R^4Syn: Relative Referenceless Receiver/Receiver Time Synchronization in Wireless Sensor Networks

Djamel Djenouri

***Abstract*—A new time synchronization protocol for wireless sensor networks (WSN) is proposed. It uses the receiver-to-receiver principle introduced by the Reference Broadcast Synchronization (RBS), which reduces the time-critical path compared to the sender-to-receiver approach. The proposed protocol has the advantage of distributing the reference's function among all sensors, which eliminates the single point of failure (reference) shortcomings of RBS. It also allows timestamps to be piggybacked to the regular signals (beacons) and thus eliminates the need of separate transmissions for exchanging timestamps. After local synchronization, a multi-hop extension is proposed using final local estimates, with no forwarding of synchronization signals. Maximum likelihood estimators (MLE) are derived to estimate relative skew/offset for channels with Gaussian distributed delays. The Cramer-Rao lower bounds (CRLB) are accordingly derived and numerically compared with the MLE's mean square error (MSE). Results show convergence of the proposed estimators' precision to their respective CRLB with the increase of the number of signals.**

I. Related Work

The receiver-to-receiver approach introduced with the Reference Broadcast Synchronization (RBS) protocol [1] has the advantage of reducing the time-critical path, and therefore improving synchronization accuracy compared to the sender-to-receiver approach [2, Sec 3.3, P. 294]. It exploits the broadcast property of the wireless communication medium, where receivers- located within listening distance of the same sender- 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 signals (beacons) from a dedicated sender (reference), which make periodical broadcasts. Reception events are timestamped with local clocks. The timestamps are then exchanged between nodes and used as samples for estimating relative skews/offsets.

However, the major drawback of RBS is the need of a fixed reference, which might be inappropriate for some self-organized wireless sensor network (WSN) applications. The purpose of this letter is to tackle this drawback and propose a fully distributed solution. In [3], Sari et al. define joint skew/offset MLE for RBS. The model used in this work is different from the one of Sari et al. In the latter, synchronization is related to a single reference, while there is no such a common reference with the proposed solution's model. Further, Sari et al. [3] consider exponentially distributed delays, while the proposed one considers Gaussian distributed delays. Note that according to [1, p. 151], Gaussian distribution is more appropriate to receiver-to-receiver-based protocols like the one proposed herein. The model of [3] has also the shortcomings of referring to the sender's clock for synchronization, which deviates from RBS principle as it will be illustrated in the next section. [4] proposes the pairwise broadcast synchronization (PBS) as a hybrid solution between sender-to-receiver and receiver-to-receiver approaches, which has been improved in [5]. Glossy [6] exploitees IEEE 802.15.4 interferences, to couple synchronization with network flooding. Sadler [7] considers the uses of an external accurate clock whose values may be occasionally observed through broadcast signal reception (such as GPS receivers). He provides estimators to synchronize the sensor mote's clock to such an accurate clock. Some other solutions focus on global synchronization and attempt to improve the multi-hop precision, such as the flooding time synchronization protocol (FTSP) [8], [9], [10], [11]. Most of these solutions are based on continuous clock correction, and synchronization signals flooding. The protocol proposed in this letter does not propagate synchronization signals beyond one-hop. Further, only single-hop parameters are updated continuously, where multi-hop estimates between two nodes are only calculated when they initialize a communication.

For a more detailed review on distributed time synchronization in wireless networks, readers are referred to [12]. Next, the proposed protocol- termed R^4Syn- is described. It will be shown how the protocol eliminates the need of a fixed reference while taking advantage of the receiver-to-receiver synchronization's precision.

II. Solution Overview

Local (one-hope) synchronization is described in this section. It is assumed that nodes to be synchronized are in the vicinity of each other. A multi-hop extension will be presented later. Every node has its own clock that runs independently from the others. The synchronization is ensured by estimating parameters reflecting relative deviation with respect to every other node, where no local-clock's value update is needed. Further, 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 ID of every neighboring node. The network is supposed static, and node mobility is not considered. The solution is proposed at a high level of abstraction, independently of the underlying protocols. This enables its implementation with any protocol stack, but there is ample room for optimization in real implementation through the use of particular protocols

Copyright ©2012 IEEE
Djamel Djenouri is with CERIST Research Center, Algiers, Algeria.
Email: ddjenouri@mail.cerist.dz, ddjenouri@acm.org

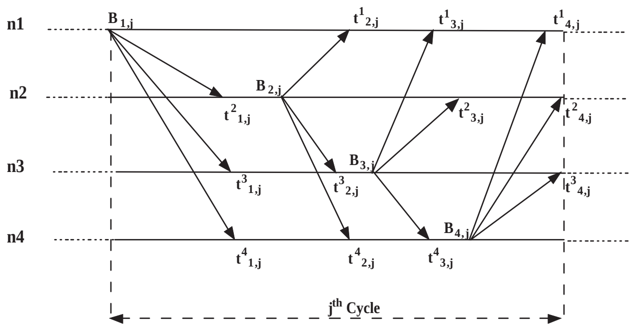

Fig. 1. Example of beacon broadcast during one cycle

and cross-layer design, such as by using/integrating MAC protocol's messages/cycles. Despite continuous beacon broadcasting, duty cycling is enabled. The nodes just need to send beacons during active periods.

R^4Syn distributes the reference role amongst all participating nodes. It runs in cycles, where nodes sequentially broadcast beacons. IDs can be used to determine the order of the sequence. A beacon carries timestamps, reporting local reception times of previous beacons. For a neighborhood 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 Fig. 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 3 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 relative synchronization parameters. Estimators will be proposed in the next section.

Neighboring set may change due to node mobility, and node failure. Supporting node mobility is out of the scope of this letter. However, dealing with node failure can be straight forward. If a node does not report its beacon during a timeout, then the next one can implicitly use its slot. Further, if the node is perceived not to reporting a beacon up to a certain number of cycles, the schedule will be updated accordingly by simply removing the faulty node's slot.

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.

III. Estimators and Analysis

[3] is the only work that considers joint skew/offset MLE estimators for RBS. The major shortcomings one can notice on this model is that it does not synchronize receivers directly but through synchronization to the reference clock, which completely deviates from the RBS concept. Note that the concept of a reference in RBS is to use a common reference for signal broadcast, but not a common reference of time. Although relative parameters can be determined by synchronizing the receivers to the reference, this way of synchronization causes cumulative errors on the estimators. Moreover, eliminating the sender uncertainty from the critical path is at the core of RBS, while this uncertainty is not eliminated by relating the transmitter's (reference's) time to the receiver's time in the model[1]. The model presented in the following is different from the one of [3]. It allows to directly estimating relative parameters without using or referring to the reference clock. This faithfully reflects the RBS concept.

Without loss of generality, synchronization between two nodes, say, n_1 and n_2, is described, i.e., n_2's estimation of synchronization parameters with regard to n_1. The same process is to be applied for each pair of communicating nodes. Let u_i and v_i, $i \in \{1, ..., K\}$, denote the i^{th} beacon reception timestamp of nodes n_1 and n_2, respectively, and d_{ui}, d_{vi} the corresponding reception delays. Only beacons received by both nodes are used to construct samples, (u_i, v_i). The protocol tolerates beacon loss that is common due to the lossy wireless channels. A beacon loss at some node engenders a miss of one sample, which will be substituted by the next bacon received by the two sides. Referring to the example of Fig. 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 $t^2_{3,1} = v_1$, $t^2_{4,1} = v_2$,..., $t^2_{3,j} = v_{2j-1}$, $t^2_{4,j} = v_{2j}$.

Each of d_{ui} (respectively d_{vi}) is composed of a fixed portion, say fd_{ui} (respectively fd_{vi}), and a variable portion, say X_{ui} (respectively X_{vi}). The fixed portions are assumed to be equal and the variable portions to be Gaussian distributed random variables (rv) with the same parameters, i.e., $X_{vi}, X_{ui} \sim \mathcal{N}(\mu, \sigma_0^2)$. It follows that $d_{ui} - d_{vi} = X_{ui} - X_{vi}$. Let us denote $X_{ui} - X_{vi}$ by X_i, and the relative skew and offset respectively by α and β. Application of the generale linear equation relating two clocks to the model yields [2, P. 289, Eq. (17)], $u_i = \alpha v_i + \beta + X_i$. Therefore,

$$X_i = u_i - \alpha v_i - \beta, \tag{1}$$

X_i is the difference between 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 gathering K samples, $\mathcal{L}(\alpha, \beta | X_1, ...X_K)$, is given by,

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

Since

$$\widehat{\alpha}_{mle}, \widehat{\beta}_{mle} = \arg\max(\ln \mathcal{L}(\alpha, \beta | X_1, ...X_K)), \tag{3}$$

$\widehat{\alpha}_{mle}, \widehat{\beta}_{mle}$ may be obtained by vanishing the partial derivatives of the likelihood function's logarithm. That is, by resolving the system of equations,

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

The resulted estimators are:

[1] Refer to Eq. (1) and Eq. (2) in [3, p. 1], v_{x,λ_x}, v_{y,λ_y} would be the noise (variable delay) due to both transmission and reception. This adds transmission delays to the time critical path

$$\widehat{\alpha}_{mle} = \frac{\sum_{i=1}^{K} u_i \sum_{i=1}^{K} v_i - K \sum_{i=1}^{K} v_i u_i}{\left(\sum_{i=1}^{K} v_i\right)^2 - K \sum_{i=1}^{K} v_i^2}, \tag{4}$$

$$\widehat{\beta}_{mle} = \frac{1}{K}\left(\sum_{i=1}^{K} u_i - \frac{\sum_{i=1}^{K} u_i \sum_{i=1}^{K} v_i - K \sum_{i=1}^{K} v_i u_i}{\left(\sum_{i=1}^{K} v_i\right)^2 - K \sum_{i=1}^{K} v_i^2} \sum_{i=1}^{K} v_i\right). \tag{5}$$

Therefore, node n_2 uses samples (u_i, v_i), and applies Eq. (4) (resp. Eq. (5) to calculate MLE for the relative skew, α, (resp. offset, β). This is without the need to estimate the unknown delays. That is, all the delay parameters used in the model are unknown; $\mu, \sigma, X_{ui}, X_{vi}, d_{ui}, d_{vi}, f_{ui}, f_{vi}$, and there is no need to estimate them. Only reception timestamps– samples (u_i, v_i)– are empirically observed and used to estimate α and β (by node n_2), where the the other parameters are vanished through the standard MLE method.

The appropriate CRLB– which represents the theoretical lower-bound for any unbiased estimator– can be derived from I^{-1}; the inverse of the 2×2 Fisher information vector, I, using the bound, $Var(\widehat{\Theta_i}) \geq (I^{-1})_{i,i}$. The result is,

$$Var(\widehat{\alpha}) \geq (I^{-1})_{1,1} = \frac{K\sigma^2}{K \sum_{i=1}^{K} v_i^2 - \left(\sum_{i=1}^{K} v_i\right)^2}, \tag{6}$$

$$Var(\widehat{\beta}) \geq (I^{-1})_{2,2} = \frac{\sigma^2 \sum_{i=1}^{K} v_i^2}{K \sum_{i=1}^{K} v_i^2 - \left(\sum_{i=1}^{K} v_i\right)^2} \tag{7}$$

Fig. 2 and Fig. 3 show simulation results that compare MSE of the proposed estimator and the corresponding CRLB, with regard to the skew (α) and offset (β), respectively. Each point of the plots is the average of 10^4 measurements. The two figures illustrate how the proposed estimators' MSE decrease and converge to the CRLB as the number of beacons (K) increases. It can be realized that the convergence is quadratic (note the logarithmic scale).

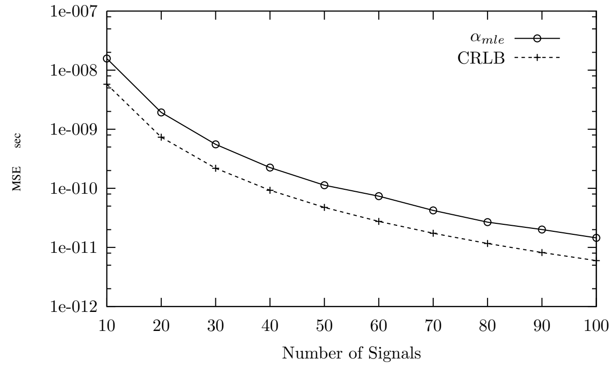

Fig. 2. MSE of α estimation vs number of signals

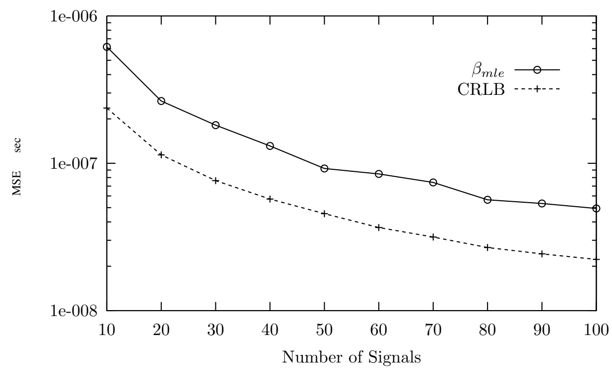

Fig. 3. MSE of β estimation vs number of signals

IV. Multi-Hop Extension

In relative synchronization, nodes estimate relative parameters (skew and/or offset) with respect to each other, while running their clocks independently. This is conceptually different from clock-update solutions that attempt to define protocols allowing convergence of all clocks to a common value. The relative synchronization used in the local synchronization of R^4Syn facilitates extension to multi-hop environments. Every node runs– locally and independently– the synchronization protocol with its neighbors, as described in the previous section. As soon as a node initiates a multi-hop communication that needs synchronization between the end-points, intermediate routers may forward local synchronization parameters to the communicating nodes and allow them to calculate multi-hop relative parameters. Therefore, the multi-hop synchronization is performed only on-demand.

Suppose node n_1 needs to synchronize to a remote node n_h, and the established route is $\{n_1, n_2, n_3, ..., n_h\}$. Each intermediate router, n_i, would have already estimated parameters relating it to the next router, n_{i+1}, through the execution of the local synchronization described in Section II. At this stage, it just needs to send its estimates to the source node, n_1. The same processes is to be applied symmetrically to synchronize the destination to the source; i.e. the intermediate node supplies the destination node with its estimate in respect of of the previous node. In the following, node n_1 synchronization to node n_h is described.

Let t_{n_i} denotes the time reading of node n_i's clock at instant t, and $\alpha_{n_i \to n_j}$ (respectively $\beta_{n_i \to n_j}$) denote the relative skew (respectively offset) relating time at node, n_i, to the corresponding one at node, n_j. That is, $t_{n_j} = \alpha_{n_i \to n_j} t_{n_i} + \beta_{n_i \to n_j}$. Time readings of nodes in the route can thus be related by:

$$t_{n_i} = \alpha_{n_{i+1} \to n_i} t_{n_{i+1}} + \beta_{n_{i+1} \to n_i}, i \in \{1, ..., h-1\}$$

By successive substitutions of $t_{n_{i+1}}$ expressions in t_{n_i} equations ($i \in \{h-2, ..., 1\}$), the following may be obtained,

$$t_{n_1} = \left(\prod_{i=1}^{h-1} \alpha_{n_{i+1} \to n_i}\right) t_{n_h} +$$

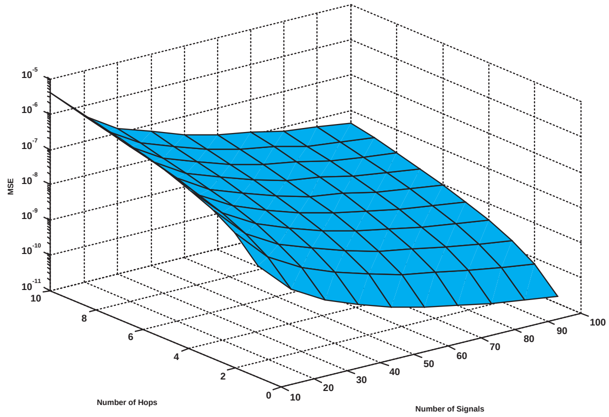

Fig. 4. MSE of α estimation vs number of signals and number of hops

$\sum_{i=2}^{h-1}[(\prod_{j=2}^{i}\alpha_{n_j\to n_{j-1}})\beta_{n_{i+1}\to n_i}]+\beta_{n_2\to n_1}$. Consequently,

$$\alpha_{n_h\to n_1}=\prod_{i=1}^{h-1}\alpha_{n_{i+1}\to n_i}, \tag{8}$$

$$\beta_{n_h\to n_1}=\sum_{i=2}^{h-1}[(\prod_{j=2}^{i}\alpha_{n_j\to n_{j-1}})\beta_{n_{i+1}\to n_i}]+\beta_{n_2\to n_1}. \tag{9}$$

A multi-hop linear network of 10 nodes has been simulated. Fig. 4 depicts the skew's MSE and shows how the increase of samples (signals) considerably improves the precision, even for configurations with high number of hops values. Results illustrate that the MSE has always been kept within acceptable range even for small number of signals and a large number of hops.

V. Conclusion

A distributed synchronization protocol for wireless sensor networks (WSN) has been proposed. It relies on the receiver-to-receiver paradigm introduced by the reference broadcast synchronization (RBS). This paradigm provides high precision by reducing the time-critical-path, which is the message path that contributes to non-determinism of the delays. The proposed protocol eliminates the need of a fixed reference and conceptually distributes the reference broadcast task to all synchronizing node, which makes it more suitable to self-organized WSN and overcomes the single-point-of failure problem. In addition to eliminating the reference, it eliminates additional steps needed by the state-of-the-art RBS-based solutions to exchange timestamps between synchronizing nodes. The maximum likelihood estimators (MLE) have been derived along with the corresponding Cramer-Rao lower bounds (CRLB), to which the estimators have been compared by simulation. The results show the proposed estimators' precision quadratically rises with the number of samples, and approaches the the theoretical optimum (CRLB). Comparing the protocol with existing protocols through a network simulator is one perspective to this work. Implementation on sensor motes and experiments is also in the agenda.

References

[1] J. Elson, L. Girod, and D. Estrin, "Fine-grained network time synchronization using reference broadcasts," in *5th USENIX Symposium on Operating System Design and Implementation (OSDI'02)*, December 2002.

[2] B. Sundararaman, U. Buy, and A. D. Kshemkalyani, "Clock synchronization for wireless sensor networks: a survey," *Ad hoc Networks*, vol. 3, no. 3, pp. 281–323, 2005.

[3] I. Sari, E. Serpedin, K.-L. Noh, Q. M. Chaudhari, and B. W. Suter, "On the joint synchronization of clock offset and skew in rbs-protocol," *IEEE Transactions on Communications*, vol. 56, no. 5, pp. 700–703, 2008.

[4] K.-L. Noh, E. Serpedin, and K. A. Qaraqe, "A new approach for time synchronization in wireless sensor networks: Pairwise broadcast synchronization," *IEEE Transactions on Wireless Communications*, vol. 7, no. 9, pp. 3318–3322, 2008.

[5] Y.-H. Huang and S.-H. Wu, "Time synchronization protocol for small-scale wireless sensor networks," in *IEEE Wireless Communications and Networking Conference (WCNC'10)*, 2010, pp. 1–5.

[6] F. Ferrari, M. Zimmerling, L. Thiele, and O. Saukh, "Efficient network flooding and time synchronization with glossy," in *IPSN*, 2011, pp. 73–84.

[7] B. M. Sadler, "Local and broadcast clock synchronization in a sensor node," *IEEE Sig. Proc. Letters*, vol. 13, no. 1, pp. 9–12, 2006.

[8] M. Maróti, B. Kusy, G. Simon, and Á. Lédeczi, "The flooding time synchronization protocol," in *SenSys*, 2004, pp. 39–49.

[9] K.-Y. Cheng, K.-S. Lui, Y.-C. Wu, and V. Tam, "A distributed multi-hop time synchronization protocol for wireless sensor networks using pairwise broadcast synchronization," *IEEE Transactions on Wireless Communications*, vol. 8, no. 4, pp. 1764–1772, 2009.

[10] C. H. Rentel and T. Kunz, "A mutual network synchronization method for wireless ad hoc and sensor networks," *IEEE Trans. Mobile Computing*, vol. 7, no. 5, pp. 633–646, 2008.

[11] C. Lenzen, P. Sommer, and R. Wattenhofer, "Optimal clock synchronization in networks," in *Proceedings of the 7th ACM International Conference on Embedded Networked Sensor Systems (SenSys'09)*, November 2009, pp. 225–238.

[12] O. Simeone, U. Spagnolini, Y. Bar-Ness, and S. H. Strogatz, "Distributed synchronization in wireless networks," *IEEE Signal Processing Magazine*, vol. 25, no. 5, pp. 81–97, 2008.