A SURVEY OF ENERGY-EFFICIENT MAC AND ROUTING PROTOCOLS

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Abstract: Energy-efficient Medium Access Control (MAC) and routing protocols are essential for minimizing power consumption in Internet of Things (IoT) networks, because devices generally function within constrained power budgets. This survey article examines multiple MAC and routing protocols developed to improve energy economy. The document classifies protocols according to their operational principles and emphasizes their advantages and disadvantages in resource-limited IoT contexts. This review emphasizes the necessity for more research to enhance energy efficiency via adaptable, scalable, and context-sensitive methods.
Keywords: Energy efficiency, Medium Access Control protocol, Routing protocol, Internet of Things, Resource-constrained networks.

I. INTRODUCTION

The Internet of Things (IoT) signifies a revolutionary change in the interaction, communication, and functioning of devices across various domains, such as industrial automation, healthcare, smart cities, and environmental monitoring. IoT networks comprise several sensors, actuators, and intelligent devices that collectively gather, process, and communicate data via wireless networks. A salient feature of these networks is that numerous devices are resource-constrained—they frequently depend on limited battery power, possess low processing capabilities, and are situated in potentially inaccessible locations, rendering energy efficiency a crucial factor for network sustainability and overall viability. With the proliferation of IoT devices, the task of managing energy use is becoming more urgent. Forecasts suggest that by the mid-2020s, billions of networked devices will exist, with each device's energy consumption affecting the network's sustainability. Historically, Medium Access Control (MAC) and routing protocols were not developed with rigorous energy limitations in consideration. Legacy protocols were largely designed for robustness and dependability, rather than energy efficiency, leading to inferior performance in IoT frameworks. These methods can result in significant energy wastage due to excessive idle listening, packet collisions, overhearing, and redundant data transmission. Medium Access Control (MAC) protocols in IoT are essential for regulating node access to the communication channel, orchestrating the timing of transmissions, receptions, or sleep modes to optimize energy consumption. An effectively engineered MAC protocol can mitigate energy expenditure resulting from collisions and idle listening, particularly in densely populated networks with several communicating nodes. For example, duty cycling in MAC protocols enables nodes to switch between active and sleep states, therefore substantially decreasing the duration of power-intensive operations. Routing protocols are crucial for guiding data packets from source nodes to destination nodes or gateways inside the network. In an energy-efficient routing protocol, data is transmitted via optimal paths, considering the remaining energy of nodes, proximity to the sink, and network structure. Routing decisions in IoT networks must be adaptive, distributing energy consumption among nodes to avert premature battery exhaustion in vital regions of the network. This strategy prevents nodes in critical places from becoming "hot spots" that rapidly deplete, hence maintaining overall network connectivity and performance. This survey study examines the progress of energy-efficient MAC and routing protocols, emphasizing their relevance in IoT contexts. We examine and classify diverse protocols based on their operational methods, including contention-based and scheduled MAC protocols, along with data-centric, hierarchical, and geographic routing protocols.

This article attempts to elucidate the tactics employed to augment energy efficiency in each protocol type, providing insights into their strengths, limitations, and applicability across various IoT scenarios.

This paper's principal contributions are as follows:

- Thorough Classification: We classify and examine energy-efficient MAC and routing protocols, providing a systematic review of methods employed to minimize energy consumption.
- We conduct a comparative analysis of these protocols, highlighting their energy efficiency, scalability, and appropriateness for various IoT applications.
- Identification of Future Research paths: Our research reveals gaps and suggests potential future paths, especially in the creation of adaptive, scalable, and intelligent protocols for the Internet of Things (IoT).

This paper emphasizes the significance of MAC and routing protocols in optimizing energy efficiency, therefore prolonging the longevity of IoT networks, improving network resilience, and facilitating sustainable IoT applications.

II. CONTEXT AND RELEVANT LITERATURE

A. Energy Limitations in IoT Networks

Energy limitations in IoT networks arise from the prevalence of battery-operated nodes, frequently situated in remote or inaccessible areas. The energy expenditure for data transmission is generally the most significant, succeeded by that of data reception and idle listening, wherein a node remains active without engaging in data transmission or reception. Research demonstrates that passive listening significantly contributes to energy inefficiency in wireless sensor networks (WSNs) and Internet of Things (IoT) networks. Numerous research initiatives have concentrated on reducing this waste by developing protocols that enable nodes to enter low-power sleep states when communication is unnecessary [1], [2]. IoT devices typically possess constrained computing and storage capacities, rendering them incapable of executing energy management algorithms that necessitate substantial processing power or memory. These constraints highlight the necessity for lightweight, efficient protocols that can function within stringent energy limitations while maintaining network dependability and communication quality.

B. Summary of MAC Protocols

Medium Access Control (MAC) protocols are essential for regulating the shared communication medium in Internet of Things (IoT) networks. The primary problem for MAC protocols in IoT is to regulate channel access to minimize energy consumption while ensuring low latency and high reliability. Current MAC protocols for IoT can be categorized into contention-based and scheduled methods, each providing distinct mechanisms for optimizing energy efficiency. Contention-based MAC protocols, such S-MAC (Sensor-MAC), mitigate idle listening by permitting nodes to enter sleep mode during inactivity, whereas scheduled MAC protocols, such as TDMA-based methods, prevent collisions by assigning unique timeslots to each node.

III. ENERGY-EFFICIENT MEDIUM ACCESS CONTROL PROTOCOLS

In IoT networks, where devices frequently possess constrained energy resources, Medium Access Control (MAC) protocols are crucial for regulating node access to the communication channel.

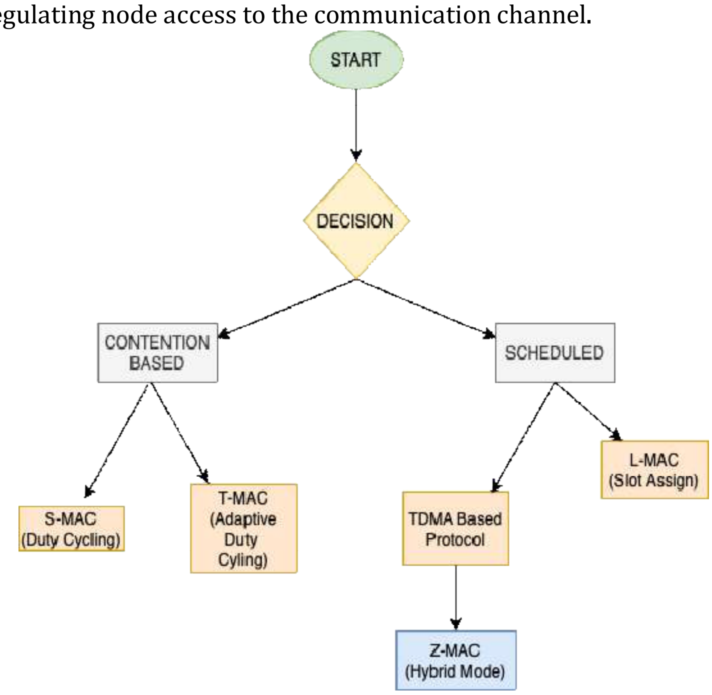

Fig 1. Flowchart of MAC Protocol Categories and Functionality

These protocols seek to reduce energy usage during data transmission, reception, and idle phases. MAC protocols can be classified into contention-based and scheduled types, each designed for distinct network characteristics and application needs.

A. Protocols Based on Contention

Contention-based MAC protocols function by permitting nodes to compete for access to the communication medium, instead of allocating particular time slots for each node. This method provides adaptability, particularly in settings where traffic volumes vary. Contention-based protocols generally integrate methods to prevent collisions and reduce idle listening, which are major contributors to energy usage.

- **S-MAC (Sensor Medium Access Control)**

S-MAC (Sensor MAC) is a prominent contention-based protocol specifically engineered for wireless sensor networks. S-MAC employs synchronized sleep periods to mitigate idle listening, a prevalent cause of energy inefficiency in wireless networks. In S-MAC, each node adheres to a predetermined duty cycle, alternating frequently between sleep and wake states. During the sleep phase, nodes deactivate their radio transceivers, significantly diminishing energy consumption. Upon activation, nodes monitor the channel for incoming communication requests. In the absence of data transmission, the nodes promptly revert to a dormant state.

Benefits:

a. Energy conservation: By minimizing idle listening duration, S-MAC enhances battery longevity, which is essential in energy-constrained IoT networks.
b. Simplicity and scalability: The duty cycling of S-MAC is straightforward to implement and may scale efficiently in networks characterized by static nodes or sporadic communication.

Constraints:

a. Increased latency: Fixed sleep schedules may result in delays, as nodes could be inactive when a communication request is received. This poses significant challenges in applications necessitating real-time data transmission.
b. Inflexibility in traffic variability: S-MAC fails to adjust effectively to fluctuating traffic conditions, as the duty cycle remains constant irrespective of network activity.

S-MAC is appropriate for IoT applications characterized by infrequent data transfer, such as environmental monitoring, where nodes intermittently gather and relay sensor values instead of maintaining continuous communication.

- **T-MAC (Timeout Medium Access Control)**

T-MAC (Timeout MAC) enhances S-MAC by implementing adaptive duty cycles, enabling nodes to modify their sleep and wake intervals according to network activity. T-MAC implements a timeout mechanism, wherein nodes activate and monitor for activity during a designated interval. If no communication is observed within this interval, the node reverts to a dormant state. Nevertheless, upon detecting activity, nodes prolong their active duration, facilitating more adaptable functioning in dynamic settings.

Benefits:

a. Adaptability: T-MAC's capacity to dynamically modify duty cycles in response to traffic levels enhances its energy efficiency in networks characterized by irregular or changeable traffic.
b. T-MAC decreases energy waste by being active solely when required, hence optimizing efficiency during low-traffic intervals, which is advantageous for applications characterized by sporadic or erratic data transmission.

Constraints:

a. The adaptive duty cycle technique introduces protocol complexity, necessitating advanced control logic and potentially increased processing power.
b. Challenges in high-traffic environments: T-MAC may encounter difficulties in networks characterized by persistent high traffic, as nodes may remain active for extended durations, hence undermining energy efficiency.

T-MAC is ideally designed for IoT networks characterized by sporadic communication, such as wildlife monitoring or smart agriculture, where sensors activate solely upon the detection of events (e.g., motion or temperature fluctuations).

- **B-MAC (Berkeley Medium Access Control)**

B-MAC (Berkeley MAC) is another significant contention-based protocol that use low-power listening and preamble sampling to identify communication requests. B-MAC enables nodes to intermittently awaken and monitor for an extended preamble before to completely activating for data reception. This method enables nodes to remain in low-power mode for prolonged durations, thereby substantially conserving energy.

Benefits:

a. B-MAC's low-power listening feature renders it one of the most energy-efficient protocols during idle states.
b. Customizability: B-MAC facilitates the precise adjustment of duty cycle characteristics, which can be tailored to application requirements for maximum energy efficiency.

Constraints:

a. Elevated transmission overhead: The extended preamble necessitated in B-MAC might prolong transmission duration, leading to augmented overhead, especially in extensive networks.

b. B-MAC has diminished performance in high-traffic networks, since the overhead associated with preamble sampling may surpass its advantages in densely populated environments.

B-MAC is frequently employed in applications such as periodic data gathering, where nodes may remain inactive for prolonged durations between transmissions, exemplified by air quality monitoring in urban environments.

B. Designated Protocols

Scheduled MAC protocols, especially those utilizing TDMA (Time Division Multiple Access), assign designated time slots to each node for data transmission, therefore obviating the necessity for nodes to compete for the communication channel. This method minimizes collisions and idle listening, resulting in significant energy efficiency in networks characterized by predictable traffic patterns.

- **Protocols Based on Time Division Multiple Access (TDMA)**

In TDMA-based MAC protocols, communication time is partitioned into fixed-length time slots, with each node allocated a specific slot for data transmission. As each node possesses a specific slot, the possibility of collision is eliminated, allowing nodes to enter a sleep state outside their assigned transmission slot. This method is especially beneficial in networks characterized by consistent and foreseeable communication, such as industrial IoT environments.

Benefits:

a. High energy efficiency: TDMA-based protocols can realize significant energy savings by preventing collisions and reducing idle listening.
b. Predictable performance: TDMA guarantees predictable performance by assigning each node a predetermined slot, which is essential for applications necessitating reliable communication.

Constraints:

a. TDMA necessitates exact time synchronization across all nodes, which can be difficult in extensive, distributed networks.
b. Limited flexibility: TDMA may lack adaptability to fluctuating traffic conditions, as time slots remain fixed irrespective of current network activity levels.

TDMA-based protocols are ideally suited for industrial automation and smart grid applications, where consistent data transmission times are prevalent and synchronization is achievable.

- **LMAC (Lightweight Message Authentication Code)**

LMAC (Lightweight MAC) is a TDMA-oriented protocol formulated for densely populated IoT networks. In LMAC, each node allocates a time slot according to its distinct identification and local data, facilitating operation with little overhead. This localized method of slot assignment minimizes the necessity for global synchronization and control messages, rendering LMAC appropriate for crowded networks.

Benefits:

a. Scalability: LMAC's slot assignment mechanism enables successful scaling across extensive networks, as nodes can autonomously select slots without centralized coordination.
b. Energy conservation: LMAC attains significant energy efficiency by preventing collisions and ensuring that nodes remain active solely within their designated time slots.

Constraints:

a. Synchronization issues in extensive deployments: Although LMAC necessitates less synchronization than conventional TDMA protocols, a certain level of temporal coordination remains essential, which can be challenging in exceedingly large or highly distributed networks.
b. Complexity in dynamic networks: LMAC is less appropriate for networks with frequent node fluctuations, as slot assignment requires continual modifications.

Applications: LMAC is well-suited for dense sensor networks, including smart buildings and environmental monitoring, where nodes are stationary and may take advantage of collision-free communication.

- **Z-MAC (Zebra Medium Access Control)**

Z-MAC (Zebra MAC) is a hybrid protocol that integrates features of both contention-based and scheduled MAC protocols. It functions in TDMA mode during peak traffic periods and transitions to CSMA (Carrier Sense Multiple Access) mode when network traffic diminishes. This hybrid methodology enables Z-MAC to adjust to fluctuating traffic volumes while preserving energy efficiency.

Benefits:

a. Flexibility: Z-MAC's dual-mode functionality allows it to adjust to diverse traffic patterns, rendering it adaptable for multiple IoT applications.
b. Enhanced energy efficiency: Z-MAC optimizes energy conservation by employing TDMA in heavy traffic conditions and CSMA in low traffic scenarios, surpassing protocols restricted to a singular access technique.

Constraints:

a. Complex control logic: The mode-switching of Z-MAC creates intricacy, necessitating supplementary coordination and control methods.

b. Increased overhead in dynamic networks: Frequent mode switching may result in significant overhead, especially in networks characterized by quickly fluctuating traffic conditions.

Z-MAC is appropriate for IoT applications characterized by heterogeneous traffic patterns, such as smart city implementations, where traffic fluctuations occur due to temporal and environmental influences.

IV. PROTOCOLS FOR ENERGY-EFFICIENT ROUTING

A. Data-Centric Routing

Data-centric routing algorithms emphasize data characteristics rather than specific node identities, rendering them particularly effective for sensor networks where nodes gather comparable data suitable for aggregation. Directed Diffusion is an innovative data-centric protocol that utilizes a publish-subscribe approach, allowing nodes to subscribe to particular data kinds and exclusively transmit data that aligns with the subscription parameters. This method minimizes unnecessary transmissions by consolidating data at intermediary nodes, thereby substantially conserving energy. Directed Diffusion has demonstrated efficacy in static sensor networks, although it may necessitate supplementary strategies to address mobility in dynamic IoT contexts [6].

B. Hierarchical Routing

In hierarchical routing, nodes are structured into clusters, with a designated node in each cluster serving as the cluster head. This hierarchical framework facilitates effective data aggregation and minimizes the overall transmission count. LEACH (Low-Energy Adaptive Clustering Hierarchy) is among the most extensively researched hierarchical techniques. LEACH periodically rotates the cluster head role across nodes to distribute energy usage, hence preventing any single node from prematurely emptying its battery. Notwithstanding its advantages, LEACH generates overhead from the necessity of frequent re-clustering, potentially diminishing its efficacy in swiftly evolving networks [7].

C. Geospatial Routing

Geographic routing techniques utilize node location data to drive forwarding decisions, facilitating streamlined routing without the necessity for elaborate route discovery procedures. GPSR (Greedy Perimeter Stateless Routing) utilizes the geographic coordinates of a packet's destination to facilitate data routing in a greedy fashion, hence minimizing the number of hops necessary to get at the destination. GPSR is efficient in sparse networks; nevertheless, its dependence on geographic information necessitates that nodes possess access to precise positioning systems, which may not always be practical in IoT implementations [8].

V. COMPARATIVE EXAMINATION OF PROTOCOLS

The protocols analyzed in this survey reveal diverse methodologies for energy efficiency, each displaying advantages and disadvantages contingent upon network design, density, and traffic patterns. Contention-based MAC protocols, such as T-MAC, are beneficial in networks with intermittent communication requirements, but scheduled methods like LMAC excel in stable, densely populated networks. Likewise, routing protocols such as LEACH are adept for clustered network architectures, whereas spatial routing techniques like GPSR are superior in situations where nodes reliably access location information.

TABLE I: Comparative Analysis of Energy-Efficient Protocols

PROTOCOL	TYPE	ENERGY EFFICIENCY	SCALABILITY	FEATURES
S-MAC	Contention-based	Moderate	Moderate	Duty cycling, synchronized sleep
T-MAC	Contention-based	High	Moderate	Adaptive duty cycles
LMAC	Scheduled	High	High	TDMA-based, low collision rate
LEACH	Hierarchical	High	Moderate	Clustering, role rotation
GPSR	Geographic	High	High	Location-based forwarding

VI. PROSPECTIVE DEVELOPMENTS

Future endeavors in energy-efficient protocol design for IoT networks will likely focus on adaptive and intelligent protocols capable of dynamically adjusting to environmental circumstances and network requirements. Hybrid protocols that integrate characteristics of both contention-based and scheduled methods may yield best energy conservation by adjusting to traffic situations in real-time. Moreover, machine learning may facilitate predictive energy management, enabling nodes to modify their communication patterns according to expected network activity. These developments will be crucial in facilitating scalable, resilient, and sustainable IoT networks.

VII. CONCLUSION

In IoT networks, energy efficiency is crucial since devices operate under inherent resource limitations in contexts with restricted or absent power sources. This article has examined diverse energy-efficient MAC and routing protocols, emphasizing their essential function in extending network longevity and facilitating sustainable operation. Medium Access Control (MAC) protocols, which regulate medium access and determine when nodes send or receive, have been examined through both contention-based and scheduled methodologies. Contention-based protocols, like as S-MAC and T-MAC, offer flexibility and adaptability, rendering them appropriate for networks with fluctuating traffic patterns, but scheduled protocols, such TDMA-based LMAC, thrive in stable and dense networks owing to their predictable energy-efficient frameworks.

Routing protocols, conversely, enhance the pathways data traverses throughout the network, equilibrating energy distribution across nodes. Data-centric routing algorithms, such as Directed Diffusion, minimize redundant transmissions via in-network data aggregation, rendering them very efficient for sensor networks. Hierarchical methods, such as LEACH, prolong network longevity by allocating the energy demands of routing across many cluster heads, whereas geographic routing techniques like GPSR decrease hop count by utilizing node positioning, hence diminishing energy consumption in data transmission. Each protocol type presents distinct advantages and disadvantages, with their efficacy mostly influenced by network factors, including traffic patterns, node density, and topology stability. The examined protocols exhibit notable progress; yet, numerous obstacles persist. Protocol adaptability presents a significant problem, since existing protocols frequently fail to dynamically react to fluctuations in network conditions, including variable traffic loads or node mobility. This underscores the necessity for hybrid methodologies that integrate the advantages of many protocol types and adjust to environmental fluctuations in real-time. Future study should examine the incorporation of machine learning for predictive energy management, facilitating protocols to proactively tune parameters based on expected network activity. Moreover, cross-layer designs that promote coordination between the MAC and routing layers could improve overall energy efficiency by enabling more integrated decision-making based on the network's complete state. In conclusion, although considerable progress has been achieved, enhancing energy-efficient protocols is crucial for unlocking the complete potential of IoT networks. Ongoing innovation in adaptive, intelligent, and cross-layer protocol design will be essential for meeting the increasing demands on IoT infrastructure and facilitating the sustainable, long-term implementation of IoT applications across various domains.

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