Distributed Receiver/Receiver Synchronization in Wireless Sensor Networks: New Solution and Joint Offset/Skew Estimators for Gaussian Delays

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Abstract. This paper proposes a new synchronization protocol for wireless sensor networks (WSN). The proposed protocols is based on the receive/reieve approach, which was introduced by the Reference Broadcast Synchronization (RBS). This approach has been chosen for its lower time-critical path compared to the sender/receiver approach. Contrary to RBS upon which rely all current receiver/receiver solutions, the proposed one is totally distributed and does not depend on any fixed reference. The reference's function is balanced among all sensors, which eliminates the single point of failure shortcomings. RBS needs additional steps for exchanging reception timestamps. On the other hand, the proposed protocol allow these timestamps to be piggybacked to the regular beacons, reducing thus the overhead and energy consumption. The protocol deals with local synchronization and allows neighboring nodes to relatively synchronize with each other by estimating relative skews/offsets. Maximum Likelihood estimators (MLEs) are derived for channels with Gaussian (normal) distributed delays, and for both offset-only and joint offset/skew models. The Cramer-Rao Lower Bounds (CRLBs) are derived for each model and numerically compared with the MLE. Results show quick convergence of the proposed estimators' precision to CRLB. To our knowledge, this is the first distributed receiver/receiver solution that eliminates the need of a fixed reference while taking advantage of the receiver/receiver synchronization's precision.

1 Introduction

Many applications and protocols of wireless sensor networks (WSN)require fine grained time synchronization between sensor nodes. Existing synchronization solutions can be divided into sender/receiver protocols vs. receiver/reciver protocols.The receiver/receiver approach introduced by the Reference Broadcast Synchronization (RBS) protocol [1] exploits the broadcast property of the wireless communication medium; The broadcast medium allows receivers located within listening distance of the same sender to receive a broadcast message at approximately the same time, with very little variability due to the reception timstamping at the receivers. RBS uses a sequence of synchronization messages (beacons) from a given sender (reference), which allows its neighboring nodes to estimate both offset and skew of their respective clocks. The reference periodically broadcasts beacons that are received at the synchronizing nodes. Reception events are timestamped with local clocks, then these timestamps are exchanged between the nodes and used as samples for estimating relative skews/offsets. The protocol exploits the concept of time-critical path, which is defined as the path of a message that contributes to non-deterministic errors in a protocol [2]. With sender/receiver protocols, the time involved in sending a message from a sender to a receiver is the result of the following four factors that can vary non-deterministically: i) Send time, which is the time spent by the sender for message construction along with the time spent to transmit the message from the sender's host to the network interface. ii) Access time; the time spent for medium access at the MAC layer. iii) Propagation time, as the time for the message to reach the receiver once it has left the sender. iv) Receive time, which is the time spent by the receiver to process the message. RBS removes the send time and the access time from the critical path, the two largest sources of non-determinism. This provides a high degree of synchronization accuracy.

The major drawback of RBS is the need of a fixed reference. In other words, it is centralized; which might be unappropriate for some self-organized wireless sensor network (WSN) applications. A new synchronization protocol for WSN is proposed in this paper. The protocol takes advantages of the receiver/receiver approach while being totaly decentralize. It considers local (one-hop) and relative synchronization, i.e, every node runs its clock independently and continuously updates the relative offset and/or skew values with regard to the other neighboring nodes. The role of the reference is equally distributed amongst all nodes, and timestamps are piggybacked with beacons. This eliminates the need of timestamp exchanges and thus reduces the overhead. Models that are appropriate to relative synchronization and receiver/receiver are defined, permitting to derive maximum likelihood estimators (MLE) and the corresponding Cramer-Rao lower bounds (CRLB). The rest of the paper is organized as follows. The Next section summarizes the related work, followed by the solution description in Section 3. Section 4 defines models for offset-only and joint offset/skew estimation, then it accordingly derives the MLE and CRLB and provides numerical analysis. Finally Section 5 draws conclusions.

2 Related Work

Papers [3] [2] are good introductive surveys to synchronization in WSN, while [4] and [5] review some more recent solutions. The big majority of protocols proposed thus far use send/receiver synchronization, where the synchronizing nodes exchange messages and use sending and receiving events to record timestamps. Some of these solutions allow nodes to run their clocks independently and define mechanisms to calculate (estimate) relative skews and/or offsets, i.e. relative synchronization. Noh et al. [6] consider local (one-hop) relative synchronization and provide general offset/skew MLE estimators for sender/receiver protocols, where only the first and last observations of timing message exchanges are used. The approach was generalized in [7]. We follow a similar mathematical approach in this paper, but the model, and consequently all the derived estimators and bounds, are completely different. The model of [6] does not apply to the proposed solution, as the latter is receiver/receiver-based. RAT [8] is another local sender/receiver synchronization protocol, which has been integrated with B-MAC to incrementally improve its performance. Since the authors' aim was to reduce the preamble period at the MAC layer, the protocol provides a weak synchronization. It calculates relative skews/offsets using linear regression.

Instead of estimating relative offset/skew, some solutions define distributed mechanisms that allow nodes to update their clocks and converge to common values, i.e. continues clock updates. In [9], [10], and [11] the authors propose solutions that deal with single as well as multi-hop synchronization. However, these solutions have the gradient property and focus on local synchronization. High precision is consequently provided for neighboring nodes (their clock values converge closely), whereas the precision decreases with the distance. Generally speaking, in clock-update solutions, nodes continuously update their clocks with respect to each other. This update generally involve jump/freez of the clock value, which may affect correctness of local events' timestamping.

Contrary to gradient solutions, other ones focus on global synchronization and attempt to improve the multi-hop precision. [12] proposes a global synchronization protocol based on spanning tree. [13] provides probabilistic lower bounds for multi-hop synchronization. Secondis [14] defines strategies to disseminate synchronization messages from the root to the whole network. In [15] and [16] the authors propose other multi-hop-centric synchronization protocols. Rentel et al. [17] define a general multi-hop solution that applies to both MANET (mobile ad hoc networks) and WSN. [18] deals with multi-hop synchronization by clustering the network. The protocol starts by synchronizing cluster-heads to the base station, then cluster-heads synchronize regular nodes. In [19] Shames and Bishop propose a centralized approach to estimate clock relative offset where considering topology constraints. The basic idea is that in a cycle, the sum of all relative offsets must be null. The authors formulated the problem with graph theory and the mean square method as a constrained optimization problem. Although these techniques can be used to extend the protocol proposed herein for multi-hop environment, the scope of this paper is limited to local synchronization.

As described previously, RBS [1] uses a completely different approach (receiver/receiver) that has the advantage of reducing the time-critical path. However, it is centralized, and important overhead is required to exchange timing information between synchronizing nodes. In [20], Sari et al. define joint skew/offset MLE for RBS. The model used herein is different from the one of Sari et al. In the latter, synchronization is proportional to a single reference, while there is no such a common reference with the proposed solution's model. Further, [20] considers exponentially distributed delays, while the proposed one considers Gaussian distributed delays. Exponential model is more appropriate when delays include queueing time, which is typical when the sending delay is affecting the time critical path. However, It has been realized that the receiving delays tend to follow Gaussian distributions [1]. Therefore, Gaussian distribution is more suitable for receiver/receiver protocols. [21] applies artificial intelligence (AI) techniques to an RBS-like solution. In addition to RBS inherited shortcomings, the AI methods applicability to resource constrained sensors is questionable. [22] proposes PBS as a hybrid solution between sender/receiver and receiver/receiver approaches, which uses overhearing of the sender/receiver message exchange. Basic sender/receiver is used to synchronize two super nodes, while all the other nodes within the range of both nodes overhear messages and synchronize to the super nodes. The solution reduces the overheard of RBS, but it is also centralized. In [23], Huang et al. tried to make the solution more distributed by proposing round-robin timing exchange protocol (RRTE), where one reference is fixed and the other changes in a round robin way. Still, one fixed reference is needed. Some other hardware solutions propose synchronization techniques to be implemented at the physical layer [24], [25], [26]. This may provide high precision but would require additional hardware modules at the sensor motes. The proposed solution described in the following does not need any such modules. It is implementable at the software level.

3 Solution Description

3.1 Assumptions

The proposed protocol deals with local (one-hop) synchronization. Although multi-hop extension is feasible, it is out of the scope of this work. Nodes to be synchronized are supposed to be in the vicinity of each other, such that any broadcast message can be captured at any node. Every node has its own clock that runs independently from the others. The synchronization is ensured by estimating parameters reflecting relative deviation of every other node, such as no local-clock value update is needed. No anchor or supper node is needed, and all nodes are sensor motes that cooperatively get synchronized. Nodes are assumed to be neighborhood-aware, i.e. each node knows the IDs of all nodes participating in the protocol. The solution is proposed at a high level of abstraction, independently of the underlaying protocols. This enables its implementation with any protocol stack, but there is ample room for optimization in real implementation with particular protocols, such as by using/integrating MAC protocol's messages/cycles.

3.2 New Solution

The protocol runs in cycles. In each one, nodes sequentially broadcast beacons. A beacon carries timestamps, reporting local reception times of previous beacons. For a network of N nodes, every beacon would carry $N-1$ timestamps. Without loss of generality, the beacon exchange process for $N = 4$ and one cycle is illustrated with the example of figure 1. $B_{i,j}$ denotes the j^{th} beacon (beacon transmitted at the j^{th} cycle) of node i, and $t^k_{i,j}$ refers to the reception timestamp at node k (recorded with its local clock) of the j^{th} beacon of node i. Every beacon piggybacks the previous $N-1$ timestamps. For instance, $B_{1,j}$ includes $t^1_{2,j-1}, t^1_{3,j-1}, t^1_{4,j-1}$, while $B_{4,j}$ includes $t^4_{1,j}, t^4_{2,j}, t^4_{3,j}$. These timestaps are then used by every node as samples to estimate synchronization parameters with the other nodes. Estimators will be proposed in the next section.

By including timstamps with the beacons, communication overhead is considerably reduced compared to RBS-like protocols, where timing information exchange between receivers are performed in different steps posterior to beacon broadcast. No such steps are needed for the proposed protocol. To allow each node to acquire K samples (timestamps) on every other node (i.e. overall, $N \times K$ samples for the N nodes), $O(K)$ transmissions (of beacons) are performed by the proposed protocol, as each transmission would carry $O(N)$ (exactly $N-1$) different samples. On the other hand, RBS would need additional $O(N)$ transmissions to exchange timestamps between nodes for every beacon, which results in $O(K \times N)$ transmissions.

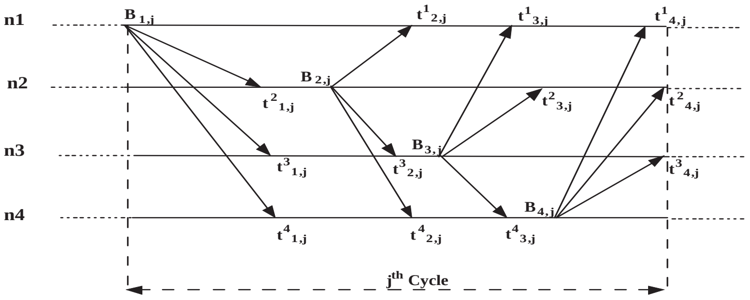


Fig. 1. Example of beacon broadcast during one cycle

4 Estimators and Analysis

In this section, maximum likelihood estimators (MLE) and the corresponding Cramer-Rao lower bounds (CRLB) are derived. First, the offset-only model is considered, and then the joint offset/skew model is derived.

4.1 Offset Model

Without loss of generality, only synchronization between two nodes, say, n_1 and $n2$, is considered, i.e. n_2 estimation of synchronization parameters with regard to n_1. The same process is to be applied at each node to estimate parameters relative to every communicating node. Let u_i and v_i, $i = \{1..K\}$, denote the i^{th} sample (i^{th} beacon reception timestamp) of nodes n_1 and $n2$ respectively, and d_{ui}, d_{vi} the corresponding reception delay. Only beacons received by both nodes are used to construct samples (u_i, v_i). Refereing to the example of Figure 1, $t^1_{3,1} = u_1$, $t^1_{4,1} = u_2$,...,$t^1_{3,j} = u_{2j-1}$, $t^1_{4,j} = u_{2j}$, and $t^2_{3,1} = v_1$, $t^2_{4,1} = v_2$,...,$t^2_{3,j} = v_{2j-1}$, $t^2_{4,j} = v_{2j}$.

Both d_{ui} and d_{vi} are assumed to be Gaussian distributed random variables (rv) with the same parameters ($\sim \mathcal{N}(\mu_0, \sigma_0^2)$). If the relative offset between n_1 and $n2$ is denoted by Θ, then

$$u_i - v_i = d_{ui} - d_{vi} + \Theta, \tag{1}$$

it results,

$$\Theta = u_i - v_i - X_i, \tag{2}$$

where X_i denotes $d_{ui} - d_{vi}$. It is the difference of two Gaussian rv with the same parameters, hence it is a zero mean Gaussian rv; i.e. $X_i \sim \mathcal{N}(0, \sigma^2)$, where $\sigma^2 = 2\sigma_0^2$.

The likelihood function $\mathcal{L}(\Theta|X_1, ...X_K)$ is given by,

$$\begin{aligned}\mathcal{L}(\Theta|X_1, ...X_K) &= \prod_{i=1}^{K} \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-1}{2\sigma^2}(X_i)^2} \\ &= (\frac{1}{\sqrt{2\pi\sigma^2}})^K e^{\frac{-1}{2\sigma^2}\sum_{i=1}^{K}(u_i - v_i - \Theta)^2}.\end{aligned} \tag{3}$$

The log-likelihood is thus,

$$\ln \mathcal{L}(\Theta|X_1, ...X_K) = K \ln(\frac{1}{\sqrt{2\pi\sigma^2}}) - \frac{1}{2\sigma^2} \sum_{i=1}^{K}(u_i - v_i - \Theta)^2, \tag{4}$$

and its derivative vs. Θ is,

$$\frac{\partial \ln \mathcal{L}(\Theta|X_1, ...X_K)}{\partial \Theta} = \frac{1}{\sigma^2} \sum_{i=1}^{K}(u_i - v_i - \Theta), \tag{5}$$

The resolution of Eq. (5)=0 gives the maximum-likelihood estimator of Θ

$$\widehat{\theta}_{mle} = argmax(\ln \mathcal{L}(\Theta|X_1, ...X_K)) = \frac{\sum_{i=1}^{K}(u_i - v_i)}{K} \tag{6}$$

The variance of any unbiased estimator $\widehat{\theta}$ of Θ can be bounded by [27, p. 327].

$$Var(\widehat{\theta}) \geq \frac{1}{I(\Theta)}, \tag{7}$$

provided that the following regularity condition holds

$$\frac{\partial}{\partial\Theta}\int \mathcal{L}(x,\Theta)dx = \int \frac{\partial\mathcal{L}(x,\Theta)}{\partial\Theta}dx, \tag{8}$$

where $I(\theta)$ is the Fisher information defined by:

$$I(\Theta) = E[(\frac{\partial \ln \mathcal{L}(x,\Theta)}{\partial\Theta})^2] = -E[(\frac{\partial^2 \ln \mathcal{L}(x,\Theta)}{\partial\Theta^2})] \tag{9}$$

and $\mathcal{L}(x,\Theta)$ denotes the joint probability function with K observations of x, i.e. $\mathcal{L}(\Theta|X_1,...X_K)$.

It is obvious that condition of Eq. 8 holds for $\mathcal{L}(\Theta|X_1,...X_K)$. The second derivative of the logarithm of the joint probability function can be obtained by calculating the derivative of Eq. 5, which is: $-\frac{K}{\sigma^2}$. The CRLB is then obtained;

$$Var(\widehat{\theta}) \geq \frac{\sigma^2}{K}, \tag{10}$$

Figure 2 compares the mean square errors (MSE) of the proposed estimator and those of CRLB (the MSE's optimum). The results are obtained by a MATLAB simulation, where real θ has been randomly selected from a $\mathcal{N}(0,1)$ distribution and delays from $\mathcal{N}(0.001sec,1)$ distribution. Each point of the plot is the average of 10^4 measurements. It is clear how the proposed estimator's MSE converges and approaches the CRLB as the number of messages (beacons) increases. They both quadratically decrease to zero as K rises.

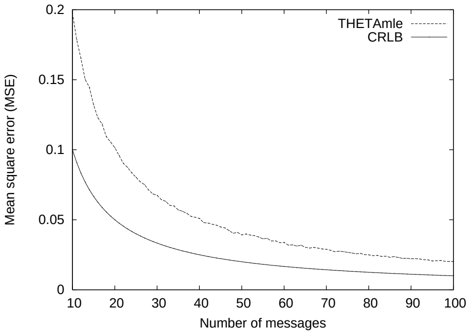
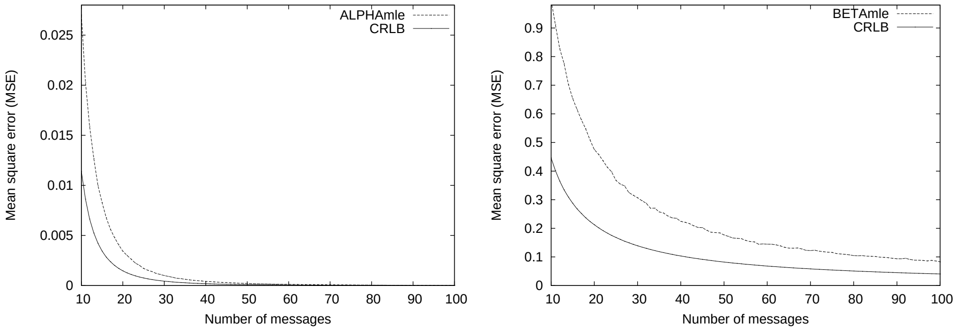


Fig. 2. MSE of Θ estimation vs number of messages

4.2 Joint Offset/Skew Model

The pervious model does not capture the skew but only translates the time difference as relative offset that changes along the time. For this model to be accurate, timestamp exchange must be performed frequently. This might be resource consuming and unpractical for long-life WSN [6].



(a) (b)

Fig. 3. MSE of α and β estimation vs number of messages

It is more practical to consider relative skew between clocks and estimate it. Let the relative skew and offset be respectively denoted by α and β. Applying the generale linear equation relating two clocks [2] to the model yields, $u_i = \alpha v_i + \beta + X_i$. It results,

$$X_i = u_i - \alpha v_i - \beta, \tag{11}$$

where X_i is the delay difference as defined previously. The likelihood function $\mathcal{L}(\alpha, \beta | X_1, ...X_K)$ is,

$$\mathcal{L}(\alpha, \beta | X_1, ...X_K) = \prod_{i=1}^{K} \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-1}{2\sigma^2}(X_i)^2} = (\frac{1}{\sqrt{2\pi\sigma^2}})^K e^{\frac{-1}{2\sigma^2}\sum_{i=1}^{K}(u_i - \alpha v_i - \beta)^2} . \tag{12}$$

The log-likelihood is thus,

$$\ln \mathcal{L}(\alpha, \beta | X_1, ...X_K) = K \ln(\frac{1}{\sqrt{2\pi\sigma^2}}) - \frac{1}{2\sigma^2}\sum_{i=1}^{K}(u_i - \alpha v_i - \beta)^2. \tag{13}$$

Since

$$\widehat{\alpha}_{mle}, \widehat{\beta}_{mle} = argmax(\ln \mathcal{L}(\alpha, \beta | X_1, ...X_K)), \tag{14}$$

$\widehat{\alpha}_{mle}, \widehat{\beta}_{mle}$ may be obtained by resolving the system of equations,

$\frac{\partial \ln \mathcal{L}(\alpha,\beta|X_1,...X_K)}{\partial\alpha} = 0$, and $\frac{\partial \ln \mathcal{L}(\alpha,\beta|X_1,...X_K)}{\partial\beta} = 0$.

$$\frac{\partial \ln \mathcal{L}(\alpha,\beta|X_1,...X_K)}{\partial\alpha} = \frac{1}{\sigma^2}\sum_{i=1}^{K} v_i(u_i - \alpha v_i - \beta), \tag{15}$$

$$\frac{\partial \ln \mathcal{L}(\alpha,\beta|X_1,...X_K)}{\partial\beta} = \frac{1}{\sigma^2}\sum_{i=1}^{K}(u_i - \alpha v_i - \beta). \tag{16}$$

By resolving the system Eq. (15)=0, and Eq. (16)=0, $\widehat{\alpha}_{mle}, \widehat{\beta}_{mle}$ are obtained:

$$\widehat{\alpha}_{mle} = \frac{\sum_{i=1}^{K} u_i \sum_{i=1}^{K} v_i - K\sum_{i=1}^{K} v_i u_i}{(\sum_{i=1}^{K} v_i)^2 - K\sum_{i=1}^{K} v_i^2}, \tag{17}$$

$$\widehat{\beta}_{mle} = \frac{1}{K}(\sum_{i=1}^{K} u_i - \frac{\sum_{i=1}^{K} u_i \sum_{i=1}^{K} v_i - K\sum_{i=1}^{K} v_i u_i}{(\sum_{i=1}^{K} v_i)^2 - K\sum_{i=1}^{K} v_i^2}\sum_{i=1}^{K} v_i). \tag{18}$$

Let us consider the vector $[\Theta_1, \Theta_2]^T = [\alpha, \beta]^T$. Its CRLB can be derived from I^{-1}; the inverse of the 2×2 Fisher information vector, I. The latter is defined by [27, p. 343],

$$I_{i,j} = E[\frac{\partial \ln \mathcal{L}(x,\Theta_1,\Theta_2)}{\partial\Theta_i}\frac{\partial \ln \mathcal{L}(x,\Theta_1,\Theta_2)}{\partial\Theta_j}] = -E[(\frac{\partial^2 \ln \mathcal{L}(x,\Theta_1,\Theta_2)}{\partial\Theta_i\partial\Theta_j})]. \tag{19}$$

Derivatives may be calculating from 13, which are:

$$\frac{\partial^2 \ln \mathcal{L}(x,\alpha,\beta)}{\partial\alpha^2} = \frac{-\sum_{i=1}^{K} v_i^2}{\sigma^2}, \frac{\partial^2 \ln \mathcal{L}(x,\alpha,\beta)}{\partial\beta^2} = -\frac{K}{\sigma^2}, \frac{\partial^2 \ln \mathcal{L}(x,\alpha,\beta)}{\partial\alpha\partial\beta} = \frac{-\sum_{i=1}^{K} v_i}{\sigma^2}.$$

I^{-1} can then be calculated,

$$I^{-1} = \frac{1}{\frac{K\sum_{i=1}^{K} v_i^2}{\sigma^4} - \frac{(\sum_{i=1}^{K} v_i)^2}{\sigma^4}} \times \begin{bmatrix} \frac{K}{\sigma^2} & \frac{-\sum_{i=1}^{K} v_i}{\sigma^2} \\ \frac{-\sum_{i=1}^{K} v_i}{\sigma^2} & \frac{\sum_{i=1}^{K} v_i^2}{\sigma^2} \end{bmatrix}. \tag{20}$$

Then the CRLB of both parameter can be obtained using the propriety, $Var(\widehat{\Theta_i}) \geq (I^{-1})_{i,i}$, [27, p. 345].

$$Var(\widehat{\alpha}) \geq (I^{-1})_{1,1} = \frac{K\sigma^2}{K\sum_{i=1}^{K} v_i^2 - (\sum_{i=1}^{K} v_i)^2}, \tag{21}$$

$$Var(\widehat{\beta}) \geq (I^{-1})_{2,2} = \frac{\sigma^2 \sum_{i=1}^{K} v_i^2}{K\sum_{i=1}^{K} v_i^2 - (\sum_{i=1}^{K} v_i)^2} \tag{22}$$

Figure 3 (a, b) compares the MSE of the proposed estimator and the corresponding CRLB, with regards to the skew (α) and offset (β), respectively. Similarly to the previous simulation, α and β have been randomly selected from a $\mathcal{N}(1, 1)$ distribution, and $\mathcal{N}(0, 1)$ distribution, respectively. Delays have also been randomly generated from a $\mathcal{N}(0.001, 1)$ distribution. Each point of the plots is the average of 10^4 measurements. The two figures illustrates how the proposed estimators' MSE decreases and converges to the CRLB as the number of beacons (K) increases. It can be noted that the convergence is quadratic.

5 Conclusion

A distributed synchronization protocol for wireless sensor networks (WSN) has been proposed. The protocol permits nodes to cooperatively and mutually synchronize, by estimating relative skews/offsets. This enables nodes to run their clocks independently at their own rate without the need to be tuned to a fixed reference. It is based on the receiver/receiver paradigm that provides high precision by reducing the critical path, which is the message path that contributes to non-determinism of the delays. To our knowledge, the proposed protocol is the first distributed receiver/receiver synchronization protocol. In addition to decentralization, it eliminates additional steps needed by the state-of-the-art RBS-based solutions to exchange timestamps between synchronizing nodes. This reduces the communication overhead, as well as the energy consumption. Given that the proposed protocol is the first distributed one based on receiver/receiver synchronization, and that it relies on relative synchronization, none of the models proposed in the literature directly applies to it. Offset-only estimation as well as joint offset/skew estimation has been considered, and the maximum likelihood estimators (MLE) have been derived along with the corresponding Cramer-Rao lower bounds (CRLB). The results show the proposed estimators' precision quadratically rises with the number of samples, and approaches the CRLB.

Simulation of the proposed solution through a network simulator - to investigate network performance metrics and compare with existing solutions - is a perspective of this work. Considering other channel models- such like channels with exponentially distributed delays- is also in the perspectives. Finally, our agenda includes real implementation of the solution on sensor motes.

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