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A Global Clock Skew Estimation Scheme for Hierarchical Wireless Sensor Networks

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ABSTRACT Time synchronization is extremely important for wireless sensor networks (WSNs). For large-scale WSNs, hierarchical clock synchronization, which can effectively save energy by reducing communication overhead, has become an attractive approach in practical networks. Based on the hierarchical network, in this paper, we present a global clock skew estimation scheme with immediate clock adjustment. The maximum likelihood estimator and corresponding Cramer–Rao lower bound of the clock skew are derived under the Gaussian delay model, and the simulation results verify that the proposed method is efficient.

INDEX TERMS Wireless sensor networks, parameter estimation, maximum likelihood estimation, time synchronization, clock skew estimation.

I. INTRODUCTION

Time synchronization is one of the challenging issues for many applications and protocols in Wireless Sensor Networks (WSNs). It can provide a common notion of time for sensor nodes when performing some fundamental operations, such as data fusion, power management and transmission scheduling. Early researches on clock synchronization mainly focused on protocol design. In fact, the time synchronization problem is inherently related to parameter estimation, and estimation of clock skew has been shown to be an attractive scheme to compensate time errors and reduce energy overheads [1].

In recent years, a wide variety of powerful signal processing algorithms of global clock synchronization have been investigated in the literature [2]–[5]. Basically, these approaches are mainly focused on two network architectures: distributed flat architecture and hierarchical architecture. The former is easier to implement, and the latter can help further reduce transmission overheads. For hierarchical WSNs, it needs to first build the synchronization level in the network and then to perform synchronization by passing clock messages level by level. In contrast, many of the existing clock synchronization schemes assume wireless sensor networks have a distributed architecture, which is easier for deployment. It only requires passing clock messages between neighboring nodes, which can be achieved in parallel, and clock synchronization is also achieved in a parallel and distributed way [6]. A similar scheme of network-wide synchronization is considered in [7]. Each node corrects its own clock via exchanging messages with its direct neighbors and conducts computations locally. This approach is robust to dynamic topology changes and node failures. In [8], the clock skew and clock offset estimation problem is transformed into a tracking problem, and the clock is adjusted at every synchronization cycle. Besides, accurately synchronized for gradient time synchronization in a completely decentralized architecture was presented in [9]. A testbed implementation for distributed synchronization recently made in [10] shows that an improved precision below one microsecond is possible. However, for large-scale WSNs, it suffers from bigger communication overheads and higher probability of packet collisions, which may impact the connectivity of the communication graphs [11]. On the other hand, research shows that the hierarchical structure has become a preferences in practical networks [12]–[14], especially for monitoring applications.

In hierarchical protocols, several optimization issues, *e.g.*, media access and local skew were investigated in [15]. Based on fast network flooding and accurate time synchronization, the authors of [3] proposed an efficient flooding architecture for WSNs that used interference to its advantage. However, the clock of the node could not be readjusted immediately after obtaining a timing observation. Hence, it may result in error accumulation and even a system outage when time errors beyond the threshold what system could allow in industrial WSNs, such as ISA100.11a networks.

We note that two clock synchronization approaches are available in hierarchical WSNs. One is "forwarding" method, in which timing message is transmitted level by level, and then time synchronization is carried out along the levels. Another is "transparent transmission" method where the process time of the intermediate nodes is assumed as additional fixed delays and random delays. Therefore, the intermediate nodes can be regarded as transparent. In this paper, we develop a global clock skew estimation scheme based on "transparent transmission" method for hierarchical network. The main contributions of this paper are as follows:

1) Based on the hierarchical network model, we propose a global synchronization scheme through which any node can directly establish the synchronization relation with the reference node and estimate the clock skew between them. Instead of synchronizing nodes between adjacent levels and eventually achieving global synchronization, the proposed scheme can reduce the number of message exchanges and energy consumption.

2) We analyze and derive the estimators for a network-wide synchronization where node clock is immediately readjusted upon every resynchronization before the clock parameters are estimated. Hence, the synchronization errors can be reduced to a small scale at every message exchange, thus achieving a longer time synchronization.

3) Considering the delays at the intermediate nodes may vary greatly, the clock skew estimation of proposed scheme can be obtained without any prior knowledge of the fixed delays as well as the correction times.

The rest of this paper is organized as follows. Section II mainly introduces the system model, including synchronization process for hierarchical networks and the corresponding formula derivation. The clock skew estimation for the Gaussian random delay model is derived in Section III. Simulation results are presented in Section IV, and Section V concludes the work.

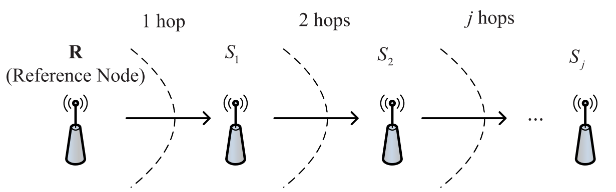

FIGURE 1. A global time synchronization scheme in hierarchical network.

II. SYSTEM MODEL

We consider a hierarchical network, as depicted in Fig. 1, where the node in each level can be synchronized with reference node R (root node with level 0). The reference node R sends time message which contains its sending time to node S_1 located in level 1. After receiving the timing message, node S_1 immediately forwards this message to the next level node (such as node S_2 located in level 2). And node S_1 then adjusts its current time by the differences between sending and receiving timestamps. Similarly, node S_2 receives the message from node S_1 and obtains sending timestamp (the send time of node R). Then node S_2 forwards this message to the next level node and adjusts its time by the differences of timestamps. Eventually, a global synchronization can be achieved. After several rounds of the above process, the clock skew between each synchronized node and reference node could be directly estimated. To achieve multi-hop time synchronization (such as L hops) in the network, we propose a "transparent transmission" method, *i.e.*, time messages are transmitted from node R to node S_j (j = 1, 2, ..., L) via the forwarding of intermediate nodes (such as node $S_1, \ldots, S_{j-1}$), and the time spent in this process is considered as variable delay, and this process can be regarded as transparent. As shown in Fig. 2, in the i^{th} message exchange, node R sends synchronization message which contains its send time $T_i^{(R)}$ to node S_1 locates in level 1. After node S_1 receives it and timestamps $T_{1,i}^{(S_1)}$, it transmits to node S_2 in level 2. Then node S_2 receives message which contains timestamp $T_i^{(R)}$ and records its current time as $T_{2,i}^{(S_2)}$. The variable delay $X_i^{(S_1)}$ is defined as the transmission time of message in node S_1. After a short while, node S_2 transmits this message to the next node and then adjusts its clock by the differences $\Delta_i^{(RS_2)} = T_{2,i}^{(S_2)} - T_i^{(R)}$ at $T_{adj,i}^{(S_2)}$. The aforementioned procedure is assumed to be N rounds, and node S_2 obtains a set of timestamps $\left\{T_i^{(R)}, T_{2,i}^{(S_2)}\right\}_{i=1}^{N}$. For node S_j locates in level L can also be synchronized by the same way.

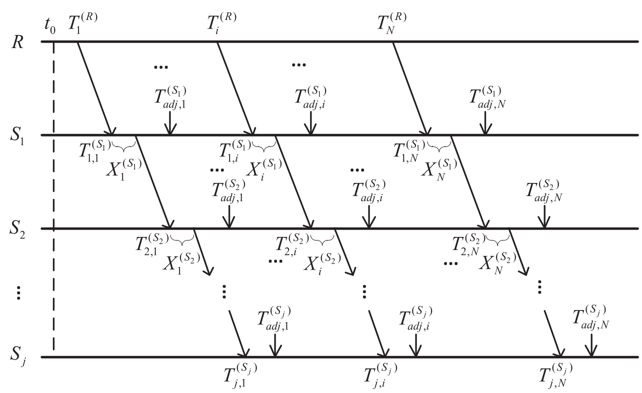

FIGURE 2. Timing message exchanges between node R and node S_j via a number of intermediate nodes.

Firstly, we illustrate the two-hop time synchronization between node R and S_2. As shown in Fig. 2, time message is transmitted from node R to S_2 via the forwarding of intermediate node S_1, following the aforementioned steps. In the first message exchange round, $T_{2,1}^{(S_2)}$ is given by

$$T_{2,1}^{(S_2)} = T_1^{(R)} + \theta_{t_0}^{(RS_2)} + \rho^{(RS_2)}(T_1^{(R)} - t_0) + (1 + \rho^{(RS_2)}) \times (X_1^{(S_1)} + d^{(RS_1)} + X_1^{(RS_1)} + d^{(S_1S_2)} + X_1^{(S_1S_2)}), \quad (1)$$

where we assume that t_0 is the initial time of local node, $\theta_{t_0}^{(RS_2)}$ denotes initial phase between R and S_2, $d^{(RS_1)}$ and $d^{(S_1S_2)}$ are the fixed delays, which are usually unknown but constant. $X_1^{(RS_1)}$ and $X_1^{(S_1S_2)}$ are the variable delays, and $X_1^{(S_1)}$ is the message transmission time of node S_1. $\rho^{(RS_2)}$ stands for the clock skew of node R with respect to node S_2.

Then node S_2 adjusts its clock by subtracting the correction value $\Delta_1^{(RS_2)} = T_{2,1}^{(S_2)} - T_1^{(R)}$ at the first correction time $T_{adj,1}^{(S_2)}$, and the reference time of the second synchronization cycle becomes $T_{adj,1}^{(S_2^*)} = T_{adj,1}^{(S_2)} + \Delta_1^{(RS_2)}$. In fact, from t_0 to $T_{adj,1}^{(S_2)}$, the true clock offset between node R and node S_2 can be written as

$$\Delta T_{true,1}^{(RS_2)} = \theta_{t_0}^{(RS_2)} + \rho^{(RS_2)}(T_{adj,1}^{(S_2)} - t_0). \quad (2)$$

Subtracting (1) from (2), we have

$$\theta_{t_1}^{(RS_2)} = \rho^{(RS_2)}(T_{adj,1}^{(S_2)} - T_1^{(R)}) - (1+\rho^{(RS_2)}) \times (X_1^{(S_1)} + d^{(RS_1)} + X_1^{(RS_1)} + d^{(S_1S_2)} + X_1^{(S_1S_2)}), \quad (3)$$

where $\theta_{t_1}^{(RS_2)}$ represents the "new" offset between node R and node S_2 after the first time synchronization cycle.

In the second synchronization round, we can obtain the time of node S_2 by the above steps. $T_{2,2}^{(S_2)}$ is given by

$$T_{2,2}^{(S_2)} = T_2^{(R)} + \theta_{t_1}^{(RS_2)} + \rho^{(RS_2)}(T_2^{(R)} - T_{adj,1}^{(S_2^*)}) + (1+\rho^{(RS_2)}) \times (X_2^{(S_1)} + d^{(RS_1)} + X_2^{(RS_1)} + d^{(S_1S_2)} + X_2^{(S_1S_2)}). \quad (4)$$

Similarly, from time $T_{adj,1}^{(S_2^*)}$ to $T_{adj,2}^{(S_2)}$, the true clock offset between node R and S_2 can be written as

$$\Delta T_{true,2}^{(RS_2)} = \theta_{t_1}^{(RS_2)} + \rho^{(RS_2)}(T_{adj,2}^{(S_2)} - T_{adj,1}^{(S_2^*)}). \quad (5)$$

Therefore, the "new" clock offset $\theta_{t_2}^{(RS_2)}$ is obtained as

$$\theta_{t_2}^{(RS_2)} = \Delta T_{true,2}^{(RS_2)} - \Delta_2^{(RS_2)} = \rho^{(RS_2)}(T_{adj,2}^{(S_2)} - T_2^{(R)}) - (1+\rho^{(RS_2)})(X_2^{(S_1)} + d^{(RS_1)} + X_2^{(RS_1)} + d^{(S_1S_2)} + X_2^{(S_1S_2)}). \quad (6)$$

Substituting $\theta_{t_1}^{(RS_2)}$ and $T_{adj,1}^{(S_2^*)}$ into (4), we get

$$T_{2,2}^{(S_2)} - T_2^{(R)} = \rho^{(RS_2)}(T_2^{(R)} - T_{2,1}^{(S_2)}) + (1+\rho^{(RS_2)}) \times [X_2^{(S_1)} - X_1^{(S_1)} + X_2^{(RS_1)} - X_1^{(RS_1)} + X_2^{(S_1S_2)} - X_1^{(S_1S_2)}]. \quad (7)$$

Similarly, for i^{th} time synchronization cycle, the final expression is given by

$$T_{2,i}^{(S_2)} - T_i^{(R)} = \rho^{(RS_2)}(T_i^{(R)} - T_{2,i-1}^{(S_2)}) + (1+\rho^{(RS_2)}) \times [(X_i^{(S_1)} - X_{i-1}^{(S_1)}) + (X_i^{(RS_1)} - X_{i-1}^{(RS_1)}) + (X_i^{(S_1S_2)} - X_{i-1}^{(S_1S_2)})]. \quad (8)$$

Therefore, assume that node S_j located in level L, following above steps, the expression of time synchronization between node R and node S_j is obtained as

$$T_{j,i}^{(S_j)} - T_i^{(R)} = \rho^{(RS_j)}(T_i^{(R)} - T_{j,i-1}^{(S_j)}) + (1+\rho^{(RS_j)}) \times [(X_i^{(S_1)} - X_{i-1}^{(S_1)}) + \cdots + (X_i^{(S_{j-1})} - X_{i-1}^{(S_{j-1})}) + (X_i^{(RS_1)} - X_{i-1}^{(RS_1)}) + \cdots + (X_i^{(S_{j-1}S_j)} - X_{i-1}^{(S_{j-1}S_j)})], \quad (9)$$

where $\rho^{(RS_j)}$ denotes the clock skew of node R with respect to node S_j, $X_i^{(S_{j-1})}$ is the transmission time of message in node S_{j-1} of level $L-1$ and it is variable delay, $X_i^{(S_{j-1}S_j)}$ represents the variable delay between node S_{j-1} and node S_j. Assuming that variable delays are independent and identical distributed (*i.i.d.*) and follow Gaussian distribution, let us define $(X_i^{(S_1)}) \sim N(\mu_1, \sigma_1^2)$, …, $(X_i^{(S_{j-1})}) \sim N(\mu_{j-1}, \sigma_{j-1}^2)$ and $(X_i^{(RS_1)}) \sim N(\alpha_1, \beta_1^2)$, …, $(X_i^{(S_{j-1}S_j)}) \sim N(\alpha_j, \beta_j^2)$. Hence the term $W_i \triangleq (X_i^{(S_1)} - X_{i-1}^{(S_1)}) + \cdots + (X_i^{(S_{j-1})} - X_{i-1}^{(S_{j-1})}) + (X_i^{(RS_1)} - X_{i-1}^{(RS_1)}) + \cdots + (X_i^{(S_{j-1}S_j)} - X_{i-1}^{(S_{j-1}S_j)})$ is zero-mean Gaussian RV, *i.e.*, $W_i \sim N(0, \sigma^2)$, where $\sigma^2 = 2\sigma_1^2 + \cdots 2\sigma_{j-1}^2 + 2\beta_1^2 + \cdots + \beta_j^2$. Therefore, (9) can be further written as

$$T_{j,i}^{(S_j)} - T_i^{(R)} = \rho^{(RS_j)}(T_i^{(R)} - T_{j,i-1}^{(S_j)}) + (1+\rho^{(RS_j)})W_i. \quad (10)$$

III. PARAMETER ESTIMATION

This section presents the parameter estimation of clock skew and the corresponding Cramer–Rao lower bound (CRLB). In addition, to reduce computation overhead, a simplified model is presented.

A. MAXIMUM LIKELIHOOD ESTIMATION

For (10), let us define $Q_i \triangleq T_{j,i}^{(S_j)} - T_i^{(R)}$ and $Y_i \triangleq T_i^{(R)} - T_{j,i-1}^{(S_j)}$. Based on the observations $\left\{T_i^{(R)}, T_{j,i}^{(S_j)}\right\}_{i=1}^N$, the log-likelihood function with respect to clock skew $\rho^{(RS_j)}$ and the variance σ^2 can be given as

$$\ln f(\rho^{(RS_j)}, \sigma^2) = -\frac{N}{2}\ln\left(2\pi\sigma^2\right) - \frac{1}{2\sigma^2} \times \sum_{i=1}^N \left\{\frac{Q_i - \rho^{(RS_j)}Y_i}{1+\rho^{(RS_j)}}\right\}^2. \quad (11)$$

Then differentiating the log-likelihood function (11) with respect to $\rho^{(RS_j)}$ and equating it to zero, the Maximum Likelihood Estimator (MLE) of clock skew can be obtained as

$$\hat{\rho}_{MLE}^{(RS_j)} = \frac{\sum_{i=1}^N [(Q_i + Y_i)\, Q_i]}{\sum_{i=1}^N [(Q_i + Y_i)\, Y_i]}. \quad (12)$$

For (12), we note that the expression of the clock skew does not contain the fixed delays and the correction times.

B. THE CRLB FOR MLE

In this section, we assume that the variance σ^2 is unknown as well as the clock skew $\rho^{(RS_j)}$. The CRLB for the vector parameter $\theta = [\rho^{(RS_j)}, \sigma^2]^T$ can be derived by taking the inverse of 2×2 Fisher information matrix $I(\theta)$.

Firstly, taking the partial derivative of the second order on (11), then taking the negative expectations on these equations, results are given by (13), (14), and (15) as follows.

$$-E\left[\frac{\partial^2 \ln f(\rho^{(RS_j)}, \sigma^2)}{\partial \rho^{(RS_j)} \partial \sigma^2}\right] = \frac{N}{\sigma^2(1+\rho^{(RS_j)})}, \quad (13)$$

$$-E\left[\frac{\partial^2 \ln f(\rho^{(RS_j)}, \sigma^2)}{\partial {\sigma^2}^2}\right] = \frac{N}{2\sigma^4}, \quad (14)$$

$$-E\left[\frac{\partial^2 \ln f(\rho^{(RS_j)}, \sigma^2)}{\partial {\rho^{(RS_j)}}^2}\right] = \frac{3N\sigma^2 + \sum_{i=1}^{N}(Y_i)^2}{\sigma^2\left(1+\rho^{(RS_j)}\right)^2}. \quad (15)$$

Therefore, the Fisher information matrix is given by

$$I(\theta) = \begin{bmatrix} \frac{3N\sigma^2 + \sum_{i=1}^{N}(Y_i)^2}{\sigma^2\left(1+\rho^{(RS_j)}\right)^2} & \frac{N}{\sigma^2\left(1+\rho^{(RS_j)}\right)} \\ \frac{N}{\sigma^2\left(1+\rho^{(RS_j)}\right)} & \frac{N}{2\sigma^4} \end{bmatrix}. \quad (16)$$

Refering to [16], taking the inverse of the Fisher information matrix, the CRLB of $\rho^{(RS_j)}$ can be obtained as

$$Var(\hat{\rho}_{MLE}^{(RS_j)}) \geq \frac{\sigma^2(1+\rho^{(RS_j)})^2}{N\sigma^2 + \sum_{i=1}^{N}(Y_i)^2}. \quad (17)$$

C. THE SIMPLIFIED ESTIMATION

In order to reduce the computational overhead of the proposed scheme, this section illustrates a simplified model for Gaussian delay.

In (10), as the noise W_i is an *i.i.d.* zero-mean Gaussian RV and the clock skew $\rho^{(RS_j)}$ is relatively small and its effect is negligible, therefore, (11) becomes a linear model which is given as

$$T_{j,i}^{(S_j)} - T_i^{(R)} = \rho^{(RS_j)}(T_i^{(R)} - T_{j,i-1}^{(S_j)}) + W_i, \quad (18)$$

where $O_i \triangleq (T_{j,i}^{(S_j)} - T_i^{(R)})$ and $K_i \triangleq (T_i^{(R)} - T_{j,i-1}^{(S_j)})$. (18) can be further expressed as matrix notation

$$O = K\rho^{(RS_j)} + W, \quad (19)$$

where $O = [O_1\ O_2\ \ldots\ O_N]^T$, $W = [W_1\ W_2\ \ldots\ W_N]^T$, and $K = [K_1\ K_2\ \ldots\ K_N]^T$. Note that the noise vector $W \sim N\left(0, \sigma^2 I\right)$, and the observation matrix K is known. Then referring to [16, Th. 4.1], the estimation of clock skew $\breve{\rho}^{(RS_j)}$ can be obtained as (20), and the corresponding CRLB of $\breve{\rho}^{(RS_j)}$ can also be obtained as (21).

$$\breve{\rho}^{(RS_j)} = (K^T K)^{-1} K^T O = \frac{\sum_{i=1}^{N}(O_i \cdot K_i)}{\sum_{i=1}^{N}(K_i^2)}$$
$$= \frac{\sum_{i=1}^{N}[(T_{j,i}^{(S_j)} - T_i^{(R)}) \times (T_i^{(R)} - T_{j,i-1}^{(S_j)})]}{\sum_{i=1}^{N}(T_i^{(R)} - T_{j,i-1}^{(S_j)})^2}, \quad (20)$$

$$Var(\breve{\rho}^{(RS_j)}) = \sigma^2(K^T K)^{-1} \geq \frac{\sigma^2}{\sum_{i=1}^{N}(T_i^{(R)} - T_{j,i-1}^{(S_j)})^2}. \quad (21)$$

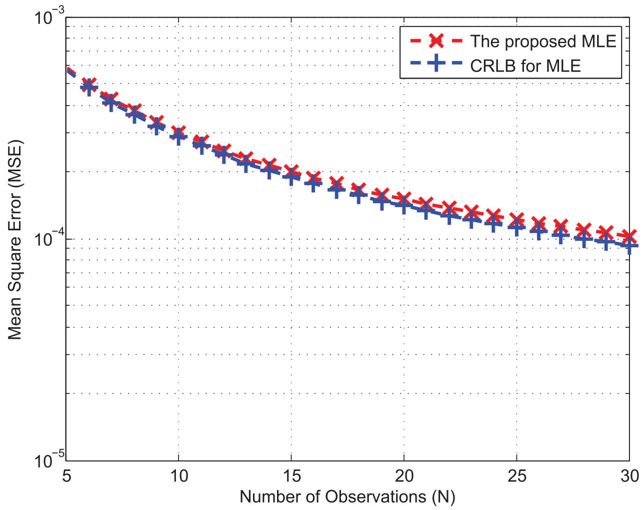

FIGURE 3. The MLE of the proposed scheme and CRLB ($\sigma = 0.5$).

IV. SIMULATION RESULTS

In this section, we present the simulation results and verify the efficiency of the proposed MLE for Gaussian delay, then compare the performance of the proposed MLE with the simplified estimation.

Fig. 3 depicts the performance of the Mean Square Error (MSE) with respect to the MLE of clock skew $\hat{\rho}_{MLE}^{(RS_j)}$ in (12) and the corresponding CRLB in (17) for Gaussian delay. When $\sigma = 0.5$, from the curves it is obvious to see that the clock skew estimators remain efficient and their performance can be predicted by the CRLBs well.

Fig. 4 compares the performance of the Normalized Mean Square Error (NMSE) of the proposed MLE with the simplified estimator, for observations $N = 5 : 30$ and $\sigma = 0.25$, $\sigma = 0.4$, and $\sigma = 0.6$, respectively. It can be seen that the proposed MLE is slightly superior to the simplified estimator. The main reason is that the proposed MLE considers the effect of clock skew (such as the term $\rho(d+X_i)$) in message exchanges, hence it provides better performance than the simplified estimator. In addition, we can

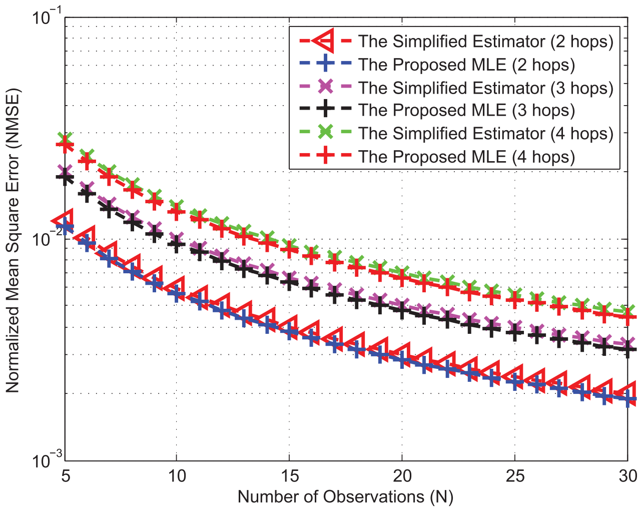

FIGURE 4. **The NMSE comparison of clock skew estimators.**

see that the performance of the estimation decreases as the number of hops increases since the system suffers from more and more random delays as the number of hops increases. Note that the delay at the intermediate nodes may vary in real networks, so some efficient approaches such as immediately forwarding in data linking layer, which is commonly used in practical sensor networks, can be taken into account to relieve the impact on synchronization accuracy.

V. CONCLUSION

This paper investigated a global clock skew estimation scheme for hierarchical network. The times spent in intermediate nodes were assumed to be variable delays and corresponding Gaussian delay model was established. Meanwhile, the clock of the node was periodically adjusted at every message exchange. The MLE and corresponding CRLB with respect to clock skew were obtained for Gaussian model. In addition, a simplified delay model was proposed. Considering that the time message transmission of one node suffers similar random delays for each round during the estimation process, the variable delays are assumed to be *i.i.d.* in the proposed estimator for simplicity. Besides the MLE proposed in this work, we believe that it is an important area for future research to investigate more estimators for clock synchronization in hierarchical WSNs.

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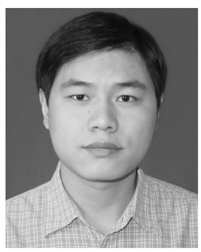

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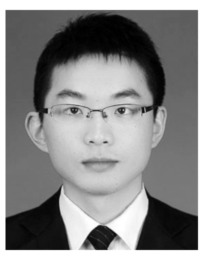

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