Research on Adaptive Energy-Efficient Reference Broadcasting Synchronization

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ABSTRACT For large-scale photovoltaic module monitoring, wireless sensor network technology has been widely used, in which time synchronization is a significant factor. However, there are still outstanding issues in existing time synchronization algorithms for large-scale networking. To this end, this paper proposes a new Adaptive Energy-efficient Reference Broadcasting Synchronization method (AERBS) for wireless sensor networks, aiming to reduce the energy consumption whilst improving the synchronization precision. Moreover, the proposed method can reduce the number of synchronization information exchanges and self-adaptively determine the re-synchronization cycle. Simulation experiments demonstrate that our proposed AERBS outperforms the existing ERBS algorithm, in terms of reducing the synchronization number and the achieved reduction in energy consumption. The algorithm herein can be fully applied in the monitoring of large-scale photovoltaic module. At the same time, as a typical application of IoT (Internet of Things), it also provides a reference for distributed edge computing.

INDEX TERMS Large-scale photovoltaic module, state monitoring, WSN, time synchronization, AERBS.

I. INTRODUCTION

In the time synchronization agreement on wireless sensor network, such factors as the scale of the network, data fusion, safety and tracking, synchronization precision, energy consumption, topology and robustness should be taken into consideration. Among them, the most crucial parameter is the time synchronization precision and energy consumption [1], [2]. In an attempt of enhancing the synchronization precision, information transmission is generally increased, which results in excess energy consumption. Wireless sensor network nodes usually characterize limited battery power and hence it is important to conserve their energy consumption, since energy consumption is directly related to the life cycle of wireless sensor network nodes. Some of the existing relative synchronization algorithms have not fully considered the problem of energy consumption. Some existing energy conserving algorithms have ignored the problem of precision, and some have failed to achieve a balance between energy conservation and the achieved level of precision. Time synchronization in large-scale networks is being researched widely in the recent past. H. Shafieirad et al. proposed a maximum SNR opportunistic routing for large-scale energy harvesting sensor networks [3]. In this method, an energy aware opportunistic routing protocol is used in large-scale EH-WSN that involves multi-hop communication. The available energy on the sensor node, the distance between the sensor and FC and the amount of data to be transmitted are considered when selecting the best forwarding information, which significantly improved the data transmission rate. K. Ang et al. proposed to optimize energy consumption whilst collecting large-volumes of big data in large-scale wireless sensor networks using mobile collectors [4], which is used to determine LS-WSN MDC analysis method of node energy consumption in MDC scheme, and further a model for determining the optimal number of clusters and minimizing energy consumption is provided. H. Byun proposed a design of distributed node scheduling scheme inspired by gene regulatory networks for wireless sensor Networks [5], which applies the cellular mechanism of gene regulatory network (GRN) to WSN, and establishes a potential connection between multi-cell system and WSN system. Each sensor node adjusts its state independently through local interaction according to sensor variable signaling, and realizes a global
object defined by the application program or user in order to ensure an energy balance and stability of the system. Reference [6] proposed a clock synchronization algorithm for large-scale WSN. By establishing a spanning tree using the gateway as the root node and the cluster head as the child node, the accumulated hops during synchronization are effectively reduced. The unidirectional ROS within the cluster and the bidirectional SRS synchronization mechanism between clusters are used to greatly reduce the energy consumption during synchronization without affecting the synchronization accuracy. In reference [7], a group consensus time synchronization protocol based on group consistency is proposed (GCTS), which works by firstly collecting the time stamp information of a group of nearby related nodes, and then uses the group consistency protocol to conduct distributed computing on the collected time stamp information. After the fusion process, it is used as a new clock. This protocol adopts a distributed computing mode, with minimal calculation and faster convergence, thus resulting in a low energy consumption. Reference [8] proposed the modeling of large-scale WSN based on OPNET. OPNET is used to model the nodes, large-scale networks and network processes, and a greedy perimeter stateless routing (GPSR) algorithm is used for optimization simulation, which provided a visualization method for WSN routing protocol. Reference [9] studied the simulation of heterogeneous data exchange method for large-scale WSN, and proposed a large-scale heterogeneous data exchange method based on OCHS. OCHS algorithm is used to select the best data exchange cluster set to complete the data exchange process. The biggest characteristic of this method is to provide a theoretical basis for data preprocessing. Reference [10] proposed a method, named as low energy adaptive clustering hierarchy large scale (LEACH-LS) for large-scale networks, which basically meets the needs of large-scale networks, but has a short life cycle.

In order to balance the synchronization precision and energy consumption, and to meet the needs of global synchronization, this proposes a forward adaptive time synchronization algorithm based on AERBS, which, with an adaptive time synchronization method and an ERBS time synchronization algorithm, effectively meets the requirements of wireless sensor network time synchronization as required by large-scale photovoltaic module monitoring. Our proposed AERBS algorithm determines the nodes those participate in the synchronization and determines the resynchronization period adaptively, which greatly reduces the exchanged number of synchronization information, and significantly reduces the energy consumption without any loss of synchronization accuracy.

II. MONITORING OF LARGE-SCALE PHOTOVOLTAIC MODULE

A. LAYOUT DESIGN OF THE LARGE-SCALE PHOTOVOLTAIC PLANT

In practice, it is not feasible to install a large-scale photovoltaic plant on the roof, and so they are mostly installed on the ground. The large-scale photovoltaic plant studied in this paper is composed of 10,000 photovoltaic modules, and the specification size of photovoltaic modules is as follows: the size of 72 battery modules is 1960mm×990mm×40mm, and the size of 60 battery modules is 1650mm×990mm×40mm (slight differences from different manufacturers). Seventy-two conventional photovoltaic modules with a power of 250~300W are selected for layout. Due to topography, the installation of photovoltaic modules may vary from rectangular array, square array, to circular array or even any abnormal array as long as lighting are not affected, land resources can be saved and are easy to install. The vertical double-row layout is herein adopted with closely arranged rows and a certain space left between the front and rear rows. According to engineering in practice, the space between the front and rear arrays of photovoltaic modules is roughly 6 meters. Arrays of photovoltaic modules can be arranged as follows: 10,000 photovoltaic modules can be divided into 50 string formations of 2 × 100. Each string formation consists of 200 photovoltaic modules so that each one is in the area approximately equal to 4m×100m. There are two vertical rows in each string formation and 100 photovoltaic modules are closely arranged in every row. A space of 5-6 meters between the rows is reserved for installation, patrol and avoiding occlusion etc. Meanwhile, installation of photovoltaic plant requires a certain angle [11] (the angle is adjusted in the range of 0 – 90° depending on the latitude). Therefore, each string formation can be regarded as an area approximately equal to 4m×100m. The 50 string formations are arranged symmetrically, and the whole layout of the photovoltaic plant is arranged within the range of 220m×220m. The layout of string formations is shown in Fig. 1. The layout of photovoltaic module arrays is shown in Fig. 2.

FIGURE 1. Layout of string formations.

B. DESIGN OF WSN NETWORK STRUCTURE

According to the layout design of photovoltaic module arrays presented in Fig. 1, the topology of wireless sensor network monitored by photovoltaic modules should be considered, and collection nodes should be installed in an embedded way in the terminal box on the back of modules, which is useful for the network topology structure layout of wireless sensor network due to the previous layout of photovoltaic modules. Suppose that 200 nodes in every rectangle array of 20m×20m share the same channel, these 200 nodes are managed by one router. The router and 200 nodes are regarded...
as one partition. All nodes in the partition function on a single allocated channel. There are 50 similar partitions in the topology network structure layout for wireless sensor networks, which means that there are 50 routers. However, subject to the IEEE 802.15.4 communication protocol, only 16 channels are available for wireless sensor networks in the 2.4GHz band. Thus, allocation and multiplexing of channels should be solved.

Some studies show that channels do not interfere with each other as long as they are not too close to each other [12]. Some are concerned about the channel allocation issues in wireless sensor network [13]. Due to the limitations of wireless sensor networks such as low power, short communication distance and low price, channel allocation in wireless sensor networks experience different challenges from those of ordinary wireless networks. But the exploration of the problem of channel allocation is considered to be out of scope of this paper.

According to the above-mentioned design, the network is divided into three layers based on partition routing. The first is the layer of collection nodes at the bottom, the second is the layer of the partition route node and the third is the layer of coordinator. The hierarchical structure is shown in Fig. 3.

According to the above topology structure of a wireless sensor networks, the design is described as follows. A single coordinator at the top of the whole network controls 50 routing nodes. Each node are distributed with a different channel and assigned with an ID number. Each routing node manages 200 collection nodes and every collection node has its own ID number. These collection nodes can communicate with each other through the channel managed by the routing node, which means that collection nodes can only communicate with 200 nodes on the same layer and also with the management routing node. Such a kind of topology can divide the network into multiple routing zones and every zone is made up of one routing node and many collection nodes. Collection nodes send the data to the routing node and then the routing node gathers all the data in the entire zone to fuse and calculate. The data after fusion are sent to the coordinator. Multi-hop transmission route is adopted between the collection nodes, and between the collection nodes and routing nodes. Direct communication is achieved between routing nodes and coordinator. Besides, multiple routing nodes can make up a higher level network, which is managed by the coordinator. This kind of network design can significantly reduce unnecessary information transfers in order to effectively avoid unnecessary communication energy consumption incurred by a large number of disordered and redundant wireless ad-hoc network.

The wireless sensor network topology has significant advantages. In order to avoid unnecessary energy losses brought by the ad-hoc network, the network structure requires reasonable planning. The routing nodes and the collection nodes are responsible for different tasks in data transmission. Collection nodes send perceived data to the routing nodes and the routing nodes send the data to the coordinator after distribution, calculation and fusion. In this way, the channel resources of the wireless sensor network can be reasonably utilized to reduce redundant data and energy consumption.

C. PROBLEMS OF WSN TIME SYNCHRONIZATION

In general, when the network exceeds a certain size (such as more than 10,000 nodes), many time synchronization methods fail to work, which becomes a new problem for the realization of time synchronization in large-scale wireless sensor networks.

A significant difference between the wireless sensor network and other computer network is the limitation of energy. Due to different applications in various circumstances, the sensor nodes are often of small size. Moreover, the power supply of the nodes from a battery is limited, and with a number of nodes in a large-scale network, the distribution covers a wide area. Since most of the distributed photovoltaic power stations are built in remote areas, maintenance becomes harder. Therefore, it is impossible to solve the problem of node energy consumption by recycling the batteries replaced from nodes.
After time synchronization is achieved, given the instability of hardware and delay of signal transmission, time precision is decreased over time. Therefore, the process of time synchronization is repeated based on a certain time interval. This is to say that time synchronization cycle and frequency should be defined again over time passing. The adaptive time synchronization algorithm based on ERBS proposed in this paper can efficiently enhance the time synchronization in wireless sensor networks.

III. INTRODUCTION OF RELATED TIME SYNCHRONIZATION ALGORITHM

In 2002, J. Elson and K. Romer of the University of California first proposed the research topic of WSN time synchronization at the HotNets-I international academic conference. In the same year, they formally proposed the broadcast synchronization (RBS) scheme, which is suitable for WSN. RBS protocol is a very typical synchronization algorithm that works based on receiver-receiver mechanism. The algorithm makes full use of the broadcast channel characteristics of the link layer in wireless transmission to broadcast reference messages to the nodes in the layer. The receiver records the local time when receiving the reference broadcast message, and then exchanges the time recorded by each other. The core idea of the algorithm is to select a reference node to send the broadcast beacons to all the nodes in the network. Each node compares the received broadcast beacon time information, estimates the time error by mathematical methods, and realizes the relative network time synchronization between all the receivers.

In 2019, Xianbo Sun et al. proposed a time synchronization protocol with Gaussian delay model (TSP-GDM). According to the characteristic that the time delay of PV module monitoring node conforms to the Gaussian delay model, the node clock bias estimation method in the Gaussian model layer is used to solve the problem of node clock offset estimation in the module monitoring area layer. On this basis, the local exchange and sharing of data packets in the monitoring subnet is realized by modeling, and the phase offset and frequency offset of nodes are resolved based on the statistical signal characteristics.

In 2020, Xianbo Sun et al. proposed an energy-efficient reference broadcast synchronization algorithm (ERBS) for WSN. Initially, only the non-adjacent nodes in the PV module monitoring sub-network are used to calculate the average phase deviation after receiving the message. Then, the least square method is used to solve the clock offset. In the process of solving the clock offset, considering the impact of environmental temperature on the clock offset, the phase offset and frequency offset of the node are resolved based on signal parameter estimation, which can effectively save parts of the network overhead. This enables the PV module monitoring network to achieve a high-precision synchronization of the entire network, and provides the basis for photovoltaic module monitoring and fault diagnosis.

IV. ADAPTIVE TIME SYNCHRONIZATION BASED ON RBS

PalChaudhuri among others has postulated to change the parameter settings of RBS and further extended the RBS agreement to proposed the adaptive probabilistic synchronization algorithm [14], in order to seek a balance between synchronization provision and energy consumption. If the relative clock frequency offset error $\varepsilon$ between two nodes is a Gaussian random variable, whose mean value is 0 and variance is $\sigma^2$, then the probability of synchronization while broadcasting $N$ messages in given by equation 1.

$$P_r(|\varepsilon| < \varepsilon_{\text{max}}) = 2\text{erf}\left(\frac{\sqrt{N}\varepsilon_{\text{max}}}{\sigma}\right)$$

In this equation, $\varepsilon_{\text{max}}$ is the maximum allowable time offset. Error function $\text{erf}$ is used $\text{erf}(x) \triangleq (1/2\pi) \int_0^x \exp(-t^2/2)dt$ because the clock phase offset always exceeds a certain limitation $\varepsilon_{\text{max}}$ by a certain probability, so performance index is a kind of probability measure. To effectively reduce the probability to a small random value, the number of information $N$ in each round of RBS broadcasting can be increased to an appropriate value.

According to the above algorithm, the clock frequency offset is limited with a certain probability. Over time, the clocks of nodes experiences gradual drift due to various factors. So it is necessary to use RBS algorithm periodically to complete synchronization. PalChaudhuri has proposed the following formula [14] to determine the maximum re-synchronization cycle:

$$\tau_{\text{max}} = \frac{\gamma_{\text{max}} - \varepsilon_{\text{max}} - d_{\text{max}}}{\rho}$$

In this formula, $\gamma_{\text{max}}$ is the maximum clock frequency offset, $\rho$ is the maximum clock phase offset, $d_{\text{max}}$ is the maximum time delay in exchanges of timestamps in RBS. According to different requirements of time synchronization precision designated by $\gamma_{\text{max}}$, the required re-synchronization cycles $\tau_{\text{max}}$ can be determined.

V. ADAPTIVE TIME SYNCHRONIZATION ALGORITHM BASED ON ERBS

The ERBS algorithm can efficiently resolve the problem of time synchronization in small and medium-sized WSN [15]. Photovoltaic modules in large-scale WSN cannot be resolved by the RBS algorithm, as it involves multi-hop implementation during the entire network synchronization. Once the size is large enough, the hop count increases without limits, although it can guarantee synchronization precision, it inevitably brings colossal energy consumption. Although the improvement of ERBS can reduce energy consumption to some extent, issues around time synchronization in large-scale wireless sensor networks still prevails.

A. SYNCHRONOUS CORRECTION OF CLOCK PHASE OFFSET AND FREQUENCY OFFSET

Synchronization precision is the primary problem that should be considered to ensure WSN time synchronization. Phase
In this formula, $T_{\text{cons}}$ timestamps between nodes A and B are exchanged which is then sent to node B in the channel. Accordingly, receiving the $i$ timestamp. Consider, nodes A and B as examples. After networks and then relative nodes receive and record this beacons to channels in the routing zones of wireless sensor networks and then relative nodes receive and record this beacons to channels in the routing zones of wireless sensor networks.

In this formula (3) minus (4) then we can get the time difference between node A and node B.

$$T_{2,i}^A - T_{2,i}^B = \phi_{po}^{PA} + \phi_{fo}^{PA} \times (T_{1,i} - T_{1,1}) + d^{PA} - d^{PB} + Y_i^{PA} - Y_i^{PB}$$  \hfill (5)$$

Here, $\phi_{po}^{PA} = \phi_{po}^{PA} - \phi_{po}^{PB}$ is the relative phase offset value between node B and node A when receiving $i$ beacon, $\phi_{fo}^{PA} = \phi_{fo}^{PA} - \phi_{fo}^{PB}$ is the relative frequency offset value between node B and node A when receiving $i$ beacon. In order to describe the equation easily, the following assumptions are made:

$$\omega[i] = Y_i^{PA} - Y_i^{PB} = z[i] - d$$ \hfill (6)$$

$$d \triangleq d^{PA} - d^{PB}$$ \hfill (7)$$

$$y[i] = T_{2,i}^A - T_{2,i}^B$$ \hfill (8)$$

$$D_i = T_{1,i} - T_{1,1}$$ \hfill (9)$$

$$\varphi = [\phi_{po}^{RA}, \phi_{fo}^{RA}]^T$$ \hfill (10)$$

According to the assumption, formula (5) can be simplified as the form of matrix equation:

$$Y = H \varphi + \omega$$ \hfill (11)$$

In this formula

$$Y = [y[1], y[2], \ldots, y[N]]^T$$

$$\omega = [\omega[1], \omega[2], \ldots, \omega[N]]^T$$

As shown in formula (11), $\omega$ can be seen as the distractor of time delay whose distribution conforms to Gaussian.

Matrix $H$ is the matrix of measures of timestamps in nodes; its dimension is $2 \times N$. Relevant literature shows that the estimation matrix of phase offset and frequency offset can be obtained by the method of least variance estimation and the matrix theory and matrix are as follows.

$$\hat{\varphi} = (H^T H)^{-1} H^T Y$$ \hfill (12)$$

$$H = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ T_{1,2}^A - T_{1,1}^A & \cdots & T_{1,N}^A - T_{1,1}^A \end{bmatrix}^T$$ \hfill (13)$$

$$I(\varphi) = \frac{H^T H}{\sigma^2}$$ \hfill
Mathematically, from the above estimation matrix, we can get the estimated value of the phase offset and frequency offset needed.

\[ \hat{\varphi}_{po} = \frac{\sum_{i=1}^{N} D_i^2 Y[i] - \sum_{i=1}^{N} D_i \sum_{i=1}^{N} D_i^2}{N} \]  
(14)

\[ \hat{\varphi}_{fo} = \frac{\sum_{i=1}^{N} D_i^2 Y[i] - \sum_{i=1}^{N} D_i \sum_{i=1}^{N} Y[i]}{N} \]  
(15)

Therefore, we can realize the time synchronization of node A and B by using the estimation formula (14) and (15) of the phase offset and frequency offset. All the nodes in the routing zone can realize time synchronization in the form of peer nodes by this method. Since there is no other extra information transmission in routing node P, energy consumption can be reduced.

Moreover, the influence of random delay is almost the same and there is no much difference in synchronization precision. Assuming that phase offset is ignored (which means that \( \hat{\varphi}_{po} = 0 \)), then maximum likelihood estimation of time error can be expressed as \( \hat{\varphi}_{fo} \), so the evaluation of node time error is given by formula (16).

\[ \hat{\varphi}_{BA} = \frac{1}{N} \sum_{i=1}^{N} [T_{2,i}^A - T_{2,i}^B] \]  
(16)

Now, we can get the minimum limit of phase offset and frequency offset through the matrix theory.

\[ (\hat{\varphi}_{po})_{\text{min}} = \frac{\sigma^2 \sum_{i=1}^{N} D_i^2}{N} \]  
(17)

\[ (\hat{\varphi}_{fo})_{\text{min}} = \frac{\sigma^2 N}{N} \]  
(18)

The derivation of equations (16), (17) and (18) is a necessary preparation for the follow-up study of the adaptive synchronization cycle.

B. ADAPTIVE SYNCHRONIZATION CYCLE

There will be some shifts in clocks of all nodes in a wireless sensor network, and the variations are often limited in the range of smaller constant \( \rho \). Usually, the value of \( \rho \) is \( 10^{-6} \) second or \( 10^{-5} \) second of orders of magnitude. At any real-time \( t \), the time of node \( i \) and \( j \) in wireless sensor network will not be equal, which is \( c_i(t) \neq c_j(t) \). If \( |c_i(t) - c_j(t)| \leq \varphi \), then the clock achieves the synchronization of \( \varphi \). Realizing and maintaining the synchronization of \( \varphi \) in the whole network, time synchronization implies that every peer of node clocks needs to realize the synchronization of \( \varphi \).

To maintain the time synchronization in the whole network, the aforementioned three layer network topology structure is adopted. After the start-ups of the synchronization process, the first stage is the communication period between routing nodes, where the coordinator sends synchronization beacon in a random cycle. All the routing nodes should maintain consistency with this beacon after receiving it, and should apply the AERBS algorithm to realize the time synchronization of routing nodes and to determine the adaptive re-synchronization cycle. The second stage is the communication period between collection nodes in channels of routing zones. All the collection nodes in the channels should switch to the communication channels and receive synchronization beacons from routing nodes. Meanwhile, all the collection nodes in zones should realize the time synchronization of nodes according to AERBS algorithm.

1) ADAPTIVE TIME SYNCHRONIZATION OF COLLECTION NODES

Nodes adjust clocks to achieve time synchronization due to the algorithm. This process needs a certain time which starts from the beginning of the synchronization process of routing nodes to its end. The process is called synchronization cycle \( T \), which describes the full execution time of a round of synchronization performed by the time synchronization algorithm.

Appropriate condition constraints are added based on the previous algorithm. Such constraints mainly include two collection nodes: one is used to judge whether to send synchronization requirement information and whether to participate in a certain round of time synchronization process according to the preset value of the node’s time precision; the other is the decision of some nodes with excessive energy consumption on whether to participate in a certain round of time synchronization process through distributed computing. The nodes participating in each round of time synchronization will be adaptively determined by the above two constraints, and the specific implementation is as follows:

At the initial stage of synchronization, all the nodes will exchange \( i \) information very quickly and frequently (assume that routing node has sent \( k \) synchronization beacons in this round), and then achieve an initial synchronization (not real synchronization yet). In the next stage of \( i + 1 \rightarrow k \), according to the minimum value of phase offset and frequency offset as per formula (16) and (17), we can judge whether nodes can continue to participate in the synchronization process in the previous stage. The non-participating nodes record the information of received time stamp and conduct data fusion through distribution and calculation. Also, it calculates the mean value of time error in this period by using equation (15) and exchange the information of mean time stamp before the end of the synchronization to participate in the final synchronization of this round and also wait for the next round of synchronization beacon. The schematic diagram of the transmission of time stamps merged by nodes is shown in Fig. 5, and the flow chart of the algorithm is shown in Fig. 6.
This method can effectively shorten the synchronization cycle $T$ of collection nodes, and the synchronization cycle $T$ is adaptively changing subjected to the number of nodes participating in each round of time synchronization, thus greatly reducing the communication burden and energy consumption.

2) ADAPTIVE RE-SYNCHRONIZATION CYCLE

Due to phase offset and frequency offset, time precision decreases over time and even may exceed allowable range, which then needs a new round of time synchronization. Assuming that at real-time $t_0$, the clock $\varphi_0$ is synchronized until a real time $t_0 + T'$ when the clock $\varphi_0 + 2\rho T'$ is synchronized. According to the above assumption, if time precision is set as $\varphi$, and at a certain point time precision is $\varphi_0$ after a round of synchronization, then every interval $T' = (\varphi - \varphi_0)/2\rho$ needs a round of time synchronization again, so $T'$ is called as a re-synchronization cycle.

Based on node synchronization and synchronization requirements of the routing node, adaptive adjustment is made during the re-synchronization cycle $T'$ which is the determination of re-synchronization cycle due to requirements, but time intervals are changeable. Unnecessary synchronization consumption are eliminated through distributed computing to achieve the balance of energy consumption.

This algorithm adjusts the frequency offset and phase offset of node clocks and makes adaptive adjustments of the node synchronization cycle and re-synchronization cycle. Under the premise of ensuring synchronization precision, synchronization times, and energy consumption is reduced effectively, and life cycle of nodes, in turn, can be prolonged.

VI. SIMULATION AND ANALYSIS OF RESULTS

In order to evaluate the functions of the AERBS algorithm, we conduct the simulation analysis by writing file M in MATLAB. The validity of the algorithm is mainly verified in the aspects of synchronization accuracy, synchronization times and synchronization energy consumption. Due to random data simulation, the following simulation environment is designed: the spatial area is arranged as 220 × 220 meters, a coordinator, 5 routing nodes, and 1000 collection nodes are settled. The communication distance of the node is set as 50 meters, the node power is 10-50 mW, the data transmission rate is set as 100Kb/s, and the initial value of phase offset and frequency offset are both set as 0.

To verify the effectiveness of RBS, TSP-GDM [19], ERBS and AERBS algorithms in terms of the synchronization precision, in the above simulation environment, four algorithms are applied to correct the time synchronization error in the case of 500 nodes. The simulation results are shown in Fig. 7.
between receivers from the very beginning, and the precision has not improved with the increasing rounds. Compared with RBS algorithm, TSP-GDM algorithm has a significant improvement in synchronization precision. With the increase of rounds, the error gradually decreases, and the precision is improved continuously. Compared with the TSP-GDM algorithm, ERBS algorithm also has a certain degree of improvement in synchronization precision. However, it is not apparent because the focus of ERBS algorithm is to reduce energy consumption. Compared with the ERBS algorithm, the synchronization error of AERBS algorithm is improved to a certain extent, but not obviously. The simulation results are consistent with the assumption. The aim of improvement is to reduce energy consumption as much as possible under the premise of ensuring synchronization precision along with the balance between accuracy and energy consumption. In this way, it is suitable for the large-scale WSN network.

In order to compare the differences of RBS, TSP-GDM, ERBS and AERBS algorithms in terms of synchronization times, in the above simulation environment, simulation of synchronization times are observed for the four algorithms. The simulation results are shown in Fig. 8.

![Figure 8. Curves of the number of synchronization of different algorithms.](image)

Simulation results show that synchronization times exhibit more significant differences when 100 nodes are involved. With a further increase in the number of nodes, the change of synchronization times is more prominent. The increasing trend of AERBS is relatively gentle, but the patterns of RBS, TSP-GDM and ERBS are considerably steep, especially that of RBS algorithm. Synchronization times of RBS, TSP-GDM and ERBS are more than that of AERBS. Meanwhile, with an increasing number of nodes, this gap tends to increase. This implies that the synchronization times of AERBS is much less than that of the other three algorithms.

At last, a comparison of the energy consumption of RBS, TSP-GDM, ERBS and AERBS algorithms due to the different number of nodes is presented in Fig. 9. Analysis of simulation results reveals that with a growing number of nodes, network energy consumption is increasing accordingly. But the energy consumption of AERBS algorithm exhibits the slowest growth, and the RBS algorithm has the fastest growth of energy consumption with the most noticeable increasing trend. Compared with AERBS, the energy consumption of TSP-GDM and ERBS have shown faster growth and widening gap. This verifies the advantages of AERBS algorithm over the TSP-GDM and ERBS in terms of energy consumption. It is easier for AERBS to get widely used in large-scale WSN network. It is consistent with the simulation results of synchronization times under different algorithms.

### VII. CONCLUSION

This paper has put forward a new AERBS time synchronization algorithm for wireless sensor network while considering to reduce energy consumption and ensuring time synchronization precision. Based on RBS broadcasting synchronization, and adaptive method of determining the number of nodes in synchronization with node precision and energy consumption is considered, where nodes can achieve synchronization with correct exchanges of double time-stamps of sensor nodes. Simulation experiments show that given the same time synchronization precision, compared with ERBS, AERBS has dramatically reduced the number of synchronization and total energy consumption for realizing global synchronization. This kind of algorithm can be fully or partly applied to improve functions of previous agreement or design new agreement and also can be fully applied in the monitoring of large-scale photovoltaic module.

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