IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 10, 2020, accepted December 19, 2020, date of publication December 22, 2020, date of current version January 7, 2021.

Digital Object Identifier 10.1109/ACCESS.2020.3046619

QoS-Aware Energy Management and Node Scheduling Schemes for Sensor Network-Based Surveillance Applications

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This work was supported in part by the Taif University, Taif, Saudi Arabia, through the Taif University Researchers Supporting Program, through the Taif University Researchers Supporting Project, under Grant TURSP-2020/10, and in part by the International Macquarie University Research Excellence Scholarship.

ABSTRACT Recent advances in wireless technologies have led to an increased deployment of Wireless Sensor Networks (WSNs) for a plethora of diverse surveillance applications such as health, military, and environmental. However, sensor nodes in WSNs usually suffer from short device lifetime due to severe energy constraints and therefore, cannot guarantee to meet the Quality of Service (QoS) needs of various applications. This is proving to be a major hindrance to the widespread adoption of WSNs for such applications. Therefore, to extend the lifetime of WSNs, it is critical to optimize the energy usage in sensor nodes that are often deployed in remote and hostile terrains. To this effect, several energy management schemes have been proposed recently. Node scheduling is one such strategy that can prolong the lifetime of WSNs and also helps to balance the workload among the sensor nodes. In this article, we discuss on the energy management techniques of WSN with a particular emphasis on node scheduling and propose an energy management life-cycle model and an energy conservation pyramid to extend the network lifetime of WSNs. We have provided a detailed classification and evaluation of various node scheduling schemes in terms of their ability to fulfill essential QoS requirements, namely coverage, connectivity, fault tolerance, and security. We considered essential design issues such as network type, deployment pattern, sensing model in the classification process. Furthermore, we have discussed the operational characteristics of schemes with their related merits and demerits. We have compared the efficacy of a few well known graph-based scheduling schemes with suitable performance analysis graph. Finally, we study challenges in designing and implementing node scheduling schemes from a QoS perspective and outline open research problems.

INDEX TERMS Coverage, energy management, node scheduling, QoS, WSN.

I. INTRODUCTION

Wireless sensor networks (WSNs) play a significant role in surveillance applications [1]. The monitoring applications include structural monitoring, habitat monitoring, health monitoring, and so forth, [2], [3]. The surveillance application (targeted monitoring) include military surveillance, coal mine surveillance, landslide detection, forest fire detection, smart city surveillance, etc. In these applications, small-sized sensor nodes or motes are deployed in the

The associate editor coordinating the review of this manuscript and approving it for publication was Deyu Zhang.

sensory field to provide necessary services on a timely and on-demand basis. A key factor that is used to assess the operational efficiency of a tiny sensor device is its battery power [4]. In this context, power can be defined as the energy supplied to the sensor node per unit of time. Sensor nodes are battery-driven and have a limited energy capacity with high communication costs and overhead [5]. It is not possible to replenish the battery in sensor nodes at all times [5].

Fig. 1(a) show the main components of a sensor node. Each component of a sensor node requires energy to operate. However, micro-controller (processing component) and transceiver (communication component) often consume more energy compared to other components [6]. In addition, a sensor node consumes more energy when it is in the "active" state. When in the "sleep" state, its energy consumption is fourfold less [7]. This is due to the fact that in the "active" state, all the components are in the ON mode, thereby incurring high energy usage. The state diagram of the sensor node is shown in Fig. 1(b).

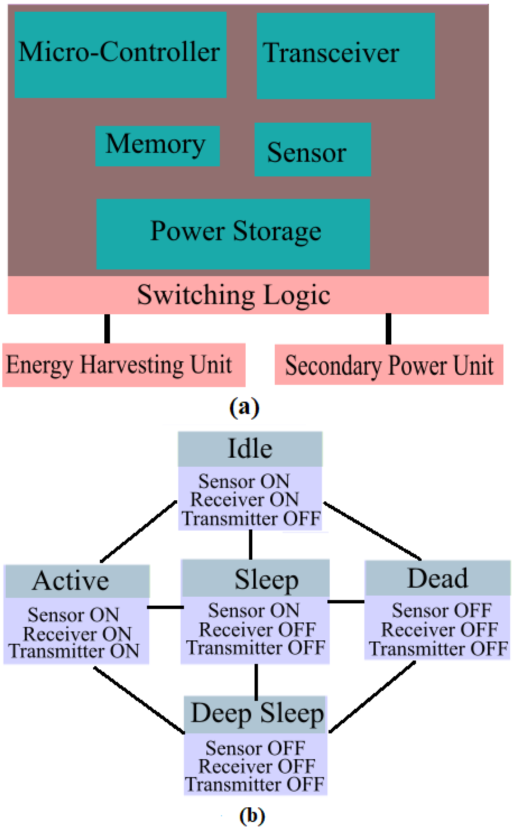


FIGURE 1. Sensor node, (a) Component diagram, (b) State diagram.

Sensor nodes are often tiny and, as a result, have a very limited amount of energy and battery capacity. The overall energy of a sensor node rapidly drains off due to its continuous usage. A sensor node is said to be in the "dead" state when the total amount of energy consumed reaches its maximum capacity. The trade-off between the power constraint and the size of the sensor node poses a major challenge in the longevity of the entire network. Therefore, an efficient energy management scheme needs to be in place to overcome this challenge.

The underlying energy management schemes dictate how various mechanisms that supply energy to a sensor are managed and how efficiently this energy can be consumed and conserved to ensure energy-efficient network operations. Accordingly, energy management schemes are classified into energy provisioning schemes and energy conservation schemes [17]. The energy provisioning schemes deal with the identification and provisioning of primary and secondary sources of energy to power up the sensor nodes, whereas the energy conservation schemes deal with the management of available energy with a broader objective of extending the network lifetime.

The efficacy of an energy management scheme depends not only on its ability to satisfy the energy needs of energy-hungry sensor nodes, but also on how well the scheme meets other application-driven QoS requirements. The key QoS requirements are, namely coverage, connectivity, fault tolerance, and security. Node scheduling is a flexible energy management scheme that can satisfy all the aforementioned requirements [18]–[20].

Node scheduling schemes identify multiple sets or schedules of non-redundant sensor nodes in the network and then activating each of such sets in a distinct time slot of a communication cycle. Non redundant nodes have minimally overlapping or mutually exclusive sensing ranges with a node. Non-redundant nodes are selected to prevent multiple nodes from sensing the same area concurrently, as this may lead to unnecessary wastage of sensing power. In contrast to other energy management schemes [21]–[27], node scheduling exploits redundancy to identify and activate multiple schedules of sensor nodes, thereby providing a cost-effective solution to conserving energy.

Several research work on energy management and node scheduling schemes for WSN have been conducted in the recent past. For instance, Babayo *et al.* in [13] reviewed energy management schemes for energy harvested WSNs. Similarly, energy provisioning schemes for such a network are discussed in [12]. A discussion on energy conservation schemes with a special emphasis on duty cycling scheme can be found in [11]. Node scheduling schemes for SDN are discussed in detail in [8]. Node scheduling schemes have been identified as an energy-efficient data acquisition scheme in [14] whereas it is considered as network lifetime maximization techniques in [15]. A few node scheduling schemes that address coverage and connectivity issues are reviewed in [9], [10], [16]. To the best of our knowledge, this article is the first to provide a comprehensive detailing of node scheduling schemes from a QoS perspective. The major contributions of this article are summarized in Table 1 and are listed as follows:

TABLE 1. Related articles.

Research	Scope	Contribution
[8]	Software Defined Network (SDN)	Discusses node scheduling schemes specific to software-defined sensor networks.
[9]	WSNs	Explain coverage based node scheduling schemes with a special focus on Q-coverage and P-connectivity problem.
[10]	WSNs	Discuss only four coverage and connectivity based node scheduling schemes with a greater emphasis on coverage and connectivity issues.
[11]	WSNs	Investigated state-of-the-art duty-cycled MAC protocol only.
[12]	WSNs	Detailed energy provisioning schemes with a major emphasis on energy harvesting schemes.
[13]	WSNs	Review energy management schemes designed for efficient use of harvested energy.
[14]	WSNs	Discusses the node scheduling schemes as an energy-efficient data acquisition scheme.
[15]	WSNs	Consider node scheduling scheme as one of the network lifetime maximization techniques and provided an extensive discussion on lifetime maximization techniques.
[16]	WSNs	Discusses coverage based node scheduling schemes for flat and clustered network.
Our paper	WSNs	An extensive taxonomy, life-cycle model, and related works of energy management schemes with special emphasis on node scheduling schemes for WSNs is provided. We consider node scheduling scheme as an energy conservation scheme and classify node scheduling schemes based on QoS requirements of surveillance applications such as energy-efficiency, coverage, connectivity, fault-tolerance, and security. Also, we further classify the scheme based on the features and characteristics of QoS. Finally, we discuss the issues, challenges, and open research problems in the design, development, and operation of node scheduling schemes.

- We propose an energy management life-cycle model and an energy conservation pyramid to extend the network lifetime of WSNs.
- We broadly classify energy management schemes and discuss underlying challenges that need to be addressed in future research work. Furthermore, we categorize the energy conservation schemes based on the network topology, protocol, and operational characteristics.
- We present a systematic and categorized overview of node scheduling from a QoS perspective. The paper briefly covers some of the wider background of node scheduling but focuses on key QoS aspects of node scheduling namely energy efficiency, connectivity and coverage, fault tolerance and security. We also classify and discuss the selection strategies utilized in such schemes.
- We enumerate and provide a summary of current challenges related to node scheduling and outline new research directions to address those challenges.

The rest of the paper is organized as follows. In Section II, first propose an energy management lifecycle model that will assist in conserving energy and extend the lifetime of WSNs. Thereafter, we present a taxonomy of energy management schemes for WSNs and highlight key challenges in WSN energy management. In Section III, we describe and classify existing energy conservation schemes. In Section IV, we provide an overview of node scheduling. This section also gives an insight into the taxonomy and classification of existing node scheduling schemes with the aid of detailed taxonomy trees. Section V presents state of the art QoS aware node scheduling schemes. Section VI highlights the key issues, challenges, and open research problems in node scheduling. Finally, Section VII concludes the paper with a brief summary of the highlights. The detailed organization of the paper is shown in Fig. 2. A list of acronyms used throughout the paper is presented at the end of the section.

II. ENERGY MANAGEMENT SCHEMES

A. A LIFE-CYCLE MODEL

In the context of WSNs, energy management focus on saving energy and thereby extending the lifetime of sensor nodes. To minimize energy wastage and to ensure proper energy usage in the network, an efficient scheme precludes a sensor node from being under or over utilized. Such a scheme usually progresses through the following three stages: detection, prevention, and avoidance, as shown in Fig. 3. The detection stage aims to detect and measure the energy wastage [28]. The major causes of energy wastage in a sensing node are idle listening, collision, re-transmission of packets, overhearing of packets, the overhead due to transmissions of control packets, and redundant sensing (i.e., more than one sensor concurrently sense the same area) [29]. Energy consumption can be measured either at the hardware or at the software level.

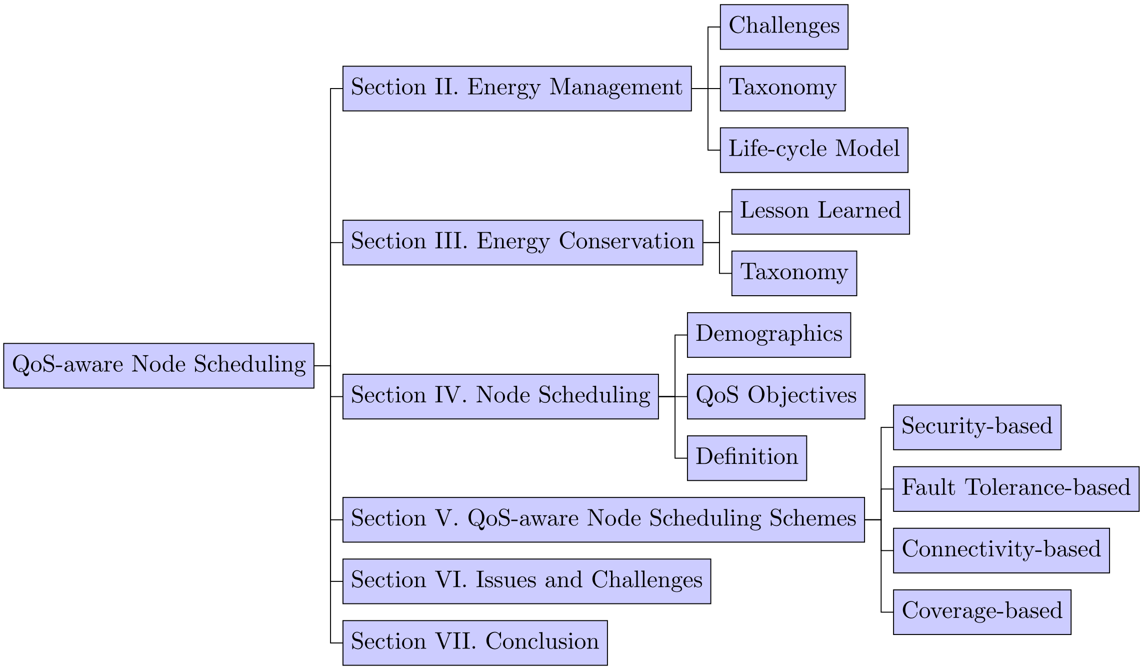


FIGURE 2. The organizational structure of the paper.

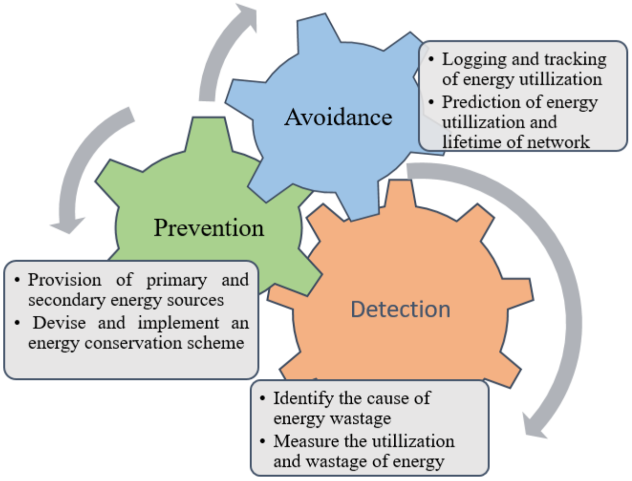


FIGURE 3. The life cycle of energy management schemes.

Hardware-based energy measurement schemes measure the residual energy of a sensor battery based on discharge characteristics of voltage and also on current consumption level [30]–[36]. The software-based measurement schemes consider different factors such as reduction in sensing range and packet throughput. In a software-based scheme proposed by Kim *et al.* [35], temperature and load characteristics are also taken into account for measuring the overall energy consumption. The transmission and reception quality of sensor nodes (in terms of total number of packets transmitted and received) is considered as a metric to measure energy consumption by Khriji *et al.* [37].

One major drawback of a hardware-based energy measurement scheme is that it mandates a periodic measurement of energy expenditure which require support of additional hardware based measuring tools, such as Advanced Measurement Algorithms for Hardware Architectures (AMALGHMA) in conjunction with an oscilloscope and a micrometers [38], [39]. So, this scheme is not cost effective in the long run for sensor networks that are large and densely deployed. On the other hand, a software-based energy measurement scheme is more economical since it does not require any extra hardware for measurement. Such a scheme involves the use of simulation and analytical models for measurement [40]–[43].

The prevention stage is triggered when the energy depletion rate goes beyond a threshold [15]. Prevention can be done either through the provision of external sources of energy or by executing energy conservation algorithms within the nodes in a network, as discussed in the following section. Once the prevention scheme is in place, timely logging and tracking of the rate at which the energy gets used must be done to avoid any wastage. The logging and tracking of energy usage also help to accurately predict the network lifetime [15], [43]. Prediction helps to estimate optimal energy settings in a sensor node. Readers are referred to [44]–[46] for a detailed discussion of machine learning-based energy prediction models. It is observed that deep neural network-based model is a commonly used energy prediction model in a variety of applications [46].

B. A TAXONOMY OF ENERGY MANAGEMENT SCHEMES

Energy management focuses on provisioning and conservation of available energy. As reported by Khan *et al.* in [17], it is a set of standards that manages the provisioning and

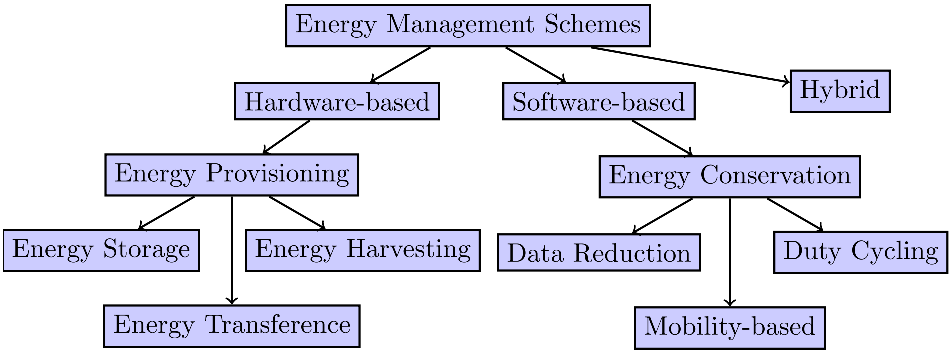


FIGURE 4. Categorization of energy management schemes.

Acronym (cont.)	Definition (cont.)
QoS	Quality of Service
AMALGHMA	Advanced Measurement Algorithms for Hardware Architectures
BPK-Means	Ballenced Parellel K-Means
EECPK	Energy Efficient Clustering Protocol based on K-Means
LEACH	Low Energy Adaptive Clustering Protocol
SPIN	Sensor Protocol for Information via Negotiation
ACQUIRE	Active Query Forwarding In Sensor Network
RPL	Routing Protocol for Low power and Lossy Network
ARIMA	AutoRegressive Integrated Moving Average
STEM	Sparse Topology and Energy Management
PTW	Pipelined Tone Wake-up
EHGAF	Extended Hierarchical Geographical Adaptive Fidelity
PEAS	Probing Environment and Adaptive Sleeping
ECNS	Energy Aware Common Neighbor Scheme
CSCAN	Correlation-based Scheduling Algorithm for Network
ESense	Energy Efficient Stochastic Sensing Framework
FAN	Fault-tolerant Adaptive Node Scheduling
CPNS	Coverage Preserving Node Scheduling

optimal usage of the available energy in sensor devices. We can broadly categorize energy management schemes into hardware-based schemes, software-based schemes, and hybrid schemes, as shown in the taxonomy tree in Fig. 4. Hybrid schemes are a combination of software and hardware-based schemes.

Recent innovations in hardware have led to the development of mechanisms through which energy can be supplied from different sources to prolong a sensor device's operation. The energy provisioning schemes are hardware-based. Such schemes can be classified into the following categories: energy storage, energy harvesting, and energy transference schemes, as shown in Fig. 4.

Different energy storage options are available to store the power required to run sensor nodes. This includes battery storage, capacitor, fuel cells, heat engines, and radio active cells. Most sensor nodes use a battery as the primary energy storage option. This is because the cost, size, power leakage, overheating, and other environmental concerns are minimal here compared with other energy storage options.

Energy harvesting is another prominent energy provisioning approach for sensor nodes besides the aforementioned primary energy storage options. The energy harvesting module attached to a sensor node converts the ambient energy to electric power as and when it is required by sensor nodes. Some commonly used ambient energy sources for harvesting are solar, wind, thermal, radio signals, thermoelectric, piezoelectric, and vibration. Amongst these options, solar energy-based energy harvesting is the most commonly used because of its wide availability and low-cost energy efficiency measures. Recently, energy harvesting schemes that use radio frequency signals are receiving some attention. Radio frequency-based energy harvesting schemes are discussed in [6], [13], [47]–[61].

Energy transference is a very promising and upcoming energy provisioning scheme that relies on the wireless transfer of electrical energy from one sensor node to another. In this scheme, high-powered sources transfer the energy to low powered devices. The energy transference is accomplished through the use of technologies such as electromagnetic waves, lasers, magnetic resonance. Energy transference becomes critical in situations wherein the use of alternate energy provisioning options such as energy harvesting is just not viable. Such schemes are best suited for a densely connected network. A system based on the energy transference scheme is discussed in [62]. The system uses a power-packed mobile sensor node called wireless charging vehicle that moves through the network and supplies energy to energy-deficient nodes by applying a magnetic-resonance based technique. Readers are referred to [63]–[68] for a detailed discussion on wireless energy transference schemes. This technology is most often used energy provisioning scheme.

Limitations of energy provisioning scheme (hardware-based schemes) are summarized in Table 2. For a more detailed description of hardware-based schemes, the readers are referred to [12], [69]. This article discusses only energy conservation schemes (software-based scheme), more specifically node scheduling schemes. Node scheduling is receiving increased consideration in the deployment of monitoring and unmanned surveillance systems due to its increased ability to satisfy QoS demands of such applications. In this article, we discuss node scheduling schemes that are QoS aware i.e., they meet the key QoS requirements, namely coverage, connectivity, fault-tolerance, and security. A detailed description of energy conservation and QoS aware node scheduling schemes are given in Section III-V.

TABLE 2. **Limitations of energy provisioning schemes.**

Category	Options	Limitations
Energy Storage	• Battery • Super capacitor • Fuel cell • Heat engine • Radio active	• Toxic chemical usage • Limited battery capacity and shell life • Energy leakage • Increased cost and size • Environmental concern
Energy Harvesting	• Solar • Thermal • Wind • Piezo electric	• Increased cost of equipment • Bulky equipment (Not portable) • Temporal and spatial variation of energy • Line of sight requirement • Not suitable for sparse network
Energy Transference	• Electro magnetic waves • Laser • Magnetic resonance	• Not suitable for sparse network • Increased operational cost • Increased operational cost

C. CHALLENGES OF ENERGY MANAGEMENT SCHEMES

Power constraints and the highly volatile environment in which sensor nodes operate pose several challenges for implementing energy management schemes. Critical challenges encountered at different stages of the energy management life cycle include the following:

- The energy provisioning scheme provides a primary or secondary source of energy to power up the sensor nodes. However, such schemes are prone to limitations such as a low capacity battery, lower discharge rate, difficulty in the prior estimation, prediction, and the validation of total energy consumed. Because of these limitations, it becomes imperative to use energy conservation schemes in conjunction with energy provisioning schemes to maximize the network lifetime.
- Currently there are no long-range energy transference schemes which can facilitate energy transfer from the source to the sensor nodes regardless of the distance between them. Furthermore, with such schemes, it becomes difficult in addressing the energy demands of all nodes uniformly. Besides, there is a need for accurate event prediction models that can help calculate energy consumption well in advance. This helps to store excess energy and release it when the demand is high.
- The performance of energy harvesting schemes heavily depends upon the temporal and spatial variations in the network. There is a compelling need to develop an energy-harvesting scheme that can operate efficiently regardless of temporal and spatial variations in the network.
- Data aggregation as an energy conservation scheme has been widely deployed. The efficacy of such a scheme depends heavily on how efficiently it addresses some design challenges such as an optimal selection of data aggregator nodes, the synchronization between the aggregator nodes and other sensor nodes in the field, and energy efficient selection strategies to represent the collected data.
- A critical challenge in mobility based approaches is network latency which is introduced because there are no mobile relay and sink nodes in the immediate vicinity of the node requiring their services.
- Compared to other energy conservation schemes, duty-cycling is efficient in terms of simplicity in design and operation, however there are challenges such as high control traffic overhead and lack of QoS support that must be overcome.

III. ENERGY CONSERVATION SCHEMES

The goal of an energy conservation scheme is to either to create a new functionality or modify the existing functionality of a sensor node to facilitate preservation of energy. Such schemes aim at improving the continuity of network operations. The energy conservation schemes include data reduction techniques, such as clustering, mobility-based schemes that use mobile sinks or relay nodes, and duty cycling schemes such as node scheduling, as depicted in Fig. 4.

A. TAXONOMY

1) DATA REDUCTION SCHEMES

Data reduction schemes aim to significantly reduce the amount of data transmitted through the network, thereby cutting down the cost incurred in the transmission of unnecessary data packets. This, in effect, eliminates the wastage of energy in the network. Gelvin *et al.* [70] mentioned that transmission of one bit consumes more energy compared to processing a few thousand instructions (processing of data and control packets). Therefore, a reduction in the amount of data transmitted through the network amounts to lowering the overall energy consumption rate of sensor nodes. The data aggregation at intermediate nodes and data prediction are two most commonly used data reduction techniques discussed in the literature. A broad classification of the existing data reduction schemes and data aggregation techniques is illustrated in Fig. 5.

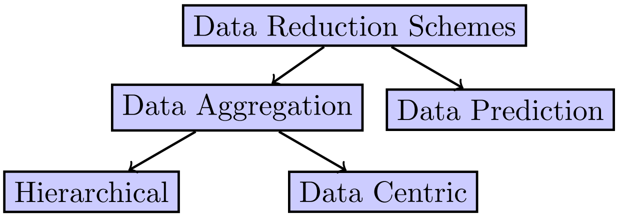


FIGURE 5. **Classification of data reduction schemes.**

- *Data aggregation techniques*: Clustering is a type of a data reduction technique that promotes the notion of data aggregation at intermediate nodes [71]. It is a hierarchical data aggregation technique [72]. In clustering, the sensor nodes in the network are grouped to form clusters. An intermediate node in each cluster is chosen to perform data aggregation and processing functions. In clustering terminology, these nodes are also called cluster heads. Data transmission is restricted to inter-cluster head communication, resulting in energy savings for other cluster nodes. Some well-known clustering protocols in the literature include K-Means [73], Ballenced Parellel K-Means (BPK-Means) [74], Energy Efficient Clustering Protocol based on K-Means (EECPK) [75], Low Energy Adaptive Clustering Protocol (LEACH) [76], and weighted clustering protocols [77]–[79].

  Apart from hierarchical protocols (clustering protocols), there are data-centric protocols such as direct diffusion [80], rumor routing [81], Sensor Protocol for Information via Negotiation [82], Active Query Forwarding In Sensor Network (ACQUIRE) [83], Routing Protocol for Low power and Lossy Network [84]. Using these protocols, data are collected based on attribute-value pairs (metadata) that describe the event of interest. In other words, a source sensor node that provides the required data is identified based on the data it collects and relays rather than physical identification such as location ID or address. One drawback of this approach is that there are often redundancy in the data collected by different nodes. Some measures should be taken at intermediate nodes to reduce the redundant data being relayed to the base station. To accomplish this, these protocols are used with clustering techniques. In such a scenario, either the cluster head or cluster member nodes can be entrusted with the tasks of aggregation and redundancy removal before relaying the data to the base station. This reduces the amount of data transmitted in the network and in turn leads to a reduction in the overall transmission energy cost. For example, in [85], [86] an in-network data aggregation protocol is proposed that incorporates hierarchical clustering for energy-efficient processing of data. In [85], the cluster head carries out the task of data aggregation and redundancy removal, whereas in [86], such tasks are partially performed by both, individual cluster members and the cluster head.

  Data aggregation schemes can also be classified based on the network topology, timing, and type of the aggregation function, as shown in Fig. 6. Structured, unstructured, and hybrid topologies are taken into account in the classification of topology-based aggregation schemes, as shown in Fig. 6. In structured aggregation, the network is modeled as a tree [87]–[90], chains [91]–[94] or in hierarchical clusters [79], [85], [95], [96]. The unstructured approach does not depend on any specific tree or a cluster structure to carry out aggregation. Instead, the data is passed on to the base station where aggregation is done. Some examples of this type of aggregation are discussed in [97]–[102]. The best features of the above two schemes are used in the hybrid approach to data collection discussed in [103], [104].

  Data aggregation schemes can be divided into periodic and aperiodic. Unlike aperiodic aggregation, the aggregated data is transmitted to the sink at regular intervals.

  Depending on the type of aggregation being carried out at the aggregator nodes, we can classify aggregation into *lossy*, *lossless*, *duplicate sensitive*, and *duplicate insensitive*. In lossy data compression, the aggregated data is first compressed and then forwarded to the base station. One key limitation of a lossy data aggregation scheme compared to its counterparts is its inability to reproduce the original information at the base station as some data are lost during the compression process at the aggregator node. Another category of data aggregation uses various filtering techniques to eliminate duplicate data from the aggregate. Unlike duplicate insensitive schemes, the duplicate sensitive schemes compare the similarity within the aggregated data and to filter the duplicate data out before forwarding the data to the base station, thereby reducing the overall transmission cost.
- *Data prediction techniques*: Data prediction is another popular data reduction scheme proposed in the literature. In this scheme, a prediction model is built based on the sensed data collected from the network, and this model is used to address the application-specific queries issued over the network. Stochastic, heuristic, or machine learning approaches are used to build the prediction model. The model is then deployed at the sink or in an individual sensor node, or alternatively, it may reside in both. In this scheme, the transmission is initiated only

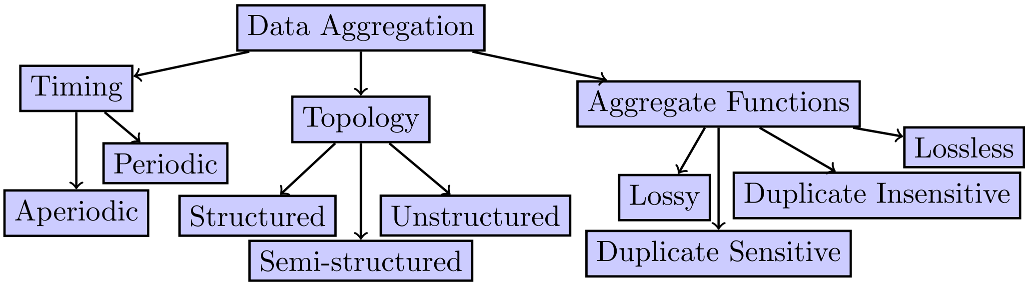


FIGURE 6. Taxonomy of data aggregation scheme.

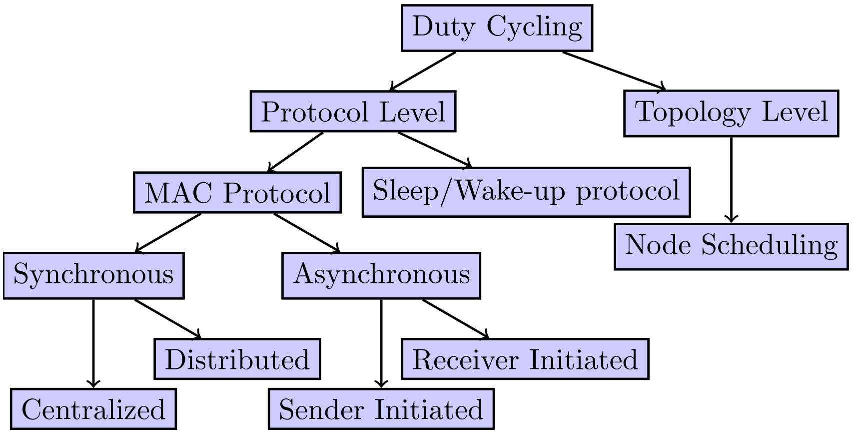


FIGURE 7. The classification of duty cycling schemes.

when there is a discrepancy between the two: collected and predicted data. Thus, the scheme avoids unnecessary data transmission. One drawback of this approach is that it compromises query results for energy efficiency and is suitable only for those applications in which the accuracy of the query results is not a matter of concern. A few prominent data prediction models proposed for wireless sensor networks include AutoRegressive Integrated Moving Average (ARIMA) technique [105], least mean square technique [106]–[108], dual prediction scheme [109]–[111].

2) DUTY CYCLING SCHEMES

The strategy of keeping all the sensor nodes in a high-energy active state at all times is undesirable for event detection based applications such as forest fire detection wherein events occur with a low frequency. In such scenarios, activating all the nodes during the communication cycle incurs a tremendous amount of energy wastage, specifically because of unnecessary idle listening of sensor nodes. A duty cycling approach or sleep/wake up approach eliminates the overall energy wastage in the network. It also helps in conserving the energy of a node by periodically switching it from ''active'' to ''sleep'' state and vice versa. The functionality of duty cycling is built into the medium access control (MAC) layer in the protocol stack.

The duty cycle of a sensor node refers to the fraction of the total communication cycle time in which the sensor node is in the ''active'' state. This scheme aims to minimize the duty cycle of a node to conserve its energy. This scheme can be implemented at the protocol level and at the topology level. An extensive classification of duty cycling schemes is shown in Fig. 7.

At the protocol level, the duty cycling scheme is integrated as a separate functional module of the MAC or a separate independent upper-layer protocol or a cross-layer protocol operating on top of the MAC protocol. The duty cycling based MAC protocol can be synchronous or asynchronous [112], [113]. In a synchronous protocol, each node in the network is aware of its neighbors' active/sleep schedule. The nodes have pre-defined duty cycles, and they synchronize with one another via the periodic transmission of SYN/Beacon packets. The responsibility for initiating synchronization rests either on the centralized node or delegated to each individual node.

On the other hand, a preamble based sampling approach is employed in asynchronous MAC protocols. An asynchronous MAC protocol can be either sender or receiver initiated. In a receiver-initiated approach, the receiver periodically expresses its willingness to receive packets from other nodes, whereas in the sender-initiated approach, it is the sender who initiates communication by first sending out a preamble. Asynchronous protocols are more energy efficient when compared to their synchronous counterparts since they incur lower control overheads.

Sleep/Wake-up protocols rely on duty cycling. These protocols are independent functional modules that can either integrate into the MAC protocol or as layered approach adapted to operate over an existing MAC layer protocol. Some are even implemented using a cross-layer design approach to further improve energy efficiency. The wake-up protocol discussed in [114] is an example of an asynchronous protocol integrated with a geographical routing protocol [115]. Other examples of independent sleep/wake-up protocols are Sparse Topology and Energy Management (STEM) [58] and Pipelined Tone Wake-up (PTW) [116]. These are asynchronous and on-demand protocols. The clustering protocol (essentially a network layer protocol) discussed under data aggregation schemes is also an example of the layered approach.

A topology level duty cycling scheme is a type of node scheduling scheme. This scheme exploits the redundancy in the network for energy conservation purposes. The network redundancy is a metric that represents the number of nodes that collectively sense the same area. In this scheme, only a subset of sensor nodes is chosen and activated. Other nodes in the network are placed in the ‘‘sleep’’ state to conserve energy. As a result, redundant nodes whose sensing range completely overlaps with a target node are only activated in mutually exclusive time slots. At each time slot, the scheduled nodes work on behalf of their redundant nodes to ensure that no two nodes concurrently end up sensing the same area, thereby preventing energy waste. This approach is also called the topology control scheme [117], [118] as it controls the topological structure of the network by reducing the number of activated sensor nodes.

Duty cycling-based approaches incur control overheads, making them less energy-efficient and scalable compared to other topology-level duty cycling approaches. Most of the protocol level duty cycling-based approaches can operate effectively either over one specific topology or with one specific type of MAC or network protocol. Thus they are less flexible compared to their counterparts. Moreover, unlike their topology driven counterparts, duty-cycle protocols are also less flexible in meeting the underlying QoS requirements of applications such as coverage and connectivity.

3) MOBILITY BASED APPROACHES

In a multi-hop wireless sensor network, data gathering, and forwarding of data from sensors to the sink are the major sources of energy consumption. Downstream sensors close to the sink or the base station tend to experience more traffic than those upstream closer to the data source. This phenomenon is commonly referred to as the funneling effect. The funneling effect can be detrimental to the longevity of the network since sensors that are close to the sink tend to experience a rapid exhaustion of energy and hence die out quickly, thereby isolating the base station from the rest of the network [119]. Similarly, nodes with a high degree (many neighbors) experience more traffic than those with a lower degree, causing energy imbalances within the network.

Mobility based approaches are designed to tackle the funneling effect and energy imbalance in a sensor network. A mobility-based approach is implemented either by using external mobile sensor nodes or by making a few internal sensor nodes or sink node mobile. Examples of external mobile sensor nodes are unmanned aerial or ground vehicles, mobile robots, or sensors attached to moving objects such as vehicles, persons, or animals. The nodes perform the tasks of data collection and data forwarding. The internal static sensor nodes store the data to be forwarded until a mobile node is within their vicinity. The mobile node can act as a mobile sink or as a mobile relay node. Using a mobile sink or a mobile relay is more energy efficient than using internal mobile nodes since in the latter case, the energy consumption is high. These approaches also suffer from increased network latency or packet delay because of the store and forward approach strategy, followed by the network’s sensor nodes. Thus mobility based approaches are more suited for delay tolerant networks.

Mobile sink and mobile relay based approaches are discussed in [120]–[123] and [124]–[127] respectively. Some mobility based approaches [128]–[130] also attach sensors to moving objects such as vehicles and animals.

B. LESSON LEARNED

Because of sensor hardware limitations, most energy management schemes currently employed in wireless sensor networks are software-based. These schemes overcome sensor nodes’ energy limitations by balancing energy supply and consumption without relying on an external source of energy. Some hybrid schemes such as Extended Hierarchical Geographical Adaptive Fidelity (EHGAF) [132] combine the benefits of both hardware-based and software-based schemes. In EHGAF, a clustered approach to data aggregation is used in conjunction with energy harvesting based provisioning scheme. Software-based energy conservation schemes are very beneficial in wireless sensor networks that are operated with battery-driven sensor nodes such as MICA, Telos, and Iris. But the benefits are doubled when hybrid energy management schemes are employed.

Compared to hardware, software-based energy conservation schemes are more prevalent in environments that are hostile and hazardous where recharging and replacing the battery in a sensor node is quite challenging. When compared with other energy conservation schemes, the duty-based approach is gaining some traction since it can effectively cut the total energy cost of the sensor nodes. On the contrary, most of the other schemes tend to focus solely on minimizing the sensor nodes’ energy transmission overheads. Fig. 8 and Table. 3 summarizes the classification and comparison of energy conservation schemes discussed above. The following sections present a detailed and more comprehensive analysis of node scheduling based approaches.

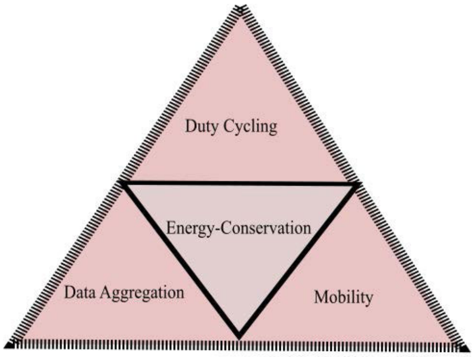


FIGURE 8. **Energy conservation pyramid.**

TABLE 3. **Energy conservation scheme's objectives and minimization parameters.**

Scheme	Objectives	Minimization parameters
Duty cycling [117], [118]	• To reduce the active period of each sensor node. • To reduce the number of active sensor nodes	• Sensing cost • Processing cost • Energy cost
Data aggregation [73]–[75], [131]	• To reduce the number of transmissions • To reduce the message size	• Transmission cost
Mobility-based [124]–[127]	• To reduce the transmission range	• Transmission cost

IV. NODE SCHEDULING SCHEMES

A. DEFINITION

As discussed in Section III, in node scheduling schemes, the activation of sensor nodes follows a schedule that can either be pre-defined or dynamic. Node scheduling is the process that decides the ON-duty and OFF-duty eligibility of the sensor nodes [133], [134]. A schedule is a subset of the sensor nodes to be activated in a specific time slot. The schedules are chosen such that no two sensor nodes in the schedule are simultaneously made redundant.

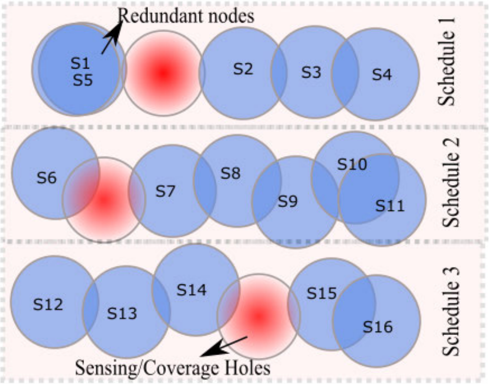


FIGURE 9. **Node scheduling.**

An example of a topology comprising of redundant nodes is shown in Fig. 9. The nodes $S1$ and $S5$ are redundant as their sensing region (represented by a solid circle in Fig. 9) almost completely overlaps. All possible schedules are shown in Fig. 9. Schedule 1 will be either $\{S1, S2, S3, S4\}$ or $\{S5, S2, S3, S4\}$ at time slot 1 of the communication cycle. The scheduling algorithm will ensure that each such schedule comprises a set of non-redundant sensor nodes. The redundant node that is not chosen (say $S5$ in this example) for the current schedule will be either activated once the battery power of currently activated node (say $S1$) for whom it is redundant is completely drained off or alternatively it may be selected and activated during the formation of a schedule.

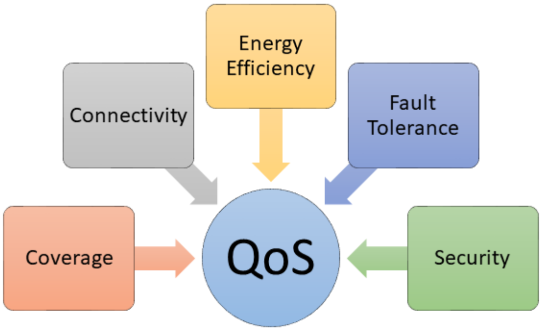
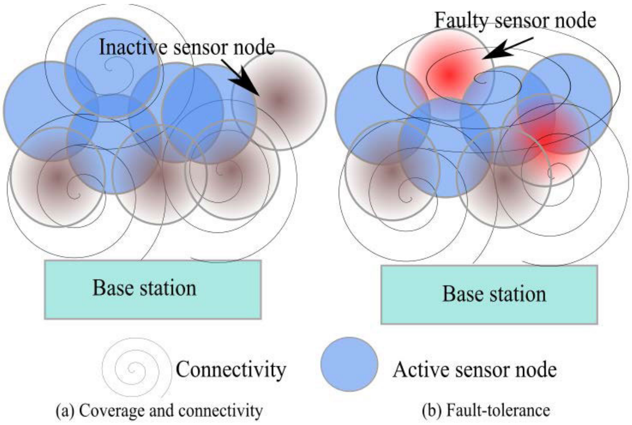


FIGURE 10. **QoS objectives.**



(a) Coverage and connectivity (b) Fault-tolerance

FIGURE 11. **Quality of Service and node scheduling.**

B. QoS OBJECTIVES OF NODE SCHEDULING SCHEMES

Compared to other energy management schemes, node scheduling schemes offer an easy energy conservation alternative [135], [136]. Furthermore, these schemes can meet the QoS requirements of various applications as mentioned above and illustrated in Fig.10 and Fig.11. This adaptable feature of node scheduling makes it the most sought-after energy conservation scheme for critical IoT applications. The scheme's benefits become more obvious when it is used in conjunction with energy harvesting and data aggregation techniques.

1) COVERAGE AND CONNECTIVITY

A high degree of coverage and connectivity are the most critical requirements of applications such as military surveillance

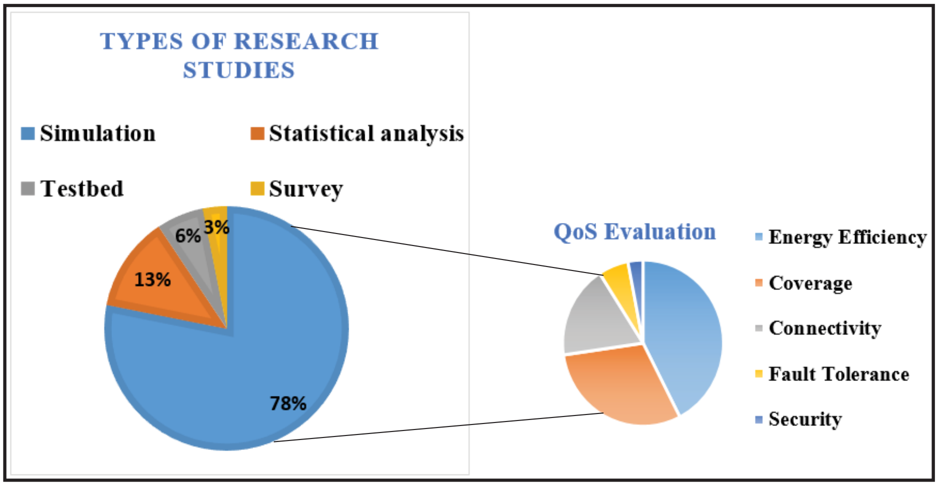


FIGURE 12. Demographics of research studies and QoS evaluation.

or forest fire detection [135]. In such applications, it is essential to detect the occurrences of events, with the base station being notified at the earliest. To this effect, coverage must be maximized for event detection, and reliable and continuous connectivity is essential to transfer detected information to the base station with minimum delay. The detection probability and detection delay are the two key performance indicators used to evaluate a node scheduling scheme's coverage and connectivity efficiency.

2) FAULT TOLERANCE

Fault tolerance is a measure of reliability and is necessary for an uninterrupted availability of a network and its services [136]. A node scheduling system is fault-tolerant if it can detect and dynamically recover the network system from a node failure with minimum delay. The Fault in a sensor node can be internal or external. Internal faults include battery depletion or other flaws in node's software and hardware components. External faults are caused by external agents such as a vehicle, a human, or an animal that may physically damage the sensor nodes. The faults can also be classified into intentional or unintentional faults. An active security attack is a concrete instance of an intentional fault whereas an unexpected hardware or software failure best epitomizes an unintentional fault.

3) SECURITY

Because of the unattended and open nature of deployed sensor devices, these devices also become prone to different passive and active attacks [137]. Security attacks can severely impact and impair a sensor's scarce resources. These attacks can be considered as intentional faults that trigger the failure of sensor nodes. Active attacks are proven to be more fatal when compared to passive ones, such as eavesdropping and traffic analysis. Examples of active attacks include Sybil, wormhole, and black-hole. A more potent form of an active attack is the Denial of Service (DoS) attack by which an attacker floods the bandwidth or diminishes a targeted system's resources. This attack renders a network inaccessible through physical intrusions that often tend to go undetected. As a result, the denial of service attack is a threat to network availability, an important security requirement of mission-critical surveillance applications.

The denial of sleep attack is a type of DoS attack in which the attacker's goal is to prevent the sensors from going into the "sleep" state, thereby draining their battery power. Examples of such attacks include physical layer attacks such as jamming attacks, network layer attacks such as black hole attacks, transport layer attacks such as replay attacks, flooding attacks and so on. These attacks are often referred to as vampire attacks because the compromised device acts like a vampire, depleting other nearby devices' battery and eventually rendering the entire network inoperative.

Security needs to be integrated into node scheduling to defend the network from such attacks and in effect help to extend the network lifetime. Secure node scheduling ensures sensor nodes that are selected and activated in a schedule is both robust and can handle any violations of security. Even though security is an important requirement of any application, there is no adequate body of knowledge concerning security-aware scheduling. Hence there is a large scope of extensive research in this area.

C. DEMOGRAPHICS OF RESEARCH STUDIES AND QoS EVALUATION

Fig. 12 shows the statistical data on research studies related to node scheduling schemes and their QoS objectives. We make statistical inferences from a sample of 150 research papers on node scheduling addressing different QoS requirements.

A vast majority of research on node scheduling are based on simulation-based studies rather than real-time experiments. This is because most schemes are suited to operate in a dense network and consequently incur high cost in terms of deployment, implementation, and evaluation. Therefore, these studies prefer to opt for simulation-based statistical analysis. The most commonly used simulation tools include MATLAB, NS2, TOSSIM, OMNET++, NetSim, and a few customs made tools in C, C++, python [138]. Real-time experiments are mostly performed using MICA sensors over a Tiny OS platform. MATLAB and R are the two main analysis tools that are utilized for statistical analysis in most work.

While most schemes aim to improve energy efficiency, a special class of node scheduling schemes called barrier coverage scheduling boosts network coverage while providing energy efficiency gains. A small percentage of existing research work addresses the fault tolerance and security aspects of node scheduling. The following sections discuss all these aspects.

V. QoS-BASED NODE SCHEDULING SCHEMES

A node scheduling scheme's primary objective is to conserve sensor nodes' energy and extend the network lifetime. These schemes extend network lifetime and guarantee the required QoS of IoT applications namely coverage, connectivity, fault tolerance, and security which are discussed in detail in this section.

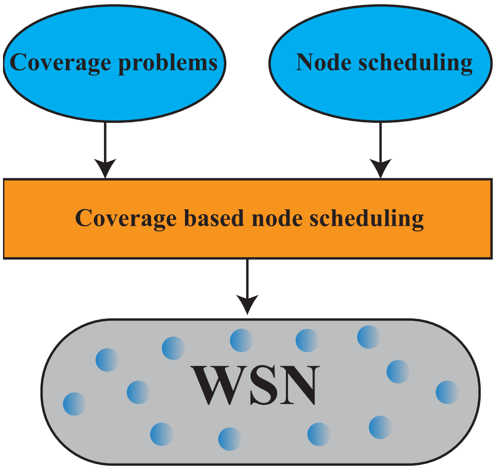


FIGURE 13. Coverage based node scheduling.

A. COVERAGE BASED NODE SCHEDULING SCHEMES

This section reviews various node scheduling schemes that aim to meet the coverage requirements of applications. This is also commonly referred to as coverage scheduling problem [139], as shown in Fig. 13. In such schemes sensors are organized into a group of disjoint/non-disjoint cover sets which are alternatively scheduled to run to extend the network lifetime. The cover sets are designed to provide the required coverage with a high degree of detection probability by reducing the number of coverage/sensing holes in a given area. The number of coverage holes is a key indicator to measure the efficacy of coverage based node scheduling schemes. The detection probability is directly proportional to the number of concurrent coverage holes and serves as a key performance indicator for such schemes.

1) COVERAGE CHARACTERISTICS

The coverage characteristics that should be taken into account in the design of node scheduling schemes are discussed below.

- *The coverage ratio*: The coverage ratio is defined as the total sensing area covered by all nodes in the sensory field to the total area of the sensory field. Node scheduling can be classified into schemes that provide either complete or partial coverage. Schemes providing complete coverage ensure every static or mobile target in the field irrespective of its position or trajectory, is guaranteed to be detected by at least one sensor node. In other words, these schemes achieve a coverage ratio of 1. In contrast, schemes providing partial coverage provide a coverage ratio of less than 1. As a result, there is no guarantee that every point or an event in the sensory field will necessarily be covered by sensor nodes. An intrusion event can occur outside the sensing range of active sensor nodes and thereby may go unnoticed. A point or area in the sensory field that is not sensed by any deployed sensor nodes is called a sensing holes or coverage hole. Fig. 9 shows coverage holes in barriers. The performance of such schemes is evaluated based on factors such as the coverage efficiency, which is a function of detection probability, the number of coverage holes, target trajectory and speed, residual energy of sensor nodes, etc.

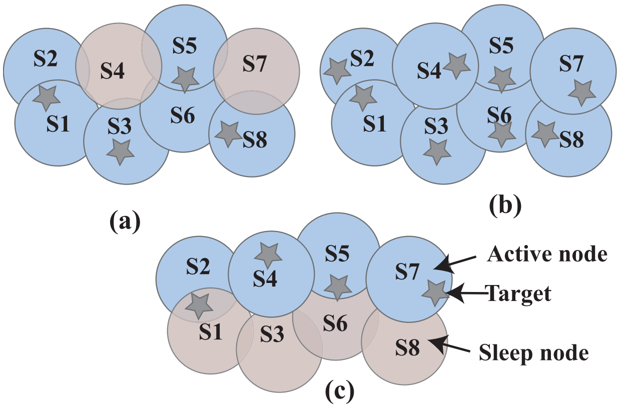


FIGURE 14. Node scheduling based on Coverage type, (a) Point/Target coverage, (b) Area coverage, (c) Barrier coverage.

- *The coverage type*: The coverage type determines the coverage provided by the cover set. The schemes are further classified into point/Target, area, and barrier coverage scheduling, as shown in Fig. 14. In point coverage scheduling, the cover sets are chosen such that each target is sensed by at least one sensor nodes in the cover set. This type of scheduling is usually employed in applications where a target is usually static or immobile. Examples include coal mine surveillance or habitat monitoring. In area scheduling, the cover sets cover each point in the area, and the underlying assumption being an event can likely occur anywhere within the sensory field. The targets considered in this scheduling can be static or moving. Area-based scheduling is an example of scheduling schemes which provide complete coverage. Barrier coverage node scheduling is applied specifically in intrusion detection applications such as military surveillance where the cover sets form virtual barriers. Barriers are forged along field boundaries. These schemes provide partial coverage since it guarantees coverage across but not throughout the surveillance field. Such schemes are also designed to provide better connectivity if the sensing nodes in a cover set have partially overlapping sensing ranges.

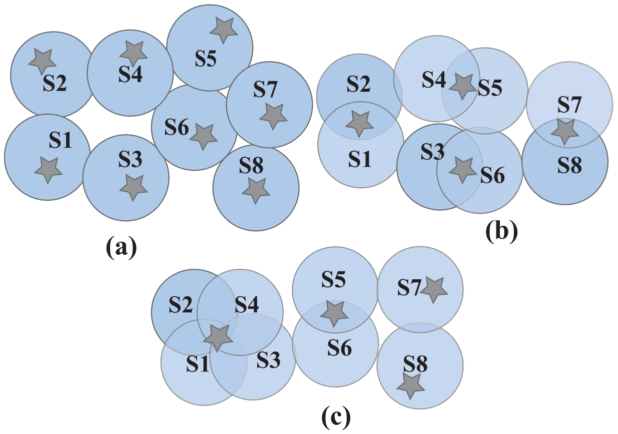


FIGURE 15. Node scheduling based on coverage degree, (a) 1-Cover, (b) 2-Cover, (c) Q-Cover.

- *Coverage degree*: The third category of node scheduling schemes is based on the coverage degree and is categorized into 1-cover, k-cover, and Q-cover scheduling, as shown in Fig.15. The total number of sensor nodes required in an area to sense an event is called the coverage degree. 1-cover scheduling schemes select and activate the cover set such that each event or target is detected by at least one sensor, whereas in k-cover scheduling, each event or target is detected by a minimum of 'k' sensors. Here 'k' is an arbitrary integer and is set to application specific values. The k-cover scheduling schemes are utilized in mission-critical applications that require a high degree of reliability and detection probability. Q-cover scheduling [140] is a type of target/point scheduling wherein each target is guaranteed to be detected by at least 'Q' number of sensors. Q is an arbitrary integer just like 'k,' but the main difference between the two is that in Q-cover scheduling, Q's value may vary for different events, whereas in k-cover scheduling, the value of k remains static across each target/event in the surveillance field.
- *The cover set*: A cover set in a node scheduling scheme is usually of two types: a *disjoint cover set* and an *overlapping cover set*. In a disjoint cover set, a sensor node belongs to at most one cover set. Such cover sets are therefore mutually exclusive, as they do not have any nodes in common. Whereas an overlapping cover set may contain a sensor node that may belong to other cover sets as well. In a general sense, given that all the sensor nodes have a uniform energy dissipation rate, a node scheduling scheme that supports disjoint cover sets is proven to be more efficient. It can also balance the overall energy usage in the network, such that no node in the network is under or over utilized. According to work done in [140], overlapping/non-disjoint sets are more efficient in scenarios wherein the sensor nodes have varying energy dissipation rates. When an individual sensor node powers off, then the cover set in which it is participating is no longer available. However, other sensor nodes in this cover set can be re-utilized in the formation of newer cover sets, thereby providing redundancy and extended network lifetime. We can, therefore, safely conclude that the efficiency of the two set types depends on the energy dissipation rate of the sensor nodes and the number of available cover sets.

An extensive taxonomy of the node scheduling schemes based on the coverage characteristics and selection strategies is illustrated in Fig. 21. Table 4 highlights the existing literature work on node scheduling that focus on coverage characteristics.

2) SELECTION STRATEGIES

Previous research work classifies coverage based node scheduling schemes based on selection strategies, as summarized in Table 5. Key network, sensor, and application characteristics of node scheduling schemes are discussed in Table 7 and schemes based on those characteristics are summarized in Table 6. Coverage characteristics, such as the cover type, the degree of coverage, and the cover set type, are also considered while discussing these schemes.

- *Operational phases of node scheduling schemes*: Any node scheduling scheme's operation can be broadly classified into two main phases, as shown in Fig. 16. The first phase is the redundant node identification and active node selection phase, which includes identifying sensor nodes that cover the same area and then deciding which specific node can be made active to participate in the formation of cover sets. The second phase is the active node scheduling phase, in which all the cover sets that are created in the first phase will be scheduled into an "active" state at different time slots of the communication cycle.

  Many different coverage-based selection strategies are discussed in the literature for implementing the first phase. Some prominent approaches are discussed below and also summarized in Table 4. Table 4 highlights the

TABLE 4. Coverage based node scheduling schemes.

Research	Cover type	Coverage ratio	Degree of coverage	Cover set type	Selection strategy
[141]	Target	Partial	1-Cover	Disjoint	Probing based
[144], [145]	Area	Complete	1-Cover	Disjoint	
[142], [143]	Area	Complete	k-Cover	Disjoint	
[167]	Target	Partial	k-Cover	Overlapping	
[146]–[150]	Area	Complete	1-Cover	Disjoint	Voronoi based
[152]	Area	Partial	1-Cover	Overlapping	Machine learning based
[154]	Target	Partial	Q-Cover	Overlapping	
[168], [169]	Target	Partial	1-Cover	Overlapping	
[153]	Target	Partial	k-Cover	Overlapping	
[170]	Target	Partial	1-Cover	Overlapping	
[140]	Target	Partial	Q-cover	Disjoint	
[154], [155]	Area	Complete	1-Cover	Disjoint/Overlapping	Game theoretic-based
[156]	Target	Partial	1-Cover	Disjoint	
[157]	Target	Partial	1-Cover	Disjoint	Data correlation based
[158]–[163]	Area	Complete	1-Cover	Disjoint	
[165], [166]	Area	Complete	k-Cover	Disjoint	
[164]	Target	Partial	k-Cover	Disjoint	
[171]	Area	Complete	1-Cover	Overlapping	

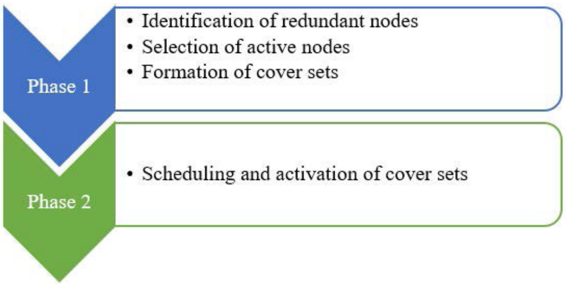


FIGURE 16. Phases in node scheduling scheme.

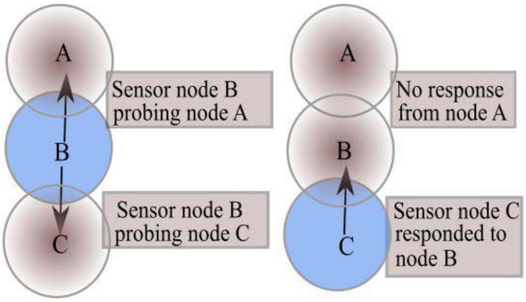


FIGURE 17. Probing scheme.

selection strategy in use along with coverage characteristics it meets.

- *Probing based node scheduling schemes*: Probing-based scheme is one of the earliest approaches used for active node selection. Probing based distributed and localized node scheduling schemes are proposed in [118], [141]–[145] wherein the sensor nodes independently decide when to switch over to low-power "sleep" state by probing the neighboring nodes as shown in Fig. 17. One prominent probing based scheme is Probing Environment and Adaptive Sleeping (PEAS) [141] which uses a probing and adaptive sleeping strategy. In PEAS, sensor nodes probe the network by sending messages to only those neighboring nodes which lie within their sensing range. Reply messages received in response to the probe indicate which neighbors are currently active and is used to determine whether this querying node should switch to "sleep" state or not. One drawback of this approach is that a node implicitly trusts these reply messages. In other words, it believes these neighbors will provide the necessary cover in its absence. As the responder node's location is not verified, the decision of the querying node to switch off may lead to the creation of sensing holes. This results in partial rather than full coverage. PEAS-L1 proposed in [144] extends and overcomes this drawback of PEAS. In PEAS-L1, a source node determines the responder's exact location to check if the sensing range of this source overlaps with that of the responder. If there is an overlap, the source node powers off. This scheme can be applied both in homogeneous and in heterogeneous network environments. PEAS-L1 has a better coverage ratio than PEAS.
  The probing methods proposed in [142], [143] provide complete 1-cover coverage over the sensory field. In these methods, nodes discover their neighbors using a hello message passing scheme, and then each node probes its immediate neighborhood to determine the degree of overlap between itself and its neighbor. The decision is taken by applying an off-duty eligibility rule

TABLE 5. Coverage and connectivity based node scheduling schemes.

Research	Cover type	Degree of coverage	Network type	Execution strategy	Selection strategy	Expected complexity
[172]	Area	1-Cover	Homogeneous	Distributed	Message passing and dominating set theory	$\mathcal{O}(n \log n)$, n is the total number of nodes in the network
[173]	Area	1-Cover	Homogeneous	Centralized	Greedy heuristic on bipartite graph	$\mathcal{O}(V \log V)$
[174]	Area	1-Cover	Homogeneous	Centralized	Prims algorithm on minimum spanning tree	$\mathcal{O}(V \log V)$
[175]	Target	1-Cover	Homogeneous	Distributed	Message passing	$\mathcal{O}(n)$, n is the total number of nodes in the network
[176]	Target	k-Cover	Heterogeneous	Centralized	Ford-Fulkerson algorithm on flow Graph	$\mathcal{O}(\mid V \mid\mid E \mid^2)$
[177], [178]	Barrier	k-cover	Heterogeneous	Distributed	Edmond-Karp algorithm on flow graph	$\mathcal{O}(\mid V \mid\mid E \mid)$
[179]	Barrier	k-cover	Homogeneous	Distributed	Relabel-to-front algorithm on flow graph	$\mathcal{O}(\mid V \mid^3)$
[180], [181]	Barrier	k-cover	Heterogeneous	Centralized	Depth first search on flow graph	$\mathcal{O}(\mid V \mid^3 /log \mid V \mid)$
[182]	Barrier	1-Cover	Homogeneous	Centralized	Minimum dominating set concept	NP-Hard (Complexity not given)
[183]	Barrier	1-Cover	Heterogeneous	Distributed	Greedy approach on flow graph	$\mathcal{O}(V \log V)$
[184]	Barrier	k-Cover	Heterogeneous	Distributed	Combination of grid and graph-based approach	Not given
[185]	Barrier	k-Cover	Heterogeneous	Distributed	Random search on undirected graph	$\mathcal{O}(\log V)$
[186], [187]	Barrier	k-Cover	Heterogeneous	Distributed	Message passing	$\mathcal{O}(n)$
[188]	Barrier	k-Cover	Homogeneous	Centralized	Breadth first search on undirected graph	$\mathcal{O}(\mid V \mid^2\mid E \mid)$

based on the sponsored sector. The sponsored sector of a sensor node is a sector of its circular sensing area sensed by its neighboring nodes. If the sum of the sponsored sectors equals its complete sensing area, then it is safe for this node to switch off. One major shortcoming of such a probing-based scheme is that two or more sensor nodes that sense the same area may simultaneously decide to switch over to the "sleep" state, thereby creating a sensing hole. To avoid such a situation, a back-off mechanism is discussed in [142], [145]. The back-off mechanism allows a node to switch to the "sleep" state after a random wait time to prevent overlapping nodes from simultaneously switching over to the "sleep" state. The Energy Aware Common Neighbor Scheme (ECNS) proposed in [143] extends the work proposed in [142]. In contrast to the range-based neighbor discovery method proposed in [142], the ECNS scheme uses a range and residual energy-based neighbor discovery method. In [145], a scheduling protocol which dynamically schedules the nodes in a cluster region, is proposed. Each node in the cluster has three operational states: "sleep", "active", and "probe" state. A sensor node in an "active" state moves to "probe" when its lifetime is about to expire. In the "probe" state, the sensor node sends HELLO packets to neighboring nodes requesting to substitute its role. The node moves to "sleep" state if it receives a response from all or at least one neighbor; otherwise, it continues in its "active" state until the lifetime expires. The state diagram is shown in Fig. 18.

- *Voronoi based node scheduling schemes*: Complete coverage and location-independent node scheduling based on the Voronoi diagram is proposed in [146]–[150].

TABLE 6. Comparison of node scheduling schemes based on its network, sensor and application characteristics.

Research	Topology type	Deployment type	Network type	Sensing model	Sensor type	Execution type	Sensing power
[177]	Hierarchical	Random	Static	Boolean	Location aware	Static	Non-adjustable
[181]	Hierarchical	Random	Static	Boolean	Location aware	Static	Non-adjustable
[182]	Hierarchical	Random	Static	Boolean	Location aware	Static	Non-adjustable
[186]	Hierarchical	Random	Static	Boolean	Location aware	Static	Non-adjustable
[187]	Hierarchical	Random	Static	Boolean	Location aware	Static	Non-adjustable
[189]	Hierarchical	Random	Static	Boolean	Location aware	Static	Non-adjustable
[160]	Hierarchical	Random	Static	Boolean	Location unknown	Static	Non-adjustable
[180]	Hierarchical	Deterministic	Mobile	Boolean	Location aware	Static	Non-adjustable
[185]	Flat	Deterministic	Static	Boolean	Location aware	Dynamic	Adjustable
[140]	Hierarchical	Deterministic	Static	Probabilistic	Location aware	Dynamic	Non-adjustable

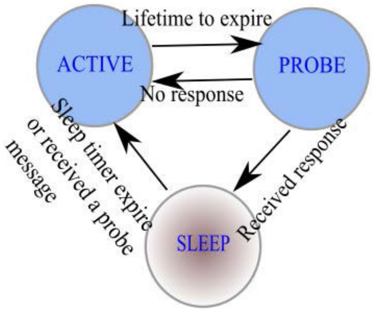


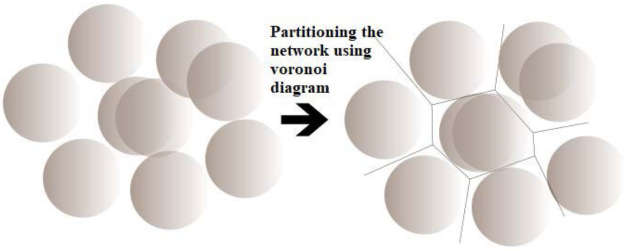
FIGURE 18. State diagram of OBSP protocol.

In the Voronoi diagram-based computation, the sensor nodes' sensing region is modeled as a Voronoi diagram. In [146], the active node selection problem is formulated as an optimization problem, and a sleep benefit function is defined to decide whether a sensor node should switch over to the "sleep" state. The sleep benefit function is defined as a function of the energy required by a sensor to provide the required coverage and the energy required by its neighbors to extend their sensing radius to provide complete coverage when this node switches over to the "sleep" state. The sensor nodes with the highest sleep benefit value will be made active. This method is an extension of the work reported in [147]. A centralized, Voronoi based computation scheme is employed in [147]. The proposed scheme assumes that all sensors have the same sensing radius. One of the drawbacks of the centralized scheme is redundant coverage because of the non-adjustable sensing range. This limitation is addressed using the benefit function with an adjustable sensing range to improve the overall energy conservation significantly. The non-critical redundant nodes are identified using 3D Voronoi diagram in [149] and using 2D Voronoi diagram in [150]. The sensor nodes that lie in small Voronoi cells are considered non-critical for guaranteeing coverage and hence are put to "sleep" state in both the approaches above. Fig. 19 and Fig. 20 show the 2D and 3D Voronoi diagrams used in those approaches. It should be noted that the computational complexity of Voronoi based schemes is greater than other node scheduling schemes.

- *Machine learning-based node scheduling schemes*: There are just a few proposals for node scheduling schemes based on machine learning. These schemes utilize a reinforcement learning-based strategy for active node selection. In [152], a machine learning based node scheduling scheme is proposed. The scheme was primarily developed for energy harvested (solar-powered)

TABLE 7. Network, sensor, and application characteristics.

Category	Characteristics	Types	Definition
Network	Topology	Flat	All the sensor nodes in the network are at the same level and with the same functionalities.
		Hierarchical	The sensor nodes in the network are grouped into different levels and sensor nodes at each level have different functionalities
	Types	Static	All the sensor nodes in the network are immobile
		Mobile	Few or all the sensor nodes in the network are mobile.
Sensor	Deployment	Deterministic	The position to deploy the sensor nodes are known in advance and are deployed in those known positions.
		Random	The position to deploy the sensors is not known in advance.
	Sensing Model	Boolean	The detection probability of the sensor node to detect a target is equal to 1 if the target is inside the sensing area of sensor node and 0 otherwise.
		Probabilistic	The detection probability of the sensor node decreases with the increase in the distance between the sensor node and target.
	Sensing Power	Adjustable	The sensor node can adjust the sensing power according to the requirement of application.
		Non-adjustable	The sensor node cannot adjust the sensing power.
	Types	Location-aware	The sensor node with a GPS module.
		Location unknown	The sensor node without a GPS module and depends on localization methods.
Application	Types	Static	The execution strategies to generate the cover sets doesn't change with the dynamics in the environment.
		Dynamic	The execution strategies to generate the cover sets changes with the dynamics in the environment.



(a) Input Sensor network (b) Network with voronoi partition

FIGURE 19. 2D Voronoi diagram of sensor network.

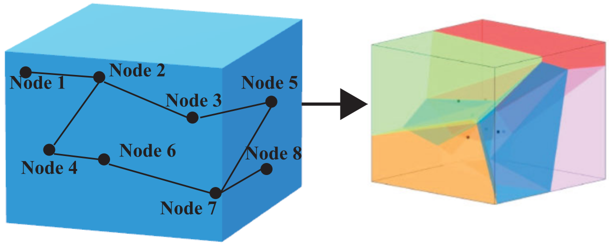


FIGURE 20. 3D Voronoi diagram of 3D sensor network, (a) 3D Sensor network, (b) 3D Voronoi diagram [151].

wireless sensor networks. The scheme runs a range based group formation algorithm and Q-learning based active node selection algorithm in each execution round. A message broadcasting technique is used to form groups. Q-learning is a reinforcement learning strategy adopted for active node selection and generation of overlapping cover sets. The learning parameters such as the current residual energy, recharging frequency, and the solar radiations influence the node selection process. In the approach proposed in [153], a Q-learning strategy is applied to generate cover sets for dynamic sensor networks. Each sensor node in the generated cover set learns from the network and can adjust its communication range in order to conserve energy.

- *Game theoretic-based node scheduling schemes*: An emerging research paradigm in node scheduling schemes is the adoption of selection strategies based on game theory. A game theoretic approach is proposed in [154], in which all sensor nodes in the surveillance field are players or competitors in the coverage game. A strategy set is associated with each player. The strategy set is the set of decisions taken by the player in the game. In the coverage game, the decision taken by a player will be to switch to "sleep" or to "active" states. A strategy set is associated with each event to be monitored. This set contains a set of decisions taken by the sensor nodes that are responsible for monitoring an event. A payoff function is defined for each strategy profile that returns a payoff value based on the decision taken by the player. All the players are considered

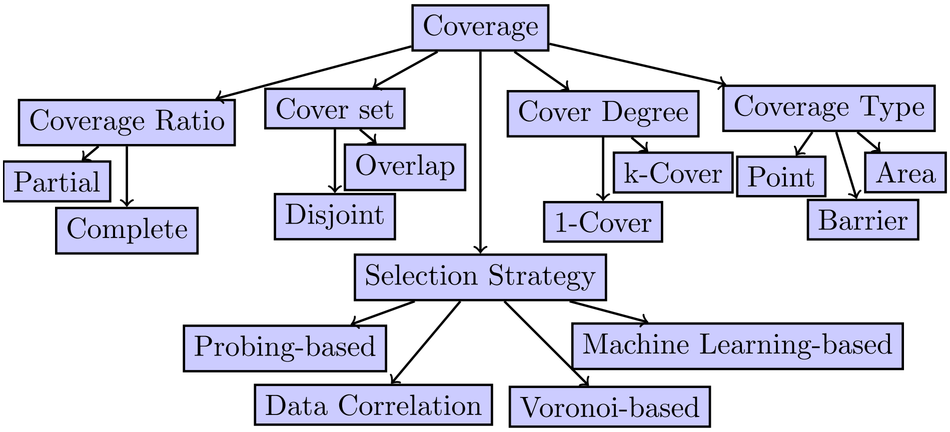


FIGURE 21. A taxonomy of coverage based node scheduling schemes.

to be selfish and their goal is to maximize their own payoffs. All those players with the maximum payoff may switch to the "sleep" state. The proposed approach is a non-cooperative game theoretic approach because the sensor nodes do not interact with one another to make a decision. The approach is designed to generate both disjoint and overlapping cover sets to provide Q-coverage. One notable merit of this approach is that it can operate independently of the topology of the sensory field.

The work in [155] proposes a dynamic node scheduling scheme using non cooperative game theoretic strategy to significantly cut down idle listening and improve the energy efficiency of WSNs. The minimum dominating cover set selection strategy based on game theory is discussed in [156] and a game theory-based approach for target coverage in a directional sensor network is described in [157]. Most approaches based on a game theory that are discussed in the literature are non-cooperative and perform better than their counterparts since are not constrained by the underlying network topology.

- *Data correlation based node scheduling schemes*: Node scheduling schemes based on sensed data correlation perform a trade off between data precision and energy consumption of a sensor node.

  Firstly, the data that is sensed over time are correlated to build a prediction model at each sensor node. The decision to remain in "active" or in "sleep" state depends on the output of the prediction model. If the discrepancy between the actual and the expected sensed data from the prediction model is beyond a threshold value, then the sensor node switches over to "active" state. If there are no variations, then it remains in "sleep" state to save energy. This is an example of partial coverage scheduling where the primary goal is to extend the network lifetime by prolonging the sleep duration of the sensor nodes while ignoring the coverage requirements. Node scheduling schemes built on this idea include the Correlation-based Scheduling Algorithm for Network (CSCAN) and Energy Efficient Stochastic Sensing Framework (ESense) as proposed in [158]–[160] respectively. These are dynamic scheduling algorithms that aim at controlling the duty cycle of a sensor node by establishing a correlation between the sensed data that was collected in real-time and data furnished by the prediction model. The decision to change the state is taken dynamically by each sensor node based on the outcome of the algorithm. Thus these algorithms combine a prediction model with a scheduler to fine-tune the duty cycle of the sensor nodes. Moreover, these algorithms support both habitat monitoring and military surveillance applications where data accuracy is a key QoS requirement. In the approach proposed in [160], an active sensor node alerts and prompts its sleeping neighbor nodes to wake up if it check any discrepancy between the sensed and predicted data. Thus the responsibility to check the error or the discrepancy in the sensed data and to alert neighboring nodes if the difference goes beyond a threshold is levied only on active nodes. Thus, unlike in the previous approach, this scheme conserves energy by prolonging the "sleep" state of nodes.

  Secondly, the correlation between the sensed data of adjoining nodes can also be utilized to identify a redundant node in the sensory field. A node is flagged as redundant to another node if there is a correlation between their sensed data. This idea of identifying redundancy based on the correlation between sensed data of any two neighboring nodes is adopted in node scheduling schemes discussed in [161]–[163].

  A cluster-based node distributed scheduling scheme is discussed in [161], wherein to establish data correlation, the cluster head performs computations on the sensed data gathered from cluster members. The scheme proposes a power exponential data correlation model, and computations are done on the model to calculate the optimal number of active sensor nodes required for the operation. The authors in [164] discuss a centralized approach different from the one discussed above. In this approach, a data aggregation tree of the collected data is built by the sink node, and then a support vector machine scheme is applied on the data aggregation tree to classify data based on data correlation. Thereafter, redundant nodes that send the same data are identified. The sink forces these redundant nodes to switch over to the "sleep" state.

A centralized and distributed approach to construct the cover set based on data correlation is considered in [165]. In [166], data correlation is represented as a Markov random field model and a service-oriented node scheduling scheme is then proposed based on this model. While there are some existing studies that use data correlation to identify redundant nodes, this approach is still not considered appropriate for scheduling purposes since data that is collected for comparison may be a noisy version of the actual data. Thus the decision to switch a redundant sensor node to the "sleep" state is likely to create a coverage hole. A more pragmatic approach towards identifying redundant nodes involves a combination of data, temporal, and location correlation schemes.

3) REMARKS

The proposed selection strategies range from message passing or probing-based to game theory, machine learning, and automata-based. Most research on node scheduling has focused on designing and devising effective selection strategies to implement the first phase of node scheduling while keeping the second phase simple and straightforward. The complexity analysis of coverage-based node scheduling schemes reveals that probing-based strategy incur more communication overhead in comparison to other strategies. The computational complexity is higher in Voronoi-based approaches. Machine-learning based, game-theoretic-based, and data correlation strategies seem to perform well in identifying redundant nodes using straightforward mathematical computations with no constraints imposed.

B. CONNECTIVITY BASED NODE SCHEDULING SCHEMES

Connectivity is an important requirement of surveillance applications and always goes hand in hand with the coverage requirement. Good coverage also guarantees better connectivity [142]. The connectivity between sensor nodes and the base station is a must ensure that the sensed information reaches the base station with a minimum delay. The 1-cover area coverage scheduling scheme proposed in [172] utilizes message passing and connected dominating set theory principles to identify both forwarding nodes and sensing nodes required to fully cover the sensing area. The forwarding nodes are included in the cover set to meet the connectivity requirements. The scheme trades off the requirement of energy efficiency to meet the connectivity demand of the application. A centralized graph-based approach to meet the connectivity requirement is applied in the area coverage scheduling scheme discussed in [173]. The authors consider the problem as a maximum matching problem on the bipartite graph and implement a greedy heuristic on the graph to discover the connected cover set. In [174], a centralized flow graph-based approach and distributed message passing approach is implemented to meet both coverage and connectivity requirements. In the proposed approach, the network is divided into grids and then a flow graph of the sensor nodes in each grid is constructed and finally, a minimum spanning tree algorithm called Prim's algorithm is executed on the flow graph to generate the cover sets. Each edge in the MST cover set is a Max-Flow pair of sensor nodes in each grid. A connected target coverage scheduling scheme for a heterogeneous network is discussed in [175] in which each sensor node in the cover set identifies a relay node to connect to the sink. In [176], the network is transformed into a flow graph, and then an approximation algorithm is applied to generate the connected cover set for target coverage. The algorithm is based on the classical Ford-Fulkerson algorithm. The coverage and connectivity based node scheduling schemes are summarized in Table 5.

Barrier scheduling is superior when it comes to meeting both coverage and connectivity requirements of an application compared to other coverage based schemes. Barrier scheduling schemes ensure coverage by forming cover sets called barriers comprising sensor nodes which partially overlap with one another to cover an area. To guarantee connectivity, the sensor nodes in the barrier are connected to the base station seamlessly through the cluster head (as in cluster-based barrier scheduling strategies), or alternatively, a node from the barrier acts as a relay to provide connectivity to the base station. The approaches used in barrier scheduling can be broadly classified as graph-based, message passing, and grid-based approaches. These approaches attempt to find a solution to a multi-objective optimization problem with objective functions based on network lifetime, coverage, and connectivity. Some prominent approaches based on barrier scheduling are discussed below.

1) THE GRAPH-BASED APPROACHES

The scheme in [177] constructs multiple disjoint barriers by transforming the monitored region to a flow network graph with sensors in the segments and strips as vertices of the graph. An edge between a pair of vertices in the graph indicates that the corresponding sensors' sensing range overlaps. The standard Edmond-Karp algorithm is then applied to find the maximum flow paths in the graph. These paths correspond to barriers described in barrier scheduling literature. The proposed approach becomes less scalable when the density of node deployment increases. A similar approach that applies the same strategy for the construction of k-barriers is discussed in [178]. Unlike the approach mentioned above, a relabel-to-front algorithm is applied in the flow graph to generate k-barriers in [179]. In [180], the network is transformed into a bipartite graph and then subsequently to a flow graph. A maximum flow algorithm similar to the Ford-Fulkerson algorithm is executed on the graph to determine the optimal location for a node to move to. Thereafter, a depth-first search strategy is employed on the same graph to construct barriers. The barrier so constructed is then scheduled to run in a specific time slot. The work in [181] introduces the notion of reinforced barriers. A reinforced barrier in a rectangular region being monitored is a barrier that runs along the diagonal of the rectangle. The network is modeled as a graph, and the approach similar to the one proposed in [180] is applied to construct the barrier. A graph-based approach discussed in [182] uses the notion of a minimum dominating set to identify the barriers. The set is generated by priority based iterative pruning of the graph. A greedy approach is adopted in [190] to discover barriers on the transformed flow graph of the network, whereas, in [183], the Kruskal minimum spanning tree algorithm is applied to generate connected barriers. An efficient distributed k-barrier construction algorithm is proposed in [184], which is a combination of grid and graph-based approaches. The primary goal of the algorithm is to construct disjoint k-barriers. The cover sets are transformed into a graph where each cover set forms the vertices and the edges of a graph that connect the two neighboring cover sets. Once the graph is constructed, a heuristic approach based on residual energy constructs the barriers. The computational complexity of this approach increases as the size of the network increases. In [185], [188], the network is converted to an undirected graph, and then a combination of random and greedy search methods is applied to generate k-barriers for scheduling. It is seen that this approach finds barriers with minimum communication costs. An Integer Linear Programming (ILP) formulation of the problem is presented in [191]. A branch and bound approach is applied to obtain an optimal solution to the problem. Additionally, a heuristic based on Dijkstra's algorithm called Multi-round Shortest Path Algorithm (MSPA) is also utilized to identify a maximum number of vertex disjoint barrier paths. The heuristic is applied over a directed coverage graph of the network. In [192], the network is modelled as a fully-weighted static graph and a greedy heuristic is applied to construct the barrier. The proposed graph model is extended to fully-weighted dynamic graph model in [193] to meet fault-tolerance requirement, and a weight-balancing greedy heuristic is applied over the dynamic graph to construct the barriers.

2) THE MESSAGE PASSING OR PROBING BASED APPROACHES

A coverage protocol for barrier coverage is proposed in [186]. The work introduces a 2D zone concept and is based on the premise that if this 2D zone barrier is covered, then the entire monitoring region is also covered. A message-oriented scheme is employed by each node to check whether the 2D zone is k-barrier covered for an arbitrary value of k. if it is the case, the node goes back to ''sleep'' state; otherwise, it remains in ''active'' state. The decision to be in ''active'' or in ''sleep'' state is taken at runtime by each node individually. Since a message-oriented scheme is employed, the communication overhead will be high. A localized and distributed scheduling scheme is discussed in [160], [187], [189] in which all sensors collaborate to decide on whether to remain ''active'' or go back to ''sleep''. This is done by employing a priority-based message-passing scheme. Preference for sleep is given to sensor nodes with minimal residual energy.

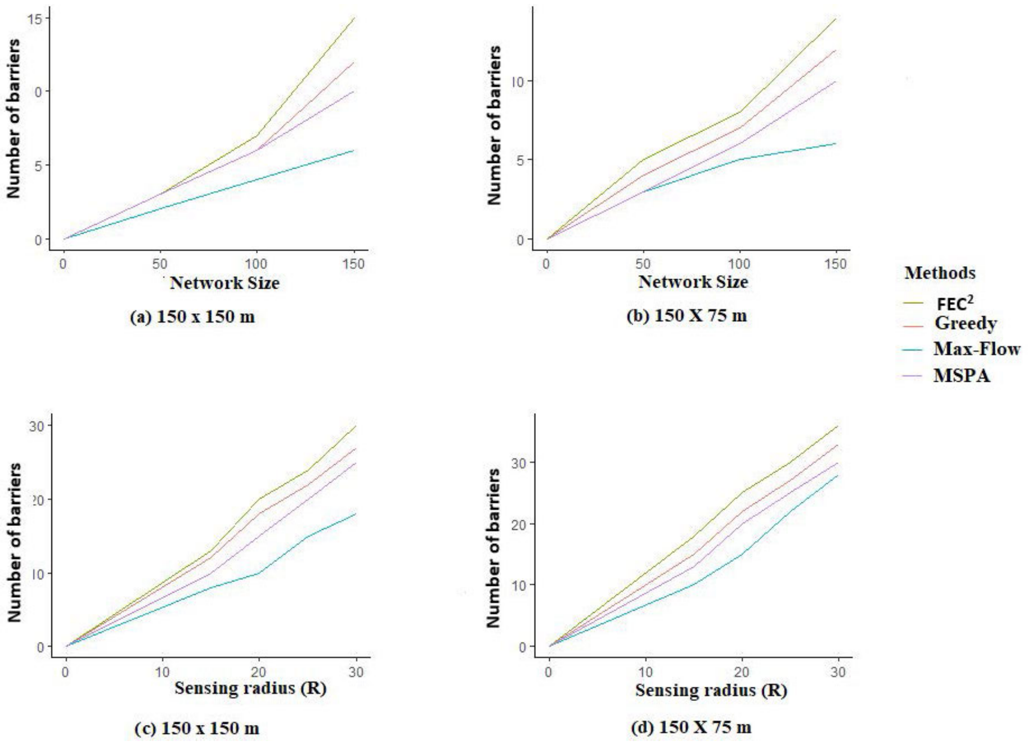
3) REMARKS

Graph-based schemes are proven to effectively meet coverage and connectivity requirements compared with message passing and grid-based schemes. As noted in coverage based node scheduling schemes, message-passing schemes incurred high communication costs and are not effective in a dense network. Grid-based and graph-based approaches can be applied in a dense network, but computational complexity increases as the network size increases (as stated in Table 5). Most of the research work on graph-based approaches utilize generic graph models such as unweighted/weighted graph, flow-graph, bi-partied graphs, and algorithms such as Max-Flow, Dijkstra's (MSPA), Greedy on these models. Several research efforts aim at developing a novel graph-model and approaches (E.g., dynamic graph model proposed in [193]) that can construct the barriers efficiently without compromising QoS. Thomas *et al.* in [193] have compared the barrier construction efficiency of these approaches by varying the network size and sensing radius. The results obtained are shown in Fig. 22. It can be observed that the weight-balancing greedy approach (called FEC^2) in [193] outperform other generic approaches.

A hybrid approach that combines the benefits of both grid and graph-based approaches is always better than using one approach alone. Similarly, we have observed that the distributed approach are better than centralized approaches in all the discussed connectivity based node scheduling schemes. Also, it can be noted that most of the research work on connectivity based node scheduling schemes utilizes a graph-based approach because of its efficacy in addressing the problem in a cost-effective and efficient way. The network, sensor, and application characteristics in these schemes are summarized in Table 6. From our observation, there are very few proposals on dynamic node scheduling schemes over a heterogeneous network using mobile sensor nodes with probabilistic sensing model (realistic sensing model) and adjustable sensing range. Hence, there is a pressing need for further research in this direction.

C. FAULT TOLERANCE BASED NODE SCHEDULING SCHEMES

There are few approaches [194]–[197], [201] that address fault tolerance. In [194], a novel scheduling algorithm is proposed to address coverage, connectivity, and fault tolerance (Hybrid approach). A dynamic cover tree (representing cover



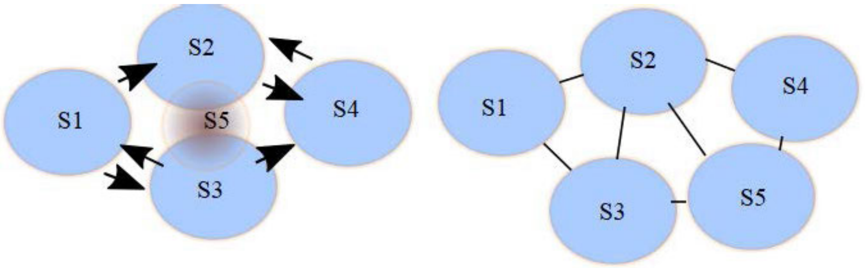
(a) 150 x 150 m

(b) 150 X 75 m

(c) 150 x 150 m

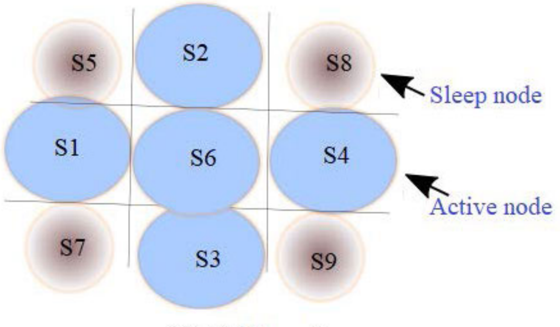
(d) 150 X 75 m

FIGURE 22. Comparison of barrier construction efficiency of graph-based barrier coverage scheduling approaches.



(a) Message passing-based

(b) Graph-based



(c) Grid-based

FIGURE 23. Connectivity based node scheduling schemes.

set) is constructed to meet both coverage and connectivity requirements. The network lifetime can be extended by activating one dynamic cover tree at a time. If a node in an activated cover tree fails, it is immediately replaced with a node from the reserved node-set to ensure complete coverage at all times. The reserved node set includes nodes that do not belong to any cover tree and those with residual energy that were once part of cover trees that are currently deactivated.

TABLE 8. Secure and fault tolerance based node scheduling schemes.

Research	Strategy adopted	Coverage	Connectivity	Fault Tolerance	Security	Node Mobility Assumption
[194]	Load balancing cover tree	✓	✓	✓	×	×
[194]		✓	✓	✓	×	×
[195]	Message Passing	✓	×	✓	×	×
[196]	Cascading node movement	✓	✓	✓	×	✓
[197]	Probing and adaptive sleeping	✓	✓	✓	×	×
[198]	Greedy Approach	✓	×	✓	×	✓
[199]		✓	✓	✓	×	×
[167], [168], [200]	Trust computation of cover set	✓	×	×	✓	×
[169]	Fuzzy inference rule	✓	×	×	✓	×
[170]	Dynamic programming	✓	×	×	✓	×

If the system cannot find an alternate node to replace a failed node in a cover tree, then this cover tree is decommissioned and a new cover tree is activated. Thus, the system guarantees better connectivity and coverage with dynamic recovery.

A Fault-tolerant Adaptive Node Scheduling (FAN) [195] is an extension of Coverage Preserving Node Scheduling (CPNS) algorithm based on sponsored coverage proposed in [142]. A message-passing scheme is employed in FAN to identify back-up nodes for substituting power depleted active nodes. Given that each backup node is not in the sponsored coverage of other back-up nodes, the FAN algorithm guarantees that the minimum and the maximum number of back-up nodes required to cover an active node's sensing area is 3 and 5, respectively. Thus the FAN algorithm explores and limits the number of backup nodes for each active node to a maximum 5 nodes. An adaptive scheduling method with fault tolerance is proposed in [196]. It extends the zone-based clustering scheme proposed in [201]. Fault tolerance is based on a cascading node movement scheme that moves a redundant node to the failed node's location to recover from failure. This scheme is suitable only if the sensor node has some mobility and can move to a new location and hence is not appropriate for networks comprising solely of static nodes.

In [197], a probing-based fault tolerance scheme is proposed for both homogeneous and heterogeneous networks. The scheme exploits probing and adaptive sleeping proposed in PEAS [141] to probe a network for failed active nodes. The redundant nodes are used for probing purposes and may also act as a substitute for a failed node. The failed node detection accuracy in this scheme depends on the rate at which the probes are sent out. A greedy based fault-tolerant barrier construction algorithm is proposed in [198], which is an extension of the work reported in [202]. The proposed algorithm follows a greedy approach to identify the substitute node closest to the failed node. The algorithm ensures that this substitute is currently not a member of any active barrier. By doing so, no coverage holes are created in the adjoining activated barriers. A fully weighted dynamic graph model and weight balancing greedy strategy are proposed in [199] to avoid faults due to unexpected battery depletion and recover from unexpected dynamic failures of sensor nodes. The aforementioned fault tolerance schemes are summarized in Table 8.

1) REMARKS

The sensor nodes in an activated cover set fail because of different types of faults. It can be due to unintentional faults (software and hardware faults) or intentional faults (security attack). Schemes that are fault tolerant address intentional faults and are discussed in the following sub-section. A fault-tolerant node scheduling scheme must withstand node failures. There are different strategies discussed in the literature to address such faults and these include the use of backup [196], [201] and mobile sensor nodes [197] or cascading node movements [201]. Latest research on fault-tolerant node scheduling aims to develop dynamic self-healing strategies to address faults dynamically with minimum delay and minimum percentage of coverage holes [199].

D. SECURE NODE SCHEDULING SCHEMES

A secure node scheduling scheme aims to identify and activate a subset of reliable and fault tolerant sensor nodes. The subset of nodes chosen can prevent physical intrusions (person or object crossing the surveillance field), and logical intrusion (logical break-in) caused because of malicious attack. In logical intrusion, an intruder gains unauthorized access to a system to misuse, steal or leak confidential information/resources. A logical intrusion can be

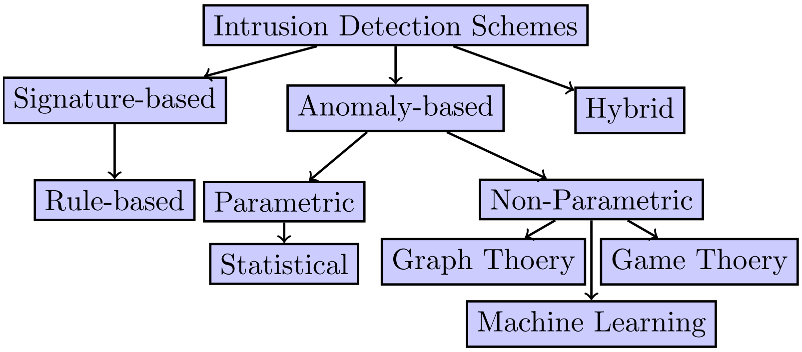


FIGURE 24. Taxonomy of security approaches.

considered an activity that compromises security services such as availability, confidentiality, and network integrity. An intrusion detection system is necessary to detect security breaches and can be broadly classified into *signature-based*, *anomaly-based*, and *hybrid intrusion techniques*. A detailed taxonomy of the security approaches is illustrated in Fig. 24. A rule-based IDS checks whether the network or node behavior matches any pre-defined rule set (signature) of a known attack. The signature-based IDS are also called rule-based IDS. Two commonly used approaches to extract rules are fuzzy set theory and association rule mining [169], [170]. Genetic programming and genetic algorithm based approaches are also well known in generating optimal rules. In rule-based approaches, there is always a trade-off between the quantity and quality of rules mined. Moreover, rule-based approaches cannot identify novel security attacks. In an anomaly-based IDS, a profile for a network under normal operating conditions is generated, and an anomaly is flagged if there is any deviation from the generated profile. An anomaly-based IDS can be broadly categorized into parametric and non-parametric approaches [167], [168], [200], [203]. A parametric approach is preferred when the statistical distribution is known in advance, whereas in case of uncertain data distribution a non parametric approach is preferred. Some recent research on secure node scheduling is discussed below and summarized in Table 8.

A secure node scheduling method for a heterogeneous environment is proposed in [200]. In the proposed approach, cover sets are generated by taking trust into account to facilitate reliable and energy efficient communication. Thereafter, an energy prediction model is used to schedule the cover sets. In [200], a trust selection model, namely the Naive Bayesian model with a Clark distance algorithm, is proposed to estimate the trust degree and establish a trust relationship between nodes in a cover set. In [167], a feedback mechanism is developed to assess and evaluate trust on sensor nodes that belong to a cover set selected for scheduling. A secure dynamic scheduling scheme is discussed in [168]. It is trust based and considers considers direct trust, recommended trust, and indirect trust. Each node's trust value is computed and then fed as input into a fuzzy inference model to assess the degree of trustworthiness of sensor nodes. Nodes with a high degree of trust values are included in the cover set. A secure target coverage node scheduling scheme is proposed in [169], which is an extension of the work reported in [168], [170]. The fuzzy inference rules used to evaluate sensor nodes' trustworthiness are optimized by applying the rough set theory principles. In [170], a hidden Markov model with dynamic programming is used to compute trust values, which are then used to influence scheduling decisions. All state-of-the-art secure node scheduling schemes discussed above are mostly use the notion of trust to thwart denial of sleep attacks [204].

1) REMARKS

Wireless sensor networks deployed for surveillance applications are prone to different security attacks due to open communication medium, unattended environment, lack of tamper-proof hardware, and lack of a physical line of defense such as a firewall. Any node scheduling scheme that is designed for such applications should operate efficiently in the event of node failures because of such attacks. The sensor node failures are a significant threat to meeting QoS requirements, such as energy efficiency, coverage, and connectivity. Most of the conventional cryptography and authentication mechanisms with intense computation are not suitable for detecting an attack in a resource-constrained WSN. A lightweight authentication and cryptography framework similar to the one proposed in [205] is more suitable. IDS can form a second line of defense where such cryptography solutions fail. Amongst different types of IDS, the vast majority of research on secure node scheduling are anomaly based. Those schemes apply machine learning, trust, and game theory-based approaches to detect and avoid security attacks. Rule-based techniques are seldom applied due to the uncertainty in the type of attack. The research work in this area is not fully explored, and there is a broad scope for quality research work. We observed that the lack of a properly labeled or an unlabelled WSNs attack dataset is a key reason for the lack of quality research work in this domain.

VI. ISSUES AND CHALLENGES IN NODE SCHEDULING SCHEMES

A range of factors potentially affect the performance of any scheduling scheme [8]–[12], [14]–[16], [171], [206]. A node scheduling scheme must consider these factors to provide the desired levels of QoS. In this section, we discuss key issues and related challenges in node scheduling schemes and outline new research directions to address those challenges.

A. ENERGY EFFICIENCY

1) ENERGY SOURCE

Sensor nodes in WSNs usually use internal energy storage solutions such as batteries. These batteries may be rechargeable or non-rechargeable. Besides batteries, energy harvesting and energy transference are two other commonly used external energy sources. Any scheduling strategy must have the capability of fully exploiting the sources available to power up the sensor nodes. For example, if energy harvesting is used as an additional energy source, then sensor node activation and deactivation should be scheduled so that a node gets sufficient time to replenish its energy through energy harvesting [207]. In other words, the energy harvesting time and scheduling time must complement each other.

2) ENERGY UTILIZATION

Though there are many analytical and prediction tools available, the prediction of energy consumption still poses a challenge because of the uncertainties in the occurrence of events, and this may impact sensor node operation. Developing a node scheduling scheme that can guarantee a uniform energy distribution with no node being under or over-utilized is a challenge and requires researchers' attention.

B. RELIABILITY

A node scheduling scheme should be able to adapt its operational strategy as and when a sensor node fails. The faults that cause the failure of sensor nodes can be broadly classified into intentional and unintentional faults. Unintentional faults are software and hardware failures. The strategies adopted to address unintentional faults are described in Section V-C. Intentional faults are active security attacks and are described in Section V-D. A research challenge in this setting is to design a node scheduling scheme that can thwart both intentional and unintentional faults without compromising QoS [199]. A node scheduling scheme should operate fairly, even at the time of node failures caused because of such faults.

Any node scheduling strategy designed to meet the security requirements of an application must employ a selection strategy in which a subset of the sensor nodes (cover set) selected is reliable and fault resistant. The strategy to detect compromised nodes should work hand in hand with such a selection strategy. Moreover, the detection strategy adopted to identify malicious/compromised nodes should be lightweight in storage and computational complexity.

C. SCALABILITY

The sensor nodes' deployment pattern varies depending on the type of the terrain and the nature of the intended applications. The deployment can be of two types, namely, sparse and dense. A sparse deployment generates a higher number of sensing holes. On the other hand, the degree of overlap among sensor nodes is high in a dense deployment. A major research challenge is to develop an inter-operable node scheduling scheme that can operate efficiently independent of the deployment scheme chosen [208]. An increase or decrease in the number of sensor nodes deployed in the network should not affect the node scheduling scheme's efficacy in identifying and activating the cover set.

D. PORTABILITY

A node scheduling scheme should be able to operate effectively irrespective of the heterogeneity in network composition. The heterogeneity in network composition is an issue that should be considered while devising a node scheduling scheme [209]. Heterogeneity arises because of the range and direction of sensing, the sensing model, the number of targets/events monitored, and the sensors' initial battery capacity in the network. To develop a portable (or flexible) node scheduling scheme that efficiently works on different types of networks without compromising the QoS requirements is a challenge and it needs to be addressed in future research studies.

E. ADAPTABILITY

1) UNCERTAINTY

Due to a lack of efficient localization techniques, there is always a spatial uncertainty in sensor nodes' position and the monitored event/target. Also, the temporal uncertainty in the occurrence of the monitored event/target makes the problem worse [210]. An efficient node scheduling scheme should consider both location and temporal uncertainty [211] and adapt its execution strategy accordingly. Ignoring these uncertainties may lead to the creation of coverage holes in a sensing field.

2) EXECUTION STRATEGY

A node scheduling scheme may adopt a static or a dynamic execution strategy. In a static execution strategy, all possible cover sets are identified before their actual activation, whereas in the dynamic strategy, the cover sets are identified and activated on-demand depending upon the occurrence of events [140], [185]. A node scheduling scheme based on a static execution strategy needs to handle unexpected node failures that would lead to coverage holes, whereas a node scheduling scheme based on a dynamic strategy needs to react to events spontaneously with a minimum detection delay. Thus an efficient node scheduling scheme should be able to address the challenges in these two cases and must adapt itself accordingly.

FIGURE 25. Issues and challenges in node scheduling schemes.

F. SERVICEABILITY

A sensor network's serviceability is defined as the usability of the network in providing the required QoS levels. Addressing all the above-defined challenges also contributes and enhances the serviceability of the network. The operation of a node scheduling scheme should not affect the serviceability of the network. Devising a node scheduling scheme that maintains improved network serviceability during the entire lifetime of the network is a major challenge that is yet to be addressed. A critical factor that can severely impact a network's serviceability is unexpected coverage holes created due to the failure of the sensor node or inaccurate calculation of the location of sensor nodes [212]. Node scheduling schemes should circumvent such coverage related issues and operate efficiently in meeting the required QoS levels. One way to achieve this would be by combining an efficient sensor node localization and energy prediction strategy with node scheduling. This would yield a solution which would be lightweight in terms of energy consumption.

G. APPLICABILITY

Node scheduling schemes are used for a variety of mission-critical surveillance applications. The applicability of node scheduling schemes is not limited to such applications. They can also be used for data fusion tasks in a distributed target detection and classification system [213], [214]. An optimal data fusion task demands low energy consumption with reduced network bandwidth usage. The optimal data fusion task's objectives can be achieved by combining it with an efficient node scheduling strategy. In such a case, node scheduling scheme can identify a subset of sensor nodes that need to be activated for data fusion tasks. This helps to reduce energy consumption and bandwidth usage. Additionally, node scheduling schemes can also be used for traffic flow monitoring and packet routing, as discussed in [215], [216]. Developing a generic node scheduling scheme that can operate effectively regardless of the type of applications involved is a challenge that needs to be addressed for its applicability to various critical applications.

VII. CONCLUSION

Energy management is a critical issue for wireless sensor networks since the sensors are equipped with non-rechargeable batteries that have a limited lifetime. As a result, a commonly used approach to prolong a sensor network's lifetime is to use a strategy to schedule duty cycles of sensor nodes dynamically. In this article, we provided a comprehensive taxonomy of energy management schemes for WSNs, with a particular emphasis on quality of service (QoS) aware node scheduling and discussed their pros and cons. Node scheduling exploits the idea of redundancy to identify and activate multiple schedules of sensor nodes, thereby providing a cost-effective solution to conserving energy. We classify and evaluate node scheduling schemes in terms of their ability to fulfill key QoS requirements, namely coverage, connectivity, fault tolerance, and security, and discuss their merits and drawbacks. We believe that any node scheduling scheme that satisfies these requirements will hold a capacity to extend the network lifetime significantly and can thereby provide support to a wide range of applications. The paper concludes by highlighting key issues and challenges in node scheduling schemes to drive future research.

ACKNOWLEDGMENT

The authors are thankful to Dr. Varun G. Menon, SCMS School of Engineering and Technology, India, for useful discussions and the comments in improving the presentation of the manuscript.

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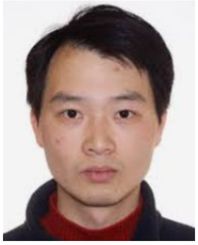

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