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Routing Protocols in Wireless Sensor Networks

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ABSTRACT

Wireless Sensor Networks (WSNs) are widely deployed in a variety of application domains that require large-scale sensor node deployment over extensive geographic areas. Due to limited transmission ranges and energy constraints, direct communication between all nodes is often infeasible, making multi-hop communication a fundamental requirement. Routing protocols play a critical role in enabling reliable and efficient data transmission by establishing and maintaining communication paths among sensor nodes. The performance of these protocols is strongly influenced by node capabilities, energy limitations, and application-specific requirements.

This paper presents a comprehensive survey of prominent routing protocols designed for wireless sensor networks, with emphasis on their operational principles and suitability for different application scenarios. In addition, the study highlights optimization techniques proposed by Spanish research institutions, focusing on improving routing efficiency and reducing energy consumption in WSNs. The objective of this review is to assist researchers in understanding key design considerations and trade-offs involved in selecting routing protocols for resource-constrained sensor network environments.

Keyword: - Wireless Sensor Networks, Routing Protocols, Energy Efficiency, Multi-hop Communication, Quality of Service, Data Aggregation

1. INTRODUCTION

Wireless Sensor Networks (WSNs) are designed to observe and monitor physical or environmental conditions through the collection of data by distributed sensor nodes. Each node is capable of sensing, local data processing, and forwarding information to a sink node, where application-level processing is performed. Direct communication between individual sensor nodes and the sink typically requires high transmission power, which rapidly depletes the limited energy resources of sensor nodes.

To mitigate this limitation, cooperative communication among nodes is employed, allowing data to be forwarded through intermediate sensors. This approach enables multi-hop routing, significantly reducing energy consumption and extending network lifetime.Early communication mechanisms in WSNs did not utilize routing protocols. Flooding, one of the simplest techniques, broadcasts data packets to all neighboring nodes, which then retransmit the message until it reaches the destination. Despite its simplicity, flooding suffers from several disadvantages, including excessive energy consumption, data redundancy, and message implosion.

Designing routing mechanisms for sensor networks presents unique challenges, particularly with respect to node identification. Assigning globally unique identifiers manually is impractical due to the large number of nodes. Furthermore, identifiers such as MAC addresses or GPS coordinates introduce significant communication overhead. As a result, attribute-based addressing—where nodes are identified using properties such as location or sensor type—is better suited to WSN environments.

Routing protocols exploit these addressing schemes to establish and maintain communication paths. Since routing requirements vary across applications, understanding the characteristics of different routing strategies is essential. This paper reviews major routing approaches, including attribute-based, geographic, hierarchical, and multipath routing protocols.

2. ALGORITHM PARADIGMS IN WIRELESS SENSOR NETWORKS

Wireless Sensor Networks (WSNs) consist of a large number of low-power sensor nodes that collaboratively monitor physical or environmental conditions such as temperature, humidity, vibration, or pressure. In order to achieve application objectives, sensor nodes must exchange information and execute algorithms that coordinate sensing, data processing, and communication. Based on the organization of computation and the scope of information used, algorithms executed in WSNs can be broadly categorized into three paradigms: centralized, distributed, and localized algorithms [4].

2.1 Centralized Algorithms

Centralized algorithms rely on a single node, typically the sink or base station, which maintains a global view of the network. Sensor nodes collect raw data and transmit it to the central entity, where all processing, analysis, and decision-making tasks are performed. This paradigm simplifies algorithm design and enables the use of sophisticated optimization techniques due to the availability of complete network information. However, centralized approaches are rarely adopted in practical WSN deployments. The frequent transmission of data toward a single node result in high communication overhead, rapid energy depletion of intermediate nodes, and increased network congestion. Moreover, centralized solutions introduce a single point of failure, making the network vulnerable to sink failures. As a result, centralized algorithms are generally limited to small-scale networks or applications where energy constraints are less critical.

2.2 Distributed Algorithms

Distributed algorithms divide computation across multiple sensor nodes. Each node performs partial processing based on locally available information and exchanges messages with neighbouring nodes to achieve a global objective. This collaborative approach significantly improves scalability, robustness, and fault tolerance. Distributed algorithms are well-suited for large-scale WSNs, as they reduce reliance on a central entity and allow the network to adapt dynamically to node failures and topology changes. Nevertheless, the design of distributed algorithms is more complex, as it requires careful coordination to avoid excessive message overhead, synchronization issues, and inconsistencies in network state.

2.3 Localized Algorithms

Localized algorithms represent a subclass of distributed approaches in which nodes make decisions solely based on information obtained from their immediate neighbours. By limiting communication to a small local region, localized algorithms significantly reduce energy consumption and improve network longevity. Despite their efficiency, localized algorithms often require additional mechanisms to provide spatial awareness, such as GPS modules or localization protocols. These mechanisms increase system cost, energy consumption, and hardware complexity. Consequently, the suitability of localized algorithms depends on application requirements and deployment constraints.

The choice of algorithm paradigm plays a fundamental role in routing protocol design. Localized algorithms require routing protocols that emphasize efficient neighbour-to-neighbour communication, while centralized algorithms benefit from aggregation-oriented routing toward a single node. Distributed algorithms, in contrast, demand flexible routing strategies that support communication between arbitrary node pairs across the network.

3. DESIGN CONSTRAINTS FOR WSN ROUTING

Routing protocol design in WSNs is strongly influenced by the inherent limitations of sensor nodes and the unpredictable nature of deployment environments. The most significant constraints include:

3.1 Autonomous Operation

Wireless sensor networks are typically deployed in unattended or hostile environments, where centralized control is infeasible. Consequently, routing decisions must be made autonomously by individual nodes. This decentralized operation enhances reliability and eliminates single points of failure, but it also increases the complexity of routing protocol design.

3.2 Energy Constraints

Energy efficiency is arguably the most critical consideration in WSN routing. Sensor nodes are powered by limited battery resources, and battery replacement is often impractical due to random deployment, inaccessibility, or hazardous conditions. Routing protocols must therefore minimize communication overhead and balance energy consumption across nodes to extend overall network lifetime.

3.3 Scalability

Many WSN applications involve large-scale deployments comprising hundreds or thousands of sensor nodes. Routing protocols must scale efficiently without incurring excessive control overhead or performance degradation as network size increases.

3.4 Fault Tolerance

Sensor nodes are prone to failures caused by battery depletion, hardware malfunction, or environmental interference. Routing protocols must dynamically adapt to such failures by discovering alternative paths and maintaining network connectivity.

3.5 Heterogeneity
Modern WSNs may include heterogeneous nodes with different processing capabilities, communication ranges, and energy resources. Routing protocols that effectively exploit node heterogeneity can significantly improve network performance and reliability.

3.6 Mobility Support
Although many WSNs assume static nodes, certain applications require support for mobility, including mobile sinks, mobile sensor nodes, or moving targets. Routing protocols must be capable of handling frequent topology changes while maintaining communication efficiency.

4. CLASSIFICATION OF ROUTING PROTOCOL

Taking into account their procedures, routing protocols can be roughly classified according to the following criteria.

4.1 Node Hierarchy
Based on node roles, routing protocols can be divided into flat and hierarchical schemes.

4.1.1 Flat Routing Protocols
In flat routing protocols, all sensor nodes are assigned equal responsibilities in routing and data forwarding. While this approach simplifies protocol design, it can lead to excessive energy consumption and poor scalability in large networks.

4.1.2 Hierarchical Routing Protocols
Hierarchical routing protocols organize nodes into clusters, each managed by a cluster head. Cluster heads coordinate data collection within their clusters and communicate aggregated data to higher-level nodes or the sink. This hierarchical structure reduces redundant transmissions, improves scalability, and enhances energy efficiency. Cluster head selection may be static or dynamic, depending on network conditions and application requirements [8].

4.2 Data Transmission Models
The data transmission model defines how information flows from sensor nodes to the sink [7].

- **Continuous Model:** Sensor nodes periodically transmit sensed data at fixed intervals, suitable for applications requiring constant monitoring.
- **Event-Driven Model:** Data transmission occurs only when a predefined event is detected, conserving energy during idle periods.
- **Query-Driven Model:** Nodes remain silent until explicitly queried by the sink, reducing unnecessary communication.
- **Hybrid Model:** Combines periodic reporting, event-based notifications, and query responses to support diverse application requirements.

5. ROUTING OPTIMIZATION TECHNIQUES

The particular characteristics of wireless sensor networks and their constraints have prompted the need for specific requirements to routing protocols. When compared to mobile *ad hoc* networks routing protocols, the algorithms in wireless sensor networks usually realize the following specifications:

5.1 Attribute-Based Routing
Rather than using explicit node addresses, attribute-based routing relies on descriptive attributes and queries. Intermediate nodes inspect packet contents to determine forwarding decisions, enabling flexible and application-driven routing.

5.2 Energy-Aware Routing
Energy-aware routing protocols select paths that maximize network lifetime by considering residual node energy. This approach prevents premature node failures and balances energy consumption across the network.

5.3 Data Aggregation and Fusion
To minimize redundant transmissions, intermediate nodes aggregate similar data collected from nearby sensors. When advanced signal processing techniques are applied, this process is referred to as data fusion, further reducing communication overhead.

5.4 Addressing Mechanisms
Due to the large scale of WSNs, manual assignment of globally unique identifiers is infeasible. The use of MAC addresses or GPS coordinates introduces significant overhead [3]. Instead, routing protocols employ locally unique identifiers or field-wide identifiers as required by the application.

5.5 Location-Based Routing

Location-based routing protocols use geographic information to guide forwarding decisions, resulting in shorter paths and reduced energy consumption.

5.6 Multipath Routing

Multipath routing establishes multiple disjoint paths between source and destination to enhance reliability, fault tolerance, and load balancing.

5.7 Quality of Service (QoS) Support

Certain WSN applications impose Quality of Service requirements related to latency, data accuracy, or sampling frequency. Meeting these requirements often involves trade-offs between performance and energy efficiency.

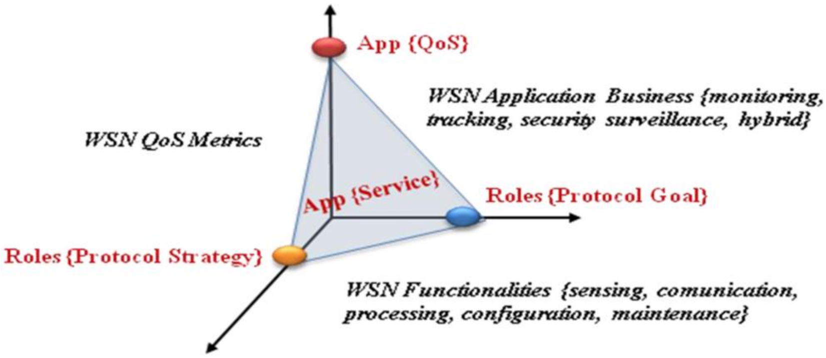

Figure 1. Quality of Service (QoS)

6. CONCLUSIONS

The proliferation of smart, light-weight sensors has made wireless sensor network popular. The constrained capabilities of the devices should be taken into account for the development of applications for these networks. Concerning the routing protocols, the reduced energy resources, the scalability and the resilience arise as the main limitations in wireless sensor networks. This paper presents a survey on how routing protocols are adapted to these characteristics. Additionally, the paper includes the efforts carried out by Spanish universities on developing optimization techniques in the area of routing protocols for wireless sensor networks, focusing on our contribution: a proposal of routing protocol for wireless sensor networks, called SHRP (Simple Hierarchical Routing Protocol). Aiming at prolonging network lifetime, this protocol decides the best route according to three different metrics: battery availability, number of hops and link quality. The algorithm also includes a load-balance technique so that the traffic is distributed among the possible routes. To be flexible and to contribute with new metrics for others routing protocols, the SHRP architecture uses SP that allows network protocols to choose neighbors wisely, taking into account information available at the link layer, providing a great modularity.

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