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Energy Efficiency in Internet of Things: An Overview

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Abstract: Energy efficiency is very important for the Internet of Things (IoT), especially for front-end sensed terminal or node. It not only embodies the node's life, but also reflects the lifetime of the network. Meanwhile, it is also a key indicator of green communications. Unfortunately, there is no article on systematic analysis and review for energy efficiency evaluation in IoT. In this paper, we systemically analyze the architecture of IoT, and point out its energy distribution, Furthermore, we summarized the energy consumption model in IoT, analyzed the pros and cons of improving energy efficiency, presented a state of the art the evaluation metrics of energy efficiency. Finally, we conclude the techniques and methods, and carry out a few open research issues and directions in this field.

Keywords: Internet of things, wireless sensor network, energy efficiency, energy consumption model.

1 Introduction

With the continued development of the computer and network technology, the ability of human society to store, analyze and process information has been greatly improved, Internet of Things (IoT) just one of the bridge between the real physical world and the virtual informational world. Furthermore, the standardization of 5G technology has greatly accelerated the information communication between the two worlds.

IoT contains business layer, application layer, intermediate service layer, network layer and perceptual layer [Liu and Liu (2018)]. As shown in Fig. 1, network layer and the sense layer belonging to the information sense level, mainly collect and convert information, aggregate and transmit data; business layer, application layer, intermediate service layer belonging to the application operation level, mainly grade and process information to realize classification management, which makes the global decision according to the available information to develop the practical application. From the

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bottom sense layer to the top service layer, the information experiences the process of collecting and analyzing the original data to obtain the value. Conversely, from the top layer to the bottom layer, it is a dynamic control process for decision execution and feedback. Information perception system provides information for processing and analysis of the application operation system. It is a key technology to develop the IoT application, and wireless sensor network as a key component, also plays a vital role.

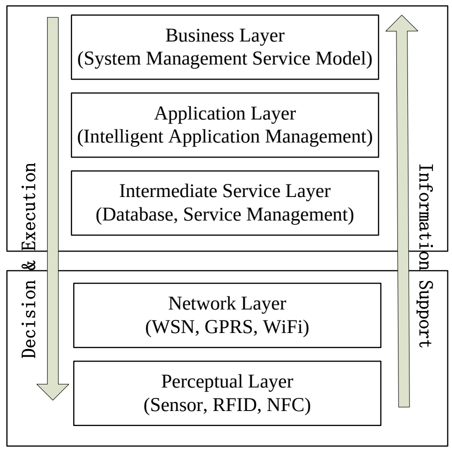


Figure 1: IoT structure diagram

Wireless sensor network (WSN) consists of mass sensors with self-organization and multi-hop that can sense, collect, process and transfer monitoring information for specific scenarios and report the terminal user as an important portion in IoT front-end information perception, all nodes can be static or mobile [Fang, Zhang, Shi et al. (2016)]. WSN has the characteristics of wide range, low cost, real-time acquisition and flexible deployment and so on. WSN contains different types of sensors to achieve a variety of sensory functionality such as monitoring temperature, humidity, pressure, noise and so on. Because sensor nodes are mostly located in harsh environment and unattended areas, it is unrealistic to replace batteries or charge the nodes, and the limited energy supply greatly restricts the improvement in safety, accuracy and delay reduction. Therefore, how to improve the efficiency of energy utilization and reduce energy consumption is a major technical challenge for WSN under the condition of limited energy.

2 WSN architecture and energy consumption analysis

2.1 System architecture of wireless sensor network

As shown in Fig. 2, sensor nodes are typically deployed in the area to be monitored, and each node can collect information and send the data to the sink node and ultimately to the management node or the user [Akyildiz, Su and Sankarasubramaniam (2002)].

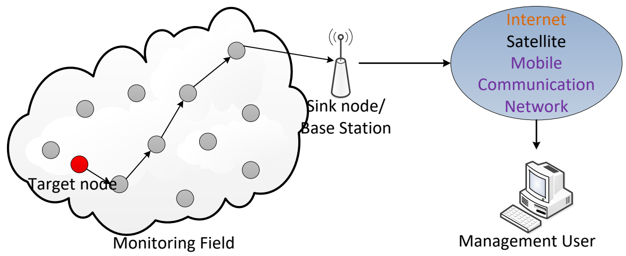


Figure 1: Typical WSN architecture diagram

2.2 Framework of sensor node

Sensor nodes usually consist of four basic units: sensing unit, processing unit, communication unit, and power unit [Hoblos, Staroswiecki and Aitouche (2000)]. It is shown in Fig. 3.

1. Sensing unit

The sensing unit is generally composed of a Micro-Electro-Mechanical System (MEMS) chip integrated with a sensor and a simple analog-to-digital converter (AC/DC) and its peripheral circuits. The sensor gathers the required information from the real world. The analog signal collected by the sensor is converted into digital signals by analog-to-digital converter. The sensing unit is the basis of the sensor node, and all the applications of WSN are based on the data obtained from the sensing unit.

2. Processing unit

The processing unit is generally composed of a micro control unit, a corresponding memory cell and a peripheral circuit. It is responsible for data processing, and can manage the program so as to cooperate with other nodes to complete the sensing task.

3. Communication unit

The communication unit is generally composed of data interface and RF transceiver chip to realize wireless communication and automatic networking between the sensor nodes.

4. Power unit

The power unit is generally made up of batteries or other sources of power, which provide the energy needed for the work of the sensor nodes.

After abstracting the application scenario the WSN, WSN must have the following characteristics: reliability, self-organization and adaptability, low cost, low energy consumption, data-centric and so on.

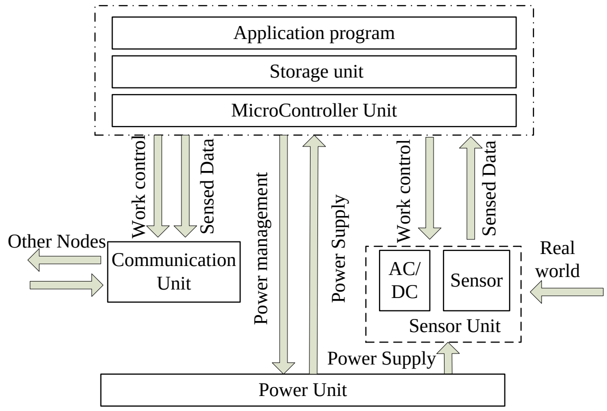


Figure 3: Sensor node architecture diagram

2.3 Network protocol and structure

The protocol stacks of sink node and sensor node is divided into five layers from bottom to top: physical layer, data link layer, network layer, transport layer and application layer. Each layer includes three platforms: energy management, mobile management and task management. It is shown in Fig. 4.

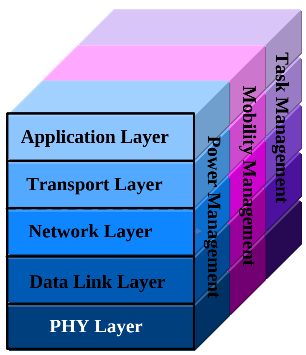


Figure 4: Network layer architecture diagram

2.3.1 Physical layer

It is responsible for frequency selection, carrier frequency generation, signal detection, modulation, etc.; provides simple but robust modulation, transmission and reception functions.

2.3.2 Data link layer

It is responsible for data stream multiplexing, data frame detection, media access and error control. The main function is to create a network structure and enable nodes to share communication resources fairly and effectively. Due to the environmental noise and the mobility of the sensor nodes, the data link layer should have the function of sensing energy and minimizing the conflict caused by neighbor node broadcasting. With the characteristics of the limited energy, self-organized, and the dynamic topology, it makes that the traditional cellular network, Bluetooth and mobile Ad Hoc MAC protocols are not suitable for WSN. The typical WSN protocols in this layer are SMACS and EAR [Sohrabi, Gao, Ailawadhi et al. (2000)], based on CSMA [Woo and Culler (2001)], based on hybrid TDMA//FDMA [Shih, Cho, Ickes et al. (2001)] and so on. These three protocols respectively employ the random wake-up at startup and the off-receiving function when idle, hardware-based energy minimization, and timing monitoring to save energy.

2.3.3 Network layer

The network layer further manages the data communication in the network, and chooses a suitable routing for transferring the data from source to destination. The routing protocols at the network layer are usually designed based on the following principles: considering energy efficiency; data-centric; data aggregation without affecting node cooperation; the ability of addressing and sensing. Due to the vast monitoring area, the limited transmission capacity of the nodes, the inability to reach the sink node in one hop and the large increase in energy consumption caused by the long distance, the multi-hop method is often adopted to transmit information. Various routing protocols are proposed [Singh and Sharma (2015)]:

- According to the different communication senders, the WSN routing protocol can be divided into two kinds: initiation based source and initiation based destination;
- According to the different ways of path establishment, it can be divided into three categories: active establishment, passive establishment and hybrid establishment. Active establishment is to establish all paths before data transmission, with low transmission delay, but with high probability of path failure and high maintenance overhead. Passive establishment refers to the establishment of appropriate routes when data needs to be sent;
- According to the network structure: routing protocols can be divided into three categories: planar, hierarchical and location-based routing. For planar routing, each node has equal status and functions, and can relay and forward information. However, the problem is that the sensor nodes near the sink node need to forward more information, which consumes more energy and is more likely to die. Therefore, hierarchical routing arises at the historic moment, which divides the network into many clusters. Intra-cluster nodes send information directly or indirectly to the cluster head, and the cluster head sends the information to the sink node according to the appropriate path. LEACH [Heinzelman, Chandrakasan and Balakrishnan (2000)], PEGASIS [Lindsey and Raghavendra (2002)], TEEN [Manjeshwar and Agrawal (2000)] are typical protocols. In recent years, improvements in energy efficiency, delay, cluster head stability and algorithm complexity have emerged in endlessly. Location-based routing refers to the node can perceive its location and know the location of the target node, and choose the routing based on these location information;
- According to the operation of the protocol: the routing protocols can be divided into four categories: multipath based, query based, negotiation based and QoS based;

- According to the selection method of the next hop: the routing protocols can be divided into four categories: node-based broadcasting, location based, text based and probability selection based.

2.3.4 Transport layer

It is used to maintain data flow in the case of sensor network application, and it is necessary when WSN needs to access the Internet or other external networks, so there is little research on WSN transport layer protocol at present.

2.3.5 Application layer

The services are required to achieve a series of business processes, and the application layer protocol is mainly used to provide an efficient interface for the user software to manage the bottom layer. There are several typical application layer protocols, such as node manage protocol that is used to realize the functions of introducing rules of data aggregation and clustering, exchanging data related to location finding algorithm, time synchronization, shifting node and so on [Elson and Estrin (2001); Shen, Srisathapornphat and Jaikaeo (2001)]; task allocation and data advertising protocol; node query and data dissemination protocol (SQDDP).

The energy, mobility, and task management platform monitors the energy, movement and task distribution of sensor nodes to help the nodes cooperate in task completion and reduce the total energy consumption. The energy management platform is used to determine the use of node energy, for example, in order to avoid receiving duplicate information, the node can turn off the receiver after receiving the information, or when the power of the node is low, the broadcast neighbor node itself exits the routing transmission because of the low power quantity, and uses the energy in the sensor unit; The mobile management platform monitors and records the moving of the node to update the neighbor nodes to balance the energy and task usage of the nodes and optimize the routing selection; the task management platform balances and arranges the tasks of node in particular area.

3 WSN energy consumption model and improving energy efficiency

3.1 WSN energy consumption model

Halgamuge et al. [Halgamuge, Zukerman and Ramamohanarao (2009)] proposed seven energy consumption sources for WSN: sensing, recording, processing, communication, transient, driving and clustering (hierarchical routing for cluster head rotation). The following classification method introduces the energy consumption model. We first make several basic assumptions:

1) In view of the advantages of hierarchical routing in energy consumption and its popularity compared with planar routing, WSN adopts hierarchical clustering routing;

2) All nodes are homogeneous;

3) Intra-cluster nodes sends message to cluster head in a single hop;

4) The time division multiple access (TDMA) is employed when all the intra-cluster nodes send message to the cluster head;

5) Clusters send messages to sink in a multi-hop manner, so each cluster head node processes aggregated data not only from the node in the cluster, but also from the previous cluster head on the path, and sends the information to the cluster head of the next hop;

6) Assuming that there are k clusters in the network, each cluster consists of n intra-cluster nodes and a cluster head.

Each sensor generates b-bit data in one round, the cluster head node j (j {1, 2, …, k}) received b_{1j} -bit messages in total that comes from its intra-cluster nodes and cluster head node of the former path. After the cluster head processing aggregation, the data b_{2j} of the cluster head to the next hop is less than b_{1j}.

The behavior pattern of intra-cluster node is that the node will complete multiple rounds of tasks during its deployment to the inoperation, each round of which will perform the process shown in the following Figs. 5 and 6: initialization; target perception; sending data to the cluster head after processing calculation; getting into sleep and then starting to do the next round of tasks.

The behavior pattern of cluster head node similar to intra-cluster is: initialization; sensing; receiving; calculating data; sending data to the next hop; performing powering (depending on the application), going into the sleeping pattern then starting to do the next round of tasks. The energy consumption is analyzed for each round as follows:

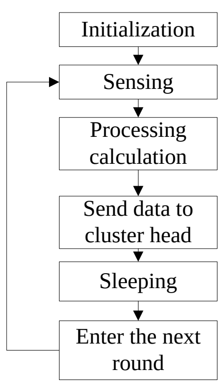


Figure 5: Intra-cluster node behavior pattern

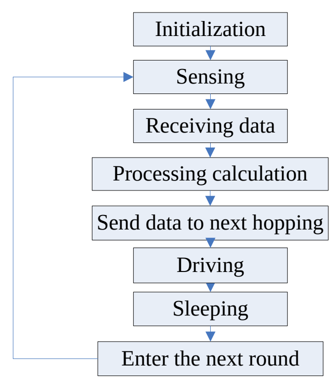


Figure 6: Cluster head node behavior pattern

1. Sense

The sensing unit is used to perceive the real world, and the energy consumption of this module is mainly in the four parts of signal sampling, the conversion from physical signal to electrical signal, signal modulation, the conversion from analog signal to digital signal. The energy consumption of the sensing unit can be expressed as follows:

$$E_{sense}(b_{sense}) = b_{sense} V_{\sup} I_{sense} T_{sense} \quad (1)$$

b_{sense} represents the node sense and generate b_{sense} bit data in one round; V_{sup} represents supply voltage; I_{sense} represents the current required for sensing activity; T_{sense} represents the time required for perception.

2. Record

The node reads and writes b_{log} bit data (b for the intra-cluster node and b_{1j} for the cluster head node) in the processing unit, and the energy consumption is:

$$E_{\log g}\left(b_{\log}\right)=E_{write}+E_{read}=\frac{b_{\log}V_{\sup}}{8}\left(I_{write}T_{write}+I_{read}T_{read}\right) \tag{2}$$

E_{read} is the energy required for reading; E_{write} is the energy required for writing; I_{read} and I_{write} are current for reading and writing respectively; T_{read} and T_{write} are the required time for reading and writing one each byte respectively.

3. Microcontroller processing

The microcontroller processes and aggregates data, the energy consumption of which consists of two parts: the energy consumption E_{switch} caused by level shifting and the energy waste E_{leak} generated by the leakage current. Leakage current is generally introduced into the earth by the power supply. The energy consumed by intra-cluster nodes in processing data is expressed as follows:

$$E_{ctrN}\left(b_{pro}\right)=\underbrace{b_{pro}N_{cyc}C_{avg}V_{\sup}^{2}}_{E_{switch}}+\underbrace{b_{pro}V_{\sup}\left(I_0e^{\frac{V_{\sup}}{n_pV_t}}\right)\left(\frac{N_{cyc}}{f}\right)}_{E_{leak}} \tag{3}$$

b_{pro} represents the amount of data to be processed, specially the intra-cluster node is b and cluster head node is b_{1j}. N_{cyc} is the number of clock cycles in each task; C_{avg} is the average conversion capacitance per cycle; I_0 is the leakage current; n_p is the constant associated with the processor; V_t is the thermal voltage, and f is the frequency.

Because it not only deals with the information generated by itself and the information sent by the cluster head nodes in and before the cluster, but also uses a weighting factor h_1 greater than one to represent that the cluster head node consumes more energy than the intra-cluster node, so the energy consumed by the cluster head node to process the aggregated data is:

$$E_{ctr_{CH}}\left(b_{pro}\right)=h_1\left(b_{pro}N_{cyc}C_{avg}V_{\sup}^{2}+b_{pro}V_{\sup}\left(I_0e^{\frac{V_{\sup}}{n_pV_t}}\right)\left(\frac{N_{cyc}}{f}\right)\right) \tag{4}$$

4. Wireless transceiver

Nodes communicate with the surrounding nodes by radio. The energy consumption of communication can be divided into two parts: receiving and sending data. Wang et al. [Wang and Chandrakasan (2002)] showed that the transmission energy consists of circuit energy and power amplifier energy consumption and the power of the amplifier is proportional to the power of the distance from the transmitter to the destination. The power selection is proposed in Rappaport [Rappaport (1996)]. Generally, it is believed that when the communication distance is greater than a certain value, or when there are many obstacles on the communication path, the free space energy model cannot accurately describe the energy loss, so the multipath attenuation model should be adopted. The energy consumption required to send b_t bits is:

$$E_t\left(b_t, x\right) = b_t\left(E_{elec} + d_x^n E_{amp}\right) \tag{5}$$

For intra-cluster node and cluster head node, b_t represents b and b_{2j} respectively. E_{elec} and E_{amp} represent circuit energy consumption and amplifier energy assumption for transmitting 1 bit data respectively. d_x is the distance between the corresponding node and the destination node x. The x of the intra-cluster node is its cluster head node j while the x of the cluster head node is the next hop node $next_j$. When the free space model is employed, n is 2, and when the path loss model is employed, n is 4. The energy consumption of receiving b_r bits is:

$$E_r\left(b_r\right) = b_r E_{elec} \tag{6}$$

b_r of the cluster head node j is b_{1j}.

5. Control message overhead

When a channel contention protocol such as CDMA/CA is adopted, it needs to Processing of requests, confirmation packages, etc. While there is no channel contention in TDMA, so it is not necessary to consider the cost of controlling packets.

6. Driving

The drive energy E_{actu} is related to the application. When a particular condition triggers an event, the sensor provides the driving energy. For example, the motor fans open when the sensor detects that the ambient temperature is higher than the fixed value, so the sensor needs to provide the driving energy. But this energy consumption is not considered in most applications.

7. Transient energy

Both the communication unit and the processing unit of the sensor support a variety of modes, including activity, idle and sleep. Switching between different modes requires extra energy. It is shown in Fig. 7. It is assumed that T_{tranON} and $T_{tranOFF}$ are the transient time required for the transition from sleep mode to idle mode and from idle mode to sleep mode respectively. In one round, the node monitors the busy tone of the channel, is awakened and active for T_A seconds, and then sleeps for T_S seconds, and assuming T_A is much less than T_S. Similarly, thec wake-up time of the cluster head is defined as $T_{A_{CH}}$, and the sleep time is $T_{S_{CH}}$, then the time of each round T_{tr} is:

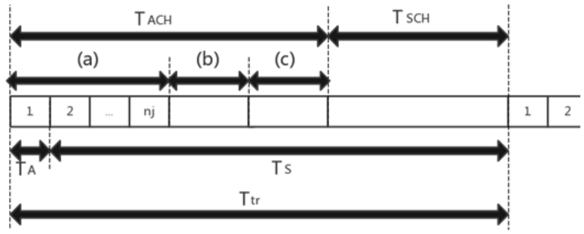
$$T_{tr} = T_A + T_S = T_{A_{CH}} + T_{S_{CH}} \tag{7}$$

The duty ratio of the intra-cluster nodes c_N is

$$c_N = \frac{T_{tranON} + T_A + T_{tranOFF}}{T_{tranON} + T_A + T_{tranOFF} + T_S} \tag{8}$$

The duty ratio of the cluster head nodes c_{ch} is

$$c_{CH} = \frac{T_{tranON} + T_{A_{CH}} + T_{tranOFF}}{T_{tranON} + T_{A_{CH}} + T_{tranOFF} + T_{S_{CH}}} \tag{9}$$



(a) Time at which the cluster head node receives node information in cluster; (b) Time at which the cluster head node receives the previous cluster head node information on path; (c) Time at which the cluster head node sends data to the next hop

Figure 7: Wake-up and sleep time of intra-cluster/cluster head node per round

The average current of intra-cluster node per round is $I_N = c_N I_A + (1 - c_N) I_S$. The energy consumption of each round of nodes to maintain each mode is as follows:

$$E_{tranN} = T_{tr} V_{\sup} \left(c_N I_A + (1 - c_N) I_S \right) \tag{10}$$

I_A and I_S are wake-up and sleep current respectively. The average current of cluster head node is $I_{CH} = c_{CH} I_A + (1 - c_{CH}) I_S$, and the transient energy of a cluster head node is:

$$E_{tranCH} = T_{tr} V_{\sup} \left(c_{CH} I_A + (1 - c_{CH}) I_S \right) \tag{11}$$

From the above analysis, in the round of completing the task, the intra-cluster node perceives and processes the information and then sends the information to the cluster head node. While the cluster head node perceives and processes the self-generated and transmitted information, and sends the processed data to the next hop. In this process, the sensor unit of the sensor, whose energy consumption is E_{sense} (b_{sense}). For processing units, the energy consumption is the sum of the transient energy converted by the recording, processing and processing unit mode: $E_{pro}(b_{log}, b_{pro}) = E_{log}(b_{log}) + E_{ctr}(b_{pro}) + E_{tran(pro)}$, and the control and transient energy are determined by the type of nodes. The energy consumption of the communication unit of the intra-cluster node sensor is the sum of the transmission data and the transient energy of the communication unit mode conversion: $E_{comN}(b_t, x) = E_t(b_t, x) + E_{tran(com)}$. The energy consumption of the cluster head node communication unit is the sum of the transient energy of a transmission, receiving data and mode conversion: $E_{comCH}(b_t, b_t, x) = E_t(b_t, x) + E_r(b_r) + E_{tran(com)}$.

The total energy consumption of the intra-cluster nodes to complete a round of tasks is as follows:

$$E_{N_{fns}} \left(b_{sense}, b_{\log}, b_{pro}, b_t, x \right) = E_{sense} \left(b_{sense} \right) + E_{pro} \left(b_{\log}, b_{pro} \right) + E_{comN} \left(b_t, x \right) \tag{12}$$

The total energy consumption of cluster head nodes to complete a round of tasks is as follows:

$$E_{CH_{fns}} \left(b_{sense}, b_{\log}, b_{pro}, b_t, b_r, x \right) = E_{sense} \left(b_{sense} \right) + E_{pro} \left(b_{\log}, b_{pro} \right) + E_{comCH} \left(b_t, b_r, x \right) \tag{13}$$

It is noted that in the multi-hop routing protocol between clusters, the closer the cluster head is to the sink, that is, the more the number of previous cluster heads on the path is, the more information the cluster head needs to receive, process and send, and the faster the energy consumption will be. When the task is sent from the sink node, the cluster head receives and distributes the information, and the nodes in the cluster receive the information. The energy consumption of intra-cluster is

$$E_{N_{get}} = E_{pro_{get}} + E_{r_{get}} + E_{tranN_{get}} \tag{14}$$

The energy consumption of cluster head node is as follows:

$$E_{CH_{get}} = E_{pro_{get}} + E_{r_{get}} + E_{t_{get}} + E_{tranCH_{get}} \tag{15}$$

The total energy consumption of cluster head nodes is $E_{CH}(j) = E_{CH_{get}}(j) + E_{CH_{fns}}(j)$, and the total energy consumption of intra-cluster nodes is $E_N(ij) = E_{N_{get}}(ij) + E_{N_{fns}}(ij)$, where *ij* represents the cluster head node of the node *i* is *j*.

Table 1: Work and energy consumption of different nodes at different stages

Task composition Node unit		Task Assignment: intra-cluster node	Task Assignment: cluster head node	Complete the task: intra-cluster node	Complete the task: cluster head node
Sensing unit		--	--	√	√
Processing unit	record	√	√	√	√
	process	√	√	√	√
	transient	√	√	√	√
Communication unit	receive	√	√	--	√
	transmit	--	√	√	√
	transient	√	√	√	√

Assuming that WSN is divided into k clusters, each cluster is composed of *n* intra-cluster nodes and one cluster head node. The total number of network nodes is $N_S=k(n+1)$, the total energy consumption per round of the network is:

$$E_{tot} = \sum_{j=1}^{k}\left(E_{CH}(j) + \sum_{i=1}^{n} E_N(ij) + E_{form} \right) \tag{16}$$

E_{form} is the energy for proposing the new cluster head to re-form the cluster in the protocol to change each cluster head such as LEACH.

The total energy consumption of the network is the sum of the energy required by the ad hoc network and the product of the total number of rounds of the network and the energy consumption per round. Under the ideal conditions of assuming the same cluster size and the same perceived information generated by each node, this method takes into account the aggregation of data and other factors, and establishes a more comprehensive energy model.

3.2 Mechanisms and algorithms of improving energy efficiency

The energy of WSN nodes is limited, so extending the network life cycle on the premise of guaranteeing the function is the basic goal of the network. The definition of satisfying the function varies according to the application, such as security level, delay and tolerance of error rate, etc. Therefore, how to improve energy efficiency has always been the focus of WSN research. Halgamuge et al. [Halgamuge, Zukerman and Ramamohanarao (2009)] calculated the proportion of all kinds of energy consumption in the network at the same time, and it can be found that the energy consumption of communication accounts for about half of the total energy. There has a research indicates that the energy consumed by sending 1-bit data 100 m away can be used to process millions of instructions by a processor with a performance of 100 MIPS [Pottie and Kaiser (2000)], while the energy overhead of transmission, reception, and monitoring states in the communication unit are almost equal which is all much higher than the sleep mode [Estrin (2002)]. Therefore, reducing the energy consumption of communication unit is an effective direction to improve energy efficiency. It is shown in Fig. 8.

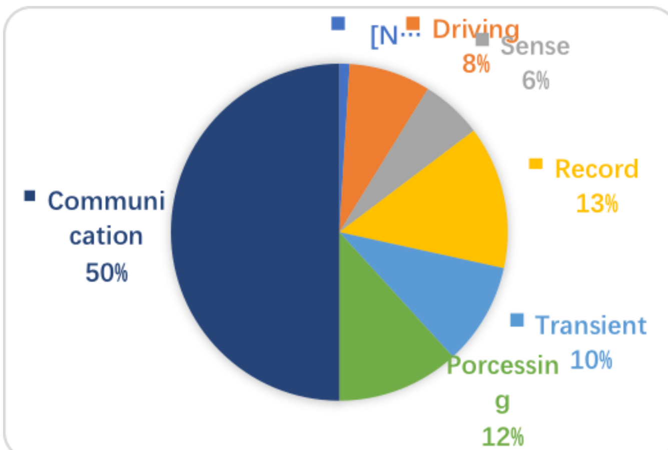


Figure 8: WSN energy consumption distributions

The following is a brief introduction of measures to reduce energy consumption from the view of each layer of the network protocol stack, and then some mechanisms and algorithms improve energy efficiency are introduced later.

Physical layer: It is responsible for frequency selection, carrier frequency generation, signal detection, modulation and so on. The improvement of energy efficiency mainly focuses on the frequency and the modulation.

Data link layer: It is responsible for data stream multiplexing, data frame detection, medium access and error control. How to deal with and arrange the idle time of nodes is the important consideration for reducing energy consumption in this layer.

Network layer: The network layer further manages the data communication in the network, and selects the appropriate route to transmit the data from the source to the destination. The measures to control energy consumption in this layer are mainly made from three aspects: selecting nodes with large available energy as routing nodes to balance network load and prevent some nodes from dying prematurely; choosing the path of minimum total energy consumption; and data aggregation to solve the problem of data explosion, overlap and reduce the unnecessary consumption of network energy;

For the entire wireless sensor network, energy efficiency means sending as much valid data as possible over a long lifetime. It should be considered from the following four aspects:

1) reducing the transmission of redundant data as much as possible;

2) reducing the proportion of invalid energy consumption as much as possible;

3) increasing the success rate of data transmission as much as possible;

4) balancing the network load as much as possible to prolong the whole network lifetime; and finding a balance point during the period of increasing the effective data ratio and prolonging the lifetime.

In recent years, researchers have done a lot of research and improvement on the above four aspects:

1. Reduce the transmission of redundant data

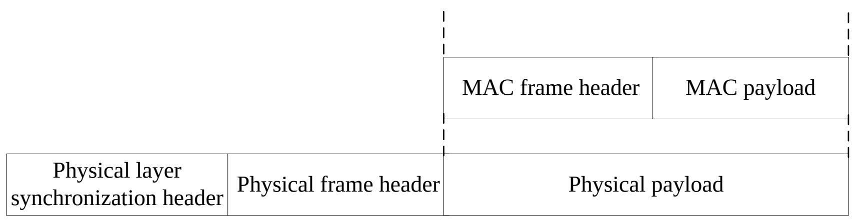


Figure 9: Physical layer and MAC layer message structure

The message structure of the physical layer and the MAC layer is shown in Fig. 9. The data frame of the MAC layer is composed of the MAC frame header and the MAC layer payload, both of which constitute the effective load of the physical layer, and the physical layer also includes the synchronous head and the physical frame header. The physical layer synchronization head and the physical layer MAC layer frame header contain necessary control information, such as synchronization information, error control information, address information, etc.

Nodes need time synchronization to facilitate communication between nodes, but if the synchronization head is too long compared to the payload, it is obviously not economical in energy utilization. In Ammer et al. [Ammer and Rabaey (2006)], it is considered that the physical layer synchronization head is redundant data. The effects of modulation methods and considerations at the system level for the length of synchronous head are discussed: compared with coherent modulation, differential coherent modulation can reduce the length of synchronous head, and non-coherent modulation such as OOK (On-Off Keying) and FSK (Frequency Shift Keying), can further reduce the length of synchronous head. Although the total energy consumption is increased, the redundant data are reduced; the energy efficiency is improved as a whole; and the influence of the choice of transmission rate on the synchronization requirement is discussed from the system level.

The MAC layer message header is considered to be redundant data, and it is proposed that selecting appropriate transmission power (TP) can reduce the transmission of redundant data [Ali, Abo-Zahhad and Farrag (2017)].

The traditional view is that when the data is transmitted, the intermediate node only needs to store and forward the data, and there is no need to modify the data. Ahlswede et al. [Ahlswede, Cai, Li et al. (2000)] innovatively put forward the idea of information flow to treat data transmission in communication networks, encoding data at intermediate nodes and decoding data at sink nodes. This view regards the network as a graph composed of vertices and edges, each of which has capacity and direction. The maximal flow-minimum cut theorem in graph theory describes the maximum rate that the network can achieve. The network coding means that the data is transferred after the operation and decoded by the target node to obtain the data. The principle is briefly explained as follows:

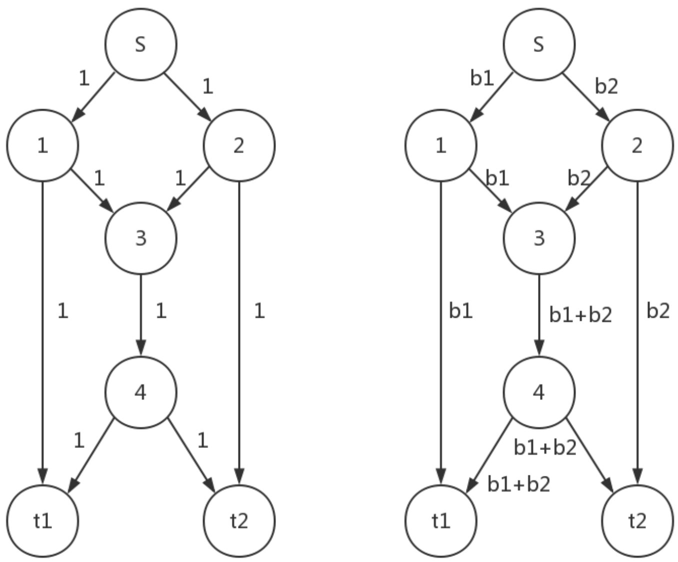


Figure 10: Network coding principle

The Fig. 10 shows a communication network, where S is the source node; t_1 and t_2 are destination nodes; the rate of each path is 1; the theoretical maximum stream of this Fig. 10 is 2. Supposing S sends data b_1 and b_2 with the same size 1, the target node can receive both data at the same time theoretically. Due to the limitation of 3 to 4, however, only one of the target nodes can receive one data without network coding, and then the node t_1 and t_2 achieve two data by encoding after receiving information at the same time, which reaches the maximum flow of the network with the network coding when b_1 and b_2 is encoded as data of size 1 (for example, using an XOR operation). Network coding improves the rate of multicast network; combines data packets; lightens the netork burden and reduces the transmission of redundant data.

Migabo et al. [Migabo, Djouani, Olwal et al. (2016)] summarized the basic classification of network coding in multi-hop WSN: According to the decoding scheme of aggregated data packets, they can be divided into local coding (decoding at each node) and global coding (decoding at destination node); according to the source of the packet, they can be divided into intra-session coding (the packets to be encoded from the same node) and inter-session coding. The former mainly solves the packet loss problem, while the latter is mainly used to reduce the number of transport packets.

Many scholars have investigated how to improve the energy efficiency of network coding. For example, Cui et al. [Cui, Chen and Ho (2007)] proposed a local inter-session network coding method based on backpressure routing algorithm COPR. Khodabakhshi et al. [Khodabakhshi and Khalily (2016)] proposed an algorithm for selecting coefficient vectors in linear programming for energy efficiency. Ribeiro et al. [Ribeiro, Tavares, Vieira et al. (2017)] proposed the data transmission protocol CodeDrip, which improved the protocol Drip employing the network coding.

Data aggregation is also an effective method to reduce redundant data. In WSN, data volume is directly related to the transmission of nodes and the consumption of propagation energy. Because of the high density deployment of nodes in WSN, the data collected by adjacent nodes have a high degree of correlation and redundancy. At the same time, the data-centric characteristics of WSN also require the aggregation of the raw data. Data aggregation uses a certain amount of computation instead of transmission, and the energy consumption of node communication is much higher than that of processing energy consumption, so data aggregation improves the energy utilization rate [Lu, Kuonen, Hirsbrunner et al. (2017)].

Patil et al. [Patil and Kulkarni (2013)] regarded the transmission of data as the structure of the routing tree. In the intermediate node, the similarity of the received data is calculated by the locally sensitive hash algorithms LSH. The LSH value is taken as the sample feature, and the data with the similar LSH values falls into one category. Then the support vector machine (SVM) method is used to judge whether the data is redundant or not, so as to reduce the data redundancy in WSN. The hash function used in the locally sensitive hash algorithm can ensure that the data near the location (Manhattan distance is used in this paper) are hashed into the same category with a higher probability, and it supports vector machine to find the hyperplane with the largest edge and ensure the minimum generalization error in the worst case.

For the wireless sensor network where the mobile agent makes the data aggregating and data processing, Lohani et al. [Lohani and Varma (2016)] improved the cost function that the next hop node selects for the mobile agent and then reduce the energy consumption and time delay through considering the information gain, the number of times that a transmission node is used, and the node energy of mobile agent. Harb et al. [Harb, Makhoul, Tawbi et al. (2017)] considered the periodic sensor network CPSN based on clustering, and proposed a data aggregation method for nodes and cluster heads. At the node level, the data collected by a single node in a cycle are aggregated into a set of weighted data according to the similarity function, which is merged into several elements. At the cluster head level, cluster head receives multiple sets of data from different nodes, and proposes three methods to aggregate data sets: 1) Calculate the similarity between the two data sets by using the Jaccard similarity function to remove redundant data, and use the PFF technology to reduce the complexity of the algorithm; 2) All data sets are composed into a default group and on the basis of barlett variance homogeneity test, the method of one-way ANOVA was employed to analyze the relationship strength between the different data sets and the data. If the relation intensity is less than the threshold value, it is considered that the difference of the data sets makes no sense on the data, that is, the data in the group is similar. If it is greater than the threshold value, the K-means clustering method is used to divide the group into k small groups until the relation intensity in each group is found to be less than the threshold value, when the data sets in each group are considered to be similar and select one data set (such as the set with the most elements) in each group to send to the sink node; 3) Using the distance formula to calculate the similarity of the two data sets, such as Euclidean distance, cosine function and so on, it is necessary standardize distances for easy comparison. If the distance is less than the threshold, the two data sets are considered to be similar and redundant.

2. Reducing the proportion of ineffective energy consumption

The effects of circuit energy consumption and start energy of transmission mode on energy efficiency are considered in Sinha et al. [Sinha and Chandrakasan (2002); Li, Wang, Yin et al. (2012)], respectively. The power of the communication unit in the idle mode is equivalent to that of the working mode, so the most obvious way to save energy is to turn off the transmitter when there is no demand. While as the packet length decreases and the sending time decreases, the starting time of the node sender is no longer a trivial part of the sending time. The energy consumption of startup transmitter increases as a proportion of the total energy consumption and the proportion of wasted work increases each time, so only when the interval between two transmissions exceeds a certain threshold, it is usefule to reduce energy consumption by starting energy saving mode. In Sinha et al. [Sinha and Chandrakasan (2002)], the dynamic energy management scheme of WSN is discussed, where five energy saving modes are proposed and the switching strategies between modes are studied. The results show that the threshold of energy saving mode transition time interval is related to the transmission time and the energy consumption of each mode. Li et al. [Li, Wang, Yin et al. (2012)] describes a method to balance between reducing the proportion of circuit energy consumption in total energy consumption and reducing the total energy consumption.

3. Improving the success rate of data transmission

The size of signal-to-noise ratio (SNR) directly affects the bit error rate. Increasing the transmit power can improve the signal-to-noise ratio and reduce the bit error rate, but the energy consumption will increase. Based on this, a parameter selection method to improve energy efficiency is proposed in Ali et al. [Ali, Abo-Zahhad and Farrag (2017)]. The network coding, data aggregation and other methods to reduce the information overlap in the network all reduce the load and improve the success rate.

4. Balancing network load, prolonging the network lifetime

In order to avoid premature death of some nodes, the methods of clustering meaning that selects different nodes to transmit and selecting the appropriate distance to reduce energy consumption can significantly prolong the lifetime of the network. Moon et al. [Moon, Park and Han (2017)] made the definition that the lifetime cycle is the time taken for the first node to run out of energy, and proposed the concept of cluster ring and use the Multi-agent reinforcement learning technology for flow control at the cluster ring level. Pati et al. [Pati, Sarkar and Panigrahi (2017)] selected the number of simulated rounds when the first node dies as the lifetime, supplemented by the average residual energy of the average node after each round of the simulation and the number of live nodes after each round of the simulation, and employed a Nash equilibrium strategy to select cluster heads. Further, it made the improvement for the possible Nash equilibrium and optimized the selection of the cluster head strategy on the basis of on the subgame complete equilibrium. The experimental results show that compared with BEEG, DEEC, UCR and so on, both the two cluster head selection protocols reduce energy consumption effectively and prolong the lifetime.

4 Energy efficiency evaluation metric and analysis

4.1 Energy efficiency evaluation metric

Energy efficiency evaluation metric and comparisons (where the protocol stack level refers to the level of measures used by the quantity efficiency evaluation metric and the measures to improve the efficiency of the metric):

As mentioned above, if the switch of the transmitter is frequently switched, the proportion of startup energy consumption increases and the wasted work increases compared with the transmission energy consumption. In Sinha et al. [Sinha and Chandrakasan (2002)], Sinha et al. proposed the threshold $T_{th,k}$ of the time interval taken to transform the energy-saving mode and the strategy of pattern transformation is also investigated.

Network efficiency (NE) assesses the factors in data collection that contribute to the successful arrival of packets to sink nodes [Kulik, Heinzelman and Balakrishnan (2004)], which is defined as:

$$\eta = \frac{\sum_{u \in U} hops(u)}{\sum_{p \in P} \sum_{h \in hops(p)} xmits(p,h)} \tag{17}$$

U is the set of packets that successfully reach the sink node; P is the set of all packets; *hops*(p) includes each hop that packet p passes; and xmits(p,h) is the number of packets p through hop h. It is also a metric that can directly reflect the energy efficiency [Yuan, Kanhere and Hollick (2017)]. This index focuses on the use of hops to measure cost, and choses the hop ratio taken for the data packets to arrive successfully at the sink node as the evaluation parameter of effectiveness. However, the relationship between the number of hops and path selection with energy consumption cannot be clearly reflected.

Ammer et al. [Ammer and Rabaey (2006)] proposed an energy efficiency evaluation metric for energy-per-useful-bit (EPUB) to evaluate the physical layer performance of WSN:

$$EPUB = \left(\frac{B_D + B_P}{B_D} \right) \left(P_{TX} + \xi P_{RX} \right) T \tag{18}$$

B_D and B_P are the mean of the data in a packet and the number of synchronous header bits respectively; T is the bit time (s); P_{TX} is the transmitting power and P_{RX} is the power of the receiver (including analog-to-digital converter and synchronous circuit), both of whose units are mW; the constant ξ determined by the MAC scheme, which represents the ratio of the time taken by the receiving mode and the transmission mode. The formula is based on the following assumptions: Sensor nodes can be composed into a trusted communication network in a self-organizing manner; any point-to-point communication can be conducted between each node; and each packet includes synchronization headers. The first part of the formula $\left(\frac{B_D + B_P}{B_D}\right)$ reflects the validity, that is, the ratio of the sum of the synchronous head used for synchronization and the packet (the MAC packet+physical layer header) to the data packet. The less useless bits (synchronous heads) corresponding to the transmission, the higher the efficiency of the transmission is. The second part ($P_{TX} + \xi P_{RX}$) reflects the energy consumption and is related to the first part. Reducing the energy consumption of the synchronous circuit in the receiver can reduce the total energy consumption. But the synchronous head becomes longer, which reduces the efficiency. The smaller the bit time T is, the higher the data rate is and the higher the transmission efficiency is. The analysis shows that long data packets, high data rate, low carrier frequency, and simple modulation scheme have positive effects on improving EPUB. The formula combines transmission and reception power and is an integrated metric inflecting the energy, effectiveness and efficiency. It can be seen from the formula that reducing the ratio of the time taken by the receiving mode time, that is the constant ξ, is to reduce the synchronization head ratio and help to improve the energy efficiency. Due to ξ determined by the MAC scheme, the formula has the same reference for the design of the data link layer.

Delivery cost per packet (DCPP) is defined as the cost of receiving a packet. The cost can be the number of transmissions. It is a metric to evaluate the energy efficiency of data collection, which can be used to evaluate the data collection protocol in the network layer [Gnawali, Fonseca, Jamieson et al. (2009)].

Li et al. [Li, Wang, Yin et al. (2012)] proposed the metric of energy consumption per unit transmits distance (EPTD) in 2012:

$$E_d = E/d \tag{19}$$

E is the energy consumption for transmitting per bit and d is the transmission distance. The evaluation metric divides E into two parts: intra-cluster broadcasting E_1 and inter-cluster transmission E_2. E1 is the sum of the inter-cluster broadcasting energy consumption of the cluster head node, the transmitter circuit energy consumption and the energy consumption of N receiver circuits used for cooperative transmission intra-cluster nodes. E_2 is the sum of the inter-cluster transmission energy consumption, the receiver energy consumption of the receiving node and energy consumption of N transmission node transmitters'circuits. And the energy consumption of inter-cluster transmission is expressed to be directly proportional to the power of the distance d.

The formula considers the circuit energy consumption of the transceiver. With the shortening of the distance, although the energy consumption of the inter-cluster transmission decreases, the proportion of the circuit energy consumption increases and the energy efficiency decreases. This method is suitable for cooperative multi-input single-output (MISO) or multiple-input multiple-output (MIMO) networks where the distance of the next hop is far away. It can maximize the energy efficiency by optimizing the inter-cluster transmission distance and the number of cooperative nodes. The evaluation metric can guide the optimization of the network layer.

Network coding is also one of the ways to improve energy efficiency. In Migabo et al. [Migabo, Djouani, Olwal et al. (2016)], Migabo et al. listed different evaluation methods for different goals of network coding. Average packet delivers rate (Average PDR) can be used as a metric to evaluate the energy efficiency. It refers to the ratio of the average number of packets received by the target node to the number of packets sent by the source node, which reflects the reliability and communication of the network. The higher the packet transmission rate is, the fewer packets failed to be sent are. The lower the energy consumption ratio of this part is, the more effectively the energy will be used. However, this metric fails to reflect the energy consumption of intermediate node coding and decoding in local coding, and the impact of data compression rate of energy efficiency in inter-session coding. At the same time, it is pointed out that data aggregation and reduction of the number of packets are the factors to improve energy efficiency.

Lu et al. [Lu, Kuonen, Hirsbrunner et al. (2017)] defined the data aggregation rate σ as the ratio of the size of the data after aggregation to the size of the data before aggregation.

Similar to EPUB, Ali et al. [Ali, Abo-Zahhad and Farrag (2017)] synthetically considered the error rate caused by physical layer parameters and the average packet length of MAC layer, and proposed that the total energy per successfully received bit (E_b) and total energy per successfully received packet (E_p):

$$E_b = \frac{E_{TX} + E_{RX}}{N_S} = \frac{E_{TX} + E_{RX}}{N_{MAC}\left(1 - P_{e,s}\right)^{L_p/b}} \tag{20}$$

$$E_p = \frac{E_{TX} + E_{RX}}{\left(1 - P_{e,s}\right)^{L_p/b}} \tag{21}$$

E_{TX} and E_{RX} are the average energy consumption of the transmitter and receiver in each data generation interval, respectively; N_{MAC} is the average length of the effective load in the packet; $\left(1 - P_{e,s}\right)^{L_p/b}$ is the probability that each bit in the packet is transmitted correctly under the assumption that bit errors occur independently of each other. The relationship between transmit power, signal-to-noise ratio and energy efficiency is investigated, and it is further pointed out that for different wireless channel types, there is a unique value that makes the E_b obtain the minimum value. The effect of physical layer and data link layer parameters on energy efficiency is considered.

Lifetime is an important metric to evaluate the energy efficiency of WSN. It refers to the time span of network from deployment to loss of function [Dietrich and Dressler (2009)], where the judgment of loss of function can be divided into three categories based on the application: based on the lifetime of the node, based on the coverage ratio and connectivity, based on the transmission and so on [Yetgin, Cheung, El-Hajjar et al. (2017)]. This metric is mainly used to optimize the network layer and optimize the network topology to balance the energy consumption. The optimization method and the consideration factor have different emphases according to the goal of application, and all the evaluation metrics are the lifetime under the application goal.

4.2 Performance analysis

The evaluation metrics of the physical layer and data link layer are more focused on the optimization of energy efficiency of a single node, while the network layer considers more energy efficiency optimization of one link or the whole network. The table below reflects the main considerations of the indicators. Because the optimization method and consideration factors have different emphases according to the application objective, the evaluation metrics is the life cycle under the application objective. Therefore, it is not included in the table below for comparison.

Table 2: Analysis of evaluation metrics

Protocol Layer	Function	Factors	Evaluation Metrics	Approaches to Improve Energy Efficiency	Characteristics
sPhysical layer	Frequency selection, carrier frequency generation, signal detection, modulation.	(1) Ratio of sync head to packet length	EPUB (1)+(2)+(3)	long packet, high data rate, low carrier frequency, simple modulation scheme	It is a comprehensive metric of energy efficiency.
		(2) Circuit energy consumption (3) Bit rate	EPTD (2)+(5)	optimizing the transmission distance	Influence of circuit energy consumption as a useless power in distance selection is considered.
		(4) SNR (5) Distance	E_p (2)+(4) E_b (2)+(4)+(6)	Selection of appropriate transmitting power	Influence of TP on SNR is investigated, and the effect of packet error on energy efficiency is considered.
Data Link layer	Data stream multiplexing, data frame detection, media access and error control	(6) Payload length in data frame (7) start-up energy of transmission mode	$T_{th,k}$ (7)	Reasonable transmission and conversion of energy-saving modes	Dynamic energy management for communication module with strong pertinence
Network layer	Manage the data communication in the network, select the appropriate route to transfer data from the source to the destination	(8) Number of data packets transmitted through (9) Success rate of reaching the sink	DCPP (8)	Reduce the number of transmissions	Evaluation method is simple and the parameters are easy to obtain.
			NE (8)+(9)	Reduce the number of transmissions and improve the rate of successful transmission	Considering the success rate of transmission
			Average PDR (9)	Data aggregation, reducing the number of packets	Success rate of packet transmission a lateral reflection of energy efficiency
Application layer	Services needed to complete a series of business processes	(10) Data compression rate	σ (10)	Data aggregation to reduce the transmission of invalid data	Invalid data is defined at the application level. Aggregation rate is related to application goals and the required granularity.

According to the aforementioned four aspects affecting energy efficiency, the considering factors of the evaluation metrics are classified in the following:

1) Minimizing the transmission of redundant data, and the factors (1), (6) and (10) in the table above are considered from this perspective;

2) Reducing the proportion of ineffective energy consumption as much as possible, (2) and (7) in the table above;

3) Increasing the success rate of data transmission as much as possible, such as (4) and (9);

4) Balancing the load as far as possible and prolong the lifetime of the whole network, such as (5) and (8).

Improving energy efficiency is a coordinated process, and each factor will influence and restrict each other. The following table reflects the main efforts of each evaluation matrix to improve energy efficiency.

Table 3: Evaluation metric analysis

	Redundant Data Ratio	Invalid Energy Consumption Ratio	Success Rate of Data Transmission	Balance Network Load
EPUB	√			
EPTD		√		
E_p			√	
E_b	√		√	
T_{thk}		√		
DCPP		√	√	
NE			√	
Average PDR			√	
σ	√			
Lifetime				√

5 Conclusion and prospect

This paper summarizes the energy model of WSN and IoT, and analyses the perceptual energy consumption, energy consumption of records and control processing of the processor (including the effective energy and leakage energy), the energy consumption of the communication unit's transceiver and the transient energy of this model. Then, some mechanisms and algorithms for improving energy efficiency in recent years are discussed. These methods mainly include reducing redundant data and the proportion of ineffective energy consumption; improving the success rate of transmission and balancing load. Considering redundant information such as frame header; duplicate data; transient energy of node mode conversion; transmission distance; cluster head election strategy, etc., some parameters are proposed or selected to improve the algorithm. Then several evaluation metrics of energy efficiency are introduced, and the application levels of each metric are compared according to the level of the network protocol stack, and compare their respective perspectives to inspire people to improve existing networks.

The applicability of the above evaluation metrics is different. The evaluation metrics of data link layer and physical layer focus on reducing energy consumption of a single node, while the evaluation metrics of network layer focus on reducing energy consumption of path or network.

At present, when scholars propose new improved algorithms, they often compare them with some existing algorithms in lifetime, delay, bit error rate (BER) and other aspects to reflect the superiority of the new algorithm. It can be considered that these metrics are the embodiment of energy efficiency in some aspects. In recent years, more energy efficiency evaluation metrics have been proposed in the article and are used to evaluate the improvement of the algorithm. However, at present, the evaluation between algorithms is mostly at the level of comparison with similar protocols, which is lacking of criteria, and mostly considers some factors as evaluation indicators to illustrate the superiority of their own methods. It is unavoidable to be too targeted. On the one hand, due to the changeable application objectives and deployment scope of WSN, it is difficult to propose a universal metric. In the future, the energy efficiency evaluation indicators proposed for various situations may be more and more complete. For example, EPTD is just an important evaluation metric for cooperative MISO or MIMO networks with the longer distances for next hop. It also provides a direction for the design and improvement of this type of network. On the other hand, we can design several simple energy efficiency evaluation indicators with easily available evaluation parameters and simple methods, which can provide a reference for the selection of the initial design types of specific sensor networks.

In the next stage, focusing on the first part, we will further investigate it, and improve the previous evaluation metrics or propose new evaluation metrics to provide reference for the improvement of a certain function or the structure of WSN.

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