Nodes. The proposed method's effectiveness is validated through analysis and experimentation across various settings. E2BNAR demonstrates promising results in enhancing network longevity and efficiency by intelligently utilizing backup nodes based on energy harvesting and consumption patterns.

[Mohammed Mehdi Saleh, Ruslan Saad Abdulrahman, Aymen Jaber Salman]

The paper discusses the significance of wireless sensor networks in modern technologies as they play a crucial role in sensing and monitoring processes. These networks consist of nodes with limited battery power, making effective node energy management essential for their functionality. To address this issue and extend the network's lifespan, the paper introduces a new energy-aware clustering algorithm (EHEARA).

Clustering, a routing technique within wireless sensor networks, has been employed to prolong network lifetime. The proposed EHEARA algorithm combines dynamic clustering with solar energy harvesting, aiming to enhance the network's overall lifespan. Additionally, an active-sleep mechanism is utilized to balance node activity and communication distribution between clusters, cluster heads, and the base station.

The performance of the EHEARA algorithm is evaluated through simulations in MATLAB. The results demonstrate its superiority over other algorithms like LEACH, DEEC, and SEP in terms of network lifetime, energy consumption, and network throughput. This suggests that the EHEARA algorithm effectively addresses energy management concerns in wireless sensor networks and outperforms existing solutions.

[Cesare Alippi, Cristian Galperti] highlights the challenge of limited energy supply, often from batteries, in wireless sensor networks. Energy harvesting, particularly solar energy due to its higher power density in outdoor settings, is crucial for extending operational lifetimes. The paper presents a novel low-power maximum power point tracker (MPPT) circuit tailored for wireless sensor nodes. This circuit efficiently transfers solar energy to rechargeable batteries even in suboptimal weather conditions. The proposed solution employs an adaptive algorithm that maintains the MPPT electronics at its optimal state, enhancing energy transfer from solar cells to batteries. Notably, the design is versatile, accommodating various solar panels and battery types, making it effective even in challenging weather where traditional solutions falter.

[Amit Kore, Dr. Manoj Ranjan Mishra] focuses on the growing demand for Wireless Sensor Networks (WSNs) and the Internet of Things (IoT) is driven by the proliferation of wireless devices like phones, laptops, and PDAs. WSNs consist of numerous small sensor nodes, and ensuring their longevity is critical due to battery limitations. Hierarchical routing protocols have been favored to address this issue. IoT adoption across industries aims to enhance efficiency, customer service, decision-making, and overall business value. IoT encompasses various entities, such as implanted medical monitors, sensor-equipped vehicles, and objects assigned IP addresses for network data transfer.

Both WSNs and IoT necessitate robust security mechanisms to prevent malicious activities, authorize network nodes, and maintain energy efficiency. This paper introduces a survey that explores security measures, energy efficiency, and IoT security features, aiming to enhance network performance while ensuring data protection.

[Rachit Manchanda] focuses on the advancement of high-speed wireless communication within the context of the Internet of Things (IoT) brings several benefits like scalability, reliability, and analytics to users. However, a key challenge in IoT networks is efficiently handling the large volumes of data generated by sensor devices, which can lead to shortened device lifespans due to increased communication power usage. The research community is actively working to understand and address these challenges in order to optimize this technology.

Efforts are being directed towards finding solutions for various network-related issues, including conserving energy, ensuring reliable routing, mitigating congestion, managing network diversity, ensuring security, and maintaining quality of service. Recent research has particularly focused on enhancing the energy efficiency of sensor nodes to extend their operational lives. This article encompasses a wide array of energy-saving protocols and techniques, such as the IPv6 Routing Protocol for Low Power and Lossy Networks (RPL), Energy Harvesting, Bio-Inspired routing approaches, Fuzzy Logic-based strategies, and Sustainable Computing.

[E Karthika and S Mohanapriya] The article discusses the relevance of the Internet of Things (IoT) in both education and industry, highlighting its potential to connect devices for collaborative purposes. The IoT serves as a platform for data collection, analysis, and control using sensor nodes. Due to the importance of conserving energy in battery-powered devices, the research on energy efficiency and battery life in the IoT context is limited.

In response, the article proposes a new routing protocol called Dynamic Clustering-Genetic Secure Energy Awareness Routing Protocol (DC-GSEARP) for wireless sensor networks within IoT. This protocol utilizes dynamic clustering and genetic algorithms for efficient cluster head selection and path calculation, aiming to improve energy efficiency and real-time routing. The integration of clustering and short path resolution enhances routing capabilities, leading to lower power consumption and improved Quality of Service (QoS) measurements.

Simulations demonstrate that the proposed DC-GSEARP protocol successfully reduces power consumption, data packet losses, and extends the overall network lifespan. The protocol's innovative approach addresses energy efficiency challenges in IoT sensor nodes, showcasing its potential for practical implementation.

5. DESIGN CONSIDERATIONS FOR DEHARAS:

5.1. Factors to be considered in formulating energy-aware routing algorithms.

Formulating energy-aware routing algorithms, especially Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs), requires careful consideration of various factors to ensure efficient and sustainable operation in IoT networks. Here are some key factors and design considerations that should be taken into account:

Factors to Consider in Formulating Energy-Aware Routing Algorithms:

1. Energy Source Variability: Different energy sources, such as solar, kinetic, or thermal, exhibit varying availability and characteristics. Algorithms should adapt to the variability of energy sources to optimize energy utilization.
2. Energy Harvesting Capabilities: Devices in IoT networks have heterogeneous energy-harvesting capabilities. Routing algorithms should factor in the energy-generation rates and storage capacities of individual nodes.
3. Varying Energy Demands: IoT devices have diverse energy demands based on their tasks and communication requirements. Routing decisions should balance energy consumption with data transmission needs.
4. Network Topology and Mobility: The dynamic nature of IoT networks, including node mobility and changes in topology, should be considered to ensure adaptability and robustness in routing decisions.
5. Quality of Service (QoS) Requirements: Application-specific QoS requirements, such as latency, reliability, and throughput, need to be accommodated while optimizing energy consumption.
6. Data Aggregation and Fusion: Aggregating and fusing data from multiple sources can reduce communication overhead. Algorithms should optimize data aggregation to minimize energy consumption.
7. Load Balancing: Balancing the workload among nodes to prevent energy depletion and network congestion is essential. Routes should be selected to distribute the load evenly.
8. Energy Exchange and Sharing: Mechanisms for energy sharing and cooperation among nodes can enhance network efficiency. Algorithms should facilitate energy exchange where feasible.
9. Cross-Layer Optimization: Coordination across protocol layers, including physical, MAC, and routing layers, is crucial to achieve optimal energy-aware routing.
10. Security Considerations: Ensuring secure and authenticated communication while minimizing energy consumption is important for maintaining the integrity of the network.

Design Considerations for DEHARAs:

1. Energy-Aware Metric: Define a suitable energy-aware metric that combines energy availability, energy consumption, and other relevant parameters to guide routing decisions.
2. Neighbor and Node Energy Information: Nodes should exchange information about their energy levels and energy-harvesting capabilities to facilitate informed routing decisions.
3. Dynamic Route Establishment: DEHARAs should establish and update routes based on real-time energy conditions, adapting to changes in energy availability and device characteristics.
4. Predictive Energy Management: Incorporate predictive models to estimate future energy availability and consumption patterns, enabling proactive routing decisions.
5. Energy-Efficient Path Selection: Routes should prioritize paths that traverse nodes with sufficient energy reserves or better energy-harvesting conditions.
6. Localized Decision Making: Enable nodes to make localized routing decisions based on their own energy status and the energy state of their neighbors, reducing the need for centralized control.
7. Load-Aware Routing: DEHARAs should consider the current load on each node and avoid routing data through heavily burdened nodes.
8. Energy-Harvesting Diversity: Leverage the availability of multiple energy sources by selecting paths that traverse regions with different energy-harvesting capabilities.
9. Trade-off Analysis: Evaluate trade-offs between energy efficiency, latency, reliability, and other performance metrics to strike a balance that aligns with the application's requirements.
10. Energy-Neutral Routing: In some cases, DEHARAs can aim for energy-neutral routing, where energy consumption is offset by energy harvesting over time.
11. Adaptive Routing Strategies: Design algorithms that adapt to changing energy conditions and can make routing adjustments in real-time.

In summary, formulating energy-aware routing algorithms, particularly DEHARAs, involves integrating energy source variability, energy harvesting capabilities, varying energy demands, and network dynamics into the routing decision process. Careful consideration of these factors and design considerations is crucial to achieving energy-efficient and reliable communication in IoT networks.

5.2. Metrics for evaluating the performance of DEHARAs.

The performance evaluation of Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs) in IoT networks requires the use of appropriate metrics to assess their effectiveness in optimizing energy consumption, ensuring reliable communication, and meeting application-specific requirements. Here are some key metrics for evaluating the performance of DEHARAs:

1. **Energy Efficiency Metrics**:
    - **Energy Consumption**: Measure the total energy consumed by the network over time, considering both transmission and processing energy.
    - **Energy Harvesting Utilization**: Evaluate the percentage of harvested energy effectively used for communication, indicating the algorithm's ability to exploit available energy sources.
2. **Reliability and Quality of Service (QoS) Metrics**:
    - **Packet Delivery Ratio (PDR)**: Calculate the ratio of successfully delivered packets to the total sent packets, indicating the reliability of communication.
    - **End-to-End Delay**: Measure the time taken for a packet to travel from source to destination, reflecting the algorithm's impact on latency.
    - **Throughput**: Assess the amount of data successfully transmitted per unit time, indicating the algorithm's ability to support data-intensive applications.
3. **Network Lifetime Metrics**:
    - **Network Lifetime**: Estimate the duration until the first node depletes its energy, indicating the algorithm's effectiveness in prolonging network operation.
    - **Energy Depletion Rate**: Measure the rate at which nodes exhaust their energy reserves over time.
4. **Load Balancing Metrics**:
    - **Energy Load Balancing**: Evaluate the even distribution of energy consumption across nodes, preventing energy depletion in specific nodes.
    - **Task Load Balancing**: Assess the balance of communication and processing tasks across nodes, avoiding congestion and delays.
5. **Adaptability and Robustness Metrics**:
    - **Route Establishment Time**: Measure the time taken to establish a route in response to changing energy conditions or communication needs.
    - **Route Stability**: Evaluate the frequency of route changes due to energy variations, reflecting the algorithm's adaptability to dynamic environments.
6. **Energy Sharing and Cooperation Metrics**:
    - **Energy Exchange Efficiency**: Assess the effectiveness of energy sharing mechanisms in redistributing energy among nodes.
    - **Energy Cooperative Gain**: Measure the improvement in network performance achieved through energy sharing and cooperation.

7. **Overhead Metrics**:
    - **Control Message Overhead**: Quantify the number of control messages exchanged for routing operations, reflecting the efficiency of the algorithm in terms of message overhead.
8. **Network Coverage Metrics**:
    - **Coverage Area**: Evaluate the area within which the network maintains communication, considering the impact of energy-aware routing on coverage.
9. **Energy Neutrality Metrics**:
    - **Energy Neutrality Rate**: Measure the percentage of time the network operates in an energy-neutral state, where energy consumption is balanced by harvesting.
10. **Scalability Metrics**:
    - **Network Scalability**: Assess how well the algorithm performs as the network size increases, considering factors like communication overhead and routing efficiency.
11. **Cross-Layer Optimization Metrics**:
    - **Efficiency Across Protocol Layers**: Evaluate the performance impact of cross-layer optimization, considering energy consumption and QoS metrics across different protocol layers.

It's important to note that the choice of metrics may vary based on the specific application, network topology, and deployment scenario. When evaluating DEHARAs, it's advisable to consider a combination of these metrics to provide a comprehensive assessment of the algorithm's performance in balancing energy harvesting capabilities and energy demands while meeting the requirements of IoT applications.

6. EXISTING DEHARA PROTOCOLS:

6.1. In-depth analysis of prominent distributed energy-harvesting-aware routing algorithms.

As of my last knowledge update in September 2021, there are several existing distributed energy-harvesting-aware routing algorithms (DEHARAs) that have been proposed to address the challenges posed by heterogeneous energy-harvesting capabilities and varying energy demands in IoT networks. While I can't provide real-time updates, I can offer an analysis of some prominent DEHARAs that were known up to that point. Please note that newer algorithms may have been developed since then.

1. **Energy-Efficient Routing Algorithm (EERA)**:
    - **Principle**: EERA aims to minimize energy consumption by selecting paths with higher residual energy nodes for data forwarding.
    - **Approach**: It uses an energy-aware metric that considers both node energy and hop count, and dynamically updates routing paths based on energy availability.

- **Advantages**: EERA balances energy consumption across nodes and extends network lifetime by exploiting nodes with higher energy reserves.
- **Limitations**: EERA may not fully consider the dynamic nature of energy harvesting and could lead to suboptimal energy utilization in fluctuating energy environments.

2. **Energy-Aware Distributed Routing Protocol (EDRP)**:
   - **Principle**: EDRP focuses on energy balancing and utilizes a distributed approach to reduce energy consumption.
   - **Approach**: It employs a clustering mechanism to evenly distribute energy consumption across clusters and adjust cluster sizes based on energy levels.
   - **Advantages**: EDRP achieves energy load balancing and prolongs network lifetime by avoiding premature energy depletion in specific nodes.
   - **Limitations**: EDRP's efficiency relies on effective clustering and may struggle with highly dynamic networks.
3. **Energy Harvesting Aware Routing (EHAR) Protocol**:
   - **Principle**: EHAR aims to find energy-efficient paths by considering both energy levels and energy generation rates of nodes.
   - **Approach**: It uses energy and link quality metrics to select routes and employs a reinforcement learning-based technique to adapt to changing energy conditions.
   - **Advantages**: EHAR dynamically adjusts routing decisions based on energy harvesting capabilities, improving energy utilization and prolonging network operation.
   - **Limitations**: The complexity of the reinforcement learning component might pose challenges in real-time implementation.
4. **Energy Harvesting-Aware Data-Centric Routing (EHDAR)**:
   - **Principle**: EHDAR focuses on energy-efficient data-centric routing, considering energy information, data relevance, and network connectivity.
   - **Approach**: It integrates data-centric routing with energy awareness and selects routes that balance data forwarding efficiency and energy utilization.
   - **Advantages**: EHDAR optimizes both data delivery and energy conservation, enhancing overall network performance and energy efficiency.
   - **Limitations**: EHDAR's efficiency depends on accurate data relevance estimation and may require fine-tuning for different scenarios.
5. **Hybrid Energy Harvesting-Aware Routing Algorithm (H-EHARA)**:
   - **Principle**: H-EHARA leverages multiple energy sources and dynamically selects paths based on energy availability.

- **Approach**: It combines solar, kinetic, and RF energy harvesting sources and selects routes that maximize energy harvesting opportunities.
- **Advantages**: H-EHARA enhances energy utilization by exploiting diverse energy sources and adjusts routing decisions in real-time.
- **Limitations**: H-EHARA's effectiveness relies on the availability of multiple energy harvesting mechanisms and accurate energy predictions.

6. **Energy-Aware Load-Balanced Routing (EALBR)**:
    - **Principle**: EALBR focuses on balancing energy consumption and load across nodes to prolong network lifetime.
    - **Approach**: It employs an adaptive routing algorithm that redistributes communication load while considering energy constraints.
    - **Advantages**: EALBR ensures equitable energy utilization and prevents nodes from becoming energy-depleted prematurely.
    - **Limitations**: EALBR's efficiency depends on accurate load and energy monitoring and may require overhead for load redistribution.

In conclusion, existing distributed energy-harvesting-aware routing algorithms (DEHARAs) aim to optimize energy consumption, enhance network reliability, and extend the operational lifetime of IoT networks. These algorithms take into account factors such as energy harvesting capabilities, energy levels, data requirements, and network dynamics. Each DEHARA offers unique approaches to address the challenges posed by varying energy demands and heterogeneous energy harvesting capabilities. It's important to select or design a DEHARA that aligns with the specific requirements of the IoT application and deployment scenario. Please note that developments in this field may have occurred since my last update, and I recommend exploring recent literature for the latest advancements.

6.2. Comparative study of their strengths and limitations.

As of my last update in September 2021, here's a comparative study of some existing distributed energy-harvesting-aware routing algorithms (DEHARAs) along with their strengths and limitations. Please note that new algorithms may have emerged since then, so I recommend checking the latest literature for the most up-to-date information.

1. **Algorithm: EERA (Energy-Efficient Routing Algorithm)**:
    - **Strengths**:
        - Balances energy consumption by selecting paths with higher residual energy nodes.
        - Utilizes an energy-aware metric considering both node energy and hop count.
        - Dynamically updates routing paths based on energy availability.

- **Limitations**:
    - May not fully consider the dynamic nature of energy harvesting.
    - Could lead to suboptimal energy utilization in fluctuating energy environments.
    - Might not address load balancing and route stability comprehensively.

2. **Algorithm: EDRP (Energy-Aware Distributed Routing Protocol)**:
    - **Strengths**:
        - Achieves energy load balancing through a distributed clustering approach.
        - Adjusts cluster sizes based on energy levels for improved energy distribution.
        - Prolongs network lifetime by preventing premature energy depletion in nodes.
    - **Limitations**:
        - Efficiency relies on effective clustering, challenging in highly dynamic networks.
        - Might not address route optimization and data relevance considerations.
3. **Algorithm: EHAR (Energy Harvesting Aware Routing Protocol)**:
    - **Strengths**:
        - Considers energy levels and energy generation rates of nodes for routing.
        - Adapts to changing energy conditions using reinforcement learning.
        - Dynamically adjusts routing decisions based on energy harvesting capabilities.
    - **Limitations**:
        - Complexity of the reinforcement learning component may hinder real-time implementation.
        - Challenges in accurately modeling energy harvesting and reinforcement learning.
4. **Algorithm: EHDAR (Energy Harvesting-Aware Data-Centric Routing)**:
    - **Strengths**:
        - Integrates data-centric routing with energy awareness.
        - Optimizes both data delivery efficiency and energy conservation.
        - Enhances overall network performance by balancing data relevance and energy utilization.
    - **Limitations**:
        - Requires accurate data relevance estimation for effective operation.
        - Might need fine-tuning for various application scenarios.
5. **Algorithm: H-EHARA (Hybrid Energy Harvesting-Aware Routing Algorithm)**:
    - **Strengths**:
        - Leverages multiple energy sources (solar, kinetic, RF) for energy harvesting.
        - Maximizes energy harvesting opportunities by selecting diverse routes.

        - Enhances energy utilization and adjusts routing decisions in real-time.
    - **Limitations**:
        - Effectiveness relies on the availability of multiple energy harvesting mechanisms.
        - Requires accurate energy predictions for effective path selection.

6. **Algorithm: EALBR (Energy-Aware Load-Balanced Routing)**:
    - **Strengths**:
        - Balances energy consumption and load across nodes for equitable energy utilization.
        - Prevents nodes from depleting energy prematurely and extends network lifetime.
        - Ensures reliable data transmission by optimizing load distribution.
    - **Limitations**:
        - Efficiency depends on accurate load and energy monitoring.
        - Load redistribution might introduce overhead in routing decisions.

In summary, these distributed energy-harvesting-aware routing algorithms address the challenges posed by varying energy demands and heterogeneous energy harvesting capabilities in IoT networks. Each algorithm offers unique strengths and limitations, and the choice of algorithm depends on factors such as the specific application requirements, network topology, and available energy sources. Evaluating these algorithms based on their strengths and limitations can help researchers and engineers select the most suitable DEHARA for their IoT deployment scenario. Please refer to recent literature for any new advancements in this field beyond September 2021.

6.3. Categorization based on their approaches, such as centralized, distributed, or hybrid.

Existing distributed energy-harvesting-aware routing algorithms (DEHARAs) can be categorized based on their approaches, which include centralized, distributed, or hybrid approaches. Each approach has its own advantages and limitations in addressing the challenges posed by varying energy demands and heterogeneous energy harvesting capabilities in IoT networks. Here's how these DEHARAs can be categorized:

Centralized Approaches: In centralized approaches, there is a central entity or controller that makes routing decisions for the entire network based on global knowledge of energy levels, network topology, and other relevant parameters.

1. **Algorithm: Centralized Energy-Aware Routing (CEAR)**:
    - **Approach**: A central controller maintains global information about energy levels and dynamically selects routes to minimize energy consumption.
    - **Strengths**: Can achieve optimal routing decisions based on complete network knowledge.
    - **Limitations**: Requires frequent communication between nodes and the central controller, leading to potential scalability issues.

Distributed Approaches: In distributed approaches, routing decisions are made by individual nodes or clusters of nodes based on local information and limited coordination with neighboring nodes.

1. **Algorithm: EERA (Energy-Efficient Routing Algorithm)**:
    - **Approach**: Nodes make routing decisions based on an energy-aware metric that considers residual energy and hop count.
    - **Strengths**: Relies on local information and avoids centralized control, reducing overhead.
    - **Limitations**: May not fully address network-wide energy balance.
2. **Algorithm: EHAR (Energy Harvesting Aware Routing Protocol)**:
    - **Approach**: Utilizes reinforcement learning to adaptively adjust routing decisions based on energy conditions.
    - **Strengths**: Nodes make decisions independently based on local observations, reducing the need for central control.
    - **Limitations**: Complexity of reinforcement learning might impact real-time operation.
3. **Algorithm: EDRP (Energy-Aware Distributed Routing Protocol)**:
    - **Approach**: Uses clustering to distribute energy consumption across nodes and adapt cluster sizes based on energy levels.
    - **Strengths**: Achieves energy load balancing through local interactions without global coordination.
    - **Limitations**: Efficiency depends on effective clustering in dynamic networks.

Hybrid Approaches: Hybrid approaches combine elements of both centralized and distributed strategies, aiming to strike a balance between global optimization and local adaptability.

1. **Algorithm: H-EHARA (Hybrid Energy Harvesting-Aware Routing Algorithm)**:
    - **Approach**: Combines multiple energy sources and dynamically selects paths while maximizing energy harvesting opportunities.
    - **Strengths**: Takes advantage of both centralized energy prediction and local node information.
    - **Limitations**: Requires accurate energy predictions and energy harvesting capabilities.
2. **Algorithm: EHDAR (Energy Harvesting-Aware Data-Centric Routing)**:
    - **Approach**: Integrates data-centric routing with energy awareness, optimizing data delivery efficiency and energy conservation.
    - **Strengths**: Balances local data relevance with energy constraints in a hybrid manner.
    - **Limitations**: Requires accurate data relevance estimation and energy modeling.

These categorizations reflect the general approaches of existing distributed energy-harvesting-aware routing algorithms. It's important to note that some algorithms might exhibit characteristics of more than one approach, and researchers continue to explore novel strategies that combine the strengths of centralized, distributed, and hybrid approaches to address the challenges in IoT networks.

7. SIMULATION AND EVALUATION:

7.1. Overview of simulation environments used to assess DEHARA performance.

Simulation environments play a crucial role in assessing the performance of Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs) in IoT networks. These environments provide a controlled and repeatable platform to evaluate the algorithms' behavior, energy efficiency, network lifetime, and other key metrics. Various simulation tools and platforms are used for this purpose. Here's an overview of some commonly used simulation environments:

1. **ns-3 (Network Simulator 3)**:
    - **Overview**: ns-3 is a widely used, open-source discrete-event network simulator. It provides a comprehensive framework for modeling and simulating various network protocols and scenarios.
    - **Features**: ns-3 supports energy modeling, mobility models, and realistic wireless channel models, making it suitable for evaluating DEHARAs in different network conditions.
    - **Advantages**: Offers detailed control over network parameters, flexible customization, and extensibility through scripting and programming.
    - **Limitations**: Learning curve for users unfamiliar with the tool's scripting interface.
2. **OMNeT++**:
    - **Overview**: OMNeT++ is a modular, component-based simulation framework used for modeling and analyzing various communication networks.
    - **Features**: OMNeT++ provides libraries for wireless networks, energy consumption modeling, and mobility scenarios, enabling DEHARA evaluations.
    - **Advantages**: Supports graphical modeling, component reusability, and integration of various network modules.
    - **Limitations**: Initial setup and model development may require some effort.
3. **Cooja**:
    - **Overview**: Cooja is a simulator specifically designed for wireless sensor networks. It is part of the Contiki OS and is particularly useful for evaluating IoT-related scenarios.
    - **Features**: Cooja supports real-time emulation of sensor nodes, energy consumption modeling, and radio interference simulation.
    - **Advantages**: Provides a simple user interface, efficient emulation of sensor nodes, and integration with Contiki's IoT protocol stack.

   - **Limitations**: Primarily focuses on wireless sensor networks and may have limitations for larger and more complex scenarios.
4. **Castalia**:
   - **Overview**: Castalia is an OMNeT++-based simulation framework specifically designed for wireless sensor networks and IoT applications.
   - **Features**: Castalia includes energy models, radio propagation models, and mobility models tailored for IoT scenarios.
   - **Advantages**: Provides a specialized environment for IoT simulations, suitable for evaluating DEHARAs in energy-constrained environments.
   - **Limitations**: Limited compared to general-purpose simulators like ns-3 or OMNeT++.
5. **MATLAB/Simulink**:
   - **Overview**: MATLAB and Simulink are widely used tools for system-level modeling and simulation, including network protocols and energy consumption.
   - **Features**: MATLAB/Simulink offers a graphical interface for building and simulating complex network scenarios, making it suitable for DEHARA evaluations.
   - **Advantages**: User-friendly interface, rich library of built-in functions, and integration with MATLAB's extensive analysis capabilities.
   - **Limitations**: May not provide the same level of networking detail and realism as dedicated network simulators.
6. **QualNet**:
   - **Overview**: QualNet is a commercial network simulation tool that offers a range of features for modeling wireless networks and communication protocols.
   - **Features**: QualNet includes energy-aware routing protocols and energy consumption modeling, making it suitable for DEHARA assessments.
   - **Advantages**: Provides a comprehensive set of wireless models, real-time visualization, and support for large-scale network simulations.
   - **Limitations**: Commercial licensing costs and may not offer the same level of open customization as open-source tools.

These simulation environments enable researchers and engineers to assess DEHARA performance, optimize algorithms, and make informed design decisions before deploying them in real-world IoT networks. The choice of simulation environment depends on factors such as the specific research goals, familiarity with the tool, and the complexity of the network scenarios being evaluated.

7.2. Evaluation criteria, including network lifetime, energy efficiency, and data transmission delays.

When evaluating Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs) in IoT networks, it's important to consider a range of criteria that reflect their impact on network performance, energy efficiency, and overall system behavior. Here are the key evaluation criteria to assess the effectiveness of DEHARAs:

1. **Network Lifetime**:
    - **Definition**: Network lifetime refers to the duration of time until the first node depletes its energy reserves, rendering it inactive.
    - **Importance**: A longer network lifetime indicates the algorithm's success in optimizing energy consumption and extending the operational period of the network.
    - **Evaluation**: Measure the time until the first node's energy depletion and compare it with other DEHARAs and non-energy-aware routing approaches.
2. **Energy Efficiency**:
    - **Definition**: Energy efficiency quantifies how effectively the algorithm utilizes available energy resources for communication and other network tasks.
    - **Importance**: Higher energy efficiency ensures that the network can operate for an extended period while minimizing the need for frequent battery replacement or recharging.
    - **Evaluation**: Calculate the total energy consumption over the simulation period and compare it across different DEHARAs. Assess how well the algorithm balances energy consumption across nodes.

3. **Data Transmission Delays**:
    - **Definition**: Data transmission delay refers to the time taken for a packet to travel from the source node to the destination node.
    - **Importance**: Lower transmission delays enhance the efficiency of data delivery, reducing latency and ensuring timely communication.
    - **Evaluation**: Measure the average end-to-end delay for packets transmitted through the network using the DEHARA. Compare delay metrics across different routing algorithms.
4. **Packet Delivery Ratio (PDR)**:
    - **Definition**: PDR is the ratio of successfully delivered packets to the total packets sent by the source nodes.
    - **Importance**: A high PDR indicates that the algorithm successfully maintains reliable communication despite energy constraints.

  - **Evaluation**: Calculate the PDR by measuring the number of delivered packets divided by the total packets sent. Compare PDR values for different DEHARAs.

5. **Load Balancing**:
   - **Definition**: Load balancing assesses the distribution of communication and processing tasks across nodes to prevent energy depletion in specific nodes.
   - **Importance**: Effective load balancing ensures that no node becomes a performance bottleneck or depletes its energy faster than others.
   - **Evaluation**: Analyze the distribution of tasks and energy consumption among nodes. Measure load balancing using metrics like energy variance or task distribution.
6. **Energy Harvesting Utilization**:
   - **Definition**: Energy harvesting utilization indicates the percentage of harvested energy effectively used for communication and network tasks.
   - **Importance**: Higher utilization demonstrates the algorithm's ability to leverage energy-harvesting capabilities to sustain network operations.
   - **Evaluation**: Calculate the ratio of energy consumed for communication to the total harvested energy. Compare utilization rates for different DEHARAs.
7. **Adaptability to Energy Variability**:
   - **Definition**: Adaptability assesses how well the algorithm adjusts routing decisions in response to changing energy conditions.
   - **Importance**: Algorithms that can adapt to fluctuations in energy availability perform well in dynamic environments.
   - **Evaluation**: Evaluate the algorithm's responsiveness to energy changes and its ability to maintain performance under varying energy conditions.
8. **QoS Metrics**:
   - **Definition**: Quality of Service (QoS) metrics include factors like latency, throughput, and reliability, which influence the user experience.
   - **Importance**: DEHARAs should maintain acceptable QoS levels while optimizing energy usage.
   - **Evaluation**: Measure latency, throughput, and reliability for different DEHARAs and compare them against application-specific QoS requirements.
9. **Robustness and Resilience**:
   - **Definition**: Robustness assesses the algorithm's ability to maintain reliable communication in the presence of node failures, energy fluctuations, and other disturbances.

  - **Importance**: A robust DEHARA ensures network stability and reduces the impact of failures on overall performance.
  - **Evaluation**: Introduce random node failures or energy variations and observe how the algorithm adapts and recovers.

10. **Scalability**:
    - **Definition**: Scalability evaluates the algorithm's performance as the network size and complexity increase.
    - **Importance**: Scalable algorithms can handle larger networks without sacrificing energy efficiency or other performance metrics.
    - **Evaluation**: Gradually increase the network size and observe changes in performance metrics like energy efficiency, network lifetime, and delay.

By evaluating DEHARAs based on these criteria, researchers and engineers can make informed decisions about the suitability of these algorithms for specific IoT network scenarios and application requirements. Keep in mind that the relative importance of these criteria may vary depending on the context and goals of the evaluation.

7.3. Discussion of simulation results and insights gained from the studies.

While I don't have access to specific simulation results from studies conducted after my last update in September 2021, I can provide a general overview of the insights gained from the studies of Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs) based on typical trends and findings observed in the literature up to that point. Researchers have conducted numerous simulation studies to evaluate the performance of DEHARAs in various IoT network scenarios. Here are some insights that have been gained from these studies:

1. **Extended Network Lifetime**: DEHARAs are designed to optimize energy consumption, leading to significantly extended network lifetimes compared to traditional routing algorithms. Studies show that DEHARAs can prolong the operational period of the network by balancing energy utilization across nodes.
2. **Energy Efficiency Improvement**: DEHARAs aim to leverage energy harvesting capabilities to achieve higher energy efficiency. Simulation results demonstrate that DEHARAs can effectively exploit energy sources and improve the overall energy utilization of the network.
3. **Adaptability to Energy Variability**: DEHARAs exhibit the ability to adapt to changing energy availability. Insights gained from simulations highlight that DEHARAs can dynamically adjust routing decisions in response to varying energy levels, ensuring continuous network operation.

4. **Impact of Heterogeneous Energy Harvesting**: DEHARAs account for the heterogeneous energy harvesting capabilities of nodes. Simulation studies reveal that routing algorithms considering energy heterogeneity can achieve more balanced energy consumption and prolong the network's overall lifetime.
5. **Trade-offs Between Energy Efficiency and QoS**: Simulation results often show a trade-off between energy efficiency and Quality of Service (QoS) metrics such as data transmission delays and reliability. DEHARAs need to strike a balance between minimizing energy consumption and maintaining acceptable QoS levels.
6. **Role of Energy Prediction**: DEHARAs that incorporate energy prediction models offer more informed routing decisions. Simulation insights indicate that accurate energy prediction is crucial for optimizing path selection and overall network performance.
7. **Scalability Challenges**: While DEHARAs offer promising results in smaller networks, simulation studies often reveal challenges related to scalability. As the network size grows, the effectiveness of DEHARAs may be influenced by factors like increased control overhead and communication complexity.
8. **Dynamic Routing Behavior**: DEHARAs demonstrate dynamic routing behavior in response to energy fluctuations. Simulations highlight that these algorithms can intelligently re-route data to nodes with higher energy reserves to ensure reliable communication.
9. **Application-Specific Considerations**: The choice of DEHARA depends on the application requirements. Simulation insights emphasize the need to tailor DEHARAs to the specific application's energy demands, QoS requirements, and network dynamics.
10. **Hybrid Approaches for Enhanced Performance**: Insights gained from simulations suggest that hybrid approaches, combining elements of centralized and distributed strategies, can offer improved performance in terms of network lifetime, energy efficiency, and QoS.
11. **Impact of Mobility**: Mobility of nodes in IoT networks can influence DEHARA performance. Simulation studies explore how DEHARAs adapt to mobility-induced energy variations and routing challenges.
12. **Evaluating Realistic Energy Models**: Effective energy models are essential for accurate simulation results. Insights from studies emphasize the importance of using realistic energy models that consider the characteristics of different energy sources.

In summary, simulation studies of DEHARAs have provided valuable insights into their effectiveness, strengths, limitations, and applicability in diverse IoT network scenarios. These insights help researchers and practitioners make informed decisions when selecting, designing, and implementing DEHARAs for specific deployment scenarios while considering trade-offs between energy efficiency, QoS, and network lifetime. It's important to refer to the latest research literature for up-to-date simulation results and insights.

8. CHALLENGES AND FUTURE DIRECTIONS:

8.1. Identification of challenges and open issues in the domain of DEHARAs for heterogeneous IoT networks.

In the domain of Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs) for heterogeneous IoT networks, several challenges and open issues persist despite significant advancements. These challenges reflect the complex nature of IoT environments, varying energy sources, and the need for efficient routing strategies. Here are some of the key challenges and open issues:

1. **Heterogeneous Energy Sources**:
    - **Challenge**: IoT devices can harness various energy sources, such as solar, kinetic, and thermal. Designing DEHARAs that effectively utilize and manage multiple energy sources is challenging.
    - **Open Issue**: Developing routing algorithms that intelligently switch between different energy sources based on availability and energy-harvesting rates.
2. **Energy Prediction and Estimation**:
    - **Challenge**: Accurate prediction of future energy availability is crucial for proactive routing decisions. However, predicting energy generation rates and consumption patterns remains a complex task.
    - **Open Issue**: Enhancing energy prediction models to account for real-world variations and uncertainties in energy harvesting and consumption.
3. **Trade-offs Between Energy and QoS**:
    - **Challenge**: Balancing energy efficiency with Quality of Service (QoS) metrics like latency, throughput, and reliability is a persistent challenge.
    - **Open Issue**: Developing routing algorithms that dynamically adapt to changing network conditions to maintain acceptable QoS while optimizing energy usage.
4. **Scalability and Network Size**:
    - **Challenge**: As IoT networks grow in size, the scalability of DEHARAs becomes a concern. Increased control overhead and communication complexity can impact algorithm efficiency.
    - **Open Issue**: Exploring strategies to optimize DEHARAs for large-scale IoT deployments while minimizing the impact on energy consumption and network performance.

5. **Distributed Decision Making**:
    - **Challenge**: In distributed DEHARAs, nodes make routing decisions based on local information. Ensuring global network optimization while avoiding centralized control is challenging.
    - **Open Issue**: Investigating mechanisms to achieve a balance between localized decision making and global network optimization in a distributed manner.
6. **Dynamic Network Topology and Mobility**:
    - **Challenge**: IoT networks often exhibit dynamic topologies due to node mobility and changing energy conditions. Adapting routing decisions to dynamic environments is complex.
    - **Open Issue**: Designing DEHARAs that can handle node mobility, topology changes, and varying energy availability without compromising network performance.
7. **Energy Sharing and Cooperation**:
    - **Challenge**: Enabling energy sharing and cooperation among nodes can improve overall network efficiency. However, incentivizing nodes to share energy is not straightforward.
    - **Open Issue**: Exploring incentive mechanisms and cooperation strategies that encourage nodes to share energy resources while maintaining fairness and efficiency.
8. **Integration of QoS and Energy Models**:
    - **Challenge**: Integrating energy-aware routing with application-specific QoS requirements is a complex task, as QoS metrics may conflict with energy conservation goals.
    - **Open Issue**: Developing holistic models that consider both energy constraints and QoS preferences to guide routing decisions effectively.
9. **Real-world Energy Constraints and Variability**:
    - **Challenge**: Real-world IoT environments face unpredictable energy harvesting conditions, device failures, and environmental changes that can impact DEHARA performance.
    - **Open Issue**: Enhancing the robustness of DEHARAs by developing algorithms that can adapt to unpredictable and dynamic energy scenarios.
10. **Cross-Layer Optimization**:
    - **Challenge**: Optimizing energy-aware routing at different protocol layers (physical, MAC, routing) requires coordination and cooperation between layers.
    - **Open Issue**: Investigating cross-layer optimization strategies that leverage information from various layers to achieve improved energy efficiency and QoS.
11. **Security and Privacy Considerations**:
    - **Challenge**: Ensuring secure communication while minimizing energy consumption poses challenges in DEHARAs, especially in resource-constrained IoT devices.

   - **Open Issue**: Developing energy-efficient security mechanisms that protect data and communication without significantly impacting energy usage.

12. **Real-world Deployment and Validation**:
    - **Challenge**: Translating simulation results to real-world deployments is challenging due to practical constraints and variations.
    - **Open Issue**: Conducting field trials and real-world experiments to validate DEHARA performance in heterogeneous IoT networks under diverse conditions.

Addressing these challenges and open issues is essential to advancing the field of DEHARAs and enabling efficient, reliable, and energy-conscious routing in heterogeneous IoT networks. Ongoing research and collaboration are necessary to develop innovative solutions that meet the diverse requirements of IoT applications and contribute to the sustainable growth of the Internet of Things.

8.2. Potential avenues for future research and improvements.

The field of Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs) continues to offer numerous opportunities for future research and improvements. As IoT networks become more diverse and complex, addressing emerging challenges and exploring innovative solutions will be crucial. Here are some potential avenues for future research and improvements in the DEHARA domain:

1. **Multi-Objective Optimization**: Develop DEHARAs that consider multiple objectives, such as energy efficiency, QoS, network lifetime, and load balancing, simultaneously. Design algorithms that dynamically adapt routing decisions to achieve a balance among these conflicting objectives.
2. **Machine Learning and AI Techniques**: Explore the integration of machine learning and AI techniques to enhance the adaptability and intelligence of DEHARAs. Deep reinforcement learning, neural networks, and other AI approaches can help optimize routing decisions based on evolving energy conditions.
3. **Edge and Fog Computing Integration**: Investigate how DEHARAs can be tailored for edge and fog computing environments, where resource-constrained devices cooperate to process data closer to the data source. Design routing algorithms that optimize energy consumption in such distributed computing scenarios.
4. **Energy Harvesting-Aware Security**: Research energy-efficient security mechanisms that protect IoT communication while minimizing energy consumption. Develop methods to ensure data confidentiality, integrity, and authentication within the constraints of energy-harvesting devices.
5. **Dynamic Energy Prediction Models**: Enhance energy prediction models with real-time data and learning algorithms to improve accuracy in forecasting energy availability. Investigate how to dynamically update energy predictions and adapt routing decisions accordingly.

6. **Decentralized Energy Sharing**: Explore decentralized energy-sharing mechanisms among IoT devices. Develop protocols that enable nodes with excess energy to share with those in need, promoting cooperation and maximizing energy utilization.
7. **Hybrid Energy Storage Solutions**: Investigate the integration of hybrid energy storage solutions, combining batteries, supercapacitors, and other storage technologies. Design DEHARAs that leverage diverse energy storage options for improved energy utilization.
8. **Energy-Efficient MAC Protocols**: Collaborate with MAC layer researchers to design energy-efficient Medium Access Control (MAC) protocols that align with DEHARAs' goals. Develop MAC strategies that reduce energy consumption during communication and idle periods.
9. **Blockchain and Distributed Ledger Technology**: Explore how blockchain and distributed ledger technology can be leveraged to enhance energy management and sharing in IoT networks. Design DEHARAs that utilize blockchain for transparent and secure energy transactions.
10. **Dynamic Network Topology Optimization**: Investigate algorithms that optimize network topology and node placement to enhance energy harvesting and routing efficiency. Design DEHARAs that adapt to topology changes and node mobility.
11. **Energy Harvesting-Aware Mobility Models**: Develop mobility models that consider energy harvesting patterns and constraints. Simulate realistic node movements and energy harvesting dynamics to evaluate the performance of DEHARAs.
12. **Real-world Deployment and Validation**: Conduct field trials and real-world experiments to validate the effectiveness of DEHARAs in practical IoT deployments. Gather empirical data to compare simulation results with real-world performance.
13. **Standardization and Interoperability**: Contribute to the development of standardized energy-aware routing protocols that can be adopted across different IoT platforms and technologies. Focus on interoperability to ensure compatibility between heterogeneous devices.
14. **Sustainable IoT Ecosystems**: Research how DEHARAs can contribute to the creation of sustainable IoT ecosystems. Explore how energy-aware routing can be integrated into smart cities, industrial IoT, agriculture, healthcare, and other application domains.
15. **Environmental Impact Assessment**: Conduct comprehensive studies to assess the environmental impact of DEHARAs in terms of energy savings, reduction in carbon footprint, and overall sustainability of IoT networks.

By focusing on these potential avenues, researchers can advance the state of DEHARAs, address current limitations, and contribute to the development of energy-efficient and resilient routing solutions for heterogeneous IoT networks. As technology evolves and IoT applications diversify, the exploration of these research directions will play a pivotal role in shaping the future of energy-aware routing algorithms.

9. CONCLUSION:

9.1. Summary of the current state and future prospects of DEHARAs for heterogeneous IoT networks.

As of September 2021, Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs) have made significant progress in addressing energy challenges in diverse IoT networks. These algorithms optimize energy usage, extend network lifespan, and ensure reliable communication, adapting to varying energy sources. Here's a summary of their status and future prospects:

Current State:

- Researchers have developed DEHARAs considering energy availability, residual energy, and communication needs. These algorithms balance efficiency and Quality of Service (QoS) while adapting to dynamic energy conditions.
- DEHARAs are rigorously evaluated through simulations using tools like ns-3 and OMNeT++. These evaluations assess metrics like network lifetime, energy efficiency, scalability, and QoS.
- Many DEHARAs adopt hybrid strategies, combining centralized and distributed approaches, aiming for global optimization and local adaptability.
- Energy prediction models have emerged to estimate future energy, aiding DEHARAs in proactive routing decisions.

Future Prospects:

- Future research will likely focus on multi-objective optimization, where DEHARAs balance energy efficiency, network lifetime, QoS, and load balancing.
- Integrating AI and machine learning can enhance DEHARAs' adaptability. Techniques like deep reinforcement learning could improve routing efficiency.
- DEHARAs will evolve to include edge and fog computing. Algorithms will optimize energy use in distributed computing settings.
- Energy-efficient security mechanisms will emerge, safeguarding IoT communication while minimizing energy usage.
- Developing accurate and dynamic energy prediction models will be a priority, enhancing forecasting accuracy through real-time data and learning algorithms.
- Standardized DEHARAs will gain importance for broader adoption. Field trials will validate their effectiveness in practical settings.
- DEHARAs will contribute to sustainable IoT ecosystems, conserving energy in domains like smart cities, agriculture, healthcare, and industrial IoT.
- Interdisciplinary collaboration will grow, as researchers in networking, energy harvesting, AI, and environmental science work together to tackle DEHARA challenges.

In summary, DEHARAs have the potential to revolutionize energy management in heterogeneous IoT networks. While significant progress has been made, ongoing research will refine and innovate these algorithms to meet evolving energy-efficient and resilient IoT communication needs. As technology advances and applications diversify, DEHARAs will play a crucial role in ensuring optimized and sustainable network operations. For the latest developments beyond September 2021, consult recent literature.

In conclusion, this survey paper presents a comprehensive exploration of the existing Distributed Energy-Harvesting-Aware Routing Algorithms (DEHARAs) designed for heterogeneous IoT networks. By addressing the challenges of energy heterogeneity and optimizing energy utilization, DEHARAs contribute significantly to sustainable and resilient IoT deployments. The survey also highlights the potential research directions and practical implementations for researchers and practitioners interested in designing energy-efficient and eco-friendly IoT infrastructures.

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