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Review Article

A Comprehensive Survey of Energy Harvesting and Conservation Techniques for Wireless Sensor Networks

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A B S T R A C T

Wireless sensor networks (WSNs) are energy-efficient systems vital for diverse applications, from industrial monitoring to extensive environmental surveillance. A critical concern in WSNs is the energy consumption of nodes, which determines the network's longevity, especially in challenging environments where battery replacement or charging is difficult. This paper offers an in-depth examination of energy conservation techniques in WSNs, categorizing them into five key areas: data reduction, control reduction, energy- efficient routing, duty cycling, and topology control. Additionally, we discuss recent advancements in energy harvesting and sensing strategies. By identifying the chief causes of energy wastage and presenting numerous solutions, this review aims to be a cornerstone reference for stakeholders in WSN energy conservation and those keen on understanding the sector's latest developments.

Keywords: Wireless Sensor Networks (WSNs), Wireless Energy Transfer, Energy Harvesting Sensors, Energy Conservation, Machine Learning (ML), Maximum Power Point Tracking (MPPT)

Introduction

Wireless sensor networks (WSNs) are composed of potentially numerous wireless sensors designed to function in potentially adverse environments for extended durations without human intervention. A typical sensor node is a compact device encompassing four primary components: a sensing unit for data collection, a microcontroller facilitating local data processing and memory functions, a communication unit enabling data transmission/reception with other devices, and a power source, often a small battery. WSNs facilitate a broad spectrum of applications, including target tracking, environmental monitoring, system control, health surveillance, and exploration in challenging environments. For data gathering, a predominant application of WSNs, the objective is to detect events within a designated area and relay this information to a central point or sink. Early research, as highlighted in,[1,2] demonstrated that when the communication range is at least double the sensing range, comprehensive coverage ensures connectivity among active nodes within the designated area. In many WSN application scenarios, battery-powered nodes are expected to remain operational for extended periods post- deployment, with minimal external human interaction. Recent literature[12-17] has introduced energy transference-based techniques wherein energy is wirelessly transmitted to nodes that are deficient in energy. Given that these low-energy sensor nodes are often situated in locations with limitedoptions for environmental energy harvesting, wireless energy transmission has emerged as a particularly promising technology. While there's a focus on energy supply technologies, other strategies, such as scheduling and routing protocols, are deemed more effective in considerably reducing sensor energy consumption compared to other techniques discussed in various studies. A significant portion of the energy management strategies documented in[19–28] primarily emphasize efficient energy utilization at the node level. These strategies aim to craft applications that consume minimal energy by deploying algorithms that operate within tight energy constraints. Nevertheless, an integrated approach that addresses both energy supply and consumption in WSNs paves the way for more holistic and efficient energy management systems.

In the authors introduce a taxonomy of energy conservation schemes. While their classification is insightful, it doesn't encompass energy-efficient routing, protocol overhead reduction, data aggregation, and cross-layering mechanisms. To address this, our survey offers a fresh classification that integrates these omitted techniques. Most prior research views on energy conservation in wireless sensor networks have primarily focused either on duty-cycling methodologies or on routing protocol techniques. To our knowledge, this literature review is the first to delve into

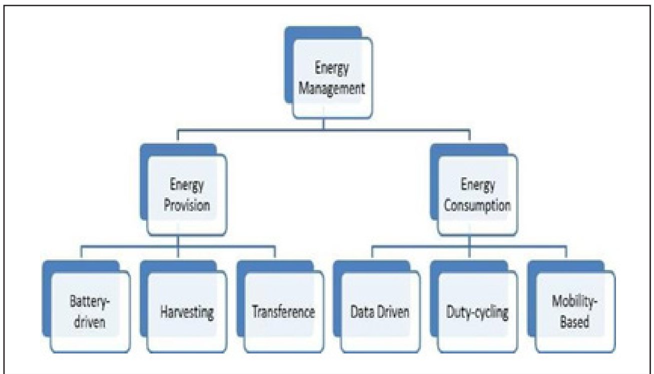

Figure 1. High-level taxonomy for Energy Management Schemes

hybrid approaches that marry duty-cycling strategies with routing protocol techniques,aiming to reduce the energy demands of wireless sensor networks.

The structure of this paper is laid out as follows: Section II delves into the definition of network lifetime, the cornerstone of all energy-efficient techniques. Section III elaborates on various schemes employed for power modeling of the energy.

Taxonomy of Energy- Efficient Techniques

We detail in this section the reasons for potential energy waste in a WSN. We then propose a taxonomy of existing energy-efficient solutions, keeping in mind the resource-constrained nature of sensors.

Reasons for energy waste In Wireless Sensor Networks

Sensors dissipate energy while sensing, processing, transmitting, or receiving data to fulfill the mission requiredby the application. The sensing subsystem is devoted to data acquisition. Minimizing data extracted from the transducer will save energy from very constrained sensors. Redundancy inherent to WSNs will produce huge similar reporting that the network is in-charge of routing to the sink. Experimental results confirm that t he communication subsystem is a greedy source of energy dissipation. Concerning communication, there is also a great amount of energy wasted in states that are useless from the application point of view, such as:

- **Collision:** when a node receives more than one packet atthe same time, these packets collide. All packets that cause the collision have to be discarded and the retransmission of these packets is required.
- **Overhearing:** when a sender transmits a packet, all nodes in its transmission range receive this packet even if they are not the intended destination. Thus, energy is wasted when a node receives packets that are destined to other nodes.
- **Control packet overhead:** a minimal number of control packets should be used to enable data transmissions
- **Idle listening:** is one of the major sources of energy dissipation. It happens when a node is listening to an idle channel to receive possible traffic.
- **Interference:** each node located between the transmission range and t h e interference range receives a packet but cannot decodeit. As network lifetime has become the key characteristic for evaluating WSN, a panoply of techniques aimed at minimizing energy consumption and improving network lifetime, are proposed. We now give a taxonomy of thesetechniques.

Classification of Energy Efficient Techniques

We can identify five main classes of energy efficient techniques, namely, data reduction, protocol overhead reduction, energy- efficient routing, duty cycling, and topology control.

1. **Data reduction:** focuses on reducing the amount of data produced, processed, and transmitted. For instance, data compression and data aggregation are examples of such techniques.
2. **Protocol overhead reduction:** this technique aims to increase protocol efficiency by reducing the overhead. Different techniques exist. Transmission periods of messages are adapted depending on the stability of the network, or the distance to the source of the transmitted information. More generally, a cross-layering approach will enable an optimization of

the communication protocols taking into account the application requirements. Another technique, optimized flooding can significantly contribute to reducing the overhead.

Energy efficient routing: routing protocols should be designed with the target of maximizing network lifetime by minimizing the energy consumed by the end-to-end transmission and avoiding nodes with low residual energy. Some protocols are opportunistic, taking advantage of node mobility or the broadcast nature of wireless communications to reduce the energy consumed by a transmission to the sink. Others use the geographical coordinates of nodes to build a route consumption of Wireless Sensor Networks. In Section IV, wediscuss diverse approaches centered on energy transference applications within WSNs. Section V is dedicated to identifying the primary sources of energy wastage in WSNs and categorizing energy-efficient strategies based on the problems they address. From Sections VI to X, these methodologies are explored in detail. Section XI offers an in-depth analysis ofthe challenges and outstanding research issues in the realmof energy optimization for wireless sensor networks. This section pinpoints unresolved matters, flags research voids, and underscores potential sectors ripe for future study and innovation. The paper culminates in Section XII, where we encapsulate the salient points, research contributions, and implications. This concluding section provides a succinct recap ofthe paper's goals, employed methods, and results, accentuatingthe research's importance and pointing towards promising directions for subsequent inquiries.

Discussion

While the text mentions that the communication subsystem contributes significantly to energy dissipation, it does not quantify this impact or provide comparative figures between different energy- consuming activities. As an improvement to this fact, we propose to set prototypes under different scenarios like different environmental conditions and measure how energy differs during transmissions and reception of bits. The paragraphs lack concrete examples of the energy-efficient techniques that are part of the proposed taxonomy. Readers may benefit from illustrative examples to better understand these techniques.

Incorporate case studies or practical examples to showcase how specific techniques have been applied in real-world scenarios and the resulting improvements in energy efficiency and network lifetime. Compare the effectiveness of different energy-efficient techniques in terms of energy However, there is no agreement in the academic literature on how to define the longevity of a network. The vast majorityof writers pick a term that works for their particular piece.As a result of this predicament, several other meanings have emerged. We summarize the most frequent definitions of WSNs based on prior publications.

The Age of a Network in Terms of its Current Number of Functional Nodes

Time when all sensors are operational is the most common definition (also written as n/n in, where n is the total number of sensors). Given that sink nodes are presumed to be more complex and potent than the rest of the nodes, they are left out of the set. This lifespan is simple to calculate since it ignores topological changes. This statistic does not, however, accurately reflect the lifespan evaluation in dense networks with redundancy. Therefore, this statistic can only be utilized sensibly if all nodes in the network are equally vital.

Time until a certain percentage of nodes in the network are still functional is one definition of the network lifespan. Unlike the previous definition, this one accounts for redundancy, but it still doesn't characterize correctly operating data-gathering applications in which the loss of only a small percentage α% of sensors close to the sink would prohibit the sink from receiving gathered data. The network lifespan is defined by the authors in the context of clustering as the duration until the first cluster head fails. However, most studies dynamically switch cluster heads to equalize power usage. savings,network lifetime extension, and applicability

Coverage determines the network's lifespan

to various WSN configurations. Use graphs or charts to visually represent the impact of different energy- consuming activities on overall energy consumption. This can help readers better understand the relative significance of each activity.

Network Lifetime Definition

How to minimize node power consumption without

How well a network can identify an event inthe monitored region is a function of its coverage. Therefore, in certain studies, the lifespan is defined as the amount of time that sensor nodes cover the target region. Unfortunately, not even complete coverage can guarantee that all data are sent to the sink.

Connectivity-dependent network lifespan

compromising on ideal network behavior is the primary design challenge in WSNs. As long as it is alive, a WSN can do its job, but once it dies, it can no longer do its job. Therefore, extending the lifespan of the network should bethe primary focus of any energy-saving strategy. This latter metric is quite sensitive to the longevity of a single node.

The capacity of the network to deliver data to a destination (the "sink") is crucial to this concept. This concept is consistent with those put out for ad hoc networks. After a certain percentage of the network's nodes die or the size of its biggest linked component falls below a certain threshold, the authors define the lifetime as the minimal period before the network fails.

Network Durability According To Usage Patterns

Once the capabilities of the applications have been guaranteed, some writers argue that the network is considered to be functioning. We define the lifespanof a WSN as the duration during which the network reliably meets the needs of its applications, as stated by Kumar et al. Another definition is proposed by Tianand Georganas The elapsed period until "the network no longer provides an acceptable event detection ratio." This concept, however, becomes useless if reliablecommunication of the event cannot be ensured. Finally, if the WSN- supported application requires it, network lifespan should account for connection and coverage. WSN designers may better define network lifespan in a way that is practical and relevant to application users if they have a thorough understanding of the application's needs.

Energy Efficient Routing Protocols

The design of routing protocols for WSNs is complicated by the energy limits of sensor nodes. The proposed protocols attempt to balance the load by avoiding nodes with low residual energy and reducing the amount of energy needed to send a packet from beginning to finish. In this section, we give a classification rather than an exhaustive list of energy-efficient routing protocols. By expanding on the categories presented in, we categorize energy-efficient routing methods as data-centric, hierarchical, geographical, and opportunistic. In the following sections, I'll go into greater depth about each class.

Topology Control

The fundamental idea behind topology control is tobuild and maintain a reduced topology that will save the small energy budget of sensors while preserving network connectivity and coverage. One way to accomplish this is by decreasing sensor transmission power. In authors prove that there is an optimal transmission range that minimizes energy dissipation while keeping a connected topology. Since in most applications, devices in WSNs are heterogeneous, we present three topology control algorithms for heterogeneous WSN: Directed LMST (DLMST), Directed RNG (DRNG), and the Residual Energy Aware Dynamic (READ) topology construction algorithm. Reduced topology is constructed using locally gathered data in both DLMST and DRNG. If the original network is strongly connected and symmetric, the reduced topologies computed by these protocols preserve these properties. On the otherside, READ takes benefits from the heterogeneity of nodes where more powerful devices play a leading role inthe network connectivity to extend the network lifetime. Instead of using the Euclidian distance between two communicating nodes to define the link cost, READ introduces a weightedcost for each pair of nodes that considers both the energy for sending and receiving data and the current residual energy at each node.

Discussion

The crux of the examined text dives deep into the realmof topology control techniques specific to Wireless Sensor Networks (WSNs). This strategic focus seeks to engineer a streamlined network topology that adeptly conserves energyall the while ensuring that the twin pillars of network connectivity and coverage stand robust. The narrative unveils three noteworthy topology control algorithms crafted for heterogeneous WSNs, namely: Directed LMST (DLMST), Directed RNG (DRNG), and Residual Energy Aware Dynamic(READ). These algorithms, despite their brief introduction, underscore their methodologies in sculpting this reduced topology, and they also grapple with the myriad challenges birthed by the heterogeneity of devices.

There's a commendable clarity of purpose in the text. The primary mission of topology control is unambiguously set out: managing the network efficiently in terms of energy,without compromising on its connectivity and breadth of coverage. This clear directive is further bolstered by the spotlight on three distinct topology control algorithms, widening the reader's purview of available strategies. An especially salient point the text delves into is the intrinsic heterogeneity within WSNs. It doesn't merely treat devicesas monolithic entities; instead, it nuances the discourse by emphasizing that varying devices play differential roles infortifying network connectivity and lifespan. However, a few chasms in knowledge emerge.

While the algorithms - DLMST, DRNG, and READ - are unveiled, and their intricate mechanics remain ensconced in shadows. This paucity of details makes it an uphill task for readersto decipher the algorithms' underlying principles and implementation tactics. Additionally, the narrative is bereftof performance metrics, leaving readers in the lurch about quantitative outcomes like energy conservation, extended network longevity, or coverage preservation. There's also a conspicuous absence of a comparative lens evaluating the merits and demerits of the algorithms.

To bridge these gaps, a few stratagems can be deployed. Firstly, illuminating the nuts and bolts of each algorithm, encompassing their foundational principles, core steps, and cardinal concepts, would elucidate readers on their modus operandi. Bolstering the narrative with performance metrics can inject quantitative rigor, offering readers tangible metrics like energy conservation percentages or network lifespan ratios. Delving into a comparative analysis can shed light on the strengths and potential pitfalls of each algorithm, guiding readers in their algorithmic selections. Visual aids, such as illustrative diagrams or schematics, can further streamline comprehension. Lastly, given the relentless march of technology, weaving in findings from contemporary research (post-September 2021) on topology control algorithms can significantly enhance the narrative's pertinence and precision.

Challenges And Open Research Problems

In this section, we highlight the most prevalent obstacles and outstanding research concerns in energy optimization in wireless sensor networks that are impeding WSN use in inaccessible places. The list provided is not complete, but it is intended to lead the reader through some of the most importantissues that must be solved to fully harness the benefitsof energy and optimization techniques as an assistance to increase the lifetime of wireless sensor networks.

The optimization of energy in wireless sensor networks presents numerous challenges and open research problems. Limited energy resources, such as batteries or energy harvesting mechanisms, require maximizing network lifetime and energy efficiency while meeting application requirements. Managing energy consumption heterogeneity, caused by variations in processing capabilities, sensing tasks, and communication distances, poses a challenge in balancing energy utilization across the network. The energy hole problem in large- scale sensor networks, where nodes near the sink consume more energy than distant nodes, leads to an imbalance and reduced network lifetime. Energy-aware routing protocols need to be developed to minimize energy consumption during data transmission by considering energy balance, network topology, and data aggregation. Exploring energy harvesting techniques from the environment and efficient power management strategies can extend the network's lifetime. Data aggregation and compression at source nodes significantly reduce energy consumption during data transmission, requiring the design of a technique that balances energy savings and data accuracy. Addressing energy optimization under dynamic network conditions, meeting Quality of Service (QoS) requirements, ensuring security and privacy, and achieving scalability in large-scale networks are all crucial research areas for improving energy efficiency and overall performance in wireless sensor networks across variousapplications.

Conclusion

In this comprehensive survey, we delved into the multifaceted realm of energy optimization techniques for wireless sensor networks (WSNs), a crucial domain given the rising significance of WSNs in diverse applications. While traditional optimization methods, such as heuristics and game theory, have been extensively utilized, our examination broadened to cover emerging paradigms like wireless energy transfer and the potential of deep learning algorithms for data transfer. In exploring the state of the art in energy sourcesfor WSNs, we underscored the ideal energy implementations across varied scenarios and dissected the nuances of different WSN deployments, spotlighting the divergent challenges intrinsic to each optimization technique. Notably, the review integrates insights from both established energy conservation strategies—spanning areas like data reduction, control reduction, and topology control— and recent advancementsin energy harvesting. As we navigate the dynamic landscapeof WSN energy management, it's evident that machine learning's application in optimization is still nascent, yet its capabilities warrant deeper exploration. Hence, we advocate for a synergistic approach, melding both conventional and MLalgorithms, to offer a holistic and forward-looking perspective on energy conservation in WSNs. This synthesis aims to bea beacon for stakeholders, steering research trajectories and fostering a mature understanding of energy harvesting and its optimization.

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