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A Time Synchronization Protocol for Large Scale Wireless Sensor Networks*

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***Abstract*—In order to improve the precision of time synchronization for large scale wireless sensor networks, a time synchronization protocol based on clock frequency dynamic detection for large scale wireless sensor networks (TSP-CF-LSN) is proposed in the paper. In the proposed protocol, by statistical analysis of the clock frequency data and adaptive clock frequency detection, a quick track strategy is adopted for abrupt clock frequency. In order to reduce the error accumulation of time synchronization in multi-hop, the proposed protocol uses a simple and efficient path selection strategy to minimize the error accumulation. Experimental results indicate that the correct detection rate for large-scale network is over 91% in the range of the clock frequency [-50ppm, 50ppm]. Tested in the same network simulation environment, TSP-CF-LSN protocol is better than FTSP protocol in synchronization accuracy, which is suitable for large-scale wireless sensor networks.**

Keywords—Wireless Sensor Networks; Time Synchronization; Clock Frequency; Dynamic Detection; Path Selection

I. INTRODUCTION

According to the mode of data packet transmission, time synchronization protocols[1-4] are usually classified into three categories : sender-receiver-based two-way synchronization mode, sender-based one-way synchronization mode and receiver-receiver-based synchronization mode. Some typical protocols are TPSN protocol [5], FTSP protocol [6] and RBS protocol [7]. These time synchronization protocols have their own advantages and characteristics, better performances in small and middle scale wireless sensor networks with a constant clock frequency. However, due to the complex and variable environment and long-run period in large-scale networks, sometimes clock frequency abruptly changes [8]. If these time synchronization protocols above are transplanted directly into large-scale networks, time synchronization accuracy will drop sharply.

So far, threshold detection method is generally used to determine the abrupt changes of node frequency [9]. However, the threshold is set according to prior information, and cannot adjust adaptively with the network environment changes. So it is necessary for reducing node clock frequency impact on the accuracy of time synchronization of whole network to take some measures to determine whether the node clock frequency abruptly changes.

To improve the accuracy of time synchronization, nodes need to modify the instantaneous deviation with standard time, and the clock frequency coefficients should be estimated and compensated in the synchronization process. The slope based estimation method[10] with a low computational complexity can achieve a synchronization process by two pairs of synchronization data. Sage-Husa algorithm [11] is an adaptive Kalman filter algorithm based on covariance matching, even though whose accuracy is good, data size to be stored is big and its complexity is high.

No matter what synchronization modes to be used, synchronization error is an inevitable problem in the practical application because of uncertain delay of packet transmission mode[7]. Even more, the accumulative errors will accumulate with the transmission distance increasement. In large-scale network with a large number of nodes, sensor nodes need to be synchronized in multiple hops for energy-saving[12], which result in accumulative errors which affect the synchronization accuracy seriously. It is necessary to propose an effective mechanism to reduce the accumulative errors influence[13-15]. A dynamic path list based time synchronization protocol proposed in [13] can reduce the impact of the accumulative errors effectively.

FTSP protocol [6] deals with root node failure by root node re-election strategy, however which takes a long time to confirm the failure, and needs all nodes to participate in root re-election, these would consume too much energy. In generally, since the node clock frequency changes continuously, the best detection threshold derived from statistical analysis of historical data can quickly and accurately check clock frequency abrupt change. To deal with the clock frequency abrupt change and serious accumulated errors against large-scale wireless sensor networks applications, in this paper, a clock frequency dynamic detection method is proposed for clock frequency detection.

In order to suppress the serious accumulation errors in large-scale networks, the best path is dynamically selected to transmit synchronization packets. Since the root node is the time standard in the network, so it is necessary to apply different failure strategies to deal with general node and the root node. Above all, we propose a time synchronization protocol based on clock frequency dynamic detection for large-scale wireless sensor networks (TSP-CF-LSN).

II. PROPOSED TIME SYNCHRONIZATION PROTOCOL BASED ON CLOCK FREQUENCY DYNAMIC DETECTION

A. Clock frequency dynamic detection method

To increase the accuracy of detecting clock frequency change and enhance the adaptability of the detection method, a dynamic method of detecting clock frequency is proposed in the section.

1) Dynamical setting noise and frequency threshold

To exactly describe the clock frequency change, we define three kinds of clock frequency statuses: the stable mode, observation mode and sudden change mode. When a node receives synchronization data in a synchronization process, firstly the clock frequency is estimated by the slope algorithm, and the instantaneous estimation value is $\hat{\theta}_A$. According to the clock frequency characteristics of sensor nodes, and clock stable performance in its initial phase, nodes could collect and store data in the initial synchronization. Then $\overline{\hat{\theta}_A}$ is the statistical average value of the clock frequency estimation based on the recorded data, and the maximum estimated difference is calculated by $\max(\text{abs}(\hat{\theta}_A - \overline{\hat{\theta}_A}))$, which is the maximum of absolute value of the difference between the estimated value and the estimated average. On the basis of the maximum estimated difference, we can set the first detection reference threshold, i.e., noise detection threshold N_t. To improve the detection accuracy, the maximum estimated difference needs to be expanded slightly as the noise detection threshold N_t. The frequency variable detection threshold S_t is set based on the noise threshold, which is the sum of N_t and the minimum value of frequency variable.

Because of the influence of the cumulative errors in large scale networks, when setting the frequency variable threshold, different cumulative errors for different levels of nodes need to be considered, the setting of the frequency variable threshold S_t needs to be adjusted according to the level the node belongs to.

$$N_t = C \cdot \max(\text{abs}(\hat{\theta}_A - \overline{\hat{\theta}_A})) \tag{1}$$

$$S_t = N_t + M \cdot N_{level} \tag{2}$$

where C is a noise threshold expansion coefficient, here we set it as 1.1; M is the clock frequency minimum detection value, the smaller M is, the higher accuracy the detection method should have. In this paper, M is set as 0.5ppm; $\mathbf{N}_{level}$ is the level number of the node, which is the minimum hop distance to the root node.

2) Dynamical processing of clock frequency

After receiving a new synchronization message, clock frequency needs to be detected first, and then process by the following three situations.

① If the difference d of $\hat{\theta}_A$ and $\overline{\hat{\theta}_A}$ is less than the noise threshold N_t, the clock frequency mode is considered in stable mode. This synchronous data information can be used to estimate the clock frequency d by least square method, update the estimated average $\overline{\hat{\theta}_A}$, noise detection threshold N_t and frequency variable detection threshold S_t.

② If the value of d is greater than the noise threshold N_t, but less than the frequency variable detection threshold S_t, then the clock frequency mode is considered in observation mode. The reason of the node clock frequency variation is that the estimated errors increase rapidly due to the large synchronization noises, so the synchronization information needs to be abandoned, and the clock frequency is estimated with $\overline{\hat{\theta}_A}$, but the history data information does not need to be emptied, and the detection threshold also does not need to be updated.

③ If d is larger than the frequency variation detection threshold, the clock frequency is considered in sudden change mode, all the historical data stored need to be discarded, then $\overline{\hat{\theta}_A}$ 、 N_t and S_t need to be reset, and the data collection will restart.

The researches show that delay error obeys the Gauss distribution with mean 0. According to the maximum likelihood estimation method[16-18], when a clock frequency keeps steady, the more data information we get, the closer to the true value of the clock frequency $\overline{\hat{\theta}_A}$ is. According to this characteristic, when a node is in stable mode for a long time, to improve the clock frequency detection performance, the noise threshold N_t should be reduced. Since the value of S_t is calculated from N_t, so S_t will decrease with the decreasing of N_t. A great deal of experiments has proved that this strategy could reduce the clock frequency detection error rate effectively.

B. Time synchronization protocol implementation process based on clock frequency dynamic detection

A time synchronization protocol based on clock frequency dynamic detection method is designed for large scale wireless sensor networks(TSP-CF-LSN). The protocol is a time synchronization protocol based on the sender-based one-way synchronization mode. Since this protocol uses flooding broadcast mechanism to send synchronous messages, which is similar to the FTSP protocol, so it insures that a new node can immediately participate in the time synchronization process, and ensures the scalability of the protocol. TSP-CF-LSN protocol is a time synchronization protocol which uses the dynamic election method to select root node. In the network synchronization process, the minimum hops from a node to the root node determine the level the node belongs to, the level information and timestamp information will be embedded into synchronous messages as an important basis to test the validity of synchronous messages data. The clock frequency transient states of nodes are accurately monitored by using dynamic detection method, and the clock frequencies of nodes are estimated by the least squares method and the slope estimation method. In order to restrain the serious accumulative errors in large-scale networks, TSP-CF-LSN protocol adopts a simple and effective dynamic path selection mechanism. TSP-CF-LSN protocol handles node failure with root node re-election and updates node information to ensure the robustness of the protocol. The following will introduce the division of time synchronization network structure, multi-hop synchroni-zation path selection and node failure coping strategies regarding to this protocol respectively.

1) The division of time synchronization network structure *a) Root node election*

The root node election strategy in TSP-CF-LSN protocol is similar to that in FTSP protocol, in the network set-up stage, a unique ID number will be assigned for each node; in the synchronization establishment stage, the root node election is initiated by any node. The root node is the time standard for the whole network.

Fig.1 shows the root node election and the level division, the grid network in Fig.1 consists of 18 nodes, the root node number saved in a node is empty, every node will set its own ID as the root node number. In Fig. 1, we suppose that the node whose ID is 4 starts root node election. The node 4 will send a root node election message to neighbor nodes in its broadcast domain, the root node number in the message is 4. When node 6 receives the root node election message, node 6 will find the root node number saved by itself is empty, and the root node number in the message is 4, which is less than its own ID, so node 6 will update the stored root node number to 4, and send the root node election message with root node number 4. When node 0 receives the root node election message from node 4, and finds that the root node number is 4, which is bigger than its own ID, the newest root node number is 0, reseal the election message and send out. When node 4 receives the root node election message from node 0 and finds the root node number is 0, which is less than the stored root node ID, so node 4 updates the stored root node ID to 0. Once the node finds the stored root node ID change, the node will send root node election message again. At last the network will elect the node with the smallest ID as the root node, in Fig.1, node 0 will become the root node of the time synchronization network.

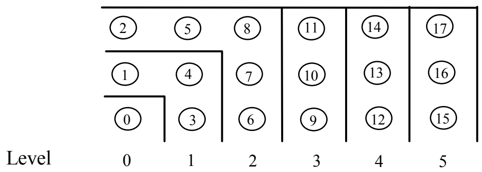

Fig. 1. The root node election and the level division

b) Level division

The level division of TSP-CF-LSN protocol just needs to determine the minimum hops between root node and the node to be divided, and set the minimum hops as own level number. The flooding mechanism is still used in the level division synchronization process, but when a node receives a synchronization message, the level information of the node will be used to test the synchronization message and determine the effectiveness of the synchronization message. This not only ensures the expandability of TSP-CF-LSN protocol but also eliminates the redundant information, and reduces the influence of the accumulative errors.

In Fig.1, the root node set its own level number as 0 and broadcasts the level discovery message with its own level number. Node 1, node 3 and node 4 in the broadcast domain of node 0 receive the level discovery message and extract the level information, then their own level number will plus 1 on the basis of the received level information, the level number of node 1, node 3 and node 4 will be set as 1 respectively. Then the nodes will update the level number in their messages to 1 and continue to broadcast, the nodes without their own level number which receive the message will update their level number to 2. The process will last to the edge nodes until all the nodes own a level number.

2) Multi-hop synchronization path selection

In large scale network, if the nodes which are out of the root node communication area want to achieve time synchronization information, they need to rely on other neighbor nodes to transmit synchronous messages. In time synchronization process, there are generally several synchronization paths to be chosen. If a node selects a path with a small synchronization accumulative error, it can effectively improve the synchronization accuracy. In the TSP-CF-LSN protocol, the dynamic detection method is used to estimate the clock frequency, the variable Num is used to save the number of the effective historical data information in the detection process, and the initial value is set to 0. If the detected clock frequency is not changed, Num increases by 1, otherwise, Num is set to 0. The greater Num is, the more stable the node clock is, the smaller the accumulative error is.

After receiving time synchronization messages, the TSP-CF-LSN protocol will adopt the earliest arrived message. In order to ensure that the node could select a path with a smaller synchronization accumulative error and make sure the time synchronization messages with better quality will sent earlier, TSP-CF-LSN protocol uses the variable Num in the dynamic detection method to control the send rate of the time synchronization messages. The greater the Num is, the faster the node sends messages, on the contrary, the smaller the Num is, the slower the node sends messages. Fig.2 shows multi-hop synchronization path selection. Nodes D can receive the time synchronization messages from node A, node B and node C. Suppose the Num values of node A, node B and node C are 10, 20 and 5 respectively, which means node B are more stable than node A and node C in the past period, we hope node D receive the time synchronization messages from node B. Before a node sends time synchronization messages, TSP-CF-LSN protocol will add a waiting delay T_{delay}

$$T_{delay} = T / Num \quad (3)$$

where T is a fixed time constant. As the existence of the processing delay, the sending delay and the channel idle listening waiting delay in the transmission of the time synchronization messages, so the value of T should not be too small and the value of T is 0.1s in this paper. The greater Num is, the smaller the waiting delay is, the shorter the waiting time before sending messages is, and the synchronization messages could be sent out early.

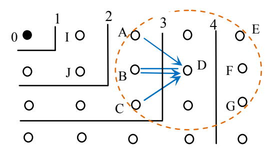

Fig. 2. Multi-hop synchronization path selection mechanism

3) Node failure coping strategies

a) Root node failure coping strategies

Because root node is the time standard of a network, so it's important for the time synchronization protocol. If the root node fails, it will cause a fatal damage to time synchronization service. So, when the root node fails, the time synchronization protocol is required to have the ability to respond quickly, and provide an effective solution strategy.

A time synchronous messages are sent by root node periodically, if other neighbor nodes cannot receive a new synchronous message for a long time. This can determine that the root node has failed and a new root node should be re-elected. In FTSP, root node failure time length is represented by TTL. Root node re-election will be started when other nodes do not receive a new synchronous message for more than one TTL time. In large scale networks, there are many numbers of nodes. If all of the nodes participate in root node re-election, the convergence rate will slowdown rapidly and it will increase energy consumption greatly. In addition, it will cost time to transmit the synchronization messages. When root node fails, edge nodes need to spend more time to determine this failure. In FTSP protocol, the value of TTL is usually depended on time edge nodes. When the scale of network is too large, it's difficult to determine the root node failure in time.

In TSP-CF-LSN protocol, to avoid too much energy and time consumption for root node re-electing, node level information strategy is fully adopted. Comparing with other level number nodes, the nodes with level numbers 1 are closest to root node, and can find the root-node's failure early, so the range of the root node re-election is narrowed to the nodes whose level number are 1. If the nodes with level number 1 do not receive a new synchronization message within 2 synchronization periods, the nodes with level number 1 will start the root node re-election and the node with the smallest ID in level 1 will be appointed as a new root node. The new root node will restart the time synchronization process. In this root node re-election strategy, the amount of data packets are reduced largely, which is benefit for energy saving.

b) Ordinary nodes failure coping strategies

The so-called ordinary nodes are all nodes except the root node in the network. Since the TSP-CF-LSN protocol uses flooding broadcast mechanism to send synchronization messages, in which a node's failure will rarely influence the whole network. As long as the nodes affiliated the failed nodes can receive the synchronization messages from other nodes, they can continue to conduct the synchronization process.

However, there is a special situation in TSP-CF-LSN protocol. In the network topology structure as shown in Fig.3, node 1 is the root node, and node 12 can receive synchronization messages from node 8 and node 2. The level number of node 8 is 2, and the level number of node 2 and node 12 are 3 respectively. According to the TSP-CF-LSN protocol, a node can only synchronize with the node whose level is smaller than itself; so, node 12 can only adopt the synchronous messages from node 8. If node 8 fails, in despite of node 12 can receive the synchronous messages from node 2, the synchronization process cannot be completed for the restriction of levels. In order to solve the problem above effectively, TSP-CF-LSN protocol assumes that if an ordinary node does not receive a new synchronization message from upper level node within 2 synchronization periods, it should update its own level number by adding 1 as a new level number. By this strategy, the protocol can effectively solve the level restriction problem on synchronization messages. Once there is a synchronized node in the node communication radius, the time synchronization can be finished.

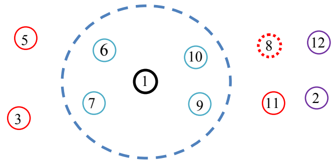

Fig. 3. Network topology structure

III. SIMULATION AND ANALYSIS

To verify the performance of TSP-CF-LSN protocol, a great deal of simulation experiments are conducted in NS2 (Network Simulator Version 2) simulation software. NS2 can be used to simulate the operation process of a real network, allow you to add all kinds of network protocols. First, verify the importance of clock frequency test based on the clock frequency change mode, and analyze the performance of the clock frequency dynamic detection method. Second, examine the inhibition effect of cumulative errors in TSP-CF-LSN with the multi-hop synchronization path selection mechanism. Final, the TSP-CF-LSN protocol is transplanted into various simulation environments such as different scales, different clock synchronizing periods and different estimation methods.

A. Performance of clock frequency dynamic detection

Fig.4 is a comparison of FTSP protocol based on constant clock frequency mode, FTSP protocol based on clock frequency change and TSP-CF-LSN protocol based on clock frequency change. As shown in Fig.4, FTSP protocol with constant clock frequency mode has a smallest synchronization error which is 2.2054μs within the scope of one hop. As the increase of hops from the root node, the synchronization errors increase gradually. When the maximum level of a net is 11 hops, the average synchronization error is 3.2483μs. When FTSP protocol is applied to clock frequency change mode, as a clock frequency detection mechanism is not used in the protocol, when the clock frequency changes abruptly, historical data couldn't be emptied in time, the rapid increased synchronization errors result in that one hop error is up to 35.862μs and average error is up to 45.062μs.

TSP-CF-LSN protocol can effectively detect the clock frequency change by a dynamic detection method. Meanwhile the cumulative errors can be suppressed by the multi-hop synchronization path selection mechanism. In TSP-CF-LSN protocol, in order to further improve the synchronization precision in one hop range, the maximum likelihood estimation method is adopted in one hop synchronization, the one hop synchronization error is 2.6062μs corresponding to FTSP protocol based on constant clock frequency mode. The average synchronization error of TSP-CF-LSN protocol is 5.9538μs, which is slightly higher than FTSP protocol based on constant clock frequency mode but far lower than FTSP protocol based on clock frequency change mode. As shown in the experimental data, it is important for time synchronization protocols based on clock frequency change mode to conduct the clock frequency detection.

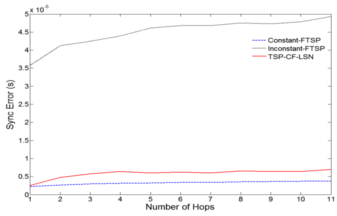

Fig. 4. Comparison of different clock frequency mode

B. Multiple hops routing selection mechanism

Fig.5 is a comparison of TSP-CF-LSN based on multi-hop synchronization path selection mechanism(MPS-TSP-CF-LSN) and without the mechanism(NMPS-TSP-CF-LSN). In the experiment we choose a net with 100 nodes, maximum level number is 11. As shown in the figure, at the former 5 levels, the synchronization errors of two teams are almost the same. But from the 6th level, the team based on the mechanism is obviously lower than the team without the mechanism. The average synchronization errors of two teams are 6.042μs and 6.5068μs respectively, which indicate that the protocol with the mechanism performs better than the protocol without it. As we can know from the experimental data, multi-hop synchronization path selection mechanism has an inhibitory effect to cumulative errors.

Fig.6 shows that there are a few networks which nodes are 300, 600 and 900 respectively, in each network the distances between the nodes are adjusted according to the number of nodes to ensure the maximum number of level is 28. In order to keep the edge nodes collect enough data, we extend the simulation time to 6000s. The experimental data show that time synchronization errors are inversely proportional to the number of nodes, more nodes, less errors. Because the nodes number is larger for the same maximum level, there are more choices for the better path selection to suppress the effect of accumulative errors and increase the accuracy.

C. TSP-CF-LSN protocol performance analysis

Fig.7 is the comparison of synchronization errors of different synchronization periods. As shown Fig.7, the synchronization periods are set 15 s、30s、45s and 60s respectively, when the synchronization period is prolonged, synchronization errors increase. We can cut down the synchronization period to get higher synchronization accuracy. But the shrinking of the synchronization period indicates that nodes need more frequent massage exchange in the same operation period, which will speed up the energy consumption. Synchronization period depends on specific application with the certain requirement of synchronization accuracy, which needs a balance between synchronization accuracy and energy control.

Nodes get the synchronization massages by transmitting packets which can be disturbed by a series of uncertain factors in the transmission. Researches show that these interferences will generate a random delay noise, which statistic feature is a Gaussian distribution with zero mean error. In the simulations, different wireless sensor network environments are simulated by changing the stochastic delay noise variance. Fig.8 is a comparison of synchronization errors with different stochastic delays, which shows that with the increasing of noise, the synchronization errors increase.

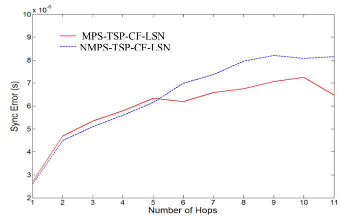

Fig. 5. Path selection mechanism synchronization error comparison

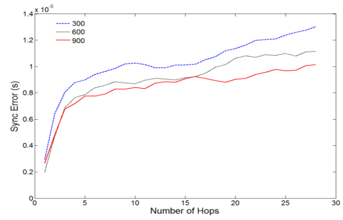

Fig. 6. Synchronization error comparison for different network scale

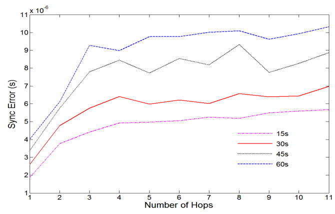

Fig. 7. Comparing synchro-errors within different synchro-periods

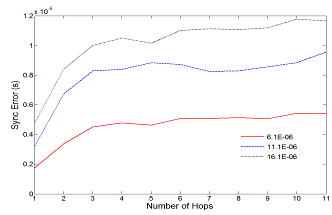

Fig. 8. Synchronization error comparison for different random delay

The fluctuation of clock frequency is influenced by factors such as temperature, pressure and humidity. In the simulation, simulating the reality status of the network, 20% of the nodes are randomly selected to change their clock frequencies. Fig.9 is the comparison of synchronization errors with different scopes of frequency change. Here we set three scopes: [-50ppm,+50ppm], [-30 ppm,+30 ppm], [-15 ppm,+15 ppm]. The larger the scope is, the higher detection accuracy is. But the data indicate that the synchronization errors grow with the increasement of frequency scope, which shows that the dynamic detection only controls the effects of clock frequency sudden change in a certain degree, cannot completely eliminate the effects on synchronous precision.

By comparing various protocols, there are many kinds of clock frequency parameter estimation methods such as least square method, based on the slope method, Sage-Husa are used widely. The method based on the slope needs a small number of nodes and has a lower computational complexity, but the

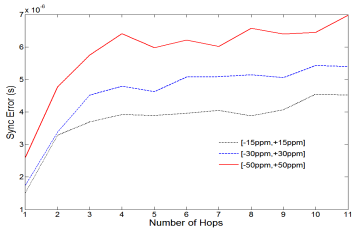

Fig. 9. Comparising synchro-errors within different clock frequency range

synchronization precision is poor. Hage-husa consumes more dedicated space to store data for a high computational complexity and precision. Least square method performs between the two above. We use least square method to estimate clock frequency in TSP-CF-LSN protocol. Fig.10 shows the comparison of the synchronization errors with different clock frequency estimation methods. Node clock is based on the clock frequency change mode, there will be two dynamic detection methods by clock frequency estimation based on the slope method and Sage-Husa, compare the two dynamic detections with designed TSP-CF-LSN protocol. It is observed that the method based on slope has the biggest errors and TSP-CF-LSN has better than the method based on slope while error of Sage-Husa is the smallest one. But Sage-Husa does not adopt multi-hop synchronization path selection mechanism so its errors will grow fast with the hops increasing to root node, as well as, the algorithm complexity is high. Therefore, we choose the less complex least square method for TSP-CF-LSN to estimate the clock frequency.

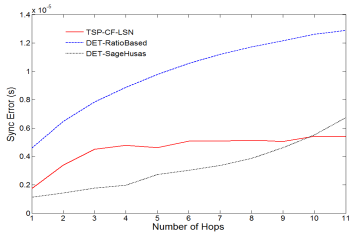

Fig. 10. Comparising synchro-errors for different clock frequency estimation

IV. CONCLUSIONS

It's a key problem for large scale WSN time synchronization to solve node clock frequency sudden change. The strategy of applying clock frequency dynamic detection method to time synchronization protocol is a preferable choice. A large amount of simulation data show that the protocol designed by multi-hop synchronization path selection mechanism in this paper has a better precision than classical synchronization protocol FTSP. Different strategies are adopted to deal with the problems of root node failure and ordinary node failure.

So far, researches on WSN time synchronization mainly focus on accuracy, while in practical applications, relative to the importance of synchronization for the whole net, the performances such as safety, energy control and convergence time are equally important. It's necessary for kinds of large-scale wireless sensor networks to study new time synchronization protocols.

Acknowledgments

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