An Asymmetric Time Synchronization Protocol for Wireless Sensor Networks

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Abstract

As an essential part of wireless sensor network applications, most of the existing time synchronization protocols currently only deal with symmetric case, where participating nodes have the same computational and communicational capacity. But in practice, we often encounter the asymmetric case, where participating nodes are of different capacity. This paper describes an Asymmetric Time Synchronization Protocol (ATSP), which works very efficiently in both symmetric and asymmetric cases. The ATSP was implemented on a simulated environment of the Berkeley Mica2 platform. The accuracy of the average synchronization error is in the range of several microseconds.

Keywords: Algorithms; Synchronization Protocols; Wireless Sensor Networks.

1 Introduction

In wireless sensor network applications, a scalable time synchronization service is often required to enable sleep scheduling, localization, in-network signal processing and coordination. Each node has different initial clock value: on one hand, the initial value is set to be different during manufacturing; on the other hand, to save up energy consumption, the node goes through a cycle of sleep and wake up based on externally detected events. In this case, the difference between time intervals can introduce different initial offset during the next time synchronization process. Moreover, handling exceptional events can have impact on the clock, for example, when using the Berkeley Mote platform for processing tasks such as dispatching data and sensing data may interrupt the clock, thus, the clock error is inevitable [1].

Although solutions for traditional Internet[17] and distributed systems or wireless ad hoc network studied for many years, they have been found out to be unsuited for wireless sensor networks [6,16], due to their computational complexity, energy issue and cost factors. The limitation of wireless sensor network calls for synchronization schemes that are energy-efficient, with low computational complexity, and easily implemented and deployed. Thus time synchronization in WSN has attracted researchers' attention as a new hot area in recent years.

The issue of synchronization in WSNs was first raised in [2]. Since then various algorithms have been proposed in the literature, most notably, RBS [3], TPSN [4], FTSP [5], TSMA [1] and RSP [6]. To the best of our knowledge, RSP has the smallest time synchronization error in WSNs. Currently, most of the existing time synchronization protocols only deal with the symmetrical case. This paper describes the Asymmetry Time Synchronization Protocol (ATSP), which is suitable for symmetric as well as asymmetric scenarios. In the following context, we use $C_A(t)$ and $r_A(t)$ to denote the local time and the local clock frequency of node A at physical time t, respectively. In engineering practice, $|r_A(t)-1|$ is always not larger than 100ppm (parts per million). For node A, we define ρ_A as the maximum of the function $|r_A(t)-1|$. Also we call the synchronization between two participating nodes with similar capability symmetrical synchronization, and synchronization between two participating nodes with different capability asymmetrical synchronization. Terms not defined in this paper can be referred to as in [5].

2 Related Work

Some fundamental work for traditional network was omitted as it was found to be unsuited for WSNs. As stated earlier, since 2002 time synchronization in WSNs has been widely researched. However, most existing time synchronization algorithms are application related, which means the algorithms only work effectively under certain conditions. Although the literature is vast, we will analyze several representative time synchronization algorithms in the following section. In particular, we will show how these algorithms break when applied to asymmetric case. Note that, except for TPSN, all these algorithms do time-stamping at MAC layer, to completely eliminate the send, access, and receive times.

2.1 Timing-Sync Protocol for Sensor Networks (TPSN)

TPSN [4] adopts the bidirectional pair-wise synchronization technique. Let D_1 be the time needed by the synchronization node A to send a synchronization packet to the reference node B (measured by the A's local clock). Let D_2 be the time needed by the reference node B to send a synchronization packet to the synchronization node A (measured by the B's local clock). Since TPSN assumes that D_1 is equal to D_2, we can conclude that TPSN is not suitable for the synchronization between two nodes with very different capability.

2.2 Flooding Time Synchronization Protocol (FTSP)

FTSP [5] adopts unidirectional broadcast and least square linear regression synchronization technique. Since the regression line of FTSP l is on the coordinate plane with the synchronization node B's local time as the horizontal axis and the reference node A's local time as vertical axis. Thus, the slope of l is the ratio of A's and B's local clock frequencies. From this, it is not difficult to see that on many time intervals the ratio of the reference node A's and the synchronization node B's local clock frequencies are constant. Therefore, the node A's and the B's capability should not be very different. Hence, FTSP is not suitable for the synchronization between two nodes with very different capability.

2.3 Ratio-Based Time Synchronization Protocol (RSP)

RSP [6] adopts quadratic unidirectional broadcast and linear interpolation synchronization technique. Since the RSP requires the synchronization node B's and the reference node A's local clock frequency constant between two synchronization instances and which means that both A and B need to have relatively good capability. As only when the time interval between two synchronizations is long can achieve the goal of energy conservation. Hence, RSP is not suitable for the time synchronization between two nodes with very different capability

3 Asymmetrical Time Synchronization Protocol (ATSP)

In some hybrid WSNs such as cluster-based sensor network, which become more and more popular recently, there are both expensive nodes and cheap nodes, and there exists huge difference between the communication and computation capabilities and the quality of local clock of expensive nodes and cheap nodes. Therefore, a good time synchronization protocol should consider both symmetrical and asymmetrical situations. Compared to most existing time synchronization protocols coping with symmetrical synchronization, our ATSP can cover both symmetrical and asymmetrical synchronization generically. To completely eliminate the send, access, and receive times, we also adopt the technique of time-stamping at MAC layer as in [5].

Let A be a reference node and B is being synchronized in reference to it. In the following we will describe the principle how the ATSP realize the synchronization between A and B. At physical time t_1, A begins to send a synchronization message SyncMsg1 with its local time $T_A^1 = C_A(t_1)$, maximal absolute value of clock skew ρ_A and rate of change of clock frequency η_A to B. At physical time t_2 (B's local time at this point is $T_B^1 = C_B(t_2)$), B begins to receive the SyncMsg1. At physical time $\hat{t}_1$ (A's local time at this point is $\hat{T}_A^1 = C_A(\hat{t}_1)$), A will send out the last byte of SyncMsg1. At physical time $\hat{t}_2$ (B's local time at this point is $\hat{T}_B^1 = C_B(\hat{t}_2)$), B will receive the last byte of SyncMsg1. At physical time t_3 (A's local time at this point is $T_A^2 = C_A(t_3)$), A begins to send a synchronization message SyncMsg2 with time-stamps $\hat{T}_A^1$ and T_A^2 to B. At physical time t_4 (B's local time at this point is $T_B^2 = C_B(t_4)$), B begins to receive the SyncMsg2. At physical time $\hat{t}_3$ (A's local time at this point is $\hat{T}_A^2 = C_A(\hat{t}_3)$), A will send out the last byte of SyncMsg2. At physical time $\hat{t}_4$ (B's local time at this point is $\hat{T}_B^2 = C_B(\hat{t}_4)$), B will receive the last byte of SyncMsg2. At physical time t_5 (A's local time at this point is $T_A^3 = C_A(t_5)$), A begin to send a synchronization message SyncMsg3 with time-stamps $\hat{T}_A^2$ and T_A^3 to B. At physical time t_6 (B's local time at this point is $T_B^3 = C_B(t_6)$), B begins to receive the SyncMsg3. At physical time t_7, A will send out the last byte of SyncMsg3. At physical time t_8 (B's local time at this point is $T_B^4 = C_B(t_8)$), B will receive the last byte of SyncMsg3. Consequently, the node B collects eleven time-stamps information as shown in Fig.1.

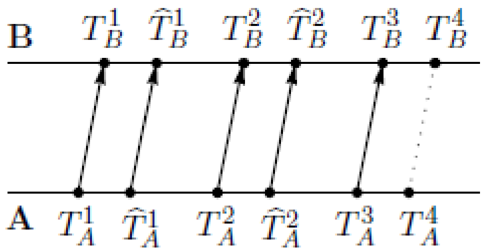

Figure 1 Timing diagram for synchronization procedure of ATSP

From [5] we know, $t_2 - t_1 = t_4 - t_3 = t_6 - t_5$ is the Propagation delays (denoted as PROP), and it is deterministic; $\hat{t}_1 - t_1 = \hat{t}_2 - t_2 = \hat{t}_3 - t_3 = \hat{t}_4 - t_4 = t_8 - t_6$ is Transmission delay or Reception delay (denoted as TR), it is also deterministic. Since

$$\hat{T}_A^2 - T_A^2 = C_A(\hat{t}_3) - C_A(t_3)$$
$$= \int_{t3}^{\hat{t}3} f_h^A(t)dt$$
$$= f_h^A(t')(\hat{t}_3 - t_3) = TR \times f_h^A(t'),$$

where $f_h^A(t)$ is node A's local clock frequency, and $t_3 \le t' \le \hat{t}_3$, therefore at physical time t_7, node A's local clock frequency is approximately equal to $\Pi = \frac{\hat{T}_A^2 - T_A^2}{TR}$. Similarly, node B's local clock frequency is approximately equal to $\frac{T_B^4 - T_B^3}{TR}$ at physical time t_8.

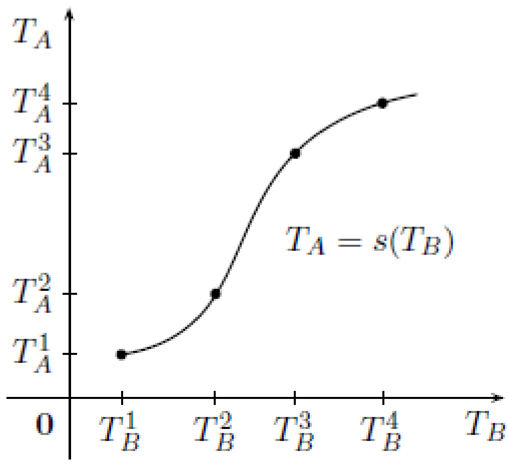

Figure 2 Quadratic spline interpolation with the six time-stamps

Hence at physical time t_8, node B obtains the clock skew compensation $\frac{T_B^4 - T_B^3}{TR} - \Pi$. At physical time t_8, the node B finds the function $T_A = s(T_B)$ such that it is the quadratic spline function through the three points (T_B^1, T_A^1), (T_B^2, T_A^2) and (T_B^3, T_A^3) on the $T_B - T_A$ plane (shown in Figure 2). Let

$a = \frac{T_A^2 - T_A^1}{T_B^2 - T_B^1}$, $b = \frac{T_A^3 - T_A^2}{T_B^3 - T_B^2}$, $c = \frac{T_B^2 - T_B^1}{T_B^3 - T_B^2}$,

$Z_2 = \frac{a + (2\times a - b)\times c}{1 + c}$, $Z_4 = \frac{a + b\times c}{1 + c}$,

$Z_6 = \frac{b(2 + c) - a}{1 + c}$, $g = \frac{Z_4 - Z_2}{2(T_B^2 - T_B^1)}$,

$h = \frac{Z_6 - Z_4}{2(T_B^3 - T_B^2)}$. It's not hard to prove that

when $T_B \in [T_B^1, T_B^2]$,

$$s(T_B) = T_A^1 + Z_2 \Delta T_B^1 + g(\Delta T_B^1)^2,$$

where $\Delta T_B^1 = T_B - T_B^1$;

when $T_B \in (T_B^2, T_B^3]$,

$$s(T_B) = T_A^2 + Z_4 \Delta T_B^2 + h(\Delta T_B^2)^2,$$

where $\Delta T_B^2 = T_B - T_B^2$.

When synchronization node B determines the coefficients of quadratic spline interpolation function $T_A = s(T_B)$, it will immediately read its local time $T_B^4 = C_B(t_8)$, and gets the estimation value of the local time $C_A(t_7)$ of the reference node A at physical time t_7 from the equation below:

$$T_A^4 = T_A^2 + Z_4 \times (T_B^4 - T_B^2)$$
$$+ \frac{Z_6 - Z_4}{2(T_B^3 - T_B^2)} \times (T_B^4 - T_B^2)^2.$$

Therefore, at physical time t_8, node A's local time is approximately equal to $\Gamma = T_A^4 + \frac{\hat{T}_A^2 - T_A^2}{TR} \times PROP$. And at physical time t_8, node B obtains the clock offset compensation $T_B^4 - \Gamma$. Subsequently, node B sets its local time as Γ, and thus finishes the time synchronization of the reference node A. If A's and B's local clock frequency is constant on the physical time interval $[t_1, t_8]$, then the above formula for T_A^4 is the same as the one in RSP [6], which shows that our proposed ATSP has more general applicability than the RSP.

Although there exists small difference between node A's and node B's local clock after synchronization, as time passes, the difference between node A's and node B's local clock will become larger and larger, because their clock frequency difference will become larger and larger. Therefore, except doing clock skew compensation to node B during synchronization, we need to do some extra clock skew compensation to node B before the next synchronization. Every physical time interval S, node B will simulate node A's local clock once, and use the simulation result to compensate its clock skew. We call this kind of compensation as simulation compensation. Before describing simulation compensation, and we will describe sensor node's property in depth.

Because of the working environment and product quality, the node's crystal frequency f is not always equal to the proper crystal frequency f_0. The research shows that the term $f - f_0$ obeys a normal distribution with zero mean. Obviously, the local clock frequency is $f_h = \frac{f}{f_0}$. Therefore, the clock skew is $\rho_h = f_h - 1 = \frac{f - f_0}{f_0}$. We denote the maximal absolute value of clock skew as ρ_0. Since $f - f_0$ follows the normal distribution with the mean 0 and $\rho_h = \frac{f - f_0}{f_0}$, by probability ρ_h also follows the normal distribution $N(0, \sigma^2)$ with the mean 0. As $|\rho_h| \le \rho_0$, we know that $P(|\rho_h| \le \rho_0) = 1$. Let $\eta = \frac{\rho_h}{\sigma}$. Then by probability η follows the standard normal distribution $N(0,1)$. Let $\Phi(x)$ and $\Phi_0(x)$ be the distribution functions of ρ_h and η, respectively. From probability we know that $P(|\rho_h| \le \rho_0) = 2\Phi_0\left(\frac{\rho_0}{\sigma}\right) - 1$. Since $\Phi_0\left(\frac{\rho_0}{\sigma}\right) = 1$, thus by probability $\sigma = \frac{\rho_0}{5}$. So far we have proved that ρ_h follows normal distribution $N\left(0, \frac{\rho_0^2}{25}\right)$. Therefore, f follows normal distribution $N\left(f_0, \left(\frac{f_0\rho_0}{5}\right)^2\right)$.

Let X_1 be a random variable that follows the standard normal distribution, therefore random variable $\frac{f_0\rho_0}{5} X_1 + f_0$ follows the normal distribution $N\left(f_0, \left(\frac{f_0\rho_0}{5}\right)^2\right)$. Hence, we can use $\frac{f_0\rho_0}{5}X_1 + f_0$ to simulate f.

Now we will describe simulation compensation. Suppose last sampling happens at physical time t_0. Let $n = \eta_A \cdot S$, where η_A is the changing rate of node A's local clock obtained during last synchronization. Therefore, on time interval $[t_0, t_0 + S]$, node A's local clock has changed for n times. At physical time $t_0 + S$, B will do n times independent experiments on the random variable $\frac{\rho_A}{5}X_1 + 1$. Let the experiment results be $f_1, \ldots, f_n$ respectively. We treat $f = \frac{1}{n}\sum_{k=1}^{n} f_k$ as reference node A's approximate clock frequency on time interval $[t_0, t_0 + S]$. Hence at physical time $t_0 + S$, node B obtains the clock skew simulation compensation $r_B(t_0 + S) - f$.

4 Error Analysis

In the last section, at physical time t_8 the synchronization node B finishes the time synchronization of the reference node A, and sets its local time and clock frequency as Γ and Π, respectively. The main result in this section is the following theorem 1 and theorem 2. In this section, we use Φ to denote $C_A(t_8) - \Gamma$, and $\rho_{\max}$ for $\max\{\rho_A, \rho_B\}$. Unless otherwise stated, the meanings of the symbols used in the following section are the same as in the last section. To prove the following theorem 1, we will first prove the three lemmas below.

Lemma 1 $|a - b| < 2.00061\rho_{\max}$.

Proof It is obvious that $t_3 - t_1 = t_4 - t_2$ and $t_5 - t_3 = t_6 - t_4$. From the Lagrange's mean value theorem, there exist $t_1 < \mu_1 < t_3$, $t_2 < \mu_2 < t_4$, $t_3 < \mu_3 < t_5$, $t_4 < \mu_4 < t_6$ such that $a = \frac{r_A(\mu_1)}{r_B(\mu_2)}$ and $b = \frac{r_A(\mu_3)}{r_B(\mu_4)}$. Therefore

$$b - a = \frac{[r_A(\mu_3) - r_A(\mu_1)]r_B(\mu_2)}{r_B(\mu_4)r_B(\mu_2)} + \frac{r_A(\mu_1)[r_B(\mu_2) - r_B(\mu_4)]}{r_B(\mu_4)r_B(\mu_2)}.$$

Since $r_A \sim N\left(1, \frac{\rho_A^2}{25}\right)$ and $r_B \sim N\left(1, \frac{\rho_B^2}{25}\right)$, from probability theory it is not difficult to see that

$$|r_A(\mu_3) - r_A(\mu_1)| < \rho_A,$$

$$|r_B(\mu_4) - r_B(\mu_2)| < \rho_B.$$

Furthermore, $|b - a| < \frac{2(1 + \rho_{\max})\rho_{\max}}{(1 - \rho_{\max})^2}$.

Because $\rho_{\max} \le 10^{-4}$, it is easy to derive that $\frac{1 + \rho_{\max}}{(1 - \rho_{\max})^2} < 1.00030006$. Furthermore

$$|a - b| < 2.00061\rho_{\max}.$$

Hence we have proved the lemma 1.

Lemma 2 Let $K = \frac{Z_6 - Z_4}{2(T_B^3 - T_B^2)}$, and let $E = K(T_B^4 - T_B^3)^2$. Then

$$|E| \le 1.00061 \cdot TR \cdot \rho_{\max}.$$

Proof Clearly $t_6 - t_4 > TR$, $c > \frac{1-\rho_B}{1+\rho_B}$ and $Z_6 - Z_4 = \frac{2(b-a)}{1+c}$. From the Lagrange's mean value theorem, there exist $t_4 < \mu_1 < t_6$, $t_6 < \mu_2 < t_8$ such that

$$T_B^3 - T_B^2 = r_B(\mu_1) \times (t_6 - t_4),$$

$$T_B^4 - T_B^3 = r_B(\mu_2) TR.$$

Therefore

$$E = \frac{(b-a) r_B(\mu_2)^2 TR^2}{(1+c) r_B(\mu_1)(t_6 - t_4)}.$$

It is easy to prove that

$$\frac{r_B(\mu_2)^2}{r_B(\mu_1)} < \frac{1+\rho_B}{1-\rho_B}.$$

Because $c > \frac{1-\rho_B}{1+\rho_B}$, it is clear that $c+1 > \frac{2}{1+\rho_B}$. Since $t_6 - t_4 > TR$ and $|a-b| \le \frac{\rho_A + \rho_B + 2\rho_A\rho_B}{(1-\rho_B)^2}$, thus

$$|E| \le \left(\frac{1+\rho_{\max}}{1-\rho_{\max}}\right)^3 \cdot TR \cdot \rho_{\max}.$$

Because $\rho_{\max} \le 10^{-4}$, it is clear that

$$|E| \le 1.00061 \cdot TR \cdot \rho_{\max}.$$

Hence we have proved the lemma 2.

Lemma 3 Let $F = Z_6(T_B^4 - T_B^3)$, and let $G = [C_A(t_7) - C_A(t_5)] - F$. Then

$$|G| \le 3.00111 \cdot TR \cdot \rho_{\max}.$$

Proof Clearly $Z_6 = b + \frac{b-a}{1+c}$. From the Lagrange's mean value theorem, there exist $t_6 < \mu_1 < t_8$, $t_5 < \mu_2 < t_7$ such that

$$T_B^4 - T_B^3 = r_B(\mu_1) TR,$$

$$C_A(t_7) - C_A(t_5) = r_A(\mu_2) TR.$$

It is easy to prove that

$$|r_A(\mu_2) - b r_B(\mu_1)| \le \frac{\rho_A + \rho_B + 2\rho_A\rho_B}{(1-\rho_B)^2}.$$

Let $L = \frac{b-a}{1+c} \times r_B(\mu_1)$. It follows from the course of the proof of the lemma 2 that $c+1 > \frac{2}{1+\rho_B}$. Hence $|L| \le \frac{|b-a|}{2} \times (1+\rho_B)^2$.

Since $|a-b| \le \frac{\rho_A + \rho_B + 2\rho_A\rho_B}{(1-\rho_B)^2}$, thus

$$|L| \le \left(\frac{\rho_A + \rho_B}{2} + \rho_A\rho_B\right)\left(\frac{1+\rho_B}{1-\rho_B}\right)^2.$$

Therefore,

$$|G| \le \frac{2(1+\rho_{\max})}{(1-\rho_{\max})^2} \cdot \left(1 + \frac{(1+\rho_{\max})^2}{2}\right) \cdot TR \cdot \rho_{\max}.$$

Because $\rho_{\max} \le 10^{-4}$, it is clear that

$$|G| \le 3.00111 \cdot TR \cdot \rho_{\max}.$$

Hence we have proved the lemma 3.

Once we have the above preparation, now we can prove the following theorem 1.

Theorem 1 $|\Phi| \le 4.00211 \cdot TR \cdot \rho_{\max}$.

Proof As the Taylor expansion of $s(T_B)$ at T_B^3 is

$$T_A^3 + Z_6 \times \Delta T_B^3 + \frac{Z_6 - Z_4}{2(T_B^3 - T_B^2)} \times (\Delta T_B^3)^2,$$

where $\Delta T_B^3 = T_B - T_B^3$, so

$$T_A^4 = T_A^3 + F + E.$$

Let $H = C_A(t_8) - C_A(t_7)$. Therefore

$$\Phi = H + G - E - \Pi \cdot PROP.$$

Furthermore

$$|\Phi| \le |G| + |E| + |H - \Pi \cdot PROP|.$$

It is not difficult to prove that

$$|H - \Pi \cdot PROP| < \rho_A \times PROP.$$

From the lemma2 and lemma3, it follows that

$$|\Phi| \le \left(\frac{2(1+\rho_{\max})[1+(1+\rho_{\max})^2]}{(1-\rho_{\max})^3} - \frac{PROP}{TR} \right) \cdot TR \rho_{\max}.$$

From [5], we know that $\frac{PROP}{TR} < 10^{-4}$. Because $\rho_{\max} \le 10^{-4}$, it is clear that

$$|\Phi| \le 4.00211 \cdot TR \cdot \rho_{\max}.$$

Hence we have proved the theorem 1.

If both the reference node A and the synchronization node B are Mica2 motes, then from [5] and theorem 1 we know that their ATSP synchronization error is not larger than $1.6\mu s$.

Theorem 2 Let T be the synchronization period. Suppose the last time synchronization happened at physical time t_0 .Let $t_1 \in (t_0, t_0 + T)$. Let Ψ be the clock difference between the reference node A and synchronization node B at physical time t_1, then

$$|\Psi| \le 0.6\mu s + 4.00211 \cdot TR \cdot \rho_{\max}.$$

Proof Let η_A be the changing rate of the reference node A's clock frequency obtained from the last synchronization. For simplicity, we assume that for reference node A any two adjacent changes of its local clock frequency is the same, and $(t_1 - t_0)\eta_A$ is positive integer. Let $n = (t_1 - t_0)\eta_A$. We use $\frac{\rho_A}{5} X_1 + 1$ to simulate $r_A(t)$, where X_1 is a random variable that follows the standard normal distribution. At physical time t_1, the synchronization node B will do n times independent experiments on random variable $\frac{\rho_A}{5} X_1 + 1$. Let the experiment results be $f_1, \ldots, f_n$, respectively. Let $f = \frac{1}{n}\sum_{k=1}^{n} f_k$. We use Δ_1 and Δ_2 to represent $C_A(t_1) - C_A(t_0)$ and $f \cdot (t_1 - t_0)$, respectively. It is easy to see that

$$\Delta_1 = \frac{t_1 - t_0}{n} \sum_{k=1}^{n} r_A\left(t_0 + \frac{t_1 - t_0}{n} \cdot \left(k - \frac{1}{2} \right) \right),$$

$$\Delta_2 = \frac{t_1 - t_0}{n} \sum_{k=1}^{n} f_k.$$

For every $1 \le k \le n$, since in the physical time interval $(t_0 + (k-1) \cdot \frac{t_1 - t_0}{n}, t_0 + k \cdot \frac{t_1 - t_0}{n})$, $r_A(t)$ is constant. By probability theory we know, in $(t_0 + (k-1) \cdot \frac{t_1 - t_0}{n}, t_0 + k \cdot \frac{t_1 - t_0}{n})$ f is also constant. Hence it is not hard to tell that $|\Delta_2 - \Delta_1| < 0.6\mu s$. The synchronization node B will first do the simulation compensation at physical time t_1 . Therefore

$$\Delta_2 = C_B(t_1) - C_B(t_0).$$

Hence $\Psi = \Delta_1 - \Delta_2 + [C_A(t_0) - C_B(t_0)]$.

By theorem 1 and the above conclusion we know

$$|\Psi| \leq 0.6\mu s + 4.00211 \cdot TR \cdot \rho_{\max} .$$

Hence we have proved the theorem 2.

If the reference node A and the synchronization node B are Mica2 motes, then from [5] and theorem 2 we know, at any time their ATSP synchronization error is not larger than $2.2\mu s$.

5 Simulation Experiments

We have proved that equality of ATSP and RSP in the symmetric cases is the same. Also, since RSP is the most accurate symmetric time synchronization algorithm to date, then we only need to verify that ATSP has less synchronization error than RSP under asymmetric conditions in order to prove that ATSP is very effective in both symmetric and asymmetric cases.

To verify the effectiveness of ATSP, we simulate the Mica2 platform by using c++ to realize ATSP and RSP.

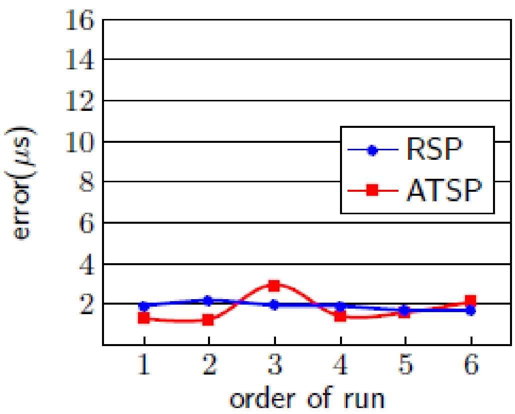

Figure 3 result of the experiment 1

In the simulation experiments, the reference node A broadcasts a synchronization message every 30 seconds. A's proper crystal frequency is 8MHz, crystal frequency's changing period is 429s, the maximal absolute values of clock skew respectively are 40ppm and 1ppm in the experiment 1 and the experiment 2; the synchronization node B has the following properties: proper crystal frequency is 4.8MHz, crystal frequency's changing periods respectively are 59.5s and 0.69s in the experiment 1 and the experiment 2, the maximal absolute values of clock skew respectively are 45ppm and 1ppm in the experiment 1 and the experiment 2.

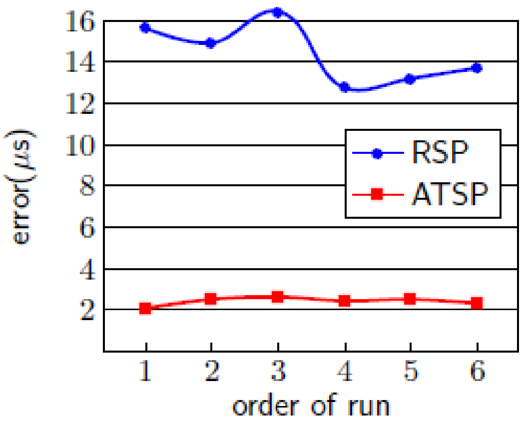

Figure 4 result of the experiment 2

In experiment 1 and experiment 2, we use RSP and ATSP to synchronize the time respectively, sampling period is 6s, and the sampling number is 201. We will repeat each experiment for 6 times, and observe the average of the absolute synchronization error, and the results are shown in Figs.3 and 4. For sake of simplicity, we can assume that Propagation Time, Byte Alignment Time, Decoding Time, Encoding Time, Interrupt Handling are 0. The figures show that ATSP has much better performance in scenarios where the crystal frequency's changing periods of participating nodes are very different, as in asymmetric synchronization.

6 Conclusion

This paper proposed a time synchronization algorithm ATSP for wireless sensor networks that can handle the clock offset compensation and clock skew compensation problems based on quadratic spline interpolation and simulation compensation. In the symmetric cases, ATSP achieves the same accuracy as RSP, which is the most accurate time synchronization protocol existing; while in the asymmetric cases, ATSP is much more accurate than RSP. The simulation results demonstrate qualitatively the effectiveness of ATSP.

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