Robust and Energy Efficient Clock Synchronization Scheme for Wireless Sensor Networks

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***Abstract*— In this paper, a robust and energy efficient clock synchronization protocol for wireless sensor networks is introduced. In the proposed scheme a pair of nodes is synchronized by a sender-receiver synchronization protocol while the third node in their range can synchronize with them by overhearing the transmitted messages. This node is synchronized by a new receiver-receiver synchronization protocol without exchanging any extra messages which helps to save its energy. Then, using this fact that this three nodes form a loop, each pair of them can reduce their synchronization error by exchanging their estimated relative clock offsets. We show that the developed receiver-receiver scheme outperforms the classic liner regression based protocols in terms of synchronization accuracy by analysis. Also, the developed scheme is robust against the link delay variance by using the exact relation between the nodes' synchronization error in the loop. Simulation results are provided to justify the analytical derivation and comparisons with another scheme.**

I. Introduction

Clock synchronization is a prerequisite for deployment of Wireless Sensor Networks (WSN) in many applications like target tracking and environmental observation. Also, for network management protocols such as sleep-awake scheduling the accuracy of clock synchronization is important.

Since the clock of each node in the network is unstable and error pron some protocols should be employed to synchronize nodes with each other. In recent years, many protocols has been introduced for clock synchronization in WSN.

Generally, in clock synchronization protocols two approaches are applied for pairwise clock synchronization. In the first approach which is refereed as Receiver-Receiver Synchronization (RRS), a reference node broadcasts a message and two receivers exchange their reception time to synchronize with each other. The most popular protocol which uses this approach for pairwise clock synchronization is Reference Broadcast Synchronization (RBS) protocol [1]. In this protocol, two receivers apply linear regression technique to estimate their relative clock. The message which is sent by the reference node does not include any time information so its length is smaller than the one with time information. Therefore, its transmission requires less energy compared with a time included message.

The other pair wise clock synchronization approach is Sender-Receiver Synchronization (SRS). In the protocols which deploy SRS approach, two nodes exchange two-way messages, in order to synchronize with each other. Generally, the synchronization accuracy obtained by SRS protocols is better than synchronization accuracy which is achieved by RRS protocols. In the other hand, as in SRS protocols two-way message exchange is required; more messages would be transmitted between nodes compare to RRS protocols.

One of the most famous SRS protocol is Timing-sync Protocol for Sensor Networks (TPSN) [2]. In this protocol, the average of relative clock offset and round trip delay of a pairwise are obtained. In recent years, many papers introduce schemes for improving performance of the TPSN pairwise clock synchronization protocol [3], [4]. In [3], Maximum Likelihood Estimation (MLE) technique is applied for finding relative clock offset between pairs. The algorithm which is introduced in [4] has less computational complexity than the one introduced in [3] and also provides better synchronization accuracy.

Both SRS and RRS approaches are applied in the recent developed protocols. In [5], it is shown that combination of both synchronization approaches is led to better clock synchronization performance for pairwise synchronization. Therefore, the introduced pair wise clock synchronization toggles the employed synchronization scheme from TPSN to RBS when their synchronization accuracy achieve to a predefined threshold.

In [6], a pairwise uses SRS scheme which is introduced in [3] to synchronize. In addition, their neighbors can receive their exchanged messages and synchronize with them using RBS protocol. Therefor, some nodes can synchronize with each other without exchanging any extra messages in this protocol. Using this protocol saves more energy in the network in comparison to the protocols which only use SRS approach for clock synchronization. In the other hand, by using RRS protocol a pairwise achieves less accuracy in their clock than using SRS scheme. Therefore, by applying this protocol the maximum synchronization error would notably increase.

There are other techniques to improve the pairwise clock synchronization accuracy. For example in [7] after synchronizing all existing pair nodes in the network, the synchronization accuracy in the network would be soften by solving

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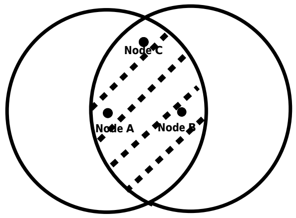

Fig. 1. Overlapping the radio range of two nodes

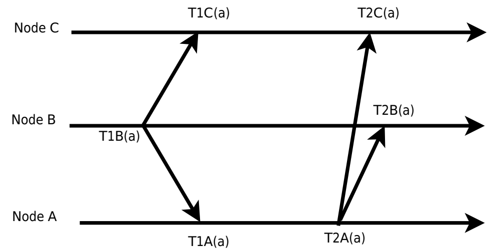

Fig. 2. Message Exchange Model

an optimization problem over all pairs which are forming a loop. This optimization problem is solved over some of loops in the network so that all nodes are included. It is shown that applying this algorithm will improve the synchronization robustness against network's links delays' variances. The proposed algorithm can't employ in the network in distributed fashion and some information should be known by nodes, e.g., the total number of nodes and network's loop information. In addition, some extra messages should be transmitted in the network for improving the synchronization accuracy, using this protocol.

In this paper, both SRS and RRS synchronization schemes are used. The maximum synchronization error in the network is improved compare to the one which is presented in [6]. Also, a distributed algorithm is applied to improve the synchronization accuracy and increase the robustness of the proposed protocol.

The rest of this paper is organized as follow. The main idea and system model are presented in section II. The pairwise clock synchronization is described in section III. An algorithm for improving the performance of clock synchronization protocol is presented in section IV. In section V, the simulation results are illustrated. Finally the conclusion and future works are represented in section VI.

II. Main Idea and System Model

The radio range of a node is assumed to be a circle shape with a defined radius which depends on its transmission power. Figure 1 shows the radio range of node A and node B, where nodes in shaded area, i.e., node C, are in the range of both A and B and thus can receive messages from both these nodes.

Let A and B use SRS approach for estimating their relative clock offset. Figure 2 shows the model of message exchange between A, B and C, where A and B use two-way message exchange and C overhears the transmitted messages between A and B. From Fig. 2 we can write the timing equations.

$$\begin{aligned} T^a_{1,B} &= t^a + \phi_B \\ T^a_{1,C} &= t^a + \xi^a_{BC} + \phi_C \\ T^a_{1,A} &= t^a + \xi^a_{BA} + \phi_A \\ T^a_{2,A} &= t^a + \xi^a_{BA} + \theta + \phi_A \\ T^a_{2,B} &= t^a + \xi^a_{BA} + \theta + \xi^a_{AB} + \phi_B \\ T^a_{2,C} &= t^a + \xi^a_{BA} + \theta + \xi^a_{AC} + \phi_B \end{aligned} \tag{1}$$

Where t^a represents the reference clock or universal clock. ϕ_A, ϕ_B, and ϕ_C are the local clocks of A, B, and C respectively. The relative clock offset of A and B is shown by $\phi_{AB} = \phi_A - \phi_B = -\phi_{BA}$. Also, the relative clock offset of B and C is shown by $\phi_{CB} = -\phi_{CB}$ and the relative clock offset of A and C is shown by $\phi_{CA} = -\phi_{CA}$.

It is assumed that when A receiving messages from node B, after θ unit time, answer to node B. This assumption doesn't cause any loss of generality as the interrupt handling delay is considered in link delay.

ξ_{AB} and ξ_{BA} are the random link delays between A and for upload link, i.e., sending message from A to B and for download link, i.e., sending message from B to A respectively. ξ_{AC} and ξ_{BC} represent the random link delays between pair wise nodes A and C and pair wise nodes B and C respectively. The link delays are assumed to have exponential probability density function(PDF) [9]. It should be mentioned that link delays can be symmetric or asymmetric. We assume the symmetric links in this paper. Therefore, ξ_{AB} and ξ_{BA} have equal mean parameter which is denoted by $\lambda_{AB} = \lambda_{BA}$. Also, λ_{BC} and λ_{AC} are shown the mean parameter of ξ_{BC} and ξ_{AC} respectively.

Let $1 \leq a \leq M$ be the number of observations where M is the total number of observations for all nodes in the network.

In the proposed algorithm, a pair of defined nodes uses the SRS protocol which is introduced in [3] to synchronize with each other. Their neighbors can receive the exchanged messages between this pairwise by overhearing. Thus, they can use RRS synchronization to synchronize with them without exchanging any extra messages. The maximum synchronization error in the network is hence reduced compare to [6]. Also, a new distributed algorithm is introduced to improve accuracy and increase the robustness of the protocol.

III. Pairwise Clock Synchronization

Let A and B synchronize with each other using SRS and node C, which is the neighbor of both A and B, independently synchronize with both of them using RRS approach.

In this section, both SRS and RRS approaches which are employed in the proposed protocol is described with more details.

A. Sender-receiver clock synchronization

As mentioned, for estimating relative clock offset between A and B, the SRS approach is employed. Node B sends its local time at $T^a_{1,B}$ to A. Node A receives and time stamps this message at $T^a_{1,A}$ and after stamping its reception time at $T^a_{2,A}$

sends the message back to B. Finally, B receives this message at $T^a_{2,B}$. So two nodes can be synchronized using (2) [3].

$$\hat{\phi}_{AB} = \frac{1}{2}\left[\min_{(1\leq a\leq M)}(T^a_{1,A} - T^a_{1,B}) - \min_{(1\leq b\leq M)}(T^b_{2,B} - T^b_{2,A})\right] \quad (2)$$

It should be mentioned that (2) is applied when the link delays are assumed to be random variables with exponential PDF.

B. Receiver-Receiver Synchronization

Since C is in the radio rang of B, it can receive the message consists of $T^a_{1,B}$ which is transmitted by B to A when they synchronize with each other using SRS algorithm. Also, since C is the neighbor of A, it can receive $T^a_{1,A}$ when A sends the synchronization message to B. Therefor, (3) can be derived.

$$\begin{aligned} T^a_{1,C} - T^a_{1,A} = T^a_{1,B} - \phi_B + \xi_{BC} + \phi_C - \\ (T^a_{1,B} - \phi_B + \xi_{BA} + \phi_A) \\ = \phi_c - \phi_A + \xi_{BC} - \xi_{BA} \end{aligned} \quad (3)$$

To achieve more accuracy in estimating relative clock offset, $|\xi_{BC} - \xi_{BA}|$ should be the smallest over all observations.

In addition, the transmitted message from B has its local time, while the reference message which is broadcasted by reference node in RBS protocol, doesn't include any time information. This extra information can be used to improve synchronization accuracy in RRS scheme.

By employing maximum likelihood estimation and using the same analysis described in [7], (4) can be derived.

$$\begin{aligned} \hat{\phi}_{CA} = min_{1\leq a\leq M}(T^a_{1,C} - T^a_{1,B}) - \\ min_{1\leq b\leq M}(T^b_{1,A} - T^b_{1,B}) = \\ min(\phi_A + \xi^a_{BA}) - min(\phi_C + \xi^b_{Bc}) = \\ \phi_C - \phi_A + min(\xi^a_{BC}) - min(\xi^b_{BA}) = \\ \phi_{CA} + \xi_{BC(1)} - \xi_{BA(1)} \end{aligned} \quad (4)$$

Where $\xi_{BC(1)}$ and $\xi_{BA(1)}$ represent the first order statistic of ξ_{BC} and ξ_{BA} respectively.

Figure 3 shows the simulation result of running this protocol 1000 times in the presence of exponential link delays with mean $\lambda = 1$. Also, its comparison with the linear regression technique is illustrated. As you can see the synchronization error is significantly improved using the proposed algorithm.

The same algorithm can be deployed for synchronizing the pair of B and C.

IV. Improving The Synchronization Error

It is obvious that the relative clock offset of a node with itself is zero. Therefore, in the cycle which consists of nodes A, B and C the simple equation can be written as follows.

$$\phi_{AB} + \phi_{BC} + \phi_{CA} = 0 \quad (5)$$

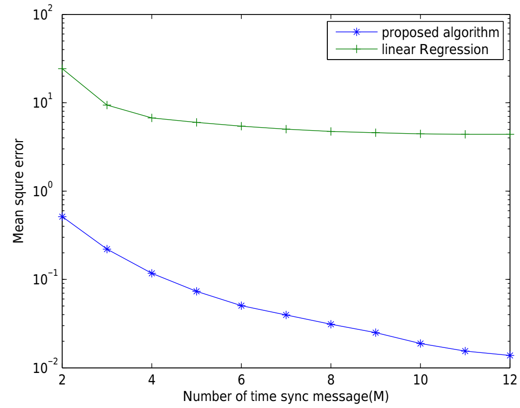

Fig. 3. comparison of proposed algorithm and the linear regression technique in presence of exponential delay with parameter $\lambda = 1$

Using this equation the exact total synchronization error of relative clock offset between pair nodes A and B, pair nodes A and C and pair nodes B and C can be determined.

$$\begin{aligned} &\hat{\phi}_{AB} + \hat{\phi}_{BC} + \hat{\phi}_{CA} \\ &= \phi_{AB} + \phi_{BC} + \phi_{CA} + \mathcal{E}_{AB} + \mathcal{E}_{BC} + \mathcal{E}_{CA} \\ &= \mathcal{E}_{AB} + \mathcal{E}_{BC} + \mathcal{E}_{CA} \end{aligned} \quad (6)$$

Where $\mathcal{E}_{AB}$, $\mathcal{E}_{BC}$, and $\mathcal{E}_{CA}$ are the synchronization error of pair nodes A and B, pair nodes B and C and pair nodes C and A respectively.

Determining the total synchronization error can boost the synchronization accuracy. If each pairwise estimates its synchronization error, the pair nodes can restore their relative clock offsets.

However, (6) just defines the total error of synchronization between three pairs and the synchronization error of each pairwise isn't recognizable.

The synchronization error depends on the link delays status. The synchronization error will be increased when the mean of link delays increase. Proposition 1 and proposition 2 show the relation between the mean of link delays and synchronization error.

Proposition 1: If A and B are synchronized using SRS scheme in (2), the synchronization error is given by (7).

$$\mathcal{E}_{AB} = \frac{\lambda_{AB}}{2M} \quad (7)$$

Proof: From (2) we conclude that:

$$\hat{\phi} = \frac{1}{2}\left[2\phi_{AB} + min_{1\leq a\leq M}(\xi^a_{BA}) - min_{1\leq a\leq M}(\xi^a_{AB})\right]$$

$$\mathcal{E}_{AB} = \frac{1}{2}(min_{1\leq a\leq M}(\xi^a_{BA}) - min_{1\leq a\leq M}(\xi^a_{AB})) = \frac{1}{2}(\xi_{BA(1)} - \xi_{BA(1)}) \quad (8)$$

Where $\xi_{AB(1)}$ and $\xi_{BA(1)}$ represent the first order statistics of ξ_{AB} and ξ_{BA} respectively and $\mathcal{E}_{AB}$ is the synchronization error between pairwise nodes A and B. As mentioned, the link delay between two nodes has the exponential probability density function. Thus the link delay can be modeled as follows.

$$f_{\xi_{BA}}(\xi_{BA}) = \frac{1}{\lambda_{BA}} e^{\frac{-\xi_{BA}}{\lambda_{BA}}} \tag{9}$$

$$f_{\xi_{AB}}(\xi_{AB}) = \frac{1}{\lambda_{AB}} e^{\frac{-\xi_{AB}}{\lambda_{AB}}} \tag{10}$$

Assuming symmetric link delays we have $\lambda_{BA} = \lambda_{AB} = \lambda$. The PDF of first order statistic of $f_{\xi_{BA}}$ after M observation can be written as follows [8].

$$f_{\xi_{AB(1)}}(\xi_{AB}) = M(1 - F_{\xi_{AB}}(\xi_{AB}))^{M-1} f_{\xi_{AB}}(\xi_{AB}) = \frac{M}{\lambda} e^{-\frac{M}{\lambda}\xi_{AB}} \tag{11}$$

$$f_{\xi_{BA(1)}}(\xi_{BA}) = M(1 - F_{\xi_{BA}}(\xi_{BA}))^{M-1} f_{\xi_{BA}}(\xi_{BA}) = \frac{M}{\lambda} e^{-\frac{M}{\lambda}\xi_{BA}} \tag{12}$$

Consider the functions $Z = f_{\xi_{AB(1)}}(\xi_{AB}) - f_{\xi_{BA(1)}}(\xi_{BA})$ and $S = f_{\xi_{BA(1)}}(\xi_{BA})$. As the Jacobian of this transformation is 1, they are independent and their joint distribution can be concluded as follows.

$$f_{z,s}(z,s) = f_{\xi_1 \xi_2}(z+s, s) = f_{\xi_{AB(1)}}(z+s) f_{\xi_{BA(1)}}(s) = \frac{M^2}{\lambda^2} e^{-\frac{M}{\lambda}(z+s)} e^{-\frac{M}{\lambda}s} \tag{13}$$

Now with the respect of Z we can write (14).

$$f_Z(z) = \begin{cases} \frac{M}{2\lambda} e^{-\frac{M}{\lambda}z}, & z > 0 \\ \frac{M}{2\lambda} e^{\frac{M}{\lambda}z}, & z < 0 \end{cases} \tag{14}$$

The expected value of Z can be derived.

$$E[Z] = \frac{\lambda}{M} \tag{15}$$

Finally the $\mathcal{E}_{AB}$ can write as equation (7). ■

Figure 4 shows the mean square error of SRS as a function of λ for synchronizing A and B by analytical and simulation.

Proposition 2: If A and C are synchronized using RRS scheme in (4), the synchronization error is given by (16).

$$\mathcal{E}_{AC} = \frac{\lambda}{M} \tag{16}$$

Proof: The proof is exactly the same as in proposition 1. However, as there is only one way message exchanging the result is twice greater than (7). ■

Figure 5 shows the mean square error of RRS as a function of λ for synchronizing A and B by analytical and simulation.

Base on propositions 1 and 2, each pair can estimate its error using equation (17) and (18) where $\mathcal{E}_{total}$ represents the total error.

$$\mathcal{E}_{BC} = \frac{2\lambda_{BC}\mathcal{E}_{total}}{\lambda_{AB} + 2\lambda_{BC} + 2\lambda_{CA}} \tag{17}$$

$$\mathcal{E}_{CA} = \frac{2\lambda_{CA}\mathcal{E}_{total}}{\lambda_{AB} + 2\lambda_{BC} + 2\lambda_{CA}} \tag{18}$$

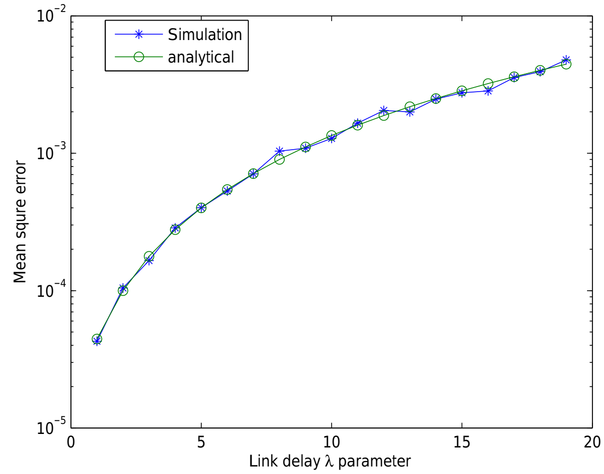

Fig. 4. Mean square error of SRS as a function of λ(analytical and simulation results)

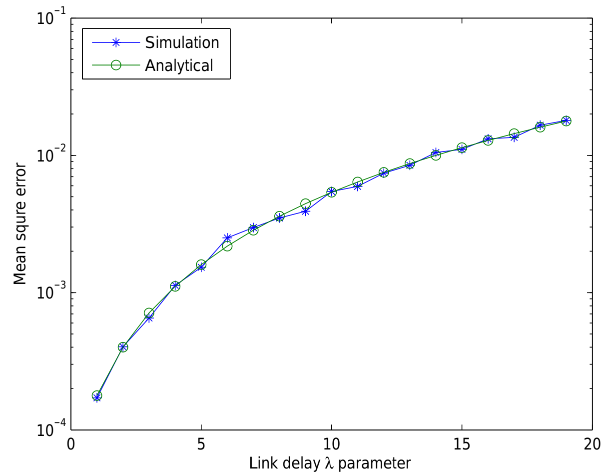

Fig. 5. Mean square error of RRS as a function of λ (analytical and simulation results)

Each node can estimate the parameter of its link to other two nodes using the protocol which was described in [2].

The pairwise nodes which use SRS for synchronization broadcast their link's parameter after the synchronization phase. Finally, the other pairs which use RRS can soft their synchronization accuracy.

V. Simulation Results

Figure 6 shows the simulation result of running the proposed protocol in three nodes A, B and C, where A and B use SRS to synchronize and C synchronizes with A and B by the proposed RRS scheme. This result obtains from 1000 times running the algorithm for different clock offset that are selected randomly. Also, the $\lambda_{AB} = \lambda_{BA}$, λ_{BC} and λ_{AC} are chosen 1, 2, and 3 respectively.

Figure 7 shows the result after using the introduced algorithm for improving accuracy in the network. The same

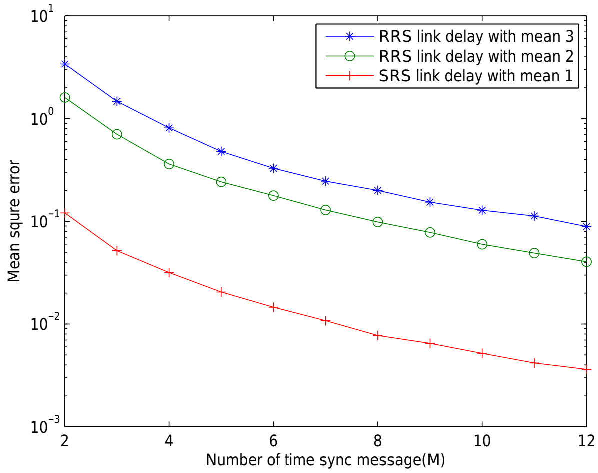

Fig. 6. mean square of synchronization error for three nodes A, B and C in presence of exponential delay with parameter $\lambda_{AB} = 1$, $\lambda_{BC} = 2$ and $\lambda_{AC} = 3$

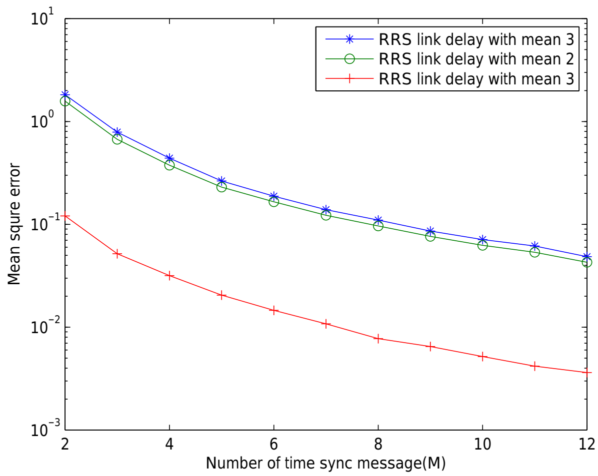

Fig. 7. mean square of synchronization error for three nodes A, B and C in presence of exponential delay with parameter $\lambda_{AB} = 1$, $\lambda_{BC} = 2$ and $\lambda_{AC} = 3$ using the loop feature for improving accuracy

parameters for all links are used. The algorithm runs over 1000 times. From this figure we find that the maximum error of all nodes is decreased compared to the case that we don't use the loop constraint.

Figure 8 shows the mean square error of running the algorithm in the presence of the exponential link delay with different mean parameter for both cases, i.e., considering the loop constraint and ignoring this constraint. As you can see, applying the proposed algorithm give better results even when the mean of link delay is increased.

VI. Conclusion and future works

We propose a new clock synchronization protocol by using the overhearing feature of wireless communication. In this protocol, each node overhears the transmitted messages which are

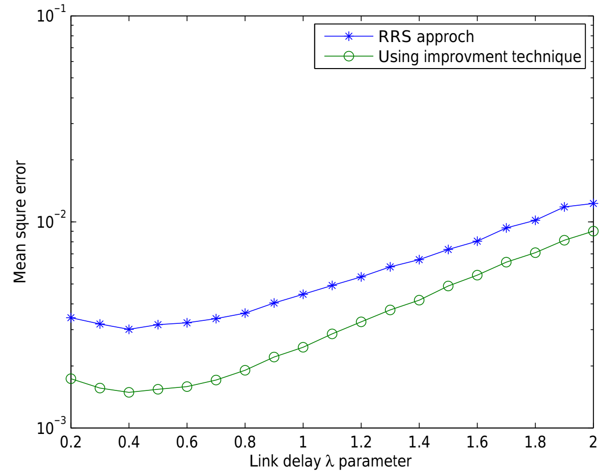

Fig. 8. The mean square error of clock synchronization in presence of different noise levels

exchanged between the pairwise nodes that are synchronized by a traditional scheme. Also, a fully distributed technique is introduced based on existing cycles in the network to improve the total synchronization error which leads to increase the robustness of synchronization against increasing the link delay. This protocol can use by all nodes or some of predefined nodes to improve the performance of clock synchronization between all nodes in the network.

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