A Survey on Energy-efficient Strategies in Static Wireless Sensor Networks[1]

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A comprehensive analysis on the energy-efficient strategy in static Wireless Sensor Networks (WSNs) which are not equipped with any energy harvesting modules was conducted in this paper. Firstly, a novel generic mathematical definition of Energy Efficiency was proposed, which took the acquisition rate of valid data, the total energy consumption, and the network lifetime of WSNs into consideration simultaneously. To the best of our knowledge, it is for the first time that the Energy Efficiency of WSNs is mathematically defined. The energy consumption characteristics of each individual sensor node and the whole network were expounded at length. Accordingly, the concepts concerning the Energy Efficiency, namely the Energy-efficient Means, the Energy-efficient Tier, and the Energy-efficient Perspective, were proposed. Subsequently, the relevant energy-efficient strategies proposed from 2002 to 2019 were tracked and reviewed. Specifically, they were classified into five categories, i.e., the Energy-Efficient Media Access Control (EEMAC) protocol, the Mobile Node Assistance Scheme (MNAS), the Energy-Efficient Clustering Scheme (EECS), the Energy-Efficient Routing Scheme (EERS), and the Compress Sensing based Scheme (CSS) respectively. A detailed elaboration on both the basic principle and the evolution of them was made. Finally, further analysis on the categories was made and the related conclusion was drawn. To be specific, the interdependence among them, the relationships between each of them and the Energy-efficient Means, the Energy-efficient Tier as well as and the Energy-efficient Perspective were analyzed in detail. Besides, the specific applicable scenarios for each of them and the relevant statistics analysis were detailed. The proportion and the number of citations of each category were illustrated by the statistical chart. In addition, the existing opportunities and challenges facing WSNs in the context of the new computing paradigm, and the feasible direction concerning the energy efficiency in the future were pointed out.

CCS Concepts: • **Networks → Network types**; Cyber-physical networks; Sensor networks; • **Theory of computation → Mathematical optimization**; Network optimization; • **Hardware → Power and energy**; Energy generation and storage, Power conversion;

KEYWORDS

Wireless sensor networks; energy efficiency; the internet of things; network lifetime.

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1 INTRODUCTION

The Wireless Sensor Networks (WSNs) belong to the systems consisting of a huge number of tiny sensor nodes which are simple in structure and low in price. In general, the sensor node is densely deployed to accomplish some complicated tasks via close cooperation. Compared with the traditional network, the Wireless Sensor Networks are featured by the following characteristics, i.e., large-scale deployment, limited-resource supplement, data-centric routing mode, and “many-to-one” traffic flow pattern[1][2]. The features of small size and low cost in nodes make WSNs gain manifold applications[3]. Specifically, recent years have witnessed their applications in the following fields, e.g., environmental detection, military monitor, medical care, endangered species track, post-disaster rescue, *etc*[4][5][6][7][8].

However, the sensor nodes are usually powered by the battery and need to work in a harsh or even untraversed environment in huge numbers, which makes it impossible or unpractical for them to be replenished once deployed[9][10]. What makes matters worse, the endurance of batteries is extremely limited. For example, a sensor node powered by an AA battery is

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only able to work for 4 consecutive days[11]. Once the proportion of the sensor nodes which are out of energy reaches a certain threshold, the network will be partitioned into separated parts[12][13]. The network partition leads to the disconnection of the network topology and the failure of data's reaching the server which usually locates far away from the network region. As a result, the Wireless Sensor Networks fail to acquire enough valid data for the application, which means the early termination of the network lifespan. However, the rapid development of the Internet of Things (IoTs) in recent years undoubtedly arouses more requirements on WSNs in terms of data support since WSNs work as its perception layer[14]. Therefore it is crucial to ensure their long-term and high-efficiency operation in order to provide enough data for the application layer of IoTs. Therefore, how to improve the Energy Efficiency (EE) and extend the Network Lifetime (NL) of WSNs has attracted sustained attention recently.

Table.1. Abbreviations Used in the Paper

Acronym	*Full Name*	*Acronym*	*Full Name*
WSNs	Wireless Sensor Networks	NC	Network Coding
IoTs	Internet of Things	CH	Cluster Head
EE	Energy Efficiency	CM	Cluster Member
LLC	Logic Link Control	OCF	Optimal Cluster Formation
EH	Energy Harvesting	CSC	Cluster Size Control
MAC	Media Access Control	RDT	Reduction of Data Transmission
TC	Topology Control	DTN	Delay Tolerant Network
EEMAC	Energy-Efficient Media Access Control	PCA	Principal Component Analysis
MNAS	Mobile Node Assistance Scheme	RDG	Raw Data Gathering
EECS	Energy-Efficient Clustering Scheme	FCDG	Flat Compressive Data Gathering
EERS	Energy-Efficient Routing Scheme	HCS	Hybrid Compressive Sensing
EHWSNs	Energy Harvesting Wireless Sensor Networks	HCDG	Hierarchical Compressive Data Gathering
CS	Compress Sensing	CSS	Compressive Sensing based Scheme

Recent years have witnessed numerous researches on improving EE and prolonging NL of WSNs. As a result, there also exist some surveys for them. For example, Aziz et al.[15] made a summary of strategies which aimed at extending the Network Lifetime via Topology Control (TC). They presented a new definition of TC and classified the relevant strategies into different categories. Besides, they also pointed out the tendency of future research direction. However, its disadvantage lies in the fact that the boundary of classifications is not very clear. For instance, some of strategies actually belonging to the Clustering strategy[16] were classified as TC. Han et al.[17] reviewed the evolution of the Media Access Control (MAC) protocol. The MAC protocol emerged from 2002 to 2011 were divided into the Synchronous MAC protocol, the Asynchronous MAC protocol, the Frame-slotted MAC protocol, and the Multichannel MAC protocol respectively. However, they mainly paid attention to the generic MAC protocol, rather than the energy-efficient MAC protocol exactly. Besides, they also failed to systematically elaborate other strategies concerning the Energy Efficiency. Gu et al.[18] summarized the mobile-sink-based strategy. The relevant strategies were divided into four categories, i.e., the Uncontrolled Mobility Model, the Path-Restricted Mobility, the Location-Restricted Mobility, and the Unrestricted Mobility respectively. Subsequently the related categories were analyzed in detail, but none of the mobile-relay-based or any other energy-efficient strategies, such as EEMAC, EECS, EERS, CSS was covered. Younis et al.[16] reviewed the existing energy-efficient clustering strategies and analyzed the main challenges facing them. However, they only paid attention to a few strategies that emerged before 2006. Pantazis et al.[19] presented a survey on the existing energy-efficient routing protocol in WSNs. The energy-efficient routing protocols appeared before 2013 were classified into four categories, i.e., the Network Structure, the Communication Model, the Topology Based, and the Reliable Routing respectively. They only detailed the strategy which works at the network layer, but ignored those based on the other protocol layers. Yetgin et al.[20] made a detailed analysis on the relevant applications in WSNs with regard to design principle and the defect for various strategies aiming to prolong the Network Lifetime. The relevant schemes were divided into the Resource Allocation Using Cross-layer Design, the Opportunistic Transmission Schemes/Sleep-wake Scheduling, the Routing/Clustering algorithm, the Mobile Relays and Sinks, the Coverage and Connectivity/Optimal Deployment, the Data Gathering/Network Coding, the Data Correlation, the Energy Harvesting, and the Beanforming. However, the energy-efficient strategy based on the Compressive Sensing (CS) theory emerged in recent years was not included. Besides, the Energy Harvesting Wireless Sensor Networks (EHWSNs) were also involved in their paper, while this paper only focused on the traditional static WSNs without any energy supplements. In addition to the surveys listed above, there also exist some other relevant conference papers[21][22][23] which summarized the recent researches concerning EE of traditional static WSNs.

However, none of them systematically expounded the Energy Efficiency in terms of the Energy-efficient Means, the Energy-efficient Tier, and the Energy-efficient Perspective respectively, let alone the corresponding mathematical definition. However, they are exactly the main contributions of this paper. Table 2 shown the focuses, drawbacks and remarks concerning the existing surveys.

Table.2. Focuses, Constraints, and Remarks on the Existing Surveys

Existing Surveys	*Focuses*	*Drawbacks*	*Remarks*
[Younis, et al. 2006][16]	The theory of Clustering strategies was briefly summarized, and some related Clustering strategies were analyzed in detail.	Only a few Clustering strategies that appeared before 2006 were included.	None of surveys listed on the left systematically expounded the existing energy-efficient strategies in terms of the energy-efficient means, the energy-efficient tier, and the energy-efficient perspective. Besides, none of them paid attention to the mathematical definition of energy efficiency. This paper aims to illustrate the problems above in detail. Besides, the emphasis of this paper was put on the static Wireless Sensor Networks without any energy harvesting modules.
[Han, et al. 2013][17]	They summarized the MAC protocols and divided the existing MAC protocols into four categories.	They only analyzed the evolution of generic MAC protocol, instead of the energy-efficient MAC protocols.	
[Aziz, et al. 2013][15]	They mainly reviewed the existing topology control strategy in detail and provided a new definition of TC.	The boundary of classifications is not very clear, some strategies of Topology Control in this survey actually belongs to the Clustering strategy.	
[Pantazis, et al. 2013][19]	The existing energy-efficient routing protocols before 2013 were classified and analyzed at length.	Only those emerged before 2013 were covered. Besides, many routing protocols included belong to the generic routing protocol only.	
[Gu, et al. 2016][18]	The current mobile-Sink-based strategy was reviewed and analyzed, and the future tendency was also pointed out.	There was not any analysis on the mobile-relay-strategy, which also belongs to the Mobile Node Assistance Strategy (MNAS).	
[Yetgin, et al. 2017][20]	They discussed the existing schemes aiming to extend NL of WSNs from 10 different aspects.	The latest energy-saving strategy which was based on CS was not covered. In addition, those applied in EHWSNs were also involved.	

This paper aims at making up for the drawbacks of the surveys mentioned above and providing a review of the existing energy-efficient strategies in the traditional static Wireless Sensor Networks which are not equipped with any energy harvesting or moving modules. At the same time, the paper also aims to provide some valuable guidelines for the academic researcher who is dedicated to the research on the Energy Efficiency of WSNs. In addition, this paper presented a novel mathematical definition of EE with the purpose of providing some quantitative metrics for the energy-efficient strategy which may be put forward in the coming future. For the sake of convenience, some relevant abbreviations used in the paper are listed in Table 1. Overall, this paper offers the following contributions compared with the existing works.

(1) A novel generic mathematical definition of EE for static WSNs was proposed, which took the acquisition rate of valid data, the total energy consumption, and the Network Lifetime into consideration simultaneously. To the best of our knowledge, it is for the first time that a comprehensive mathematical definition of EE in static WSNs is presented.

(2) The energy consumption characteristics were analyzed with regard to each individual sensor node, the whole network, and the network protocol stacks respectively. Besides, features concerning the routing mode and the traffic flow pattern were presented. Subsequently, the root cause of the “Hot Spot Problem” was pointed out. In addition, the concepts concerning the Energy Eefficiency, i.e., the Energy-efficient Means, the Energy-efficient Tier, and the Energy-efficient Perspective were proposed and detailed on the basis of the analysis on the energy consumption characteristics.

(3) The energy-efficient strategies in WSNs proposed from 2002 to 2019 were tracked and analyzed in detail. They were classified into five different categories, i.e., the Energy-Efficient Media Access Control (EEMAC) protocol, the Mobile Node Assistance Scheme (MNAS), the Energy-Efficient Clustering Scheme (EECS), the Energy-Efficient Routing Scheme (EERS), and the Compress Sensing based Scheme (CSS) respectively. Besides, the design principle of each category was analyzed and the representatives which were cited with a high frequency in recent years were listed in

the form of tables.

(4) The interdependence among the five categories, the relationships between each of them and the Energy-efficient Means, the Energy-efficient Tier, as well as the Energy-efficient Perspective were analyzed at length. Besides, the specific scenario for which each of them is suitable was also pointed out. In addition, a detailed statistic analysis on each category was conducted. Finally, the existing opportunities and challenges facing WSNs in the context of new computing paradigms and some feasible research directions concerning EE of WSNs were pointed out.

The reminder of this paper is organized as follow. The related analysis on energy consumption characteristics was detailed in section 2, followed by the introduction of the novel generic mathematical definitionof EE and the related concepts in section 3. Section 4 detailed the existing energy-efficient strategies and classified them into five different categories. Section 5 presented the analysis on the relationships, the applicable scenario, and the statistical data respectively. Finally, Section 6 drawn the conclusion, pointed out some opportunities as well as challenges facing WSNs and the feasible research direction in the future.

2 ENERGY CONSUMPTION CHARACTERISTCS

This section introduced the different modules as well as related work modes of each sensor node and the corresponding energy consumption, then presented the energy consumption model in a brief. The relationship between the energy consumption of the sensor node and the communication distance and that between the energy consumption and the data volume were presented. In addition, the traffic flow pattern of WSNs was also summarized. Subsequently, the root cause of the "Hot Spot Problem" was pointed out clearly. Finally, the network protocol stacks applied in WSNs and the energy consumption characteristics of each layer were analyzed in a brief.

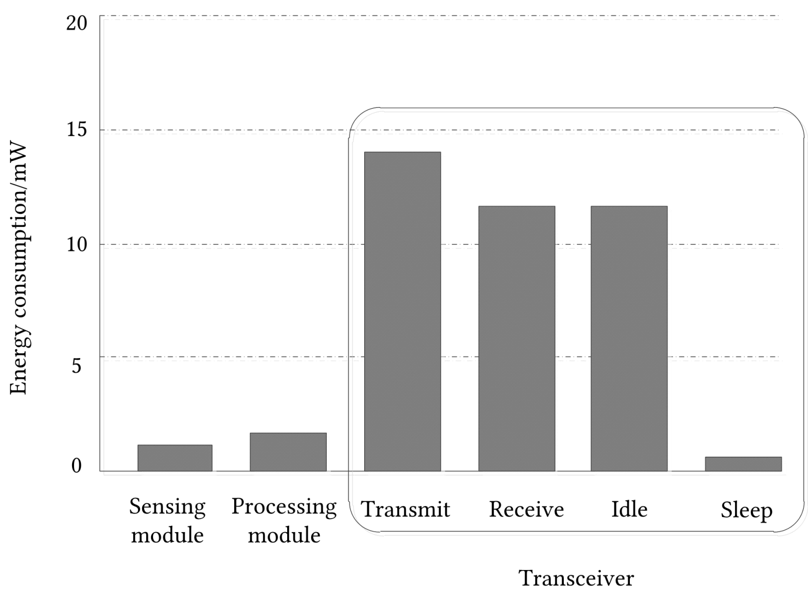

Fig.1. Energy consumption of the modules for each sensor node in different modes.

2.1 Energy Consumption Characteristics of Each Individual Sensor Node

2.1.1 Different Work Modes in the Modules and the Related Energy Consumption

In general, the sensor node consists of sensing, processing, communicating, and positioning modules as well as a mobile device. Energy is mainly consumed in the sensing, processing, and the communicating modules. On the one hand, the energy overhead of the communicating module accounts for the vast majority of the energy consumption for each single sensor node[24]. According to the research, the energy cost for transmitting 100 meters per bit message is equivalent to that for executing 3000 instructions[25]. Similarly, Shih, et al. also pointed out at the MobiCom in 2002 that most of the sensor's energy was depleted in the communicating module[26]. On the other hand, each sensor node has different work modes, i.e., transmit, receive, idle, and sleep modes, in which different amount of energy is consumed[27]. Generally speaking, most of energy consumption is exhausted for transmitting, receiving and idle listening[28]. Figure 1 presented the comparisons of energy consumption for each sensor node in different modes. Obviously, the energy consumption of the sensor node in the sleep mode is the lowest, but that in other modes is much higher relatively. According to the research by Shih, et al., the energy consumption in sleep mode can be usually negligible[26]. Therefore, the energy consumption can be effectively cut down by means of reasonably controlling media access, prolonging the sleep time or reducing the duty-cycle of each sensor node.

2.1.2 Energy Consumption Model

In the Wireless Sensor Networks, The first-order radio model is usually applied to formulate the energy consumption for each sensor node in its transmitting module[28][29][30]. To be specific, it is shown as the following expressions (1-2),

$$e_{rx} = kE_{elec} \tag{1}$$

$$e_{tx} = k(E_{elec} + \varepsilon_{amp} d^{\alpha}) \tag{2}$$

where e_{rx} or e_{tx} respectively denotes the energy consumed by each node to receive or transmit a k-bit message; E_{elec} denotes energy consumed for transmitting or receiving per bit message; ε_{amp} and d the energy consumption of the amplify circuit and the transmission distance respectively. Finally, α is the attenuation coefficient and its value usually lies between 2 and 4, which depends on the specific communication model[27][28]. Specifically, α equals 2 for the free space model and increases to be 4 for the multipath fading model. According to the energy consumption model, it can be easily concluded that the energy consumption for the transmission of each node depends on the volume of data when the communication range is fixed. At the same time, the amount of energy consumption rises with the increase of transmission range, especially when the latter is larger than 87 m[29]. Consequently, the energy consumption can be cut down effectively by means of reducing the amount of redundant data to be sensed or transmitted and adopting the "multi-hop transmission" routing mode.

2.2 Energy Consumption Characteristics of the Whole network

2.2.1 Traffic Flow Characteristics of WSNs

In traditional networks, several kinds of traffic flow patterns, such as the unicast, the broadcast, the multicast, and the anycast coexist in a single network according to the specific application[19]. However, the features of WSNs' applications make the routing protocol follow the data-centric pattern, rather than the address-centric pattern[20]. It results in a completely different traffic flow characteristics from the traditional network. To be specific, in traditional network, the destination addresses of different packets are usually distinct. However, as for WSNs, those of different packets are usually the same, i.e., the address of the Sink. As a result, WSNs' traffic flow always follows the "many-to-one" mode, or the "convergecast" pattern[19]. The "convergecast" pattern leads to an inverted funnel-shaped distribution of the traffic flow, which results in energy inequality accordingly[30][31].

2.2.2 the "Hot Spot Problem" and Its Root Cause

As illustrated above, the traffic flow of WSNs follows the "many-to-one" mode. At the same time, most existing routing protocols of WSNs follow the "multi-hop transmission" mode in order to reduce the energy depletion. As a result, it leads to an uneven distribution of energy consumption. In applications of WSNs, there exists the "Hot Spot Problem" which would lead to the early termination of network lifespan[6]. The "Hot Spot Problem" refers to the situation where the node closer to the Sink depletes its energy much faster than that lying in the further region. The emergence of the "Hot Spot Problem" is resulted from the fact that node near Sink needs to forward not only its own data, but also the data from the downstream nodes. In this paper, the region close to the Sink was denoted as the "Hot Spot Area". It is apparent that the nodes lying in the "Hot Spot Area" have to bear a much heavier burden of communication overhead. Once one or some key nodes exhaust energy, the network will be partitioned, which usually means the early termination of the Network Lifetime.

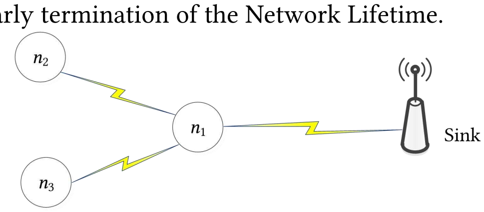

Fig.2. Simple example of the "hot spot problem".

As shown in Figure 2, an example of the "Hot Spot Problem" was presented via a simple network consisting of three nodes and the Sink. The data collected by nodes n_2 and n_3 need to be forwarded via node n_1 which acts as a relay. In addition, node n_1 also needs to propagate its own data, so the traffic burden of n_1 is equivalent to three times that of n_2 or n_3 if the data generation rate follows the independent uniform distribution. Once node n_1 depletes its energy, the data of n_2 and n_3 will not be able to reach the Sink (assume the distance from each of them to the Sink is out of transmission range). As a result, the Network Lifetime terminates even though n_2 or n_3 possesses relatively high residual energy. Therefore, it leaded to the failure of data acquisition.

As a conclusion, the inverted funnel-shaped distribution of traffic caused by the "convergecast" traffic flow pattern and the "multi-hop transmission" routing mode are the root cause of the "Hot Spot Problem". Therefore, the "Hot Spot Problem" can be alleviated through the change of the routing mode and the redistribution of the "Hot Spot Area".

2.3 Protocol Stacks of WSNs and the Corresponding Energy Consumption Characteristics

This section briefly introduced the protocol stacks of WSNs and the corresponding functions, as well as the energy consumption characteristics of each protocol layer. Subsequently, the related energy-efficient strategies that can be adopted for each layer were pointed out in a brief.

2.3.1 Protocol Stacks of WSNs

Currently, the protocol stacks of the Internet was adopted in WSNs, which consist of the physical layer, the data link layer, the network layer, the transport layer, and the application layer from bottom to top[32]. The physical layer provides the support for the process of data sampling and quantizing, bit streams transmitting, receiving, and the relevant signals decoding[33]. The data link layer includes two components, i.e., the Logic Link Control (LLC) and the Media Access Control (MAC). It is mainly responsible for encapsulating data into frames, controlling error rate during the process of data frame transmission and media access control. The routing table building, updating, and maintaining for effective data transmission happen at the network layer. The transport layer achieves the end-to-end transmission of the data flow, the Quality of Service (QoS) and multi-path multiplexing. At the same time, the transport layer can also promote energy equality by means of reasonably distributing the traffic load. As for the application layer, it is mainly responsible for meeting the requirements which are related to specific applications. Obviously, there are large differences in energy consumption at the application layer due to the distinct usage and demands on WSNs.

Application layer	Related to the specific applications
Transport layer	QoS and multi-path multiplexing
Network layer	Routing table construction, update, and maintenance
Data Link layer	Encapsulating data, error control and media access control
Physical layer	Sample of data and transmission of bit stream

Fig.3. Protocol stacks of WSNs and the corresponding functions which bring in energy consumption.

2.3.2 Energy-efficient Schemes Can be Applied at Each Layer

As shown in Figure 3, different layers present different characteristics in terms of the corresponding energy consumption. Therefore the optimization of EE can be conducted from the perspective of each individual layer via taking the related energy consumption characteristics into account. For example, at the physical layer, EE can be improved by means of cutting down the frequency of data sampling and the volume of redundant data for transmission. As for the data link layer, the energy cost resulted from idle listening, data collision, and over-listening can be largely reduced through proper-designed Media Access Control mechanism. Since the routing table is the foundation of data transmission, the frequency and scope of flooding during the process of routing establishing is a critical factor which needs to be carefully considered at the network layer. Besides, there is a probability that energy equilibrium can be achieved through the reasonable design of multi-path multiplexing technology at the transport layer. Finally, at the application layer, the scheme for improving EE can be designed with the help of lower layers according to the specific data generation pattern. For example, the energy cost can be effectively diminished through reducing the node's duty-cycle for the application with burst data.

3 MATHEMATICAL DEFINITION OF ENERGY EFFICIENCY AND THE RELATED CONCEPTS

WSNs are usually deployed to collect various monitoring data for the external data center which locates far away from the network topology. Therefore, the significance of WSNs lies in the fact that WSNs are able to work as long as possible under a given energy budget so that they are capable of acquiring as much valid data as possible for the external data center. In this section, a novel generic mathematical definition of Energy Efficiency (EE) was proposed. The three main components affecting EE were pointed out. Besides, the related concepts concerning energy efficiency were presented subsequently, whose relationships with the components of EE were pointed out in a brief.

3.1 Mathematical Definition

In this section, a novel generic mathematical definition of the non-harvesting WSNs was proposed on the basis of the concept of Energy Efficiency of the traditional wireless networks[34][35]. We presented a detailed derivation with the consideration of the characteristic of WSNs. Besides, we have also conducted a careful proof in the following and presented a detailed analysis on the definition.

3.1.1 Definition of Energy Efficiency

Definition.3.1. The Energy Efficiency of the non-harvesting static WSNs can be defined as the unit valid data acquisition rate that the Sink gets per unit energy consumption of the network before the end of the Network Lifetime (NL). To be specific, it can be mathematically formulated by the following expression

$$\eta_{EE} = \frac{r_{Valid} \cdot \min.\{\frac{e_0^i}{k_i^r E_{rx} + k_i^t E_{tx}}\}}{E_c}, \quad i \in \{1, 2, \ldots, N\} \tag{3}$$

where η_{EE} denotes the Energy Efficiency of the non-harvesting static WSNs, r_{Valid} the acquisition rate of valid data, e_0 the initial energy of each individual sensor node, k_i^r and k_i^t the amount of reception and transmission of node i respectively, N the number of sensor nodes in the whole network topology, and E_c the total energy consumption of the whole network respectively when the Network Lifetime terminates.

Proof. According to the relevant definition[36][37], the Energy Efficiency of wireless networks denotes the average valid throughput per unit energy consumed. Similarly, the valid throughput of WSNs can be measured by the Sink. Besides, the average energy consumption is closely related to the Network Lifetime of WSNs since the sensor node cannot be replenished once deployed. Therefore the Energy Efficiency of the non-harvesting static WSNs can be accordingly defined as the following expression

$$\eta_{EE} = \frac{r_{Valid}}{\overline{P}} \tag{4}$$

where $\overline{P}$ is the average power of the network during the period when the network is well-functioning. It is clear that the average power of WSNs can be defined as below

$$\overline{P} = \frac{E_c}{T_{network}} \tag{5}$$

where $T_{network}$ denotes the Network Lifetime of the non-harvesting static WSNs. According to Ref. [26], the definition of NL of the Wireless Sensor Networks can be mathematically formulated by the following expression[38][39]

$$T_{network} = \min.\{\frac{e_0^i}{E_{Comm}^i}\}, \quad i \in \{1, 2, \ldots, N\} \tag{6}$$

where E^{i}_{Comm} is the energy consumption for communication of sensor node *i*. Therefore, the Energy Efficiency of the non-harvesting static WSNs can be obtained by the following expression finally

$$\eta_{EE} = \frac{r_{Valid} \cdot \min.\{\frac{e_0^i}{k_i^r E_{rx} + k_i^t E_{tx}}\}}{E_c}, \quad i \in \{1, 2, \ldots, N\}$$

Definition 3.1 indicates the significance of WSNs is to acquire enough valid data under a limited energy budget. At the same time, it also reflects the relationship between EE and NL. Specifically, it can be easily obtained from expressions (4-5) that the Energy Efficiency of WSNs is positively related to the Network Lifetime.

3.1.2 Discussion concerning the Definition

According to expression (3), it can be easily obtained that EE of the non-harvesting static WSNs depends on three components, which are the acquisition rate of valid data, the amount of energy consumed by the end of the network lifetime, and the network lifetime respectively. For the sake of brevity, they are denoted as C_1, C_2, and C_3 respectively.

For a specific application, the data generation rate is a constant. As a result, the value of C_1 can relatively increase by means of reducing the redundant data acquired. In fact, it actually belongs to the measure of reducing energy consumption. Besides, the less energy is consumed, the higher Energy Efficiency according to the component C_2. Finally, the even distribution of energy consumption brings in a longer lifetime of WSNs according to the definition of NL which is formulated by expression (6), since NL is defined by the time when the first node runs out of its energy. In fact, it can be easily explained by the analysis on the energy consumption characteristics presented in section 2. Therefore the focus can be put on energy equality when considering C_3. As a conclusion, it can be easily obtained that the Energy Efficiency can be improved through the reduction and balance of energy consumption according to the definition above.

3.1.3 Energy-efficient Means

According to the analysis on the definition of EE above, the concept of Energy-efficient Means can be put forward accordingly. Through the concept, the effective means can be considered when the energy-efficient strategy for WSNs is designed or evaluated.

Definition.3.2. Energy-efficient Means denotes the specific method that can be applied in the Wireless Sensor Networks so as to improve its Energy Efficiency.

This paper focused on the Energy Efficiency of WSNs without any energy harvesting modules, therefore it is hard for the sensor node to be replenished manually once deployed. As a result, the importance of reducing energy consumption can be easily obtained. According to the analysis on the energy consumption characteristics above, as far as each individual node is concerned, the energy is mostly consumed in the communication module. For example, the energy consumption for communication is mainly resulted from the process of idle listening, data collision, over-listening, routing table building, as well as data processing and forwarding. In conclusion, the reduction of energy consumption is an effective means to improve EE of the non-harvesting static WSNs.

According to the energy consumption characteristics and the mathematical definition mentioned above, the energy equality plays an important role in the Energy Efficiency. To this end, the balance of the energy consumption needs to be taken into account. In fact, the random deployment of sensor nodes, the type of applications, and the traffic flow pattern of "convergecast" are the main factors which lead to the uneven energy distribution to some extent. According to the analysis in section 2.2.2, the unbalance energy consumption is the root cause of the "Hot Spot Problem" and the early termination of NL. Therefore, balancing energy consumption of network can also effectively improve the Energy Efficiency and prolong the Network Lifetime of WSNs. In general, the energy-efficient strategy should be designed from the perspective of the whole network. For instance, the energy consumption of WSNs can be balanced via pre-designed network deployment[40], the redistribution of the "Hot Spot Area" with the assistance of mobile nodes, or the rotation the role of nodes, and so on.

Based on the analysis above, it is obvious that Energy-efficient Means is related to the components of EE. To be specific, the reduction in energy consumption is directly related to component C_2. Besides, according to the definition of NL, the balance in energy cost plays an important role in extending NL of the Wireless Sensor Networks. Therefore Energy-efficient Means is also related to component C_3.

3.2 Other Concepts Concerning Energy Efficiency

In this section, additional two concepts concerning the Energy Efficiency of WSNs were proposed and detailed, which are the Energy-efficient Tier, and the Energy-efficient Perspective respectively. All these concepts are related to the energy consumption characteristics and the components which were introduced in sections 2 and 3. Besides, this section laid a foundation for the categories of energy-efficient strategies analyzed in section 4.

3.2.1 Energy-efficient Tier

Definition.3.3. Energy-efficient Tier denotes the energy-saving layer of the network protocol stacks on which the strategy is proposed to improve the Energy Efficiency and extend the Network Lifetime of WSNs.

According to the energy consumption characteristic analyzed in section 2.3, different strategies may achieve the same goal of improving the Energy Efficiency and extending the Network Lifetime of WSNs on the basis of different protocol layers. To be specific, the Energy Efficiency can be improved based on the data link layer, the network layer, or the transport layer respectively. For instance, the energy-efficient routing protocol can be applied to regulate the data forwarding so that energy equality can be achieved to some extent. In some scenarios, the multiplexing technology can be applied to achieve energy balance among different regions in the whole network topology. As for the data link layer, the strategy usually puts emphasis on the design of MAC protocol so as to reduce the energy overhead resulted from idle listening, data collision, and overhearing.

3.2.2 Energy-efficient Perspective

Definition.3.4. Energy-efficient Perspective refers to the perspective from which the strategy is designed to improve the Energy Efficiency in WSNs. In general, it consists of two aspects, i.e., individual sensor node and the whole network.

According to the discussion presented in section 2.2, the features of energy consumption for each individual sensor node and that for the whole network topology are quite different. For instance, the energy overhead of each node is usually related to the process of data acquisition and communication. As for that of the whole network, it is mainly depends on the energy depletion of both of source nodes and other nodes along the path from the source to the Sink.

Therefore, the Energy Efficiency can be improved from the perspectives of both each individual sensor node and the whole network. For example, the energy overhead can be greatly cut down through the reduction in sampling frequency or data redundancy. Besides, the energy cost can be diminished to some extent if an energy-efficient routing is applied, which is obviously related to the whole network. In general, the strategy from the perspective of the whole network put much emphasis on the energy balance, while that from the perspective of each single node is laid mainly on the reduction of energy cost.

On the basis of the discussion on the concepts above, it can be easily obtained that both Energy-efficient Tiers and Energy-efficient Perspective are closely related to the components of EE. For example, the energy-efficient routing strategy can be designed from the perspective of the whole network, with the aim of reducing and balancing energy overhead in data transmission. Obviously, the Network Lifetime of WSNs can be prolonged at the same time. In addition, the acquisition rate of valid data increases through data aggregation accordingly. In other words, it takes components C_1, C_2, and C_3 into consideration simultaneously.

4 REVIEW OF THE RECENT ENERGY-EFFICIENT STRATEGIES

Recent years have witnessed numerous strategies proposed to improve EE and extend EL of WSNs. In this paper, we have tracked the researches which emerged from the year 2002 to 2019 and conducted extensive analysis on them. On the basis of relevant surveys and analysis, the related strategies were divided into five categories, namely the Energy Efficient Media Access Control (EEMAC) protocol, the Mobile Node Assistance Scheme (MNAS), the Energy Efficient Clustering Scheme (EECS), the Energy Efficient Routing Scheme (EERS), and the Compressive Sensing based Scheme (CSS) respectively. They completely cover all the mainstream strategies concerning EE in WSNs. In this paper, the classification is also a main contribution of our work.

Table.3. Relationships among Components of EE and All the Categories

	EEMAC	*MNAS*	*EECS*	*EERS*	*CSS*
Relationships among the Components of EE and All the Categories	EE can be improved with the consideration of C_2 and C_3. To be specific, the energy-efficient MAC protocol is designed to reduce and balance energy consumption, as well	EE is improved with the consideration of C_2 and C_3. Specifically, it aims to reduce and balance the energy consumption, as well as extend NL by means of adopting	With the consideration of C_1, C_2, and C_3, EE can be improved accordingly. Briefly, Clustering and data aggregation are	It aims to improve EE with the consideration of C_2 and C_3 by means of designing low-energy and energy-equality	EE is improved via taking C_1, C_2, and C_3 into account in CSS. To be specific, CS theory is adopted to reduce and balance energy consumption

	as prolong NL of WSNs.	mobile assistance nodes, such as mobile Sink or relay.	adopted in EECS.	routing protocols.	simultaneously, along with the extension of NL.

The categories listed above aim to improve EE of the non-harvesting static WSNs with the consideration of all components. In fact, they were designed by different means, from different perspectives, and based on different tiers. As a summary, Table 3 presents an overall view of the relationship among all the components of EE and the categories. Besides, the design principle of each category is also pointed out in a clear way.

4.1 EEMAC

This section presented a brief introduction of EEMAC and divided the related strategies into four subcategories firstly. Then, a detailed analysis on the four subcategories was conduced. Finally, the timeline concerning the evolution of EEMAC emerged in recent years and the corresponding category attribution were presented in a table.

4.1.1 Brief Induction of EEMAC

In general, the MAC layer is mainly responsible for controlling the access mode of nodes to the shared media in an order manner. In WSNs, there is a possibility of data collision when the node tries to obtain the access to wireless communication links. A well-designed MAC protocol needs to effectively reduce energy overhead caused by data collision. Therefore, the design of MAC protocol is of great importance for WSNs[41]. Due to the limited energy budget, the MAC protocol of WSNs mainly focuses on the Energy Efficiency, which is quite different from that of traditional wireless networks. EEMAC aims to improve the Energy Efficiency of WSNs by means of controlling the components C_2 and C_3. Generally speaking, it can be classified based on different standards[17]. According to the access mode of sensor nodes, the current MAC protocols can be divided into four subcategories, namely, Random Access (RA), Slot Access (SA), Frame Access (FA), and Hybrid Access (HA) respectively.

4.1.2 Classifications of EEMAC

(1) RA

RA refers to the strategy through which the sensor node accesses to the wireless channel in a random way, which means that neither time slot distribution nor the channel competition is a necessary for each individual sensor node. Therefore, its great virtue is the simple implementation. In general, SA reduces the probability of idle listening by means of lengthening the frame header through the generation of a preamble. As a result, any sensor nodes always stay in sleep mode most of time except for the time for periodically channel-listening. Obviously, the fact that nodes only need little energy in sleep mode was utilized in RA. The main related strategies include the Lower Power Listening (LPL)[42], the Berkeley MAC (B-MAC)[43], the Wireless Sensor Network MAC (WiseMAC)[44][45], the Minimum Preamble Sampling with CSMA (CSMA-MPS)[46], X-MAC[47], the Sparse Topology Energy Management (STEM)[48][49], and the Another MAC(A-MAC)[50], *etc.*

(2) SA

The basic design principle of SA is that each sensor node takes turns to switch between sleep and listen modes. Therefore any sensor node works at a relatively low duty-cycle so as to reduce the energy overhead resulted from idle listening and overhearing[51]. Besides, a adaptive wake-up mechanism can be also adopted to improve EE[52]. In general, SA mainly focuses on the design of the effective competition mechanism, the scheme of collision avoidance, and the schedule of time when nodes start to sleep, such as Sensor MAC (SMAC)[53], Timeout MAC (T-MAC)[54] Scheduled Channel Polling MAC (SCP-MAC)[55], Data Gathering MAC (DMAC)[56], and distributed Delay-Efficient Data Aggregation Scheduling for Duty-Cycle (DEDAS-D)[57]. In addition, there are also some protocols aimed at achieving the goals of both high network performance and high Energy Efficiency for WSNs which are featured by high node density. Such strategies include Y-MAC[58], SLC[59], *etc.* Finally, recent years have also witnessed some MAC protocols which are applied in specific applications or integrated with other energy-efficient schemes, e.g., the SLDMAC[60] for the linear-topology WSNs with mobile relays, JRAM[61] and QTSAC[62] which combined routing and medium access control protocols, such as Asym-MAC[63] in which the transmission is triggered by both transmitter and receiver, DTMC[64] using 3-D discrete-time Markov chain model, and the State of Charge based MAC protocol (SoC-MAC)[65].

(3) FA

The MAC protocol based on the Frame Access generally aims at allocating time slots for each frame in order to properly schedule the node's access time and achieving clock synchronization among different nodes. Therefore the energy cost caused by data collision and overhearing can be reduced as much as possible, thus the Energy Efficiency can be improved at the same time. The main representatives of such protocols include the Self organization MAC (SMACS)[66][67], the Flow Aware Medium Access (FLAMA)[68], the Mobility Adaptive MAC (MMAC)[69], the Self-Stabilizing TDMA (SS-TDMA)[70], the Distributed

Activity Scheduling (DAS)[71], the Recursive Time Synchronization Protocol (RTSP) in which all the nodes in the network have a global clock accurately synchronized through a multi-Hop architecture[72], and a low energy consumption MAC protocol for WSNs (denoted as LE-MAC by the authors in this paper for the sake of convenience)[73], *etc.* In addition, some of the strategies focus on reasonably designing the frame format[74][75] to diminish the energy overhead as much as possible, such as the Bitmap-assisted Efficient and Scalable TDMA-based MAC (BEST-MAC)[76] which utilizes small time slots and applies the knapsack algorithm to schedule time slots for all the nodes effectively.

(4) HA

HA refers to the MAC protocol of mixed access modes and it is generally composed of at least two of the access modes mentioned above, with the aim of making full use of the advantage of each mode, such as the Zebra MAC (Z-MAC)[77] which combined RA and FA modes, the Funneling-MAC[78] and the Pattern MAC (PMAC)[79] which integrates the CSMA/CA and the TDMA, CrankShaft[80] combining the virtues of SA and competing access protocol SCP-MAC[55], the Intelligent Hybrid MAC (IH-MAC)[81] which achieves a high channel utilization without degrading any Energy Efficiency for the scenario under a high traffic load. There are some schemes which are integrated with the mechanisms of high-level network stack layers to provide high-performance and energy-efficient services, such as PRIMA[82], which adopts the queue model to provide QoS and divided the data flow into a four-level queue according to the degree of importance, thus provides multi-level services for distinct applications. Similar MAC protocols also included E-BMA[83] for the specific application scenario.

Table 4 shown the timeline of EEMAC emerged from 2002 to 2019 and their corresponding category attributions.

Table.4. Timeline and Subcategories of EEMAC

Year	*RA*	*SA*	*FA*	*HA*
2002	LPL	SMAC	SMACS	
2003	WiseMAC	TMAC		
2004	B-MAC, CSMA-MPS, STEM	DMAC		
2005			FLAMA, MMAC, SS-TDMA	ZMAC, PMAC
2006	XMAC	SCP-MAC		Funneling-MAC
2007				Crankshaft
2008		Y-MAC		
2009		SLC		
2010	AMAC		DAS	
2011				PRIMA
2012			LE-MAC	
2013			RTSP	IH-MAC, E-BMA
2014		Asym-MAC		
2015		SLDMAC		
2016			BEST-MAC	
2017		DEDAS-D, DTMC, JRAM		
2018		QTSAC		
2019		SoC-MAC		

4.2 MNAS

MNAS refers to the strategy in which the mobile Sink or relay moves along a predetermined or dynamically-determined trajectory throughout the whole network topology. Generally it improves the Energy Efficiency by means of considering components C_2 and C_3 simultaneously. The existing MNASs can be classified according to different standards. For instance, they can be divided into mobile Sink based scheme and mobile relay based scheme according to the type of mobile nodes, the static path strategy and the dynamic path strategy according to the way of the moving path, or single mobile node strategy and multiple mobile nodes strategy based on the number of the mobile nodes. In this paper, the classification of the current strategies is based on the first standards.

4.2.1 Brief Introduction of MNAS

In order to alleviate the uneven energy consumption resulted from the “Hot Spot Problem”, the mobile node can be adopted to transfer or ease the energy burden on the “Hot Spot Area” in the network topology. As introduced in section 2.2.1, the “Hot

Spot Area" refers to the area exhausting energy relatively faster than other areas owing to its closer location to the Sink. In general, the mobile Sink or mobile relay can be adopted. Besides, it is assumed that the mobile Sink or relay is featured by unlimited energy supply. Obviously, the area close to the Sink belongs to the "Hot Spot Area", therefore the "Hot Spot Area" in the network topology can be redistributed through the moving of the Sink. Similarly, the energy consumption burden on the "Hot Spot Area" can be also alleviated with the assistance of relay's forwarding data acquired by peripheral nodes. Therefore, MNAS contributes to a more balanced energy consumption of the whole network. At the same time, the adoption of the mobile Sink or relay can also change the routing mode of "multi-hop transmission", thus reduce the energy consumption for communication per bit message to some extent.

4.2.2 Classifications of MNAS

The existing strategies belonging to MNAS were divided into the Mobile Sink based Scheme (MSS) and the Mobile Relay based Scheme (MRS) according to the types of mobile nodes in this paper. Similarly, this section presented the timeline and the corresponding subcategory of them from 2003 to 2019 as shown in Table 5.

As mentioned above, MSS mainly takes advantage of the relatively unlimited energy supply of the Sink to alleviate the "Hot Spot Problem". Therefore the problem of energy inequality can be relieved via controlling the moving path of the Sink and redistributing the "Hot Spot Area". It brings in an evener distribution of energy consumption and an improvement of EE as well as the extension of NL for the non-harvesting static WSNs[84]. Generally, there are different classifications for those belonging to MSS. For example, Refs. [18][85] divided MSS into the UN-controlled Mobility (UNM), the Path-Restricted Mobility (PRM), the Location-Restricted Mobility (LRM), and the Unrestricted Mobility (URM) according to the way that it generates the moving path. This section divided MSS into the Single Mobile Sink based Scheme (SMSS) and the Multiple Mobile Sinks based Scheme (MMSS)[86] according to the number of mobile Sinks adopted.

(1) SMSS

SMSS generally utilizes a single mobile Sink to move around the whole network topology so as to achieve energy equality. Compared with MMSS, it is much simpler to relocate the mobile Sink. The examples of SMSS and MMSS were analyzed in detail in the following.

The trajectory of the Sink can be predetermined to simplify the control of the Sink. According to the requirement of specific applications, the regulation of the trajectory can be formulated into the linear programming, the mixed linear programming or any other optimization problems subject to the network performance, such as the network throughput, packet loss rate, network delay or the variance of residual energy of nodes in different areas, and so on. Therefore the solution of the optimization problem is the optimal energy-efficient moving path for the mobile Sink[76][87]. In addition to the trajectory, the moving velocity[88][89] and the sojourn time at each stop can be also obtained in advance. Such strategies include Ms-routing-G which aims at reducing the packet loss rate[90], the Composite Event Detection and Reporting (CEDR) with the purpose of controlling the Sink's moving path[91], *etc.* Besides, other parameters, such as the network topology, and the network energy distribution can be also applied in determining the Sink's moving path in advance, such as the $(1-\varepsilon)$ algorithm[92] which establishes the sojourn locations and the corresponding sojourn time according to the network performance requirements. Similar strategies included CSPLI[93][94] and MSFLA[95] which takes the network delay into consideration. In addition, the strategies which combine the mobile and static Sinks can be utilized to improve EE further, such as the Energy-saving Strategy by Combining Mobile and Static sink scheme (ESCMS)[96]. The mobile Sink is utilized to achieve energy balance and the static one stays at a fixed location to reduce network delay. In such a way, it can improve the Energy Efficiency by means of reducing and balancing energy consumption for communication simultaneously.

Instead of moving along a predetermined path, the trajectory of the mobile Sink can be also dynamically controlled. Therefore the adaptive movement of the mobile Sink can be achieved based on the density of energy distribution and the difference in residual energy or any other energy parameters. The movement of the mobile Sink can be adjusted dynamically so that it can be guided towards the area with sparse energy distribution. As a result, the energy burden on the low energy density area is alleviated, which contributes to the balance of energy consumption and the extension of NL. In general, the dynamic path control for the mobile Sink can be realized by classical algorithms, such as the hybrid linear programming, the Traveling Salesman Problem (TSP), and the Knapsack problem, *etc.* For example, a hybrid linear programming modeling analysis was proposed to achieve a controllable mobile path of the Sink and prolong NL of WSNs[97]. In some researches the mobile Sink can be guided towards the energy-intensive area to balance energy consumption by means of controlling the maximum movable distance and the moving speed of the mobile Sink. Similar schemes can be found recently, such as the heuristic algorithm GMRE[98], the Heuristic Obstacle Avoiding Algorithm (HOAA)[99], the Tree-Cluster-Based Data Gathering Algorithm (TCBDGA) which establishes a weight tree rooted by a Rendezvous Point[100], the Set Packing Algorithm and TSP mobility scheme (SPAT)[101], MWSN-oriented location service (MLS)[102], the Mobile Sink-based Path Optimization strategy using Artificial Bee Colony (MSPO-ABC) algorithm[103], and so on.

(2) MMSS

In addition to the SMSS analyzed above, there also exist some strategies which belong to MMSS. Compared with SMSS, several Sinks are utilized in MMSS. According to the requirements of specific applications on the network performance, such as the network delay, the network throughput, and the packet loss rate, the trajectory of the mobile Sinks can be also formulated into the optimization problem. The moving path, the moving speed, the sojourn stop as well as the corresponding sojourn time can be obtained through the solution of the related optimization problem. Through properly-designed parameters listed above, both of the reduction and equilibrium in energy consumption can be achieved under the premise of guaranteeing the application requirements. The relevant examples were listed as follows. A multiple mobile Sinks sparse Wireless Sensor Network, which utilized multiple mobile Sinks and the Opportunistic Transmission Scheduling Algorithm (OTSA)[104], was designed for the sparse Wireless Sensor Network. A Global/1-hop algorithm which determines the deployment pattern of multiple Sinks was proposed to reduce the average energy overhead for communication through mathematical modeling[105]. In addition, the relocation technology for multiple Sinks was also applied to balance the energy consumption as well as improve the Energy Efficiency of WSNs. Similar schemes include the Delay-Tolerant Mobile Sink Model (DT-MSM) which was based on the fact that the demands on network delay of the Delay Tolerant Networks (DTN) is relaxed[106]. Since DTN has relatively loose requirements on the network delay, the data of each sensor node can be temporarily buffered until the Sink arrives at a favorable position. Once a Sink reaches a preferred location, the sensor node transmits the data acquired to it immediately. Take DT-MSM for example, multiple Sinks were adopted to switch from "multi-hop transmission" into "single hop transmission" in routing modes through the reciprocal movement of multiple Sinks. Finally, MMSS can be also integrated with EECS to improve the Energy Efficiency further by taking the advantage of Clustering in reducing data redundancy[107], such as the Collaborative Mobile Sink Sojourn Time Optimization Scheme (CMS2TO)[108] which aimed to obtain the reasonable sojourn time of Sinks through cooperative mechanism on the basis of the Clustering technology to relief the "Hot Spot Problem".

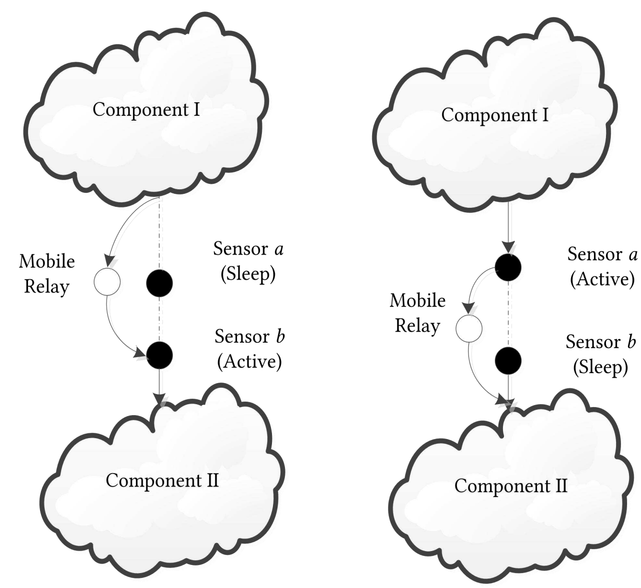

Fig.4. Mobile relay utilized in WSNs.

(3) MRS

The mobile Sink based scheme is suitable for the scenario where the Sink can move around the network topology flexibly, but not for the scenario where the Sink needs to be deployed at a fixed location. In addition, it also leads to extra overhead resulted from the relocation of the mobile Sink and frequent broadcast concerning the Sink's location information. With the feature of overcoming the above drawbacks, MRS is attracting extensive attentions from researchers in recent years. In MRS, there are a certain number of energy-unlimited mobile relays except for a large number of regular sensor nodes in the network topology.

Generally speaking, the basic principle of MRS lies in the fact that the mobile relay is able to move around the network topology freely to provide data forwarding services for other static sensor nodes. In some other scenarios, a dedicated Relay Charging Point can be deployed in the network topology, therefore the mobile relay is able to be replenished periodically at the Relay Charging Point during data forwarding, such as the Recharge Weighed Target Points Patching algorithm (RW-TPP)[109][110]. For all of the scenarios above, the relay moved around periodically to relieve the energy consumption burden on the nodes in the "Hot Spot Area".

In general, the relay acts as a forwarder for the Wireless Sensor Networks. Take MULEs[111] for example, each relay moves around the network along a random or a predefined path so as to relieve the energy consumption burden on the "Hot Spot Area". It is the relay's forwarding that makes the energy consumption for communication be evenly distributed. The reduction in energy consumption for the "Hot Spot Area" and the balance of the energy consumption for the whole network can be achieved by means of making full use of the features that the relays have unlimited energy supply and carefully designing the relay's trajectory. Such strategies include the Optimal Mobile Relay Configuration (OMRC)[112] taking the energy consumption for both movement and communication of relays into consideration and the Adaptive Relay Chain Routing (ARCR)[113] which adopts mobile relays for data forwarding.

In some other scenarios, the mobility of relays is utilized to ensure network connectivity, network longevity, and data transmission reliability. For the network with a special topology, the energy consumption burden on some key nodes can be relieved markedly by some mobile relays, which helps to achieve the improvement of EE and the extension of NL. As shown in Figure 4, with the assistance of a mobile relay, the key nodes a and b take turns to sleep with the aim of reducing the duty-cycle. It brings in the reduction in energy consumption for nodes a and b as well as stable connectivity of the whole network. As a result, it theoretically extended NL to be twofold compared with that of WSNs without any mobile relays (Joint Mobility and Routing Algorithm, JMRA[114]). Similarly, there are other classical strategies of this kind, such as the Mobile Relay Scheduling for making network Connected (MRSC)[115] designed to maintain network connectivity and the Connectivity-oriented, Lifetime-oriented, and Hybrid Deployment (CLHD)[116] considering both the connectivity and NL of the non-harvesting static WSNs.

Table.5. Timeline and Subcategories of MNAS

Year	*SMSS*	*MMSS*	*MRS*
2003			MULEs
2004			H-LES
2005			CLHD
2006	GMRE		
2007		Global/1-hop Algorithm	
2008	(1-ε) Algorithm	OSTA	JMRA
2009	MLS		
2010	CSPLI	DT-MSM	
2011	SPAT		EERMD
2012			
2013			REECR, OMRC, SHDGP
2014			RW-TPP, NCCC, CRNP
2015	TCBDGA		NDCM, LBC-DDU
2016	ESCMS		ARCR, MRSC
2017	CEDR, HOAA		
2018	Ms-routing-G, MSFLA	CMS2TO	
2019	MSPO-ABC		

To further improve EE, the strategy combined with other energy-efficient strategies, such as EECS, EERS, ESS, random Network Coding, and cross-layer protocols emerged. For instance, some of them are integrated with the MAC layer and the transport layer protocols. Such strategies include the Node Density based Clustering and Mobile collection (NDCM)[117], the Reliable and Energy Efficient Cooperative Relaying scheme (REECR)[118] which improves the Energy Efficiency through the cooperation among the nodes equipped with power control functions and the adoption of the Cooperative Automatic Repeat reQuest, the Load Balanced Clustering and Dual Data Uploading (LBC-DDU)[119] which achieves the goals of prolonging the Network Life, reducing network latency, and obtaining a high reliability at the same time, the Network Coding-based Cooperative Communications scheme (NCCC) which applies NC to achieve energy conservation and communication reliability[120], the Energy Efficient Relay and Minimum Distance algorithm (EERMD) which comprehensively considers the influence of CHs and the relays on the Energy Efficiency[121], *etc*. In addition, there are also some other strategies which combines with the EEMAC, such as the Channel-aware RN Placement method (CRNP)[122] which is integrated with the MAC layer to regulate the trajectory of relays and comprehensively takes the channel utilization of nodes into consideration to reduce energy consumption resulted from idle listening. Similar strategies also include the Single-Hop Data-Gathering Problem (SHDGP)[123] aiming at reducing the track length of the mobile relays, and the Hybrid Location Estimation Scheme (H-LES)[124] which was designed to solve the problem induced by the mobile relay that it is hard to precisely obtain the node's location.

Table 5 shown the specific examples of MNASs emerged from 2003 to 2019 and the related subcategory.

4.3 EECS

Since WSNs are featured by the dense deployment of sensor nodes, the phenomenon of data correlation exists in the raw data they acquired. In general, data correlation includes two aspects, namely, the spatial correlation and the temporal correlation. On the one hand, the fact that the data acquired by nodes close to each other in space appear a high similarity is regarded as the spatial correlation. On the other hand, the high similarity of data collected in adjacent time slots resulted from the high frequency of data acquisition is the temporal correlation. The temporal and spatial correlations lead to a large amount of data redundancy, which results in a waste of energy. Obviously, the decrease of data redundancy caused by the temporal and spatial correlation brings in the reduction in the overall energy consumption and the improvement of EE, which is the theoretical foundation of EECS aiming to improve the Energy Efficiency via clustering[16].

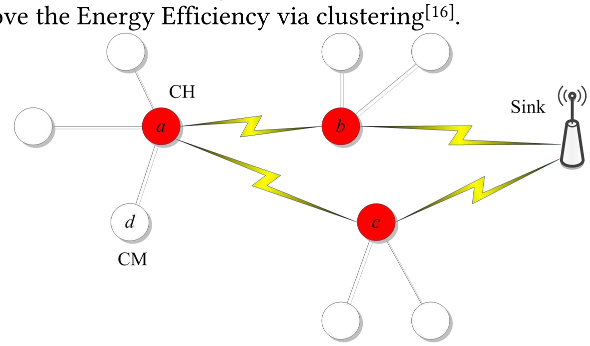

Fig.5. Schematic diagram of EECS.

4.3.1 Brief Introduction of EECS

EECS aims to improve EE with the consideration of C_1, C_2, and C_3, it usually divides the network topology into hierarchical structures logically by means of organizing nodes which are geographically close to each other into clusters. In each cluster, the intra-cluster data can be simply aggregated to remove the redundancy before transmitted towards the Sink by each CH. Therefore the energy overhead resulted from data redundancy can be reduced to some extent. In EECS, there are two kinds of different roles for all the nodes, i.e., CH and CM respectively. As shown in Figure 5, it is a schematic diagram of a Wireless Sensor Network applying EECS, in which the white circle represents CM (such as node *d*) and the red one denotes CH (such as Node *a*). The CM is responsible for collecting the raw data, while the CH is responsible for scheduling time slots according to the number of related CMs in TDMA mode and transmitting the data transmitted from the CMs to the Sink after a simple aggregating operation. CMs switch between work and sleep modes according to the time slot, which brings in the reduction in energy consumption. Generally speaking, EECS mainly includes two steps, namely, the cluster formation phase and the data acquisition phase. In the first phase, CHs are selected according to some predefined rules or regulations, then each new Cluster Head broadcasts an advertisement message (ADV) to announce its role of CH. Subsequently, CMs reply to CH with a JOIN message in the form of unicast once receiving the ADV message. The CM which has not received any ADV messages forms an isolated cluster which only contains itself. When all the sensor nodes join in specific clusters, the cluster formation phase terminates. As for the second phase, it is mainly responsible for collecting and transmitting data. After a simple aggregating operation, the data acquired in intra-cluster are sent out and forwarded to the Sink via other upstream CHs in a "multi-hop transmission" routing mode. Overall, EECS is mainly designed to cut down the energy depletion by means of reducing both data redundancy and the duty-cycle of CMs. Besides, it also aims at balancing the energy consumption by periodically changing the roles of sensor nodes.

4.3.2 Classifications of EECS

In general, the current EECS mainly focuses on the following three aspects to improve the Energy Efficiency, i.e., the Optimization of Cluster Formation (OCF), the Control of Cluster Size (CCS), and the Reduction of Data Transmission (RDT) respectively. OCF is designed to balance the energy consumption by optimizing the selection of CHs. In addition, OCF can also reduce the energy overhead resulted from clustering via cutting down the frequency of CH rotation. OCS achieves energy balance by means of regulating the size of cluster reasonably and alleviating the “Hot Spot Problem”. As for RDT, it mainly reduces the volume of the transmission for redundant data to diminish energy depletion by simple aggregation conducted by CHs. This paper mainly focuses on the EECSs which emerged from 2002 to 2019 from the three aspects mentioned above.

(1) OCF

Usually, OCF aims to control the selection of CHs so that the energy depletion among different clusters in the whole network topology appear to be more even. At the same time, the variance of residual energy between CH and CM is cut down as much as possible through periodic rotation of CH, which brings in an improvement of EE. In addition, the energy overhead during the cluster formation phase can be also reduced with the decrease of the rotation frequency for CHs. According to the selection scheme of CHs, the researches on OCF existing currently were divided into different subcategories.

In existing strategies, there are a lot of schemes controlling the selection of CHs. For instance, CHs are selected in a random distributed manner, such as the Low-Energy Adaptive Clustering Hierarchy (LEACH)[125]. In some scenarios, the node takes turns to be CH according to some specific logical topology, e.g., the Power-Efficient Gathering in Sensor Information Systems, (PEGASIS)[126]. In some schemes, the CHs selection is regulated on the basis of some predefined thresholds. For example, the similarity among nodes and the node degree are often regarded as parameters for CH selection depending on the specific requirements of applications. Related examples include a double-threshold mechanism, which adopted the Hard Threshold (HT) and the Soft Threshold (ST) at the same time, applied in the Threshold sensitive Energy Efficient sensor Network protocol (TEEN)[127] which is applied in the hard real-time scenarios. Similar strategies include the Adaptive Threshold Sensor Energy Efficient Sensor Network (APTEEN)[128] which is an improved version of TEEN adopting an adaptive algorithm to select CH, the Extending Lifetime of Clustering Head (ELCH)[129] that selects CHs based on a neighbor voting mechanism, the Threshold-Based LEACH (T-LEACH)[130] which rotats CHs on the basis of a predefined threshold, the Distributed Hierarchy Aggregation Clustering (DHAC)[131] generating CHs according to the similarity matrix induced by the input of sensor nodes, the algorithm which utilizes the Energy Delay Index for Trade-off (EDIT)[132] to achieve a trade-off between the energy consumption and the network delay, and the Energy-Efficient Adaptive Overlapping Clustering (EEAOC)[133] that adaptively selects CHs according to the residual energy of sensor nodes. In addition, the network can be also logically divided into multiple levels according to the residual energy of nodes to form a multi-level clustering architecture with the purpose of achieving a higher energy efficiency. For instance, the Hybrid Hierarchical Clustering Approach (HHCA)[134] classifies the nodes into the layer-2 Grid head, the layer-1 CH, and the layer-0 normal nodes to form a three-layer system, which adopts the distributed LEACH and comprehensively considered the residual energy of nodes during the process of cluster formation.

The process of Cluster Head selection can be also integrated with the optimization algorithms[135], such as the fuzzy logic theory, the game theory, the particle swarm optimization algorithm, and the simulated annealing algorithm, *etc.* Besides, the reduction and the equilibrium in energy consumption can be achieved on the basis of the MAC and the transport layers. Such strategies included LEACH-C[136] that centrally selects CHs through the simulated annealing algorithm, the Base-Static Controlled Dynamic Clustering Protocol (BCDCP)[137] that achieves energy equality among different clusters by means of controlling the process of CH selection, the Optimal-Compression Clustering Algorithm (OCCA)[138] which applies the concept of Slepian-Wolf coding to conduct CH selection, the Chessboard Clustering scheme (CC)[139] which is based on the chessboard clustering strategy for the heterogeneous sensor networks, the Distributed Independence Set Discovery (DISD)[140] with a node sleep management mechanism, LEACH-ERE[141] which presented the Expected Residual Energy level obtained through the fuzzy logic as well as a T2FL model for CH decision-making through a two-level fuzzy logic[142], *etc.* Related strategies also include the Fuzzy-Logic based Energy-Efficient Clustering Algorithm (FLEEC)[143] and FCM[144] that can be applied to practical applications of WSNs, the the Energy-Aware Evolutionary Routing Protocol (EAERP)[145], the Game theory based Energy Efficient Clustering (GEEC)[146] protocol for WSNs and the Energy Efficient Routing protocol based on Evolutionary Game (EEREG)[147] which are all based on the game theory, and PSO-C[148] which adopts the intelligent algorithm, i.e., the particle swarm optimization to conduct CH selection with the purpose of minimizing the intra-cluster energy consumption for communication.

(2) CSC

CSC is aimed to balance the inter-cluster energy consumption in different regions by means of regulating the number of CMs. It achieves the improvement of EE and extension of NL through the energy consumption equilibrium. By designing clustering algorithm which makes the size of the clusters in the “Hot Spot Area” be smaller than that of the clusters in edge, the energy consumption burden on the "Hot Spot Area" can be alleviated markedly. For instance, the large network region is divided into fan-shaped clusters to relief the "Hot Spot Problem" in Fan-Shaped Clustering (FSC)[149]. In addition, the relevant characteristics of the network topology, such as the hop count (EC[150]) or distance from the node to the Sink, connection density (such as the Balanced Clustering Algorithm with Distributed Self-Organization for Wireless Sensor Networks, DSBCA[151]) and the coverage, *etc.* can be also adopted to optimize the cluster size[152]. Related algorithms include the Energy Dislocation Forecast and Clustering Management (EDFCM)[153] which belongs to an improved version of LEACH and determines cluster size based on the residual energy and the energy dissipation rate, the Energy-Balancing Cluster Approach for Gradient-Based Routing (EBCAG)[154], the Localized and Load-Balanced Clustering (LLBC)[155] which is integrated with the Improved Cluster Head Rotation and the Modified Static Clustering mechanisms. In addition, the fuzzy logic theory, the optimization algorithm, the game theory, and other intelligent algorithms can be also utilized to control the cluster size properly so as to achieve the energy equality among different clusters[156][157][158][159], such as the Energy Efficient Routing Protocol Based on Evolutionary Game (EEREG)[138]. Noting that CSC can also cooperate with OCF to improve EE. For instance, selecting some nodes deployed at a certain area as the CH candidate contributes to reducing the energy overhead for Clustering[140].

Table.6. Timeline and Subcategories of EECS

Year	*OCF*	*CSC*	*RDT*
2002	LEACH, LEACH-C, PEGASIS, TEEN, APTEEN		
2003			self-adaptive Clustering
2004	HEED[160]		VGA
2005			
2006	BCDCP		
2007	PSO-C		
2008	ELCH, CC	LLBC	
2009	T-LEACH		
2010	DHAC, OCCA	EDFCM	DOC[161]
2011	EAERP	EC	
2012	DISD, LEACH-ERE	EBCAG	
2013	FCM	DSBCA	
2014	EDIT		
2015	EEREG	FSC	VELCT
2016	HHCA		
2017	GEEC, EEAOC, T2FL		
2018	FLEEC		
2019			EECSR, ECH

(3) RDT

According to the first-order radio model[133][134][135], the amount of energy consumption for communication is directly proportional to the volume of data transmission when the communication range is constant. Therefore, energy overhead can be cut down by means of reducing the amount of data transmission. For example, in some scenarios where the data generate in a burst mode, the energy overhead can be diminished through the reduction in the frequency of data acquisition[118]. Besides, the characteristics of data correlation in WSNs also needs to be alleviated through simple aggregation at each CH to reduce the energy overhead resulted from data redundancy. In general, it is achieved by means of cutting down the data transmission among different clusters. Such strategies include the Virtual Grid Architecture routing (VGA)[162] in which the CH acts as the Local Aggregator to conduct data aggregation. Besides, a Master Aggregator (MA) is selected from the LAs for global data aggregation to reduce energy consumption further. Similar strategies include the Enhanced Clustering Hierarchy (ECH)[163]. the self-adaptive clustering based algorithm[164], the Velocity Energy-efficient and Link-aware Cluster-Tree (VELCT) scheme[165], In addition to the strategies listed above, the volume of data transmission can be further reduced at the source via combining with CSS[166][167], such as EECSR[168]. In fact, the Cluster Head can conduct data aggregation further after that during the intra-cluster process to reduce the amount of data redundancy. Besides, the strategy of MANS[110][169][170] can be also integrated with EECS to balance the energy consumption. Since the details of CSS and MNAS were described at length in other sections, they were not included in this section.

Table 6 shown the main examples of EECS emerged from 2002 to 2019 and the corresponding subcategories.

4.4 EERS

As for the network, the routing protocol is responsible for building the routing table for each node to provide a guidance for data forwarding[171]. As shown in section 2.2.2, it comes to a conclusion that the energy consumption of WSNs is mainly resulted from data communication[11]. Obviously the data transmission is directly affected by the routing table. As a result, the routing protocol has a deeply influence on the distribution of energy consumption. In general, EE can be improved with the consideration of C_2 and C_3 by means of designing low-energy and energy-equality routing protocols. In this section, the strategies of EERS emerged in recent years were reviewed in detail as below.

4.4.1 Brief Induction of EERS

Different from the traditional wireless networks , the Energy Efficiency is usually regard as the main metric for routing protocols owing to the characteristics of limited energy in WSNs. Namely in WSNs, much more emphasis is put on the Energy Efficiency, which is quite different from the design principle of the traditional network routing protocol. At the same time, the design of WSNs routing protocol is affected by many other factors. For example, the following aspects needs to be carefully considered when designing energy-efficient routing protocol, such as whether the node is homogenous or heterogeneous, whether the network topology is static or dynamic, characteristics of application data flow, and the probability of data aggregation[172]. Noting that in the Wireless Sensor Networks, there exists a kind of hierarchical routing protocols, namely the clustering routing protocol. The clustering routing protocols contain intra-cluster and inter-cluster routing phases. The first phase is mainly related to the process of cluster formation and Cluster Head rotation, which was analyzed in EECS. Therefore, the clustering routing protocols mainly focused on the Energy Efficiency in inter-cluster routing and data forwarding in this section.

The energy consumption related to the routing protocol mainly includes the overhead for routing table building and updating as well as the energy depletion for data transmission from the specific source node to the Sink. In addition, the routing protocol plays an important role in the energy distribution of the whole network topology. Therefore, all the factors need to be taken into account. As for the analysis on energy-efficiency routing design, the subcategories of EERS were reviewed in detail.

4.4.2 Classifications of EERS

As mentioned above, there are mainly two means to improve EE, i.e., reduction and balance in energy consumption of WSNs. According to the energy consumption model in section 2, the energy overhead for communication per unit data is related to the transmission distance[11]. On the one hand, the routing table has a great influence on the distribution of data flow, the energy consumption for data transmission is closely related to the routing protocol. On the other hand, excessive use of an optimal route leads to an uneven energy consumption. Therefore, energy consumption balance should also be considered during the design of routing protocols. In this section, we divided the energy-efficient routing protocols into three subcategories according to the emphasis which is put on during the design of routing protocol, i.e., Energy Consumption Reduction (ECR), Balancing Energy Consumption (BEC), and Combining Reducing and Balancing energy (CRB).

(1) ECR

According to the first-order radio model[142][147], the energy overhead for communication is proportional to the square or even the fourth power of the transmission distance when the amount of data transmitted is constant. Therefore, the transmission distance between two nodes has a deeply influence on the energy consumption. In addition, from the perspective of EE in the whole network, not only the Line of Sight (LoS) from the source node to the Sink needs to be considered, but also the total energy required for the source data to reach the Sink. In general, ECR utilized the following schemes to reduce energy consumption.

By means of selecting a proportion of nodes from the network or adopting the Sink as an auxiliary node, which is responsible for obtaining and keeping the minimum energy consumption for the path from each source to the Sink, the overall energy cost can be reduced and the Energy Efficiency can be improved markedly. For example, the Multiple Winner Algorithm (MWA)[173] reduces energy consumption via making all the nodes in the topology keep records about the Central Node (CN). As a result, each individual node can establish a minimum energy path along which it can reach the data source. In addition, WMA can generate the lowest energy consumption path in global, thus reduce the energy overhead and improve the Energy Efficiency. Similar schemes include the base station assistant Hierarchy Cluster-based Routing (HCR)[174] that is able to build energy-efficient inter-cluster routes with the assistance of the Sink.

By means of reducing the volume of data exchanged, reasonably controlling the transmission power, selecting the ideal next hop, or taking the energy overhead for communication in both of the receiver and the transmitter simultaneously, the overall energy consumption of the whole network can be cut down to some extent. Besides, the physics concept of Potential can be applied in routing decision so as to figure out the routing direction from the source node to the Sink[175]. For instance, in the

Scalable Energy-Efficient Location Aided Routing (SELAR)[176], each sensor node announces its own geographic location and energy information to others by means of flooding. Once the initial information acquired, only the residual energy information needs to be contained in the subsequent information exchange. As a result, the energy consumption is diminished since the size of the data packet decreases. The Minimum Energy Relay Routing (MERR)[177] achieves the reduction in energy consumption by means of obtaining the ideal transmission power so that the data can be correctly received by the receiver without any redundant energy cost. In addition, the messages of Request-To-Send/Clear-To-Send (RTS/CTS) are applied in the Energy-efficient Beaconsless Geographic Routing (EBGR)[178] to obtain the nearest neighbor as its ideal next hop, with the aim of establishing a minimized routing table.

Some intelligent algorithms, such as the ant colony algorithm[179], the bee colony algorithm[180], *etc.*, are integrated to the clustering strategy to design the energy-efficient clustering routing. Among most of existing clustering strategies, the emphasis is put on the way that CH is selected so as to reduce the energy overhead. In fact, the data acquired by each cluster need to be transmitted to the Sink hop-by-hop owing to the routing mode of WSNs. Therefore, during the process of routing decision-making for each CH, a comprehensive consideration on the energy consumption and balance is a necessary. To be specific, when designing the inter-cluster routing algorithm, it is necessary to simultaneously consider the residual energy of each node and the minimum energy consumption for data forwarding. Besides, it is also essential to judge if the residual energy is sufficient via taking sum of energy consumption for both transmission and reception into account together. For instance, the Joint Clustering and Routing protocol (JCR)[181] applied the clustering strategy to build energy-efficient routing tables. Besides, in some scenarios, all the Cluster Heads are grouped into a dominant set[182], through which the communication problem of CHs was considered. In addition, some of the strategies of EERS are integrated with the classic clustering strategy, such as EEM-LEACH[183], *etc.* To minimize energy consumption for the intra-cluster and inter-cluster simultaneously, the distance from CM to CH and that from CH to the Sink were integrated as a compound distance[184] for routing decision-making. In some strategies, the multi-hop path with the lowest energy consumption from the source to the Sink is selected as the optimal routing[182]. Finally, the energy overhead resulted from data aggregation and data process for CHs should be considered comprehensively, with the purpose of providing a better stability, a longer lifetime, and a higher effective advertisement mechanism for CH. Therefore the energy consumption for communication per unit data is minimized[185]. For example, an energy-efficient strategy combining the flat with the hierarchical routing was proposed in the HYbrid Multi-hop routiNg algorithm (HYMN)[186] to reduce energy consumption. In HYMN, the flat routing is applied in building the energy-efficient routing table, while the hierarchical one is responsible for data aggregation.

(2) BEC

During the data transmission phase, the process of routing leads to an uneven distribution in both data flow and energy consumption. In addition, specific requirements of application also lead to the energy inequality to some extent. For example, if the routing protocol is designed to select a path with minimum energy consumption in preference, the nodes along this path will exhaust their energy quickly. As a result, the network partition happens and the Network Lifetime terminates in advance. Therefore, in order to achieve the improvement of EE and the extension of the NL to a large extent, the energy consumption balance needs to be considered when designing routing protocols.

In order to balance the energy consumption, factors such as the residual energy level of nodes, geographic location, expected energy depletion rate, *etc.*, are taken into account when building the routing table. For example, for nodes with lower residual energy, it is unreasonable to be selected as the next hop. For nodes with special geographical location, they need to be balanced in terms of energy consumption to escape from depleting the energy early by means of reducing the probability of being involved in being selected as the next hop. For instance, the Energy-aware Temporarily Ordered Routing Algorithm (E-Tora)[187] applies the energy consumption fairness of each individual node and a feedback mechanism to achieve energy equality and avoid the “Hot Spot Problem”. Similar schemes was adopted in the solution-Chain Routing with Even Energy Consumption (CREEC)[188], and strategies also include the Balanced Energy consumption based Adaptive Routing (BEAR)[189] which took the residual energy and location of nodes into account when selecting the next hop so that it can select the node whose remaining energy is higher than the average of WSNs as the next hop, and the Energy-Efficient Opportunistic Routing (EEOR)[190] that includes a kind of opportunistic routing and establishes a priority list of next hops regarding the residual energy, and EEC (Expected Energy Cost) as the main metrics for routing construction to achieve a higher EE.

In addition to those listed above, there are also some strategies which is combined with the topology control technology, the ant colony optimization algorithm, the particle swarm optimization or any other optimization algorithms, EECS, and other classical routing protocols to achieve energy balance. For example, the q-swith Routing[191] is designed to avoid the “Hot Spot Problem” by means of balancing energy consumption for a circular network topology where the sensor node follows the non-uniform distribution. The energy consumption balance is achieved by means of adopting the energy-efficient distance and the most energy-balanced distance as the optimal metrics for routing decision-making in the Optimal-Distance based Transmission Strategy (ODTS)[192] which is based on the ant colony optimization. The directed transmission-based energy aware routing (PDORP)[193] which combining direction-based transmission and the Dynamic Source Routing (DSR)[194] so that nodes with lower residual energy can adaptively escape from being selected as the next hop during routing decision-making. Other strategies include the Hybrid Multi-Hop Partitioning-Based Clustering (HMPBC)[195] which aims to present an energy-saving inter-cluster routing on the basis of a clustering strategy, the Stochastic Based Traffic Distribution (SBTD)[196], the Cost-based Energy Balanced Clustering and Routing Algorithm (CEBCRA)[197], and the Interference-Aware EE Routing algorithm (IA-EERA)[198], *etc.*

(3) CRB

The cross-disciplinary concepts, such as the physics, economics and mathematics, *ect.*, are applied in routing decision-making for the sensor nodes. All of them are supposed to construct the routing table with the lowest energy consumption for data forwarding and balance the energy consumption for whole network to some extent. To be specific, the node's residual energy, energy depletion rate, network's residual energy, and other related parameters are comprehensively considered when building the routing table. Therefore, an energy-efficient adaptive routing protocol can be achieved which is featured by low communication cost and balanced energy consumption[199][200]. For example, the Energy-Balanced Routing Protocol (EBRP)[201] utilizing the energy consumption of both each individual node and the whole network as the metrics for routing decision-making on the basis of the concept of Potential Energy in physics. The Distributed Energy Balanced Routing (DEBR)[202] is modeled as an integer programming problem. Similar schemes include the Maximum Energy Welfare (MaxEW)[203] which applied the concepts of energy equality and energy welfare to regulate the process of routing decision. A-Star and Fuzzy routing[204] is a combination of fuzzy logic and an A-star algorithm. It jointly takes the maximum remaining energy, the minimum count of transmission hops, and the minimum traffic load into consideration so as to dynamically regulate the routing decision according to the real-time requirements of the specific applications. In addition, the Adaptive Energy-aware Multi-path Routing Protocol with Load Balance (AEMRP-LB)[205] utilizes the concept of Direction Angle to achieve a kind of adaptive energy-aware multi-path routing protocol.

Table 7 shown the existing strategies of EERS from 2004 to 2019 as well as the corresponding subcategories.

Table.7. Timeline and Subcategories of EERS

Year	*ECR*	*BEC*	*CRB*
2004	SELAR		
2005		SBTD	
2006	HCR		
2007	MERR	E-Tora	
2008	MWA	q-Switch Routing	
2009			DEBR, MaxEW
2010	EBGR		
2011		CREEC, EEOR	
2012	HYMN		EBRP, AEMRP-LB, A-Star and Fuzzy
2013		CEBCRA	
2014	EEM-LEACH		
2015		ODTS	
2016	JCR	PDROP	
2017		BEAR	EIRNG[206]
2018		HMPBC	
2019		IA-EERA	

4.5 CSS

4.5.1 Brief Introduction of CSS

A new data acquisition framework which is based on the Compressive Sensing (CS) theory has been proposed in recent years in order to reduce the data redundancy and energy consumption as well. Different from EECS introduced above, it aims to reduce data redundancy caused by data correlation from the source. It usually diminishes the energy consumption of sensor nodes by reducing the frequency of data acquisition, therefore it is able to improve the Energy Efficiency largely. Compressive Sensing theory is a theoretical framework which synthetically applies the signal sparsity, mathematical statistics theory, and the optimization theory in signal processing and collecting. It was first proposed by D. Doboho, et al. [207][208][209][210][211], who made a fundamental achievement with the theoretical framework for Compressive Sensing. In tradition, Nyquist sampling theorem is the theoretical foundation for signal acquisition, i.e., the sampling frequency must be at least twice of the maximal frequency of the source signal in order to precisely acquire the source data. The proposal of CS theory has subverted Nyquist sampling theorem's requirement on sampling frequency. Namely, a signal with sparseness in nature or under a certain transform basis can be recovered with a high accuracy even though the sampling frequency is cut down to a large extent. CS theory makes it possible that the sampling frequency depends on the signal's characteristics rather than the bandwidth[212]. Moreover, different from the conventional data compression, such as the Clustered AGgregation (CAG)[213] as well as the Distributed Source Coding (DSC)[214][215], the processes of sampling and compressing are conducted simultaneously under the CS framework. Besides, only several simple multiplication and addition operations is necessary during the process of compressive sampling. Therefore, the complicated data recovery operations are conducted by the Sink which possesses relatively unlimited energy supply and process capacity. Obviously, it is exactly suitable for the Wireless Sensor Networks whose nodes are equipped with limited energy supply and process capacity. In general, CSS aims to improve EE via taking C_1, C_2, and C_3 into account and its theory foundation of data acquisition includes the following three basic components.

(1) *K*-sparse Signal

Suppose a Wireless Sensor Network consisting of *N* nodes, the data acquired by node *i* are denoted as $x_i(1 \le i \le N)$. The source data set collected by a the Sink can be denoted as $X = x(x_1, x_2, \dots, x_N)$. The signal is called to be a *K*-sparse signal if there exists a sparse transform basis meeting the following condition

$$\|\theta\|_0 \le K, \ s.t. \ X = \Psi \cdot \theta \tag{7}$$

where θ denotes the sparse coefficient matrix and $\|\theta\|_0$ is the number of non-zero elements in the matrix θ.

(2) Restricted Isometry Property (RIP)

To extract the valid information from the *K*-sparse signal, an $M \times N$ measurements matrix Φ is necessary. Therefore the measurement can be obtained as $y = \Phi X$, where $X = \Psi\theta$. The foundation of CS lies in the fact that an $M \times 1$ result matrix is finally obtained through a properly-designed measurement matrix. Since condition $M << N$ is always established, the frequency of data acquisition is far less than that of Nyquist sampling. To precisely recovery the source data from the measurements, the measurement matrix Φ needs to satisfy the Restricted Isometry Property (RIP). Namely, for any signal X, if a parameter $\delta_k (0 < \delta_k < 1)$ which meets the following inequation exists

$$(1-\delta_k)\frac{M}{N}\|X\|_2^2 \le \|\Phi X\|_2^2 \le (1+\delta_k)\frac{M}{N}\|X\|_2^2 \tag{8}$$

the measurement matrix Φ is assumed to satisfy RIP. In the measurement matrix, the row of *M* denotes the number of measurements. In general, the relationship between *M* and *K* needs to meet the following condition

$$M \ge K \log N \tag{9}$$

(3) Reconstruction Algorithm

Under the CS framework in WSNs, RIP is a sufficient condition for the measurements to be accurately recovered. As mentioned above, through the measurement matrix Φ, the measurement of y can be obtained as shown in the following expression

$$y = \Phi \cdot X \tag{10}$$

The source signal X can be precisely recovered by means of solving the following l_0-norm optimization problem

$$\min_{\theta} \|\theta\|_0, \ s.t. \ y = \Phi\Psi\theta \tag{11}$$

Therefore the form of the source data can be denoted by the following expression,

$$X' = \Psi\theta' \tag{12}$$

However, it has been proven that the solution of the l_0-norm optimization is an NP-Hard problem owing to the demand that all of the possible combinations of vector *X* should be listed to recover the source signal precisely. It becomes harder or even impossible to obtain the optimal solution with the increase of dimension. Fortunately, Donobo, et al. proven that the optimal solution of the l_1-norm is approximately equivalent to that of the l_0-norm optimization problem if the measurement matrix Φ meets RIP[190]. Therefore the acquisition of the source data can be turned into the following l_1-norm convex optimization problem

$$\theta^* = \arg\min \|\theta\|_1, \qquad s.t. \ y = \Phi\Psi\theta \tag{13}$$

Finally, the following expression is regarded as the approximate value of the source data

$$X^* = \Psi \theta^* \tag{14}$$

4.5.2 Classifications of CSS

This section made a detailed analysis on the strategies belonging to CSS proposed recently. According to the network logical topology which they are based on, the strategies of CCS can be classified into the Flat Compressed Data Gathering (FCDG), Hybrid Compressive sensing Aggregation (HCA), and the Hierarchical Compressive Data Gathering (HCDG) respectively.

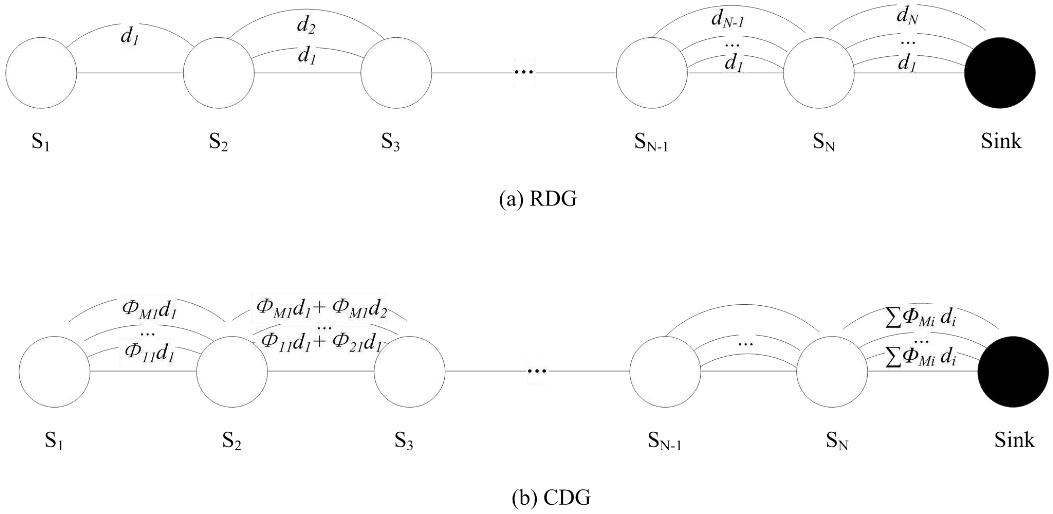

Fig.6. Comparisons of RDG and CDG.

(1) FCDG

FCDG is based on the flat network topology, where the Sink distributes the measurement matrix to all the sensor nodes to control the work mode according to the corresponding values of the measurement matrix. The row of the measurement matrix represents the amount of data acquired per round, while the column denotes the number of sensor nodes in the whole network. In general, the rows of measurement matrix are much smaller than the columns. Therefore, it brings in a significant reduction in the amount of source data for sensor nodes. Obviously the energy overhead for communication can be cut down and the overall Energy Efficiency can be improved. For example, the Compressive Sensing Gathering (CDG) mode is applied in the CS-based data gathering framework for the large-scale Wireless Sensor Networks[216][217]. According to the framework, two data acquisition modes were theoretically analyzed as shown in Figure 6. Specifically, the Raw Data Gathering (RDG) and CDG were compared in terms of the volume of data transmission. It can be easily obtained that the amount of transmission rises up with the decrease of the distance from the node to the Sink in RDG mode. However, as for CDG, the volume of data transmission keeps constant for all the nodes no matter where they locate. Therefore, it can be easily concluded that CDG mode can effectively cut down the amount of data acquisition and transmission overhead. At the same time, since the transmission load on each node is approximately equivalent, the "Hot Spot Problem" can be got rid of. However, it usually the main reason of energy inequality in the traditional Wireless Sensor Networks. In addition, in order to further improve Energy Efficiency, the network performance, such as the network capacity and network delay policies[218][219], can be taken into consideration comprehensively. In some scenarios, CDG is combined with other energy-efficient, such as routing protocols, MNAS, *etc.* Related strategies include the In-network Computation Protocol with Compressive Sensing (ICPCS)[220], the Compressive Data Persistence (CDP)[221], For instance, the Structurally Random Matrices (SRM)[222], the concepts of Group Sparse (TISD)[223] and Kernel Function (such as the Mobile CDG, MCDG[224]) were proposed to reduce the energy consumption for transmission in WSNs. Similar researches include the Compressive Data Collection (CDC)[225] which applies the power decay data model as well as CS-based opportunistic routing strategy to reduce energy consumption by means of reducing the amount of data sensed, the Compressed Data Aggregation (CDA)[226] scheme, the Random Walk (RW)[227] which is based on a structured random matrix, and the Covariogram-Based Compressive Sensing (CB-CS)[228] which applies the mixed integer programming to achieve the goals of both energy saving and data fidelity.

(2) HCS

Compared with the traditional data acquisition mode, FCDG can significantly reduce redundant data resulted from data correlation, thus achieve the improvement of the Energy Efficiency. However, the amount of data collected by the leaf nodes in the routing tree increases instead by comparison. Therefore, in order to further reduce the amount of data acquisition and the energy consumption of the leaf nodes, a hybrid Compressive Sensing data acquisition framework has been presented in recent years. The basic principle lies in the assumption that a tree which is rooted by the Sink consists of all the nodes and the Sink. The leaf node acquired the data in RDG mode while the nodes in the upstream area in CDG mode with the aim of reducing the energy overhead of the leaf nodes. Assume the parameter h denotes the function of the percentage of the leaf nodes in the data collection tree, the amount of communication data can be compressed to be $\Theta(hN)$. When condition $h << M$ is established, EE of WSNs can be improved largely. Generally speaking, the relevant strategies of HCS emerging recently are designed to reduce the energy overhead for the leaf node by means of combining modes of RDG and CDG, on the MAC layer, the network layer or combining with EECS. Related strategies include the Minimum Energy Compressed Data Aggregation (MECDA)[229], Hybrid CS[230] combining RAW with CDG for data collection, the Distributed hybrid Compressive Sensing (DhCS)[231], the Random Access Compressed Sensing (RACS)[232] which combined with the MAC layer to reduce the time for idle listening, a Cost-Aware Activity Scheduling (It is denoted as CAAS in this paper)[233][234] which combines with the MAC layer to implement a compressed sleep mechanism based on the elements of the compression matrix and the Nonuniform Compressable Sensing (NCS)[214][235][236], and so on. In addition, Lan, et al. proposed a CS-based clustering algorithm named Compressibility-Based Clustering Algorithm (CBCA)[237]. In CBCA, the network topology is transformed from a mesh topology into a logical chain topology, then it is clustered based on the spatial correlation to minimize the average compression ratio. Similarly, it applied RDG and CDG modes at the same time. Beside, in order to maximize EE, CBCA utilizes a threshold mechanism to determine the transmission mode. Therefore, it can dynamically determine the transmission mode and the cluster size according to the Compression Rate. Shen, et al.[218] proposed a Nonuniform Compressive Sensing algorithm (NCS) based on the compressibility of the signal and the generation distribution of data. Two different kinds of sampling distribution model were defined, i.e., the uniform Bernoulli distribution model and the non-uniform Bernoulli distribution model. Besides, through the extension of CS theory, the heterogeneous CS framework can recovery heterogeneous sampled signals with high probability. In this way, the CMs transmit data to the corresponding CHs through the traditional data collection model, and the CHs propagate compressed data to the Sink via CDG mode. Finally, an analysis model on the relationship between the size of each cluster and the amount of data transmission was conducted. As a result, the optimal number of CMs was obtained so that the volume of data flow can be minimized.

Table.8. Timeline of and Subcategories of CSS

Year	*FCDG*	*HCS*	*HCDG*
2009	CDG		
2010		Hybrid-CS	
2011		MECDA, RACS	
2012	SRM		SCoReI
2013	CDA	NCS	
2014	RW	DhCS	MMOA, T-CCDA
2015	CDC, CDP		ST-HDACS
2016	CB-CS	CAAS	STKCS
2017	ICPCS, TISD	CBCA	UEGCD
2018	MCDG		
2019			ST-CDGA

(3) HCDG

Although HCS can further reduce the amount of collection and transmission for redundant data, there still exists redundancy needs to be further diminished for the large-scale WSNs topology[238]. Therefore, in order to be suitable for the large-scale topology and enhance the scalability of the CS based strategy, a Hierarchical Compressed Data Collection (HCDG) framework which combines with the Clustering strategy has been put forward recently[239][240]. In general, HCDG is aimed to improve EE via combining with the hierarchical routing protocol. To be specific, it is the duty of CH to distribute the sub-measurement matrix to the corresponding CMs compared with the traditional FCDG framework. Therefore the compressed data collected by each cluster are finally transmitted to the Sink, which is responsible for recovering the related source data. In some scenarios, compressive data collection can also be conducted by means of using a snapshot and randomly selecting nodes or using the matrix optimization technique to reduce the data redundancy resulted from the Spatial-temporal correlation, such as the Spatio-Temporal Hierarchical Data Aggregation using Compressive Sensing (ST-HDACS)[241], the Spatial-Temporal Compressive Data Gathering algorithm (ST-CDGA)[242], and the Spatio-Temporal Kronecker Compressive Sensing method (STKCS)[243]. In addition, the Dispersion Wavelet Transform Matrix (DWTM) is applied in the Measurement Matrix Optimization Algorithm (MMOA) to achieve Spatial-temporal Compressive Sensing[244]. With the DWTM's acting as the sparse basis matrix, an Optimized Data Fusion Tree was constructed based on both of the CS theory and the routing topology. In addition, there are some strategies combining with the mathematics method to improve the Energy Efficiency. For instance, by means of decoupling the whole network into clusters with the help of SCoReI[245] framework which is integrated with the Principal Component Analysis (PCA), the data collection is conducted in CS data acquisition mode in each cluster[246]. An Unbalanced Expander Graph Based Compressed Data Gathering algorithm (UEGCD) which theoretically indicates that a proper sparse measurement matrix is equivalent to an adjacency matrix of an unbalanced expansion graph was proposed [247]. It is applied in the WSNs whose nodes are divided into clusters. In addition, Zhao, et al.[248] pointed out that the discrete cosine transform basis which is commonly used in signal sparse transformation is not suitable for the real signal sparse well since it weakens the advantage of CS data compression. Therefore, a Treelet-based Clustered Compressive Data Aggregation algorithm (T-CCDA) was proposed. It adopts a tree-based sparse transformation matrix to reduce the data redundancy resulted from the Spatial-temporal correlation.

Table 8 shown the strategies of CSS emerged from 2009 to 2019 the corresponding subcategories.

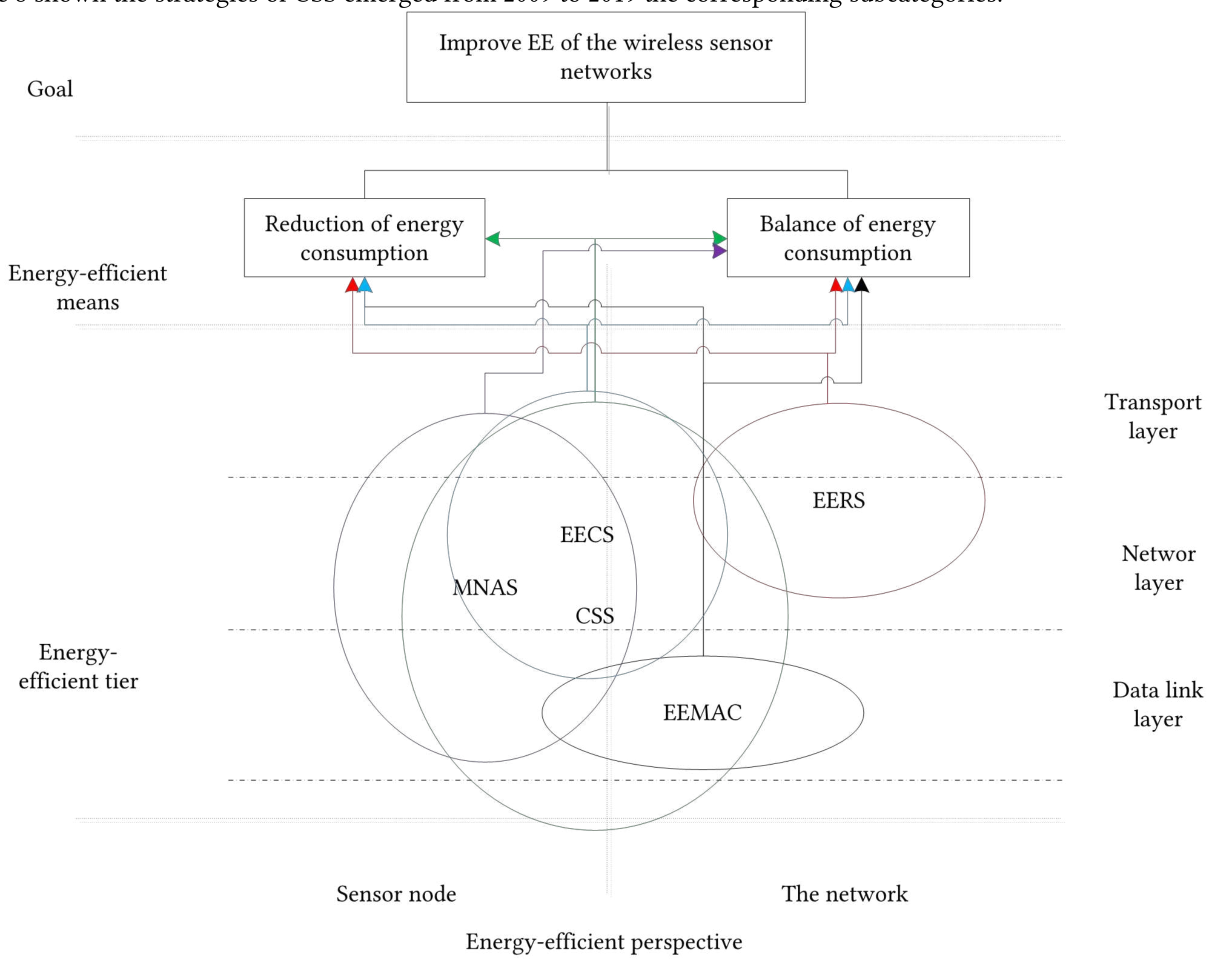

Fig.7. Overall relationships of all the categories.

5 FURTHER ANALYSIS ON EACH CATEGORY

In this section, the relationships among all the categories which were introduced in section 4 were analyzed in detail. Besides, the relationships between each of them and the Energy-efficient Means, the Energy-efficient Tier, as well as the Energy-efficient Perspective were presented respectively. Subsequently, the characteristics and applicable scenarios of each category were pointed out in a clear way. Finally, the statistic analysis on each category with regard to the number of both related papers and the corresponding citations was conducted.

5.1 Relationships among All the Categories

5.1.1 Overall Relationships among Different Categories

Figure 7 presented the overall relationships among all the categories in detail. As shown in Figure 7, it can be easily obtained that they are not independent of each other. In fact, they have close mutual interdependence of each other. Figure 7 indicated the relationship among them intuitively. The five categories were laid in Figure 7 from bottom to top on the basis of their relationships with the protocol stacks layer. Therefore, Figure 7 actually presented their relationships with the Energy-efficient Tier clearly. Take EEMAC for example, it works at the data link layer. Similar conclusions can be easily drawn from Figure 7. Besides, it also shown the interdependence of the categories in a clear way. To be specific, some of strategies of CSS are integrated with the slot access method with the purpose of reducing the duty-circle, which means it is combined with the design principle of EEMAC obviously[232]. In addition, some examples of CSS applied the concept of Compressive Sleeping[233][234] which aims to reduce the energy consumption by means of scheduling each individual node to switch between work and sleep modes according to the elements of the measurement matrix. In some other scenarios, some strategies of MANS interact with CSS[99][100][101][107][108]. Similar examples can be also found in the relationships between EECS and CCS[119][169][170], *etc.* Finally, the relationships between each of them and the Energy-efficient Means, the Energy-efficient Tier, as well as the Energy-efficient Perspective can be also easily obtained from Figure 7. The relevant illustrations were presented in the following section in detail.

Table.9. Relationships between Each Category and the Energy-efficient Means

Category	*Reduction of Energy Consumption*	*Balance of Energy Consumption*
EEMAC	√	
MNAS		√
EECS		√
EERS		√
CSS	√	

Table.10. Relationships between Each Category and the Energy-efficient Tier

Category	*Physics Layer*	*Data Link Layer*	*Network Layer*	*Transport Layer*
EEMAC	√			
MNAS		√	√	
EECS		√	√	√
EERS			√	√
CSS	√	√	√	

Table.11. Relationships between Each Category and the Energy-efficient Perspective

Category	*Each Sensor Node*	*the Network*
EEMAC	√	√
MNAS	√	√
EECS	√	√
EERS		√
CSS	√	

5.1.2 Relationships of Each Category with Different Concepts concerning EE

As analyzed above, there are different concepts concerning EE of WSNs, namely the Energy-efficient Means, the Energy-efficient Tier or the Energy-efficient Perspective. It means the Energy Efficiency of WSNs can be improved from different aspects. Sometimes several aspects can be applied in each individual category simultaneously. For instance, EEMAC usually improves EE from the perspective of each individual sensor node based on the characteristics that little energy is consumed by the node in sleep mode. At the same time, the reduction of energy consumption is also applied which obviously belongs to the Energy-efficient Means. In some scenarios, EEMAC improves the Energy Efficiency from the perspective of the whole network. For example, some of them were designed to reduce the energy overhead resulted from data collision, overhearing, *etc.* MNAS is mainly based on the data link layer or the network layers to improve EE by means of balancing energy consumption from the perspectives of both of each individual node and the whole network. EECS usually achieves the improvement of EE on the basis of the data link layer or the network layers via reducing each individual node's energy consumption and balancing energy consumption of the whole network simultaneously. As for EERS, it usually regards the energy equality as a main metric for routing decision-making from the perspective of the whole network, with the purpose of improving the Energy Efficiency. Finally, the category of CSS mainly aims to reduce the energy consumption resulted from data acquisition for each sensor node. On the one hand, CSS can also promote energy balance of the whole network to some extent. On the other hand, it usually works at the physical layer, data link layer, and network layer. As a summary, Tables 9-11 shown the relationships between each category and the Energy-efficient Means, the Energy-efficient Tier, as well as the Energy-efficient Perspective respectively.

5.2 Analysis on the Relevant Applicable Scenario

In this section, the detailed analysis on the characteristic of each category was conducted firstly. Subsequently the corresponding applicable scenario was pointed out with the aim of providing some guidelines for the reader who shows much concern about the Energy Efficiency or the relevant applicable scenario in WSNs.

Table.12. Summaries of All the Categories with regards to the Related Characteristics and Relevant Applicable Scenarios

Categories	*Characteristics*	*Applicable Scenarios*
EEMAC	The emphasis is put on the design pf media access mechanism with the aim of reducing energy cost resulted from idle listening, data collision, and overhearing.	Since it aims to improve EE on the basis of the data link layer, it can be applied in almost all of the possible scenarios.
MNAS	The mobile Sink or relay is utilized to rotate the distribution of the "Hot Spot Area", therefore the energy consumption can be balanced.	It is suitable for the application in which the Sink or relay can move around the network topology freely.
EECS	The network is divided into the hierarchical structure topologically. It mainly focuses on the energy equality of the whole network.	It is usually applied in the large scale Wireless Sensor Networks. Besides, it can be also integrated with CSS in some scenarios.
EERS	The energy overhead of the path along which the data can reach the Sink is taken into consideration from the perspective of the network layer.	it can be applied to all kinds of scenarios. In addition, it is usually integrated with EECS in the large-scale topology.
CSS	The data redundancy resulted from the Spatial-temporal correlation can be reduced largely. As a result, the energy overhead is cut down accordingly. At the same time, the energy inequality among different clusters can be also alleviated.	For the scenario where the data is sparse in nature or the nodes are densely deployed, CSS is the best choice. Besides, it is also suitable for the scenarios where the data generate in a burst trigger mode.

As illustrated above, EEMAC aims to improve EE and extend NL of the Wireless Sensor Networks on the basis of the data link layer. In general, it achieves these goals by means of properly designing the media access mechanism. Therefore the energy cost resulted from idle listening, data collision, and overhearing can be cut down markedly. In addition, EEMAC can be also integrated with EECS in some scenarios. Since it is based on the low-level of the network protocol stack, it can be usually applied in almost all of the possible scenes.

In MNAS, the mobile Sink or relay is utilized to change the location of the "Hot Spot Area". As discussed in section 2, the energy depletes quickly in the "Hot Spot Area". Consequently, it leads to the energy inequality. The adoption of the mobile

Sink or relay contributes to the energy balance by means of redistributing the "Hot Spot Area". Since some WSNs are deployed in the dangerous areas, it is usually suitable for the scenarios in which the Sink or relay can move round the network freely.

The sensor nodes are grouped into separated clusters in EECS. The energy overhead in the intra-cluster can be diminished to some extent via simple data aggregation. At the same time, the energy consumption variance among CH and its CMs can be effectively alleviated through the periodic rotation of CH. In general, EECS is based on the hierarchical topology. Therefore, the merits of EECS can be exploited to the largest extent for the application with large scale network topology. In addition, EECS is also suitable for the scenario where the node is densely distributed.

As for EERS, it puts much emphasis on the Energy Efficiency of the whole network, especially on that of a specific path along which the source node reaches the Sink. In general, EERS is designed to reduce the energy cost for the route or balance the energy for the whole network. Since the routing table lays the foundation for data transmission, it can be applied to all kinds of scenarios. In addition, it is usually integrated with EECS in the large topology to balance the energy consumption among different clusters.

The sampling frequency can be cut down markedly with the adoption of CS theory in CSS. Therefore the energy overhead resulted from the Spatial-temporal correlation can be reduced largely. The effectiveness of CS-based data acquisition in WSNs lies in the requirement that the data be sparse in nature or approximately sparse under a specific base. Therefore, to meet the above demand, the network is usually in large scale with nodes densely deployed. In addition, CSS can be also applied in the scenarios where the data generate in a burst trigger mode.

Table 12 summarized all the categories with regards to the related characteristics and the corresponding applicable scenarios.

5.3 Statistic Analysis of on Each Category

In this section, the statistic analysis on all of the categories was conducted in terms of the proportion, the total number of related papers, and the total account of citations respectively. According to the principle of the scientific evaluation, the number of citations is crucial for research output assessment, which objectively has a large influence on institution's or country's rankings, research funding allocations[249]. Besides, the related statistics data show the tendency, the focus, and the acceptance from the academic and industry to some extent.

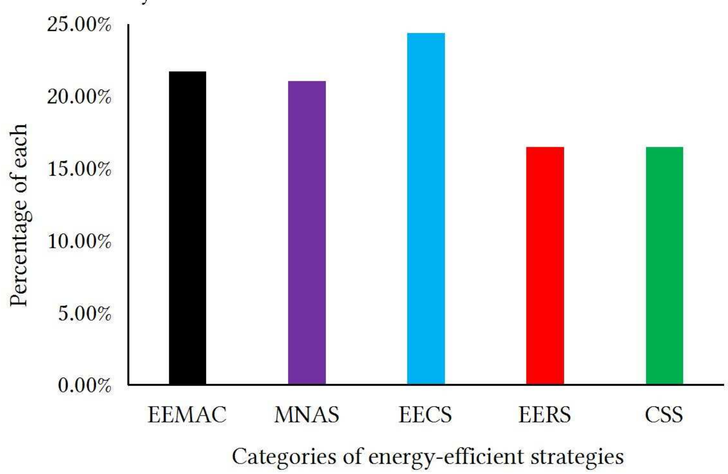

Fig.8. Bar chart of the proportions of all the categories from 2002 to 2019.

5.3.1 Statistics Analysis on the Proportions

Figures 8-9 shown the proportions of all the papers concerning all the of categories cited in the paper. They reflect the variation tendency of each category from the year 2002 to 2019. Specifically, Figure 8 shown the ratios of them from 2002 to 2019, while Figure 9 shown that from 2010 to 2019. Nothing that only those whose citation account is no less than 20 were shown in Figures 8-9. It can be easily obtained that the proportion of EECS kept steady in two different time intervals from Figures 8-9, which means EECS was paid sustained attention from the academic and industry, However, the focus on EEMAC has diminished markedly in the last ten years. It is worth mentioning that the proportion of CCS increased sharply. On the one hand, the reason lies in the fact that CS theory was firstly applied in data acquisition of WSNs in 2006. On the other hand, it means that the strategy of CSS has attracted extensive attentions. As shown in Figures 8-9, the proportions of CSS rises from 16.45% to 24.75% and it has accounted for the main proportion in the past ten years. In fact, the strategies of CSS tend to be integrated with EECS to improve EE further, which also explains why the proportion of EECS keeps steady somewhat.

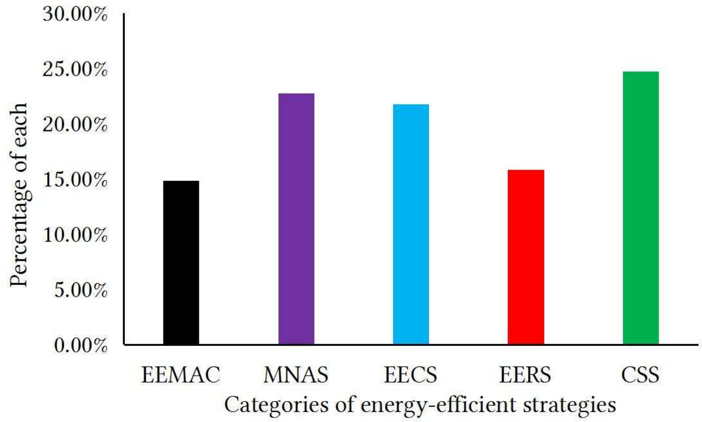

Fig.9. Bar chart of the proportions of all the categories from 2010-2019.

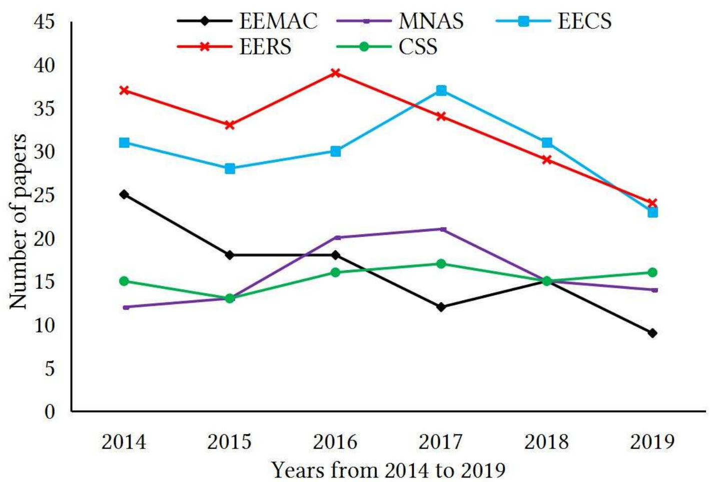

Fig.10. Comparisons on the number of papers of all the categories from 2014 to 2019.

5.3.2 Statistics Analysis on the Amounts of Papers and the Corresponding Citation

Figures 10-11 presented the number of papers and the corresponding citations from 2014 to 2019. The tendency and the degree of acceptance of each category can be easily obtained from them. Different from Figures 8-9, all the categories were counted without considering the minimal threshold of the number of individual's citation. Though the number of CSS is low, its total number of citations is rather large and steady. It means that CSS belongs to an effective strategy which has received extensive acceptance from the academic and industry. In fact, it can be easily explained that EE can be largely improved since the data redundancy can be cut down from the source[216]. In addition, both the number of papers and that of the related citations of EECS are relatively large compared with others. Since Clustering is effective in reducing data redundancy and alleviating the "Hot Spot Problem", it is applied in most of strategies which aim at improving EE and extending NL of the non-harvesting static WSNs. For instance, it is usually integrated into CSS in HCDG to improve the Energy Efficiency further. Finally, the statistic of EEMAC is the smallest compared with the others in terms of the papers and citations amount, which is consistent with what was shown in Figures 8-9. Therefore it can be easily concluded that much more emphasis was put on the higher layers of the protocol stacks concerning the Energy Efficiency.

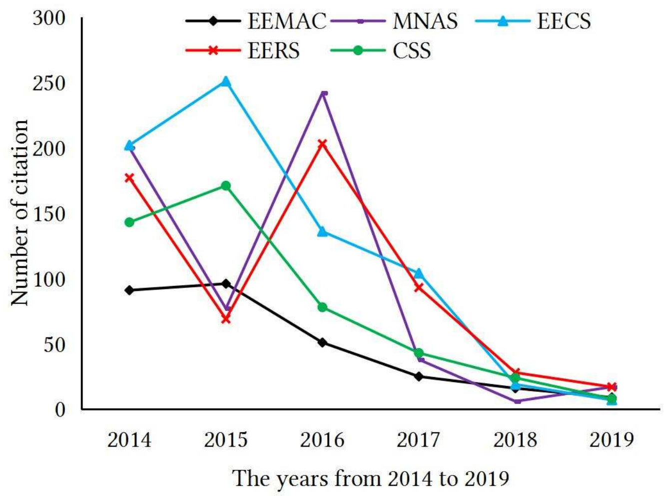

Fig.11. Comparisons on the number of citations of all the categories from 2014 to 2019.

6 CONCLUSIONS, OPPORTUNITIES & CHANNENGES, AND FUTURE DIRECTIONS

A conclusion about the energy-efficient strategy for the static Wireless Sensor Network was dawn in this section firstly. Subsequently, the relevant opportunities and challenges in the context of the new computing paradigm, such as the Internet of Things, the Fog Computing, Big Data, *etc.* were presented. Finally, the possible future research directions concerning the Energy Efficiency of static WSNs were pointed out in a brief.

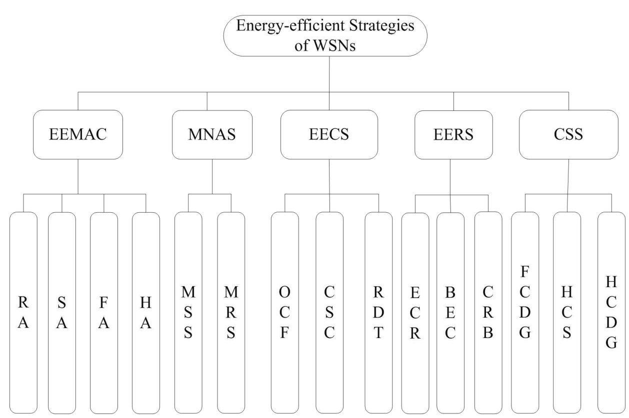

Fig.12. Existing energy-efficient strategies and the corresponding subcategories.

6.1 Conclusions

.This paper analyzed the energy consumption characteristics in terms of each individual sensor node and the whole network firstly. Specifically, the energy overhead consumed by different modules in different modes of each sensor node and the energy consumption related to each layer of the protocol stacks were illustrated. Besides, the routing mode and the traffic flow pattern of WSNs were detailed. In addition, the root cause of the "Hot Spot Problem" was pointed out accordingly.

Subsequently, the related definition and concepts, i.e., the Energy Efficiency, the Energy-efficient Means, the Energy-efficient Tier, and the Energy-efficient Perspective, were proposed. Above all, a novel mathematical definition of EE was proposed and proven, which provides a quantitative evaluation metric for the existing energy-efficient strategy or a guideline for the design of energy-efficient schemes in the future. To the best of our knowledge, it is for the first time that a generic mathematical definition of EE is presented. In addition, the design principle of each category involved in this paper was analyzed in terms of its components C_1, C_2, and C_3.

The current strategies proposed recently were reviewed in detail with regard to the design principle and the related characteristics. They were classified into five different categories, namely EEMAC, MNAS, EECS, EERS, and CSS respectively. Besides, the representatives of each were analyzed and further divided into the relevant subcategories based on the concepts mentioned above. Further more, the summaries were made in the form of tables. In order to provide a clear overall framework for the reader, Figure 12 summarized the existing categories and the corresponding subcategories through a tree-shaped graph.

Finally, the relationships among all of the categories and the those between each of them and the Energy-efficient Means, the Energy-efficient Tier as well as and the Energy-efficient Perspective were summed up. Besides, the detailed statistics analysis on the categories was made to show the tendency, the focus of energy-efficient strategies in WSNs to some extent. To be specific, the proportions of each category cited in this paper were compared in detail. At the same time, the statistics of the number of papers published and the relevant citations from the year 2014 to 2019 were also presented and analyzed at length.

6.2 Opportunities and Relevant Challenges

This section presented the opportunities and relevant challenges concerning the non-harvesting static WSNs in the context of the new computing paradigm, such as the Internet of Things, Fog Computing, and Big Data.

6.2.1 Opportunities and Challenges in the Context of the Internet of Things

The Internet of Things (IoTs) is enabled by the latest developments in RFID, ubiquitous sensors, communications mechanism, and network technology. It aims to bridge the gap between the physical world and the information world. the prosperity of IoTs in recent years undoubtedly arouses much more requirements on WSNs in terms of data support. In general, the Wireless Sensor Networks work as the perception layer of IoTs. They are responsible for digitizing and transferring enough data to the application layer through transmission channels[14]. At the same time, the combination with IoTs results in much more demands on the volume of data needed to be collected and transmitted as well as the reliability of data transmission.

6.2.2 Opportunities and Challenges Resulted from the Rise and Prosperity of Fog Computing

Fog Computing belongs to the realm of Edge Computing[250][251]. The rise of Fog Computing aims to alleviate the computing and processing burden on the Cloud server. It means that the computing burden is transferred to the Fog nodes which usually consist of sensor nodes. Therefore the paradigm of Fog Computing promotes new applications in WSNs. However, since WSNs are featured by limited energy supply, it also poses some challenges for WSNs. How to achieve longevity of WSNs so that it can provide a foundational service for Fog Computing becomes extremely important.

6.2.3 Opportunities and Challenges in the Era of Big Data

The emergence of Big Data imposes a higher requirements on the massive data acquisition. As for the Wireless Sensor Networks, they can be deployed to provide enough support for the applications in the form of "Sensing is a Service". Therefore the era of Big Data brings in a wider applications of WSNs. However, most of the WSNs which are deployed in the harsh environment, thereby the energy limitation is still a big challenge. Besides, the contradiction is exacerbated to some extent with the combination and Big Data.

6.3 Feasible Future Directions

6.3.1 Design of the Energy-efficient Strategy Combined with the Predictive Coding Theory

Since the temporal correlation exists in the data collected by the Sink, the data acquired in the adjacent time slots present a certain degree of similarity. Therefore, the predictive coding theory can be combined to reduce the energy consumption further[252][253]. Through the predictive coding, the data acquired previously can be utilized to predict the later ones, thus reduce the amount of data acquired. As far as we know, there have not been any energy-efficient strategies which adopted the predictive coding theory. Furthermore, the predictive coding can also be integrated with the CS theory to reduce the energy consumption resulted from the Spatial-temporal correlation further.

6.3.2 Design of the Energy-aware Moving Algorithm with Mobile Nodes

Combination with the Bayesian theory can be adopted to provide some moving guidance for the mobile nodes, such as the mobile Sink or relay. As a result, the mobile nodes can move towards the area with sparse energy density. Since the data collected by the Sink often present spatial correlation, which usually results in data redundancy. Therefore, the Bayesian model can be adopted to regulate the mobile nodes' trajectory according to the energy consumption for the previous sojourns. In such a way, the mobile nodes move along the path which brings in a more balanced energy consumption.

6.3.3 Design of the Cross-layer Strategy

The strategies presented in section 4 were mostly designed on the basis of a single layer of protocol stacks. In fact, the Energy Efficiency can be further improved through the cross-layer strategy. For example, the energy overhead can be reduced via the Media Access Control at the data link layer and the energy inequality can be alleviated through properly-designed routing protocol. Therefore, the energy-efficient cross-layer strategy is a feasible research direction.

6.3.4 Cross-node Strategy Based on the Social Theory

As discussed in section 2, the energy equality is deeply affected by the relationship between each individual sensor node and the whole network. The social welfare function which associates each individual with the whole society can be suitable for WSNs[254]. In WSNs, all the sensor nodes cooperate with each other to accomplish a common task, which is similar to the human society. The social welfare function which puts more emphasis on the social inequality and the achievement of social equality complies with the goal of WSNs where a more balanced energy distribution brings in a longer network lifetime. Therefore, the cross-node strategy based on the social theory can be designed to achieve energy equilibrium.

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