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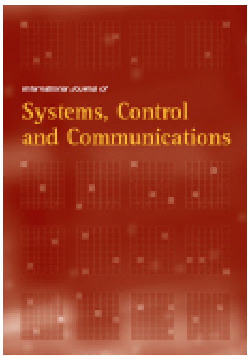


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# Clock synchronisation method for wireless sensor networks based on phase compensation

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**Abstract:** Aiming at the problems of large phase estimation error and large synchronisation time overhead in clock synchronisation method, a clock synchronisation method for wireless sensor networks (WSN) based on phase compensation is proposed. Firstly, the synchronisation deviation value is determined by calculating the broadcast information frame of general nodes, and the instability factor and clock synchronisation delay are extracted to determine the influencing factors of clock synchronisation. Then, the wireless sensor is set as an undirected graph, and the updated node state is consistent through the linear model. Finally, the local clock change frequency is determined by the least square method, the clock synchronisation compensation estimator is determined by the calculation of slope, the updated network topology of nodes is replaced, and the bounded condition of phase compensation is set to complete clock synchronisation. The experimental results show that the proposed method has small phase estimation error and small synchronisation time overhead.

**Keywords:** phase compensation; WSN; clock synchronisation; phase estimation; linear model; least square method.

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## 1 Introduction

With the continuous integration and development of network communication technology and computing technology, WSN are widely used in various fields of social development with their advantages of high flexibility, convenient installation and expanding temperament (Shi et al., 2020). WSN are not only limited to the development of communication protocols, but also include the research of clock synchronisation technology. This technology mainly completes many functions such as power management, communication access, synchronous frequency hopping and so on (Wang et al., 2021a). In recent years, with the rapid expansion of the scale of wireless communication network, the amount of information transmission is increasing. Under the background of various competition mechanisms, access protocols will produce large delay in the communication process, affecting the effectiveness of network communication (Deng et al., 2020). Therefore, keeping the clock synchronisation between different network nodes is the basis of real-time communication in WSN. Clock synchronisation in WSN is a powerful support for the network to achieve a variety of functions and protocols (Fu and Yang, 2020). However, the discontinuity between nodes and multiple nodes taking local time as reference in WSN lead to poor clock synchronisation effect, which greatly affects the coordination of nodes in WSN over time (Rossa et al., 2020). Therefore, improving the clock synchronisation effect of WSN is an important problem to be solved in this field. Therefore, studying clock synchronisation methods in wireless sensor networks (WSN) is of great significance.

Li and Guo (2020) proposes to design a double iterative algorithm based on WSN clock synchronisation. The algorithm obtains the sensor network nodes and clock parameters, analyses the state of clock parameters under different background conditions according to the constructed maximum likelihood estimator, reduces the anchor nodes studied, and designs a double iterative algorithm to realise the clock synchronisation of WSN. The synchronisation speed of this algorithm is fast, but the consistency of its synchronisation results is poor, which needs further improvement. Yu et al. (2020) proposed to design a clock synchronisation algorithm for sensor networks with random bounded communication delay. Aiming at the problem of poor synchronisation consistency caused by divergence in the process of clock synchronisation, a new synchronisation algorithm is designed. Firstly, the skew and offset rate in clock synchronisation are analysed, and the key factors of divergence in clock synchronisation are determined; Then change the relative offset rate. Ensure the convergence in the offset process, calculate the node synchronisation error, and complete the sensor network clock synchronisation. The synchronisation algorithm has good convergence, but it has the problem of large synchronisation time overhead. Kong and Liu (2020) proposed a time synchronisation algorithm for underwater sensor networks with double cluster heads based on clustering. Considering the characteristics of underwater communication, the algorithm clusters the energy consumption and depth of network nodes, selects the best egg according to the clustering results, reduces the node error with the help of the node movement model, and synchronises the general network nodes with double cluster heads to complete the clock synchronisation. The synchronisation accuracy of the node is low, but the synchronisation method needs to be further improved.

Due to the complex environment in which WSN are located, there may be synchronisation errors in the broadcast information frames of nodes, making it difficult to determine the local clock change frequency and the bounded conditions for phase compensation, resulting in large phase estimation errors and large synchronisation time overhead. To solve the problems of the above methods as the research goal, in order to achieve the research expectations of low phase estimation error and low synchronisation time overhead, this paper designs a clock synchronisation method for WSN based on phase compensation. Therefore, this method has the characteristics of low phase estimation error and low synchronisation time overhead. This method can provide an important reference for further optimising the performance of WSN, and has outstanding contributions to the development of this field. The main technical route of this method is:

Step 1 In determining the influencing factors of WSN clock synchronisation, determine the synchronisation deviation value by calculating the broadcast information frame of general nodes, analyse the sine wave in the clock oscillator, extract the instability factor and clock synchronisation delay, and complete the determination of influencing factors of WSN clock synchronisation.

Step 2 In the WSN clock node consistency pre-processing, set the wireless sensor as an undirected graph, determine different sets of nodes, and perform consistency processing on the updated node state through the linear model to complete the WSN clock node pre-processing, so as to provide consistent nodes for subsequent research.

Step 3 In the design of WSN clock synchronisation algorithm based on phase compensation, the local clock change frequency is determined with the help of the least square method, the clock synchronisation compensation estimator is determined through the calculation of slope, the updated network topology of nodes is replaced, the bounded condition of phase compensation is set, and the WSN clock synchronisation based on phase compensation is completed.

## 2 Determination of influencing factors of clock synchronisation and node consistency pre-processing in WSN

### *2.1 Determination of influencing factors of clock synchronisation in WSN*

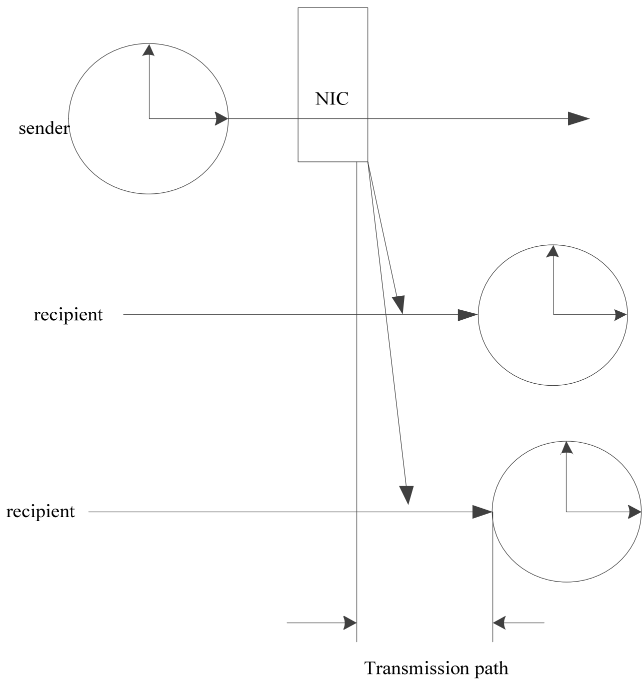
In the process of clock synchronisation in WSN, it is first necessary to identify the factors that affect clock synchronisation. The factors affecting clock synchronisation in WSN include external factors and internal factors. External factors include environment, gas, and other factors. Internal factors include WNS topology, clock source, oscillator, and node performance. Therefore, this paper first analyses the main factors affecting network clock synchronisation, and processes the different influencing factors consistently, which is convenient for the subsequent research of clock synchronisation in this paper. In the clock synchronisation of WSN, one-way message passing time synchronisation is the most common synchronisation method. The energy consumption demand of this time synchronisation method is low, but the influence of gas interference in WSN is not considered too much (Wang et al., 2020). The reference node of WSN will transmit interference information with other nodes in a certain period. The node receiving different information records the receiving time according to the instructions of its street. Therefore, this factor has a direct impact on clock synchronisation. The information received by a general node from a reference node is called a broadcast information frame. Set the current reception time to $p_k$, and $k$ is the broadcast order of the passive receiving node. The offset (Huan and Kim, 2020) of the time of arrival time can be determined. Set any two nodes in the WSN to a and b, then the offset of these two nodes is:

$$offA_{ab} = \frac{1}{m}\sum_{a,b=1}^{n}\left(p_{ak} - p_{ab}\right), \forall_i \in n \tag{1}$$

where, $offA_{ab}$ represents the offset, and $\forall_i$ represents the mean of the node clock offset.

When the transmission time is inconsistent with the time received by the channel, it leads to clock uncertainty. Assuming that the transmission channel of WSN is short, all general nodes can receive synchronisation information at the same time, and the error value of clock can be ignored. The process of generating offset of synchronisation clock in WSN is shown in Figure 1:

**Figure 1** Schematic diagram of offset generation process of synchronisation clock in WSN




Clock synchronisation in WSN is not only affected by external factors, but also unstable. The clock source used in WSN nodes is a quartz crystal oscillator, which is composed of an oscillator and a counter. The main function of the oscillator is to accumulate counts. When the obtained value is greater than the set threshold, the counter saves it through the terminal. The threshold frequency set by the oscillator and the operating frequency of the node are directly determined by Elnahas (2020). The sine wave output by the oscillator is:

$$q(t) = v_0 \cos(2\pi h_0 t + \sigma_0) \tag{2}$$

where, $v_0$ represents the adjustable voltage, $h_0$ represents the ideal frequency, $t$ represents the running time, and $q(t)$ represents the real-time output of the oscillator.

Due to the interference of external factors, the oscillator in the node has a constant change of a certain frequency. At this time, the actual operation of the oscillator; There will be a certain error in the frequency, and the error will expand with the increase of time. The change of this value directly affects the node clock synchronisation, and its operating frequency error is calculated by the following formula:

$$z(x) = \frac{d\tau t}{l} \tag{3}$$

where, the $\tau_t$ node local clock, $l$ represents the real operation time.

During the clock synchronisation of the WSN node, the root node will automatically start the root node according to the current time. Set that the transmission packet of node A at the local time is $T$, and node $B$ receives the packet within the $T$ time, and the resulting clock synchronisation delay is:

$$T = T_1 + T_i + \Delta B \tag{4}$$

where, $T_i$ represents the message synchronous transmission delay, and $\Delta B$ represents the clock offset between nodes.

In determining the influencing factors of clock synchronisation in WSN, the synchronisation deviation value is determined by calculating the broadcast information frame of general nodes, analysing the sine wave in the clock oscillator, extracting the instability factor and clock synchronisation delay, and completing the determination of the influencing factors of clock synchronisation in WSN (Karimi-Bidhendi et al., 2020).

### *2.2 Research on clock node consistency pre-processing in WSN*

According to the above determined clock synchronisation offset, clock oscillator instability parameters and key influencing factors of synchronisation time, in order to ensure the effectiveness of data in different subsequent clocks, it is necessary to pre-process the above obtained influencing factor data in a consistent manner for subsequent research. Consistency is widely used in multi-agent networks. Consistency means that the states of unrelated nodes are consistent in a certain time. Therefore, this paper deals with the consistency of WSN nodes to provide consistency nodes for subsequent clock synchronisation.

Set the WSN as an undirected graph, that is:

$$R = N(C, E) \tag{5}$$

where, $R$ represents the set of nodes, and $N$ represents the number of nodes.

Set the set of WSN node edges as $v$:

$$E \in C \times v \tag{6}$$

In node clock synchronisation, each node will continuously update iteratively and continuously update its own state through neighbour nodes (Shi et al., 2020). At this time, the updated node state is processed through linear model to obtain:

$$y_i(k+1) = y_i(k) + \sum\nolimits_{i \in k} y_i(k)\left[y_i(k) - y_j(k)\right] p_i \tag{7}$$

where, $y_i(k)$ represents the weighted adjacency matrix, and $y_j(k)$ represents the state of the current node, $p_i$ representing the degree of the node.

In the clock node consistency pre-processing of WSN, the wireless sensor is set as an undirected graph, and different sets of nodes are determined. The updated node state is consistent through the linear model to complete the clock node pre-processing of WSN, so as to provide consistent nodes for subsequent research.

## *2.3 Design of clock synchronisation algorithm for WSN based on phase compensation*

Based on the above determined clock synchronisation influencing factors and consistent node status, a wireless sensor network clock synchronisation algorithm based on phase compensation is designed to complete clock synchronisation in WSN. Phase compensation is to allow signal processing to advance or delay, achieving fine adjustments under field synchronisation, ensuring synchronisation quality and efficiency. Applying the phase compensation method to the clock synchronisation process of WSN can accurately compensate the clock delay and ensure the clock synchronisation effect of WSN.

In WSN, the operating frequency of the local clock of a node is constantly changing. Therefore, before performing network clock synchronisation, it is necessary to determine the current change value of the local clock, namely:

$$\omega(t) = (1 + \gamma(t))\omega_0 \tag{8}$$

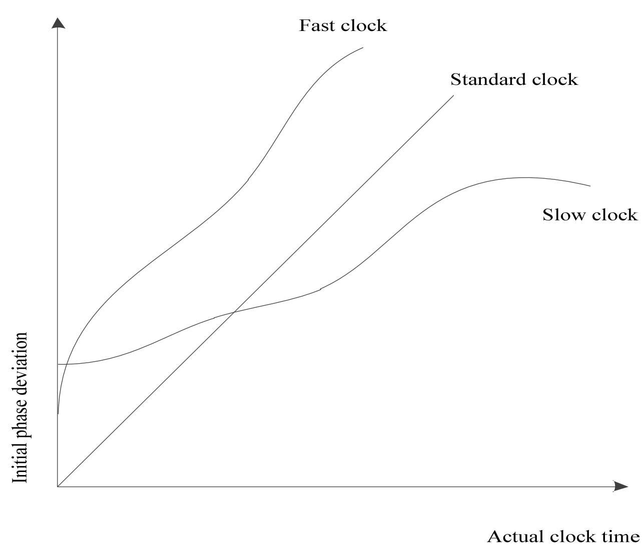
where, $t$ represents the actual operating frequency change value of the local clock, and $\omega_0$ represents the offset value that occurs in the actual frequency.

The local clock change results determined above are embodied into a local clock function model (Yang et al., 2020), and the following results are obtained:

$$f(t) = g(x)\frac{2\pi\left((1 + \gamma(t))v_0\right)}{2\pi\beta}s_i \tag{9}$$

where, $g(x)$ represents the local clock cumulative value, $v_0$ represents the clock operation efficiency, $\beta$ represents the initial phase, and $s_i$ represents the frequency offset value. This value does not change very short over time. A schematic diagram of the local clock offset frequency bias is shown in Figure 2:

**Figure 2** Schematic diagram of local clock offset and frequency offset



When the local clock frequency offset value is determined, the linear equation of the local clock in the WSN node is calculated to obtain the relative clock, that is:

$$H_i = \frac{\delta_j}{\delta_i}\alpha_i + \left(\mu_j - \frac{\delta_j}{\delta_i}\alpha_i\right) \tag{10}$$

where, $\delta_i/\delta_j$ represents the node slope and bias compensation parameter, $\mu_j$ representing the iteration coefficients.

After determining the local clock and relative clock, this paper uses the phase compensation method to realise the design of clock synchronisation algorithm in WSN. Phase compensation is a synchronisation completed by correcting the phase of the virtual clock of each node to make the virtual clock phase consistent with the actual clock phase, that is:

$$\varphi_i + \varphi_j = \overline{\varphi}, i, j \in V \tag{11}$$

Among them, $\varphi_i$ represents the virtual clock node, $\varphi_j$ represents the phase compensation amount, and $\overline{\varphi}$ represents the compensation estimation.

When the WSN node receives the data sent by another node, the phase estimation value of the virtual clock is:

$$\varphi_j = \varphi_j(t) + \rho_t\left[\tau_i\left(\tau_i - \varphi_j\right)\right] \tag{12}$$

where, $\rho_t$ represents the phase estimate, $\tau_i$ represents the runtime frequency value.

According to the determined phase estimation value, the slope of the extreme need to be compensated by the least square method (Wang et al., 2021b), that is:

$$|\zeta| = e\left(\frac{1}{d^{1+u}}\right) \tag{13}$$

Among these, e is the virtual clock slope estimates the error value, d representing the rate of slope convergence. The convergence is the best.

On this basis, when WSN nodes constantly update their virtual clock, they need to replace a new network topology. Set that all structures in the node update process are a fixed topology sub-graph, that is:

$$G(X) \in g, \forall k \in N \tag{14}$$

When the number of clock nodes included in the set sub-graph is constant, assuming that the virtual clock slope meets the conditions, the phase compensation is completed, that is:

$$U = \left|\alpha_i(k)\alpha_i - \alpha_j\right| \tag{15}$$

where, $U$ represents the phase compensation results.

When the conditions are not met, it needs to be updated continuously to meet the following conditions, namely:

$$U \geq 2, K \to \infty \tag{16}$$

$$U < 2, K \to -\infty \tag{17}$$

When the set bounded conditions are met, the phase estimation of all nodes in the network is updated, that is, the synchronisation of network clock is realised, that is:

$$X(k+1) = O\left(f - q_i l(k)\right)\alpha(k)\sum \alpha_i(k)\alpha_i - \alpha_j \tag{18}$$

In them, $q_i$ represents the clock update rule, $l(k)$ represents the virtual node change value, $\alpha(k)$ represents the consistency result of synchronisation, and $O$ represents the node clock compensation amount.

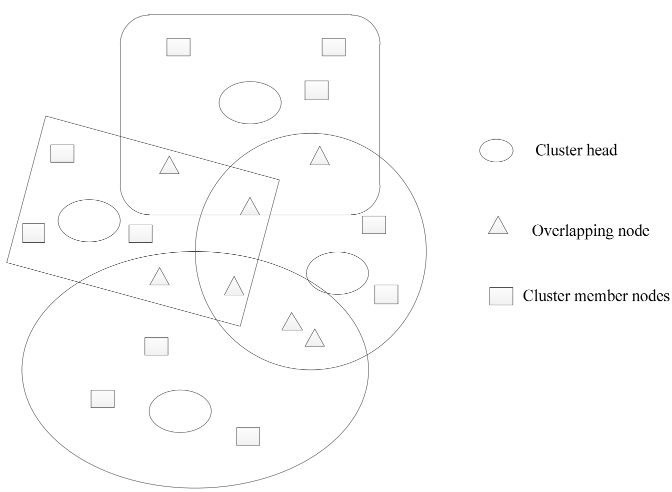
In the design of WSN clock synchronisation algorithm based on phase compensation, the local clock change frequency is determined by the least square method, the clock synchronisation compensation estimator is determined by the calculation of slope, the network topology updated by nodes is replaced, and the bounded condition of phase compensation is set to complete the WSN clock synchronisation based on phase compensation.

## 3 Experimental analysis

### *3.1 Experimental scheme*

This experiment uses a Windows 10 64 bit operating system with an Intel (R) Core (TM) i5-3470 CPU and a 4GB memory size. The MATLAB R2012a version is used. In order to verify the feasibility of the proposed method, experimental analysis is carried out. In the experiment, the topology of WSN is set, and the clock synchronisation in the network is studied. The topology diagram of the experimental network is shown in Figure 3:

**Figure 3** Schematic diagram of experimental network topology




In the Figures, 2, 3, 4 of the cluster heads communicate with each other, and the rough one between the neighbours is a double hop network. The communication between the cluster heads needs to select the overlapping nodes, forward the node messages, synchronise each node in the cluster, and then synchronise the time.

Using data crawler technology to collect wireless sensor network operation data, the collected data is divided into training and test samples in a 4:1 ratio. On this basis, the training sample data is input to the simulation software, and the optimal operation parameters of the simulation software are obtained through multiple trial runs. This parameter is used as the initial simulation parameter to ensure the authenticity and reliability of the simulation experiment results.

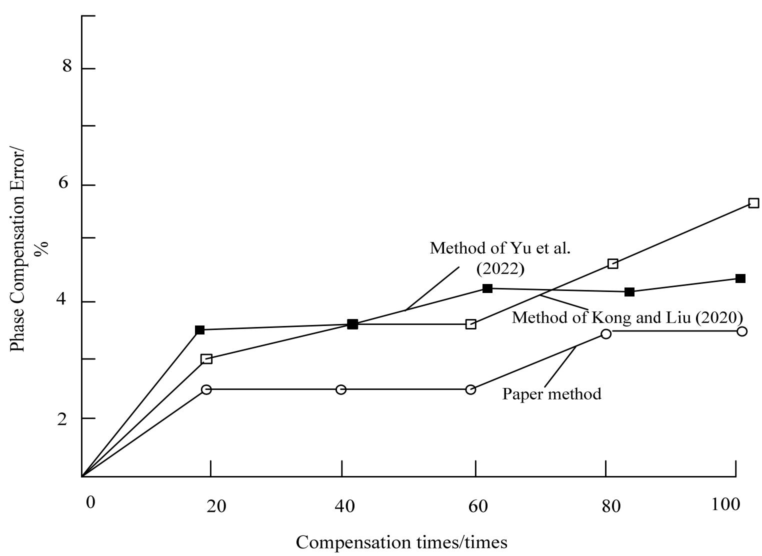
On the basis of the above experimental environment setting, the methods in this paper, Yu et al. (2020) method and Kong and Liu (2020) method are used to synchronise the sample WSN clock to verify the phase compensation error and the time cost of synchronisation respectively. Phase compensation error refers to the difference between the clock synchronisation compensation amount and the actual compensation amount for different methods of WSN. The lower the value, the better the clock synchronisation compensation effect. Clock synchronisation time overhead in WSN refers to the time spent from the beginning of compensation to the end of compensation. The smaller the time overhead, the higher the synchronisation efficiency, and the better the actual application effect.

## *3.2 Analysis of experimental results*

### *3.2.1 Analysis of phase compensation error in clock synchronisation in WSN*

The method in this paper, the Yu et al. (2020) method and the Kong and Liu (2020) method are analysed experimentally to synchronise the sample WSN clock, and the phase compensation error in synchronisation is verified respectively. The results are shown in Figure 4:

**Figure 4** Analysis of phase compensation error in WSN clock synchronisation




By analysing the experimental results in Figure 4, it can be seen that the methods in this article, Yu et al. (2020) method and the Kong and Liu (2020) method synchronise the clocks of sample WSN, respectively verifying that there is always a certain gap in phase compensation errors during synchronisation. The phase compensation error of the Yu et al. (2020) method varies between 0 and 4.3%, while the phase compensation error of the Kong and Liu (2020) method varies between 0 and 5.7%, while the phase compensation error of the method in this article varies between 0 and 3.5%, indicating that the phase compensation error of the method in this article is always low and presents a steady downward trend, while the error compensated by the other two methods is always higher than that of the method in this article. This is because the method in this paper considers the phase estimation of the node virtual clock, and performs multiple corrections to the slope and bias, which improves the compensation accuracy of the method in this paper, and verifies the feasibility of the method in this paper.

### *3.2.2 Time cost analysis of clock synchronisation in WSN*

The time cost of synchronising the sample WSN clock by the method in this paper, the Yu et al. (2020) method and the Kong and Liu (2020) method is experimentally analysed. The experimental results are shown in Table 1:

**Table 1** Time cost analysis of clock synchronisation in WSN (s)

| *Synchronisation times/time* | *Paper method* | *Yu et al. (2020) method* | *Kong and Liu (2020) method* |
|---|---|---|---|
| 10 | 2.1 | 2.5 | 3.1 |
| 20 | 2.5 | 3.9 | 3.9 |
| 30 | 2.7 | 4.2 | 4.1 |
| 40 | 2.8 | 4.5 | 4.3 |
| 50 | 3.1 | 4.8 | 4.7 |
| 60 | 3.2 | 5.1 | 4.9 |
| 70 | 3.4 | 5.3 | 5.3 |
| 80 | 3.5 | 5.8 | 5.4 |
| 90 | 3.5 | 6.1 | 5.8 |
| 100 | 3.5 | 6.3 | 6.1 |

Analysing the experimental results in Table 1, it can be seen that there are certain differences in the time cost of synchronising the clocks of sample WSN using the methods in this article Yu et al. (2020) method and Kong and Liu (2020) method. Among them, the time cost of the Yu et al. (2020) method is up to 6.3s, and the time cost of the Kong and Liu (2020) method is up to 6.1s. The time cost of the method in this paper for synchronising the clock of the sample wireless sensor network is always lower than the other two methods, and the maximum time cost is about 3.5s, while the other two methods are far higher than the method in this paper, and always show a rising trend. It can be seen that the method in this paper has the advantage of faster synchronisation speed.

## 4 Conclusions

Clock synchronisation in WSN is related to the normal operation of network communication. Therefore, this paper designs a new clock synchronisation method in

WSN based on phase compensation. By calculating the broadcast information frame of general nodes, determine the synchronisation deviation value, analyse the sine wave in the clock oscillator, extract the instability factor and clock synchronisation delay, and determine the influencing factors of clock synchronisation in WSN. The wireless sensor is set as an undirected graph, and different sets of nodes are determined. The updated node states are consistent through the linear model, the local clock change frequency is determined by the least square method, the clock synchronisation compensation estimator is determined through the calculation of slope, the updated network topology of nodes is replaced, and the bounded condition of phase compensation is set, complete the clock synchronisation of WSN based on phase compensation. The experimental results show that the phase compensation error of this method varies from 0 to 3.5%, with a maximum time overhead of 3.5 seconds. This indicates that the phase estimation error and synchronisation time overhead of this method in clock synchronisation are small. Therefore, this method has the characteristics of low phase estimation error and low synchronisation time overhead. This method can provide an important reference for further optimising the performance of WSN, and has a prominent contribution to the development of this field of wireless sensing.

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