Analysis of Existing Approaches and a New Hybrid Strategy for Synchronization in Sensor Networks*

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Abstract

Prior work on sender-receiver-based time synchronization in sensor networks can be categorized into two approaches: two-way packet exchange and one-way packet dissemination. We provide a comprehensive analysis of synchronization errors with these two approaches. We find that one-way dissemination approach provides good relative drift estimation and poor drift estimation while the two-way exchange approach provides good drift estimation but poor relative drift estimation. Consequently, both approaches can result in significant cumulative error propagation over multiple hops. We develop and analyze a hybrid one-way dissemination/two-way exchange technique. The results suggest that this hybrid approach can provide bounded error propagation in multi-hop settings.

1. Introduction

Many applications in wireless sensor networks have to be accomplished through collaboration between several nodes. Accurately synchronized clocks are not only important in integrating information, but also are essential to many other protocols, e.g. medium access and sleep scheduling. Due to the uniqueness of wireless sensor network environments, many time synchronization protocols which aim at the wireless sensor network environments have been proposed (see [1] for an excellent survey of the state of the art in time synchronization). In general, the existing works that involve sender-receiver synchronization can be categorized into two types. One can be called "one-way packet dissemination" and the other is "two-way packet exchange." While the former needs a reference node to disseminate packets to unsynchronized nodes, the latter achieves synchronization by exchanging packets between reference and unsynchronized nodes. The Flooding Time Synchronization Protocol (FTSP) [2] is one representative protocol of the one-way packet dissemination scheme. The Timing-sync Protocol for Sensor Networks (TPSN) [3] is a representative of the two-way packet exchange scheme, which requires unsynchronized nodes to exchange packets with their reference nodes back-and-forth [1].

We undertake a comparative analysis of the synchronization error of the one-way and two-way schemes. According to our analysis, the one-way packet dissemination does better on estimating relative drift, while the two-way exchange does better on estimating drift, but both approaches suffer from a biased drift estimation that can result in unbounded error propagation over multiple hops. We propose a hybrid one-way/two-way mechanism that performs more gracefully under multi-hop conditions.

This paper is organized as follows: we analyze the synchronization error for one-way, two-way and the hybrid mechanism for a single sender-receiver pair in section 2. We then investigate the multi-hop synchronization error propagation in section 3. The three approaches are compared via simple simulations in 4. We conclude with a summary and directions for future work in section 5.

2. Synchronization Error Analysis

According to [2], the possible sources of delays in packet transmission include application layer send-receive times, access time, link layer transmission and reception time, propagation time, interrupt handling time, encoding and decoding time, and byte alignment time. In the following we represent by Γ_i the total delay taken for a packet to be transmitted from one node to another, even after some of

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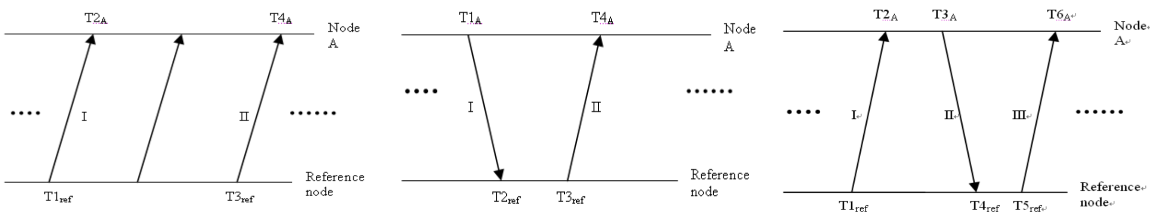
1 A different approach to such sender-receiver schemes is receiver-receiver synchronization, exemplified by the Reference Broadcast Synchronization (RBS) mechanism [4]. We do not analyze receiver-receiver mechanisms in this work.



(a) (b) (c)

Figure 1. Message timelines for (a) one-way, (b) two-way, and (c) hybrid sender-receiver synchronization schemes

Ti_j	The time Ti is the clock reading of node j.
ti	The time measured by an ideal clock corresponding to the clock reading Ti.
$D_{ti}^{j\to k}$	The drift in ideal time, measured by ideal clock ti, between node j and k.
$RD_{ti\to tj}^{k\to l}$	The relative drift between node k and l contributed by the duration from ideal time ti to tj.
$\Delta RD_{ti\to tj}^{k\to l}$	The estimation error of relative drift $RD_{ti\to tj}^{k\to l}$.
Γ_i	Total transmission and reception time for packet i as measured by an ideal clock.
$\Gamma_{i,j}$	Total transmission and reception time for packet i at level j as measured by an ideal clock.
$\Theta_{(i,k),j}$	Error between node i and k at level j as measured by an ideal clock.
Ω_i^j	Inter-synchronization error at level i by using scheme j as measured by an ideal clock.

Table 1. Notation

the component delay sources are mitigated through sophisticated time stamping techniques such as those proposed in [2].

Consider figure 1; the arrows in each figure represent directions of transmitted packets for synchronization purposes. We first present an analysis of the drift and relative drift for the different schemes for the simplest two-node one-hop setting. Drift refers to the offset of the two clocks at the moment of synchronization. Estimation of the drift thus helps reset the clocks for re-synchronization. Relative drift refers to change in this offset over some period of time. Estimating the rate of this change can be useful in mitigating further clock drift between synchronization events. The symbols used below are listed in table 1.

2.1. Analysis of One-way Scheme

In figure 1(a), the time relations of packet I and II can be written as follows:

$$T2_A = T1_{ref} + D_{t1}^{ref\to A} + \Gamma_I \quad (1)$$

$$T4_A = T3_{ref} + D_{t3}^{ref\to A} + \Gamma_{II} \quad (2)$$

Because $D_{t1}^{ref\to A} - D_{t3}^{ref\to A} = RD_{t1\to t3}^{ref\to A}$, subtracting equation (2) from (1), we get:

$$RD_{t1\to t3}^{ref\to A} \approx RD_{t2\to t4}^{ref\to A} = (T2_A - T4_A)$$
$$-(T1_{ref} - T3_{ref}) - (\Gamma_I - \Gamma_{II}) \quad (3)$$

Also, from equation (2), we can get:

$$D_{t3}^{ref\to A} = (T4_A - T3_{ref}) - \Gamma_{II} \approx D_{t4}^{ref\to A} \quad (4)$$

Thus, we can see that the one-way scheme consistently over-estimates the drift by Γ_{II}.

2.2. Analysis of Two-way Scheme

In figure 1(b), the time relations of packet I and II can be written as follows:

$$T2_{ref} = T1_A - D_{t1}^{ref\to A} + \Gamma_I \quad (5)$$

Note that $D_{t3}^{ref\to A} \approx D_{t4}^{ref\to A}$; hence,

$$T4_A = T3_{ref} + D_{t4}^{ref\to A} + \Gamma_{II} \quad (6)$$

Because $D_{t1}^{ref\to A} - D_{t4}^{ref\to A} = RD_{t1\to t4}^{ref\to A}$, adding equation (5) and (6), we get:

$$RD_{t1\to t4}^{ref\to A} = (T1_A - T2_{ref}) + (T3_{ref} - T4_A)$$
$$+(\Gamma_{II} + \Gamma_I) \quad (7)$$

According to [3], the drift estimation is: $\triangle = \frac{1}{2}[(T1_A - T2_{ref}) - (T3_{ref} - T4_A)]$. Substitute the relative drift with equation (7) we can get error of drift estimation as:

$$Error = \frac{1}{2}[(T1_A - T2_{ref}) + (T3_{ref} - T4_A)] + \Gamma_{II} \quad (8)$$

From equation (7) we can see that one serious problem of using two-way scheme is inaccurate relative drift estimation.

2.3. A Hybrid Scheme and its analysis

The synchronization errors observed with both one-way and two-way are illustrated in figure 2 (a) and (b). In these figures, the X-axis and Y-axis represents clock reading of reference node and node A, respectively. The solid line represents the real relation of clock readings of reference node and node A. The measured relation is plotted as dotted line. If Γ_I and Γ_{II} has the same distribution, then the one-way scheme produces precise relative drift estimation but over-estimates drift in average. Again, if Γ_I and Γ_{II} have the same distribution, then we can conclude that the two-way scheme over-estimates relative drift.

We propose a hybrid scheme that attempts to combine the best features of the one-way and two-way schemes to give better precision. The basic idea is to obtain a relative drift estimation expression similar to one-way but use it in the drift estimation for two-way. This hybrid scheme is shown in figure 1(c). The time relations of packet I, II, and III for this figure can be written as follows:

$$T4_{ref} = T3_A - D_{t3}^{ref\to A} + \Gamma_{II} \tag{9}$$

$$T6_A = T5_{ref} + D_{t5}^{ref\to A} + \Gamma_{III} \tag{10}$$

$$T2_A = T1_{ref} + D_{t1}^{ref\to A} + \Gamma_I \tag{11}$$

Because $D_{t5}^{ref\to A} \approx D_{t6}^{ref\to A}$, subtracting equation (10) from (9), we get:

$$2D_{t6}^{ref\to A} + RD_{t3\to t6}^{ref\to A} = (T6_A - T4_{ref}) - (T5_{ref} - T3_A) - (\Gamma_{III} - \Gamma_{II}) \tag{12}$$

Also, subtracting equation (10) from (11), we get:

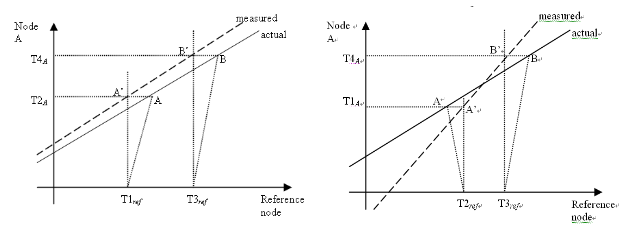
$$RD_{t1\to t5}^{ref\to A} = (T2_A - T6_A) - (T1_{ref} - T5_{ref}) - (\Gamma_I - \Gamma_{III}) \tag{13}$$

Because $RD_{t1\to t5}^{ref\to A} \approx RD_{t2\to t6}^{ref\to A}$, and $RD_{t3\to t6}^{ref\to A} = RD_{t2\to t6}^{ref\to A}\frac{T6_A - T3_A}{T6_A - T2_A}$, we can have:

$$RD_{t3\to t6}^{ref\to A} = \frac{T6_A - T3_A}{T6_A - T2_A}[(T5_{ref} - T1_{ref}) - (T6_A - T2_A) + (\Gamma_{III} - \Gamma_I)] \tag{14}$$

Therefore,

$$D_{t6}^{ref\to A} = \frac{1}{2}[(T6_A - T4_{ref}) - (T5_{ref} - T3_A) + \frac{T6_A - T3_A}{T6_A - T2_A}[(T6_A - T2_A) - (T5_{ref} - T1_{ref}) - (\Gamma_{III} - \Gamma_I)] - (\Gamma_{III} - \Gamma_{II})] \tag{15}$$



(a) (b)

Figure 2. Illustration of synchronization errors with (a) one-way and (b) two-way schemes.

From equations (14) and (15), if Γ_I, Γ_{II}, and Γ_{III} have the same distribution, then using hybrid scheme provides not only precise relative drift estimation, but also accurate drift estimation. We will further evaluate the multihop performance of this hybrid scheme in the next section.

A brief summary of the above analyses can be found in table 2.

3. Synchronization Error under Multihop Situations

Because a synchronized node, say node A, starts drifting away after it completes synchronization, node A may already posses significant error before another node tries to synchronize with it. If node A uses relative drift estimation to calibrate its clock before providing readings to other nodes, the inaccuracy of relative drift estimation still deteriorates the synchronization precision. The longer the inter-synchronization period is, the lower the precision will be. We call this kind of error as "inter-sync error," and denote it as Ω. Ω can be calculated as:

$$\Omega = \frac{\Delta RD_{ti\to tj}^{m\to n}}{tj - ti} T_{sync} \tag{16}$$

Where T_{sync} represents the time to the next synchronization request and ΔRD represents the error in relative drift estimation. Obviously, Ω is not a negligible error source, especially in multihop networks with sleep-scheduling (which can increase the inter-synchronization intervals).

If node i, which belongs to level j, synchronizes with another already synchronized node k, which belongs to level $j-1$, then we denote the synchronization error between node i and k as $\Theta_{(i,k),j}$. Consider a network with exactly one node in each level, indexed by its level number. The synchronization error between the level N node and the root node can be computed as:

$$\Theta(N) = \sum_{i=1}^{N} \Theta_{(i,i-1),i} \tag{17}$$

Based on analyses in previous sections, the $\Theta(N)$ under different synchronization schemes can be calculated as:

$$\Theta^{1-way}(N) = \sum_{i=1}^{N} (\Gamma_{II,i} + \Omega_i^{1-way}) \tag{18}$$

$$\Theta^{2-way}(N) = \sum_{i=1}^{N} [\frac{1}{2}((T1_{A,i} - T2_{ref,i}) + (T3_{ref,i} - T4_{A,i})) + \Gamma_{II,i} + \Omega_i^{2-way}] \tag{19}$$

$$\Theta^{hybrid}(N) = \sum_{i=1}^{N} [\frac{T6_A - T3_A}{2(T6_A - T2_A)} (\Gamma_{III,i} - \Gamma_{I,i}) + \frac{1}{2}(\Gamma_{III,i} - \Gamma_{II,i}) + \Omega_i^{hybrid}] \tag{20}$$

In a network where every node is equipped with the same hardware, it is reasonable to claim that all Γ terms have the same distribution. If the number of iterations is large enough, by the law of large numbers, for large values of N, the expected value of expressions in equations (18), (19), and (20) can be calculated as:

$$E[\Theta^{1-way}(N)] = N(E[\Gamma_{II}] + E[\Omega^{1-way}]) \tag{21}$$

$$E[\Theta^{2-way}(N)] = N(\frac{1}{2}(E[T1_A - T2_{ref}] + E[T3_{ref} - T4_A]) + E[\Gamma_{II}] + E[\Omega^{2-way}]) \tag{22}$$

$$E[\Theta^{hybrid}(N)] = N[\frac{T6_A - T3_A}{2(T6_A - T2_A)} (E[\Gamma_{III}] - E[\Gamma_I]) + \frac{1}{2}(E[\Gamma_{III}] - E[\Gamma_{II}]) + E[\Omega^{hybrid}]] \tag{23}$$

where the expected error of relative drift estimation of each scheme can be presented in a simple form if we consider $T_{sync} = (tj - ti)$ in equation (16):

$$E[\Omega^{1-way}] = E[\Gamma_I] - E[\Gamma_{II}] \tag{24}$$

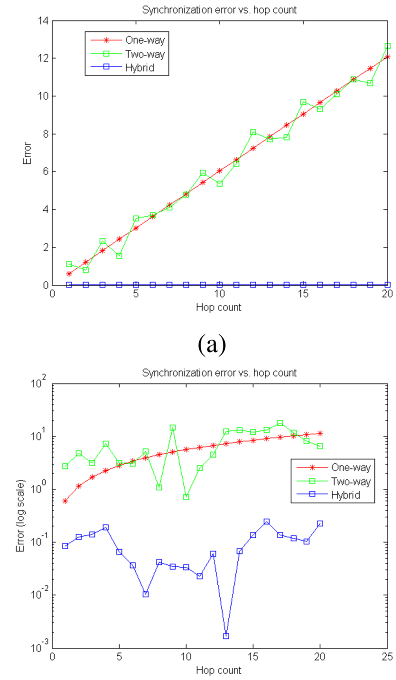
$$E[\Omega^{2-way}] = -E[\Gamma_I] - E[\Gamma_{II}] \tag{25}$$

$$E[\Omega^{hybrid}] = \frac{T6_A - T3_A}{T6_A - T2_A} (E[\Gamma_I] - E[\Gamma_{III}]) \tag{26}$$

From the above, if $E[\Gamma_I] = E[\Gamma_{II}] = E[\Gamma_{III}] = E[\Gamma]$, we have for large N that

$$E[\Theta^{1-way}(N)] = NE[\Gamma] \tag{27}$$

$$E[\Theta^{2-way}(N)] = N(\frac{1}{2}(E[T1_A - T2_{ref}] + E[T3_{ref} - T4_A]) - E[\Gamma]) \tag{28}$$



(a)

(b)

Figure 3. Simulation results showing multi-hop error propagation for one-way, two-way and hybrid schemes, in linear and log scales.

$$E[\Theta^{hybrid}(N)] = 0 \tag{29}$$

Thus, compared to the other two schemes, the hybrid scheme shows no systematic increase in error with the hop distance to root node. Note that, although we make an assumption of $T_{sync} = (tj - ti)$ here, a more general expression can be derived by using equation (16).

4. Simulations

4.1. Simulation Environment

We simulate a linear network with 20 hops, with node at each level. One-way, two-way, and hybrid schemes are used to synchronize this network, from the root node towards the leaf node. We use normalized time units in our simulations. Synchronization error is calculated as the ideal time difference between the root node and each synchronized node. The parameters used for the simulations are described in table 3. All parameters are chosen independently.

4.2. Results

The X-axis and Y-axis in figure 3(a) represent the hop distance to the root node and the absolute value of synchro-

	One-way	Two-way	Hybrid
Error in drift estimation	Γ_{II}	$\frac{1}{2}((T1_A - T2_{ref}) + (T3_{ref} - T4_A)) + \Gamma_{II}$	$\frac{T6_A - T3_A}{T6_A - T2_A}(\Gamma_{III} - \Gamma_I) + (\Gamma_{III} - \Gamma_{II})$
Error in relative drift estimation	$\Gamma_I - \Gamma_{II}$	$-(\Gamma_I + \Gamma_{II})$	$\frac{T6_A - T3_A}{T6_A - T2_A}(\Gamma_I - \Gamma_{III})$

Table 2. Summary of Estimation Errors with the Different Schemes

m_j	Uniform random variable in [0.3,0.7]
$\Gamma_{i,j}$	Uniform random variable in [m_j-0.2, m_j+0.2]
relative drift	Uniform random variable in [-40, 40] time units per million time units.
inter-synchronization period	one million time units

Table 3. Simulation Parameters ($\Gamma_{i,j}$ is the total time between time-stamps for packet i sent at hop j.)

nization error respectively. The outcomes presented are averaged over 100 runs. In this plot, the hybrid scheme possesses the lowest error. The one-way scheme and two-way schemes have similar performance scaling linearly with hops. The hybrid scheme shows almost constant error. These phenomena can be explained as follows. Synchronization error can be decomposed into the two parts described above: drift estimation error and inter-sync error, which depends on the relative drift estimation error. In our simulation, because the chosen value of inter-synchronization period, we can expect multi-hop error to be equally influenced by both inter-sync error and drift estimation error. The performance of the one-way scheme suffers due to poor drift estimation, while the performance of the two-way scheme suffers due to poor relative drift estimation. The hybrid scheme is able to do well on both counts.

Figure 3(b) shows the absolute value of the error in log scale, where the outcomes shown for a single round. The curve of hybrid scheme and the two-way schemes show fluctuations along the hop distance since the additional error terms at each hop can be positive or negative depending on the relative values of the delays.

5. Summary and Future Work

The major contributions of this work are as follows. First, we have presented a thorough comparison of two-way packet exchange and one-way dissemination schemes, whereby we find that, while one-way dissemination performs worse in estimating drift, two-way dissemination performs worse in estimating relative drift. Both schemes therefore result in unbounded error propagation. Second, we have proposed a hybrid one-way dissemination/two-way exchange synchronization scheme that can provide substantially better accuracy, and most importantly, bounded error propagation over multiple hops. Such a strategy would be most useful for very large scale network deployments.

We should emphasize that this work is very preliminary in nature. A more comprehensive evaluation study is needed to make conclusive judgements. In the future, we hope to develop a time synchronization protocol based on the hybrid scheme that will be suitable for multi-hop settings. It would then be of great value to compare the different approaches in detail through real implementations on wireless devices.

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References

[1] B. Sundararaman, U. Buy, A.D. Kshemkalyani, “Clock Synchronization in Wireless Sensor Networks: A Survey”, *Ad Hoc Networks*, 3(3): 281-323, May 2005.

[2] M. Maroti, B. Kusy, G. Simon and A. Ledeczi, “The Flooding Time Synchronization Protocol,” *SenSys*, November 3-5, 2004, Baltimore, Maryland, USA.

[3] S. Ganeriwal, R. Kumar, and M.B. Srivastava, “Timing-sync Protocol for Sensor Networks,” *SenSys*, November 5-7, 2003, Los Angeles, California, USA.

[4] J. Elson, L. Girod, and D. Estrin, ”Fine-Grained Network Time Synchronization using Reference Broadcasts,” in Proceedings of the Fifth Symposium on Operating Systems Design and Implementation (OSDI 2002), Boston, MA, December 2002.