A New Approach for Time Synchronization in Wireless Sensor Networks: Pairwise Broadcast Synchronization

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***Abstract*—This letter proposes an energy-efficient clock synchronization scheme for Wireless Sensor Networks (WSNs) based on a novel time synchronization approach. Within the proposed synchronization approach, a subset of sensor nodes are synchronized by overhearing the timing message exchanges of a pair of sensor nodes. Therefore, a group of sensor nodes can be synchronized without sending any extra messages. This paper brings two main contributions: 1. Development of a novel synchronization approach which can be partially or fully applied for implementation of new synchronization protocols and for improving the performance of existing time synchronization protocols. 2. Design of a time synchronization scheme which significantly reduces the overall network-wide energy consumption without incurring any loss of synchronization accuracy compared to other well-known schemes.**

***Index Terms*—Time synchronization, wireless sensor networks, clock synchronization.**

I. Introduction

In recent years, wireless sensor networks (WSNs) have received a huge attention due to their promising applications in a variety of areas [1]. WSNs are fundamental infrastructures for future ubiquitous communications environments. The feasibility of WSNs keeps continuously growing with the current technical developments in micro-electro-mechanical systems (MEMS), digital circuit design, and wireless communications.

Time synchronization of wireless sensor networks is crucial to maintain data consistency, coordination, and perform other fundamental operations: power management, security, and data fusion and scheduling [2], [3]. Thus far, a number of synchronization protocols for WSNs have been reported. The Reference-Broadcast Synchronization (RBS) protocol synchronizes a group of wireless sensors within transmission range of the reference sensor node [4]. The extension to a multi-cluster based network was also studied in [4]. The Time-sync Protocol for Sensor Networks (TPSN) was proposed in [5]. TPSN is based on the level hierarchy of the network, and synchronizes the entire network by exchanging timing messages along every branch (edge) of the hierarchical tree. As a variation of TPSN and RBS, the Flooding Time Synchronization Protocol (FTSP) [6] synchronizes the network by successively broadcasting the synchronization messages using MAC layer time-stamping and performing skew compensation based on a linear regression. FTSP achieves a higher level of synchronization accuracy than either RBS or TPSN.

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It is interesting to observe that various other time synchronization protocols based on the periodic beacon transmission at the physical layer have been reported as well. A distributed broadcasting time synchronization scheme was proposed by *Khajehnouri* and *Sayed* considering general multi-path fading channels [7]. In [8], a joint physical- and network-layer time synchronization scheme was proposed to overcome the effects of imperfect physical layer synchronization due to the nature of common wireless channels. A low complexity bio-inspired synchronization protocol for large scale WSNs was also reported by *Hong* and *Scaglione* in [9]. More recently, *Sadler* derived the joint maximum likelihood clock offset and skew estimators in the case of uniformly distributed quantization noise, and proposed also a detection mechanism of clock drift [10]. In addition, *Giridhar* and *Kumar* proposed a distributed clock synchronization algorithm to improve the precision of synchronization under the condition that every connected edge exchanges timing messages [11].

In general, for synchronizing a pair of nodes there are two different approaches that can be categorized as sender-receiver synchronization (SRS) and receiver-receiver synchronization (RRS). The former is based on the classical model of two-way message exchanges between a pair of nodes. In contrast, the latter compares the time readings of a beacon packet from a common sender at a set of nodes. Most of the existing time synchronization protocols rely on one of these two approaches. For instance, RBS is based on RRS since it requires pairs of message exchanges among children nodes (except the reference) to compensate their relative clock offsets, while TPSN adopts SRS since it depends on a series of pairwise synchronizations that assume two-way timing message exchanges. This paper proposes the Pairwise Broadcast Synchronization (PBS) scheme, which relies on a novel time synchronization approach, called receiver-only synchronization (ROS) to achieve network-wide synchronization.

II. Main Ideas

Due to the power constraint, the communication range of a sensor is strictly limited to a (radio-geometrical) circle whose radius depends on the transmission power (see Fig. 1). In Fig. 1, every node within the checked area (e.g., *Node B*) can receive messages from both *Node P* and *Node A*. Suppose that *Node P* is a parent (or reference) node, and *Node P* and *Node A* perform a pairwise synchronization using two-way timing message exchanges [5]. Then, all the nodes in the checked region can receive a series of synchronization messages containing the information about the time stamps of the pairwise synchronization. Here, we assume perfect communications (no data loss and no failure) at the physical

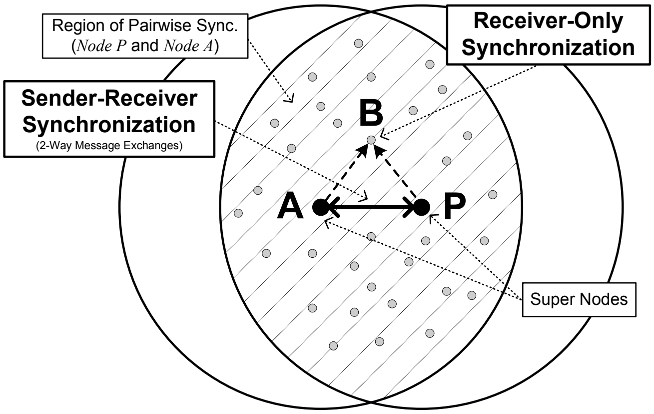

Fig. 1. Receiver-only synchronization.

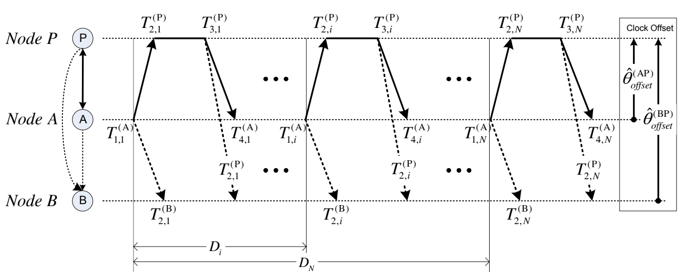

Fig. 2. Clock synchronization model of PBS.

layer. Using this information, *Node B* can be also synchronized to the parent node *Node P* by applying a similar method as in RBS and with no extra timing messages. Indeed, *Node P* and *Node A* can be regarded as super nodes since they provide synchronization beacons for all the nodes located in their vicinity.

In this letter, we develop a new synchronization approach, named receiver-only synchronization (ROS). Similarly to *Node B* in Fig. 1, a group of sensor nodes can be synchronized by only receiving timing messages of a pairwise synchronization based on ROS. The proposed PBS scheme efficiently combines both SRS and ROS approaches to achieve network-wide synchronization with a significantly reduced number of timing messages. Next we will describe and analyze the features of the proposed synchronization scheme in detail.

III. Pairwise Sender-Receiver Synchronization

This subsection illustrates how a parent node *Node P* and *Node A* can be synchronized using SRS. The clock model for the two-way message exchange is depicted in Fig. 2, where $\theta^{(\mathrm{PA})}_{offset}$ denotes the clock offset between *Node A* and *Node P*, and timing messages are assumed to be exchanged multiple (N) times [3], [5]. Hence, the number of observations (sets of time stamps) is N. Here, the time stamps transmitted during the ith message exchange $T^{(\mathrm{A})}_{1,i}$ and $T^{(\mathrm{A})}_{4,i}$ are measured by the local clock of *Node A*, and $T^{(\mathrm{P})}_{2,i}$ and $T^{(\mathrm{P})}_{3,i}$ are measured by the local clock of *Node P*, respectively. *Node A* transmits a synchronization packet to *Node P*, which contains the level and identifier (ID) of *Node A* and the value of time stamp $T^{(\mathrm{A})}_{1,i}$. *Node P* receives it at $T^{(\mathrm{P})}_{2,i}$ and transmits an acknowledgement packet to *Node A* at $T^{(\mathrm{P})}_{3,i}$. This packet contains the level and ID of *Node P* and the value of time stamps $T^{(\mathrm{A})}_{1,i}$, $T^{(\mathrm{P})}_{2,i}$, and $T^{(\mathrm{P})}_{3,i}$. Then, *Node A* finally receives the packet at $T^{(\mathrm{A})}_{4,i}$.

Packet delays can be characterized into several distinct components: send, access, transmission, propagation, receive times (see e.g., [3]). These delay components can be further divided into two parts: the fixed (deterministic) portions of delays (e.g., transmission/reception, propagation, encoding/decoding times) in up- and down-link ($d^{(\mathrm{AP})}$, $d^{(\mathrm{PA})}$) and the variable (random) portions of delays (e.g., send and receive times) in up- and down-link ($X^{(\mathrm{AP})}_i$, $X^{(\mathrm{PA})}_i$), respectively. These delay components have been carefully investigated in the literature [1], [3], [5] and [6].

Thus far, several random delay models have been proposed. A single-server M/M/1 queue can fittingly represent the cumulative link delay for point-to-point connections, where the random delays are modeled as exponential random variables [12]. The Gaussian delay model is appropriate if the delays are thought to be the addition of numerous independent random processes. In [4], the chi-squared test showed that the variable portion of delays can be modeled as Gaussian distributed random variables with 99.8% confidence. In this letter, $X^{(\mathrm{AP})}_i$ and $X^{(\mathrm{PA})}_i$ are assumed to be normal distributed with mean μ_0 and variance σ_0^2.

From Fig. 2, $T^{(\mathrm{P})}_{2,i}$ and $T^{(\mathrm{A})}_{4,i}$ can be expressed as

$$\begin{aligned} T^{(\mathrm{P})}_{2,i} &= T^{(\mathrm{A})}_{1,i} + \theta^{(\mathrm{AP})}_{offset} + d^{(\mathrm{AP})} + X^{(\mathrm{AP})}_i, \\ T^{(\mathrm{A})}_{4,i} &= T^{(\mathrm{P})}_{3,i} + \theta^{(\mathrm{PA})}_{offset} + d^{(\mathrm{PA})} + X^{(\mathrm{PA})}_i, \end{aligned}$$

where $\theta^{(\mathrm{PA})}_{offset} = -\theta^{(\mathrm{AP})}_{offset}$, and $d^{(\mathrm{AP})}$ and $X^{(\mathrm{AP})}_i$ denote the fixed and random portions of timing delays in the message transmissions from *Node A* to *Node P*, respectively. In [13], the maximum likelihood estimator (MLE) of clock offset was found to be given by

$$\hat{\theta}^{(\mathrm{AP})}_{offset} = \frac{\overline{U} - \overline{V}}{2}\,, \tag{1}$$

with the delays in up-link $U_i \triangleq T^{(\mathrm{P})}_{2,i} - T^{(\mathrm{A})}_{1,i}$ and down-link $V_i \triangleq T^{(\mathrm{A})}_{4,i} - T^{(\mathrm{P})}_{3,i}$. From (1), *Node A* can be synchronized to the parent node *Node P* by simply taking the difference of the average delay observations $\overline{U} = \sum_{i=1}^{N} [T^{(\mathrm{P})}_{2,i} - T^{(\mathrm{A})}_{1,i}]/N$ and $\overline{V} = \sum_{i=1}^{N} [T^{(\mathrm{A})}_{4,i} - T^{(\mathrm{P})}_{3,i}]/N$. Note that applying a clock skew correction mechanism guarantees a long-term stability of synchronization, i.e., a decrease of the re-synchronization frequency. In [13], the joint maximum likelihood estimator of clock offset and skew for normal delays was also derived. Although the effects of clock skew have not been considered herein, the clock skew estimators developed in [13] can be directly applied to the proposed PBS protocol with no modifications.

IV. Receiver-Only Synchronization

In Fig. 1, consider an arbitrary node, say *Node B*, in the checked region. While *Node P* and *Node A* exchange time messages, *Node B* is capable of receiving packets from both nodes. Hence, *Node B* can observe a set of time readings ($\{T^{(\mathrm{B})}_{2,i}\}_{i=1}^{N}$) at its local clock when it receives packets from *Node A* as depicted in Fig 2. In addition, the information about the set of time stamps $\{T_{2,i}^{(\mathrm{P})}\}_{i=1}^{N}$ can also be obtained by receiving packets from *Node P*. Considering the effects of both clock offset and skew in this subsection, the time stamp at *Node P* in the ith uplink message $T_{2,i}^{(\mathrm{P})}$ is given by

$$T_{2,i}^{(\mathrm{P})} = T_{1,i}^{(\mathrm{A})} + \theta_{offset}^{(\mathrm{AP})} + \theta_{skew}^{(\mathrm{AP})} \cdot (T_{1,i}^{(\mathrm{A})} - T_{1,1}^{(\mathrm{A})}) + d^{(\mathrm{AP})} + X_i^{(\mathrm{AP})} \tag{2}$$

where $\theta_{skew}^{(\mathrm{AP})}$ stands for the relative clock skew between *Node A* and *Node P*. Likewise, the time stamp at *Node B* in the ith uplink message $T_{2,i}^{(\mathrm{B})}$ can be represented by

$$T_{2,i}^{(\mathrm{B})} = T_{1,i}^{(\mathrm{A})} + \theta_{offset}^{(\mathrm{AB})} + \theta_{skew}^{(\mathrm{AB})} \cdot (T_{1,i}^{(\mathrm{A})} - T_{1,1}^{(\mathrm{A})}) + d^{(\mathrm{AB})} + X_i^{(\mathrm{AB})} \tag{3}$$

where $\theta_{offset}^{(\mathrm{AB})}$ and $\theta_{skew}^{(\mathrm{AB})}$ stand for the relative clock offset and skew between *Node A* and *Node B*, $d^{(\mathrm{AB})}$ and $X_i^{(\mathrm{AB})}$ denote the fixed and random portions of timing delays in the message transmission from *Node A* to *Node B*, respectively. Here, $X_i^{(\mathrm{AB})}$ is assumed to be a normal distributed RV with mean μ_0 and variance σ_0^2.

Similar to [8], [11], and [14], the linear regression technique (line fitting) can be applied to synchronize *Node B* and compensate the effects of the relative clock skew between *Node P* and *Node B*. Subtracting (3) from (2) leads to

$$\begin{aligned} T_{2,i}^{(\mathrm{P})} - T_{2,i}^{(\mathrm{B})} &= \theta_{offset}^{(\mathrm{BP})} + \theta_{skew}^{(\mathrm{BP})} \cdot (T_{1,i}^{(\mathrm{A})} - T_{1,1}^{(\mathrm{A})}) + d^{(\mathrm{AP})} \\ &\quad - d^{(\mathrm{AB})} + X_i^{(\mathrm{AP})} - X_i^{(\mathrm{AB})}. \end{aligned} \tag{4}$$

Since $d^{(\mathrm{AB})}$ and $d^{(\mathrm{AP})}$ are fixed values and $X_i^{(\mathrm{AB})}$ and $X_i^{(\mathrm{AP})}$ are normal distributed RVs, the noise component can be defined by $z[i] \triangleq \mu + X_i^{(\mathrm{AP})} - X_i^{(\mathrm{AB})}$, where $\mu \triangleq d^{(\mathrm{AP})} - d^{(\mathrm{AB})}$ and $z[i] \sim \mathcal{N}(\mu, \sigma^2)$. In general, the RVs $X_i^{(\mathrm{AP})}$ and $X_i^{(\mathrm{AB})}$ are correlated. However, as we will see later knowledge of the variance σ^2 of $z[i]$ is not required for the derivation or implementation of clock offset and skew estimators. Let define $x[i] \triangleq T_{2,i}^{(\mathrm{P})} - T_{2,i}^{(\mathrm{B})} - \mu$ and $w[i] \triangleq z[i] - \mu$, then the set of observed data can be written in matrix notation as follows:

$$\mathbf{x} = \mathbf{H}\boldsymbol{\theta} + \mathbf{w},$$

where $\mathbf{x} = [x[1] \ \ x[2] \ \ \cdots \ \ x[N]]^T$, $\mathbf{w} = [w[1] \ w[2] \ \cdots \ w[N]]^T$, $\boldsymbol{\theta} = [\theta_{offset}^{(\mathrm{BP})} \ \theta_{skew}^{(\mathrm{BP})}]^T$, and

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

Note that the noise vector $\mathbf{w}$ is normally distributed $\mathbf{w} \sim \mathcal{N}(0, \sigma^2\mathbf{I})$, and the matrix $\mathbf{H}$ represents the observation matrix of size $N \times 2$. From [15, Theorem 3.2, p. 44], the least squares estimator for the relative clock offset and skew is given by

$$\hat{\boldsymbol{\theta}} = (\mathbf{H}^T\mathbf{H})^{-1}\mathbf{H}^T\mathbf{x}, \qquad \mathbf{I}(\boldsymbol{\theta}) = \frac{\mathbf{H}^T\mathbf{H}}{\sigma^2},$$

where $\mathbf{I}(\boldsymbol{\theta})$ is the Fisher information matrix. After some straightforward mathematical manipulations, the joint clock

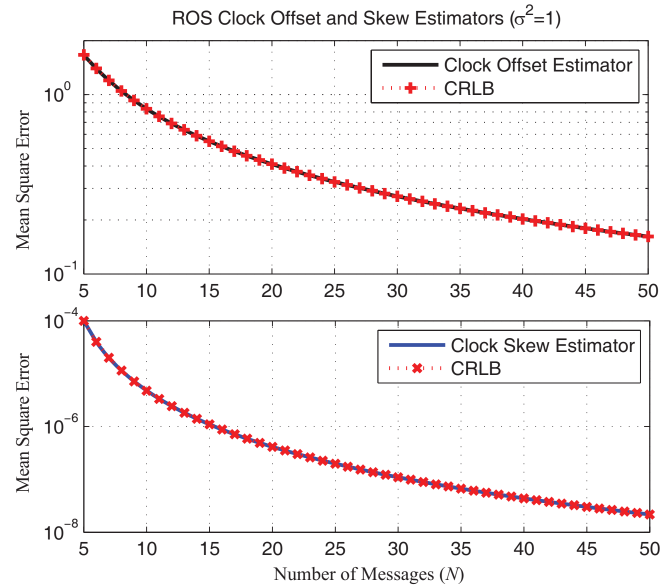

Fig. 3. Performance of PBS clock offset and skew estimation.

offset and skew estimator is given by

$$\begin{bmatrix} \hat{\theta}_{offset}^{(\mathrm{BP})} \\ \hat{\theta}_{skew}^{(\mathrm{BP})} \end{bmatrix} = \frac{1}{N\sum_{i=1}^{N} D_i^2 - \left[\sum_{i=1}^{N} D_i\right]^2} \times \begin{bmatrix} \sum_{i=1}^{N} D_i^2 \sum_{i=1}^{N} x[i] - \sum_{i=1}^{N} D_i \sum_{i=1}^{N} [D_i \cdot x[i]] \\ N\sum_{i=1}^{N} [D_i \cdot x[i]] - \sum_{i=1}^{N} D_i \sum_{i=1}^{N} x[i] \end{bmatrix} \tag{5}$$

where $D_i \triangleq T_{1,i}^{(\mathrm{A})} - T_{1,1}^{(\mathrm{A})}$. By inverting the Fisher information matrix $\mathbf{I}(\boldsymbol{\theta})$, the Cramer-Rao lower bounds (CRBs) for the relative clock offset and skew take the expressions, respectively:

$$\begin{aligned} \mathrm{var}(\hat{\theta}_{offset}^{(\mathrm{BP})}) &\geq \frac{\sigma^2 \sum_{i=1}^{N} D_i^2}{N\sum_{i=1}^{N} D_i^2 - \left[\sum_{i=1}^{N} D_i\right]^2}, \\ \mathrm{var}(\hat{\theta}_{skew}^{(\mathrm{BP})}) &\geq \frac{\sigma^2 N}{N\sum_{i=1}^{N} D_i^2 - \left[\sum_{i=1}^{N} D_i\right]^2}. \end{aligned} \tag{6}$$

Consequently, using the estimators (5), *Node B* can be synchronized to *Node P*. Likewise, all the other nodes in the checked region in Fig. 1 can be simultaneously synchronized to the parent node *Node P* without any additional message transmissions, thus saving a significant amount of energy. Fig. 3 shows the mean square error (MSE) performance of the proposed clock offset and skew estimators for ROS. The parameter μ is assumed to be known here since d is deterministic. It can be seen that both clock offset and skew estimators are efficient and their performance is well predicted by the CRBs. Besides, as we will see in the next section, ROS does not exhibit any loss of synchronization accuracy in clock offset estimation when compared to RBS.

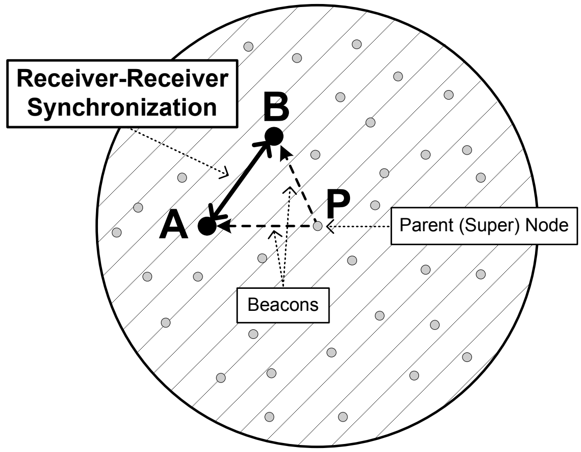

Fig. 4. Receiver-receiver synchronization.

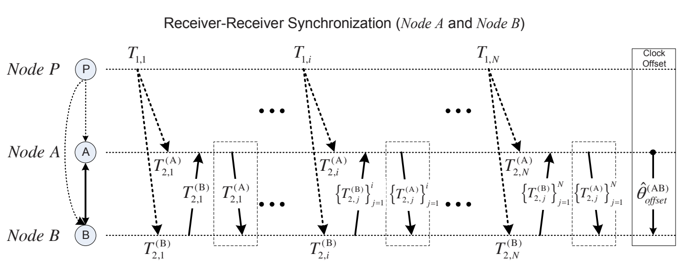

Fig. 5. Clock synchronization model of RBS.

V. Receiver-Receiver Synchronization

This section presents the RRS approach [4] and compares its performance with the proposed ROS approach. RRS is an approach to synchronize a set of children nodes that receive the beacon messages from the common sender, a reference or parent node. Consider a parent (reference) node *P* and arbitrary nodes *A* and *B*, located within the communication range of the parent node in Fig. 4. As depicted in Fig. 5, assume that both *Node A* and *Node B* receive the i^{th} beacon from *Node P* at time instants $T_{2,i}^{(\mathrm{A})}$ and $T_{2,i}^{(\mathrm{B})}$ of their local clocks, respectively. Nodes *A* and *B* record the arrival time of the broadcast packet according to their own timescales and then exchange their time-stamps. Suppose $X_i^{(\mathrm{PA})}$ stands for the nondeterministic delay component (random portion of delays) and $d^{(\mathrm{PA})}$ denotes the deterministic delay component (propagation delay) from *Node P* to *Node A*, then $T_{2,i}^{(\mathrm{A})}$ can be written as

$$T_{2,i}^{(\mathrm{A})} = T_{1,i} + \theta_{offset}^{(\mathrm{PA})} + \theta_{skew}^{(\mathrm{PA})} \cdot (T_{1,i} - T_{1,1}) + d^{(\mathrm{PA})} + X_i^{(\mathrm{PA})}, \tag{7}$$

where $T_{1,i}$ is the transmission time at the reference node, $\theta_{offset}^{(\mathrm{PA})}$ and $\theta_{skew}^{(\mathrm{PA})}$ are the clock offset and skew of *Node A* with respect to the reference node, respectively. Similarly, we can decompose the arrival time at *Node B* as

$$T_{2,i}^{(\mathrm{B})} = T_{1,i} + \theta_{offset}^{(\mathrm{PB})} + \theta_{skew}^{(\mathrm{PB})} \cdot (T_{1,i} - T_{1,1}) + d^{(\mathrm{PB})} + X_i^{(\mathrm{PB})}, \tag{8}$$

where $d^{(\mathrm{PB})}$, $X_i^{(\mathrm{PB})}$, $\theta_{offset}^{(\mathrm{PB})}$, and $\theta_{skew}^{(\mathrm{PB})}$ are the propagation (fixed) delay, the random portion of delays, and the clock offset and skew of *Node B*, respectively.

Subtracting (8) from (7), we obtain

$$\begin{aligned} T_{2,i}^{(\mathrm{A})} - T_{2,i}^{(\mathrm{B})} &= \theta_{offset}^{(\mathrm{BA})} + \theta_{skew}^{(\mathrm{BA})} \cdot (T_{1,i} - T_{1,1}) + d^{(\mathrm{PA})} \\ &\quad - d^{(\mathrm{PB})} + X_i^{(\mathrm{PA})} - X_i^{(\mathrm{PB})}, \end{aligned} \tag{9}$$

where $\theta_{offset}^{(\mathrm{BA})}$ $(= \theta_{offset}^{(\mathrm{PA})} - \theta_{offset}^{(\mathrm{PB})})$ and $\theta_{skew}^{(\mathrm{BA})}$ $(= \theta_{skew}^{(\mathrm{PA})} - \theta_{skew}^{(\mathrm{PB})})$ become the relative clock offset and skew between *Node A* and *Node B* at the time they receive the i^{th} broadcast packet from the reference node, respectively.

Note that (9) assumes exactly the same form as (4). Hence, the same steps can be applied to derive the joint clock offset and skew estimator for ROS. Likewise, define the noise component $z[i] \triangleq \mu + X_i^{(\mathrm{PA})} - X_i^{(\mathrm{PB})}$, where $\mu \triangleq d^{(\mathrm{PA})} - d^{(\mathrm{PB})}$ and $z[i] \sim \mathcal{N}(\mu, \sigma^2)$. Let also define $x[i] \triangleq T_{2,i}^{(\mathrm{A})} - T_{2,i}^{(\mathrm{B})} - \mu$ and $w[i] \triangleq z[i] - \mu$. Using similar steps as in ROS, it is straightforward to show that the same form of the joint clock offset and skew estimator (5) can be also applied to RRS. Consequently, there is no difference between ROS and RRS with regard to the accuracy of synchronization since the effects of random delays are the same. Assuming there is no clock skew ($\theta_{skew}^{(\mathrm{BA})} = 0$), the maximum likelihood estimator of the relative clock offset $\hat{\theta}_{offset}^{(\mathrm{BA})}$ becomes

$$\hat{\theta}_{offset}^{(\mathrm{BA})} = \frac{1}{N} \sum_{i=1}^{N} \left[T_{2,i}^{(\mathrm{A})} - T_{2,i}^{(\mathrm{B})} \right], \tag{10}$$

which is the equivalent to the estimator presented in [4].

VI. Comparisons and Analysis

This section compares the proposed PBS with other well-known synchronization protocols, such as TPSN, RBS, and FTSP, with respect to the amount of energy consumption (number of required timing messages) and the synchronization accuracy.

Lemma 1: Let $N_{\mathbf{RBS}}$ be the number of required timing messages in RBS, then $N_{\mathbf{RBS}} = N + L(L-1)/2$, where L is the number of overall sensor nodes in the network.

Proof: The reference node must broadcast the beacon packet N times in RBS. Also, every sensor node must send time readings upon receiving the broadcast beacons with all the other nodes in the network to compensate the relative clock offsets among each other [4]. Thus, $N_{\mathbf{RBS}} = N + L(L-1)/2$, since the number of unique pairs in the network is $L(L-1)/2$. ■

Lemma 2: Let $N_{\mathbf{TPSN}}$ be the required number of timing messages in TPSN, then $N_{\mathbf{TPSN}} = 2N(L-1)$.

Proof: Since every node in the network is connected to its parent node except the reference node, there are $L-1$ branches (edges) in a hierarchical tree. In addition, for TPSN, $2N$ timing messages are required in every pairwise synchronization. The number of required timing messages in TPSN is equal to the number of pairwise synchronizations times the number of required timing messages per pairwise synchronization, and therefore $N_{\mathbf{TPSN}} = 2N(L-1)$ [5]. ■

Lemma 3: Let $N_{\mathbf{FTSP}}$ be the number of required timing messages in FTSP, then $N_{\mathbf{FTSP}} = NL$.

Proof: For FTSP, every sensor node must send its time readings upon receiving beacons (or broadcast beacons) to other nodes so that they can estimate the relative clock offsets among each other [6]. Therefore, the number of required timing messages in FTSP is equal to the number of sensor nodes times the number of beacons: $N_{\mathbf{FTSP}} = NL$. ■

It is remarkable that the required number of timing messages for all the above mentioned protocols is proportional to the number of sensors in the network L or its square L^2. However, as discussed, PBS requires only $2N$ timing messages in every synchronization period, i.e., $N_{\mathbf{PBS}} = 2N$. Hence, $N_{\mathbf{PBS}}$ dose not depend on the number of sensors in the network, which incurs an enormous amount of energy saving. Moreover, this gain proportionally increases with respect to the scale of the network. Consequently, the benefit of PBS over RBS, TPSN, and FTSP is huge in terms of energy consumption with the cost of allocating 2 super nodes in the network. Note that RBS also requires a super node which broadcasts the reference beacons to all the other nodes in the network.

In case that there exist nodes that are located outside of the checked region in Fig. 1, likewise in RBS, the network could be divided into a number of separated groups (clusters) that can be synchronized via additional pairwise synchronizations among the super nodes located in different groups, i.e., global synchronization can be achieved by a sequence of pairwise message exchanges. Herein, a variety of different grouping and pair selection algorithms can be considered according to the network type. For instance, assuming that the level hierarchy of the network is discovered by a searching algorithm (e.g., as in [5]), there will be groups of parents and children nodes, where a group consists of a parent and its children nodes. Within each group, every parent node can investigate the connectivity among its children nodes and select the best sequence of synchronization pairs in order to minimize the required number of pairwise synchronizations, a strategy that will maximize the number of nodes performing ROS. Note that no network-wide heuristic connectivity search is required in this case because of its limited and known set of scanning nodes. The detailed extension of these preliminary considerations for the proposed PBS scheme is outside this letter scope and will be reported elsewhere due to space limitations.

The synchronization accuracy is another crucial designing factor to be concerned with. In general, it depends on a variety of different factors, such as the network platform and setup, channel status, and estimation schemes. The performance of existing protocols has been compared in terms of the synchronization accuracy in several references, e.g., [1], [2], [6], and [8]. As shown in the previous sections, the accuracy of PBS is exactly the same as that of RBS. The interested reader is referred to the above mentioned references for additional insights.

VII. Conclusions

This letter proposed a novel clock synchronization scheme for WSNs by considering an energy-efficiency synchronization approach referred to as receiver-only synchronization. The proposed scheme only requires two-way timing message exchanges of a pair of sensor nodes to achieve network-wide synchronization, which significantly reduces the overall energy consumption for achieving global synchronization. This new approach and the main ideas presented herein could also be fully or partially applied to improve the performance of existing protocols or for designing new protocols. Experimental performance evaluation and comparisons with other existing protocols represent an open research problem for future.

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