# Estimation of Clock Offsets and Skews in Wireless Sensor Networks Using Three-Way Message Exchange

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## Abstract

Performance of a wireless sensor network (WSN) depends on synchronism of clocks at sensor nodes. These clocks need to be synchronized for a network-wide, common time reference. Existing approaches to WSN synchronization ignore time-stamps that were exchanged during the synchronization process, leading undesirably to estimation errors in clock offsets and skews. This paper proposes an accurate method, called three-way message exchange, to estimate clock offsets and skews using maximum likelihood estimation, where transmission and processing delays have a Gaussian distribution. In this method, each node sends and receives time-stamps to and from the other nodes, thereby improving timing accuracy of all nodes in the network. Performance of the proposed method is evaluated through simulation of biases. Three-way message exchange is found to be accurate and achieve negligibly small biases, confirming its practical applications to WSNs.

**Key Words:** *CLOCK SYNCHRONIZATION / WIRELESS SENSOR NETWORKS*

## Introduction

A wireless sensor network (WSN) is a collection of small-sized, non-complex nodes that gather physical information such as temperatures, pressures, and transmit, via wireless links, the recorded information from the monitored area to a central computing unit for analysis (Buratti, *et al.*, 2009). A typical WSN is made up of sensing, processing, transmission, and power units (Akyildiz and Vuran, 2010).

WSNs have attracted much attention due to technological advancements that have led to manufacture of multi-functional small-sized sensors. This progress has further led to numerous applications of such sensor networks in the fields of health, civilian, environment, military, science, and industries (Buratti, *et al.*, 2009; Akyildiz and Vuran, 2010). Sensors collect data in their respective locations, transmit the data wirelessly, and perform joint tasks such as data fusion, localization, and medium-access control. Facing these cooperative tasks, sensor nodes need to maintain a common time-reference and synchronize their clocks periodically. Clock synchronization compensates the clock offsets and skews among the sensor nodes, bringing all nodal clocks to report the same time. A wide spread of WSNs, including those in the recently-found Internet-of-Things settings (Gantsog, *et al.*, 2018), demands for clock-synchronization protocols that are accurate.

Recent research has mainly focused on statistical signal-processing techniques for synchronization of WSN clocks (Freris, *et. al*, 2011). The clock parameters within the link delay can thus be estimated using distributions such as Gaussian, Gamma, Weibull, and exponential to model the random part of the link delay. In many bodies of research, the synchronization mechanisms, namely two-way message exchange and pairwise broadcast, have both employed the above distributions to varying degrees of success, alongside estimation methods such as maximum likelihood estimation (MLE) and minimum variance unbiased estimation. A common technique to WSN synchronization is to estimate clock parameters under a disturbance from random delays.

Under two-way message exchange, Jeske derives clock offset for an exponential random delay model using MLE (Jeske, *et al.*, 2005). Chaudhari derives the minimum variance unbiased estimator (MVUE) of the clock offset under both symmetric and asymmetric exponential delay models (Chaudhari, Serpedin, and Qaraqe, 2010). In both approaches, the rate of clock drift for every node is assumed to be constant, implying that the effect of clock skews is ignored. In reality, clock skews affect the relative times between clocks and should not be ignored. As such, Noh proposes the joint estimation of the clock offset and skew (Noh, *et al.*, 2007). Leng and Wu estimate the clock offset and skew jointly under a Gaussian-distribution delay model (Leng and Wu, 2010). Chaudhari derives a joint MLE of the clock offset and skew under an exponential delay model (Chaudhari, *et al.*, 2008). However, two-way message exchange ignores a broadcast nature of the wireless medium and thus does not allow every neighboring node to take part in the synchronization process. Two-way message exchange leads to high communication overhead and wastage of energy in wireless transmission.

Subsequent work has applied pairwise broadcast synchronization (PBS) to take advantage of the broadcast nature of the wireless medium. Noh, under a Gaussian model, and Chaudhari as well as Chedoloh and Suwansantisuk, both under an exponential model, apply PBS mechanism to determine clock offsets (Noh, *et al*, 2008; Chaudhari, Serpedin, Kim, 2010; Chedoloh, Suwansantisuk, 2016). To further improve accuracy, there is need to jointly estimate the clock offsets and skews with PBS. Ahmad estimates the clock offset and skew in the PBS mechanism and converts the estimation problem into linear programming

(Ahmad, Noor, Serpedin, 2011). Cao applies MLE to jointly estimate the clock offset and skew using PBS and an exponential model (Cao, *et al.*, 2013). In (Cao, *et al.*, 2013), there are nodes that do not exchange time-stamps to and from each other, thus leading to inaccuracy in clock synchronization. These recent research activities exemplify importance, yet difficulty, in synchronizing the WSNs.

Existing research in WSN synchronization is limited in a fundamental way. The broadcast nature of WSNs provides an opportunity for sensor nodes to overhear the transmission of a nearby node. Existing methods, such as two-way message exchange and pairwise broadcast, ignore some timing packets that were transmitted during the synchronization process. As a consequence, estimations of clock offsets and skews are not as accurate as they could be.

In this paper, we propose a method that takes full advantage of available timing packets to synchronize WSNs. The method, called three-way message exchange, allows each group of three sensor nodes to broadcast their local times in packets. These time-stamped packets are used as measurement data to synchronize the WSN. Main contributions of this paper are methods that fully exploit a broadcast nature to synchronize WSNs; analytical expressions and numerical method to estimate the clock offsets and skews; and performance evaluation of the proposed method. Methods to design and evaluate three-way message exchange include estimation, optimization, and Monte Carlo simulation. The simulation results show that three-way message exchange accurately estimates the clock offsets and skews, producing the biases of practically zero while using a small number of message-exchange rounds. The findings confirm a benefit of three-way message exchange.

## Objectives

In this paper, we aim to estimate clock offsets and skews and evaluate performance, in terms of biases, of the proposed estimators.

## Scope of research

1. Three nodes are considered at a time during the synchronization process. In other words, when a node broadcasts its time-stamps, two other nodes hear the broadcasts. The consideration here is appropriate for a medium-sized network where a broadcast of one node is received at a few nodes.

2. Transmission and processing delays consist of fixed portions and random portions. Fixed portions are a deterministic but an unknown real number, taking an identical value for every link in the network. The random portions are independent-and-identically-distributed (i.i.d) Gaussian random variables of unknown mean and unknown variance. The

consideration here is appropriate for sensor nodes that are of the same type and approximately have the same distances to their neighbors.

3. Clock offsets and skews are assumed to be fixed, deterministic, and unknown. The consideration here is appropriate when oscillators that generate timing signals at different sensor nodes have fixed, but perhaps different, oscillating periods.

## Research Methodology

To achieve the research objectives, we will follow these steps:

1. **Identify the system model**: we describe the system model and specify the problem statement.
2. **Derive the estimators**: we estimate the clock offsets, clock skews, mean, as well as standard deviation, of the delay, using the principle of maximum likelihood estimation.
3. **Evaluate the performance**: we simulate biases of the estimators as a function of round of message exchanges. A small value of biases indicates accuracy of the estimators.

## Research Findings

**1. System Model.** In the proposed three-way message exchange, timing information from one node is used to synchronize the other two neighboring nodes at the same time. Under this model, the symbols *R*, *P* and *Q* denote the reference node, the slave node, and the listening node, respectively. During the *i*th round of information exchange, a time stamp from every node is simultaneously sent to the other two nodes as shown in Figure 1. Here, *i* is the index of exchanging round, where *i*=1, 2, 3, ..., *n* and *n* is the total number of rounds.

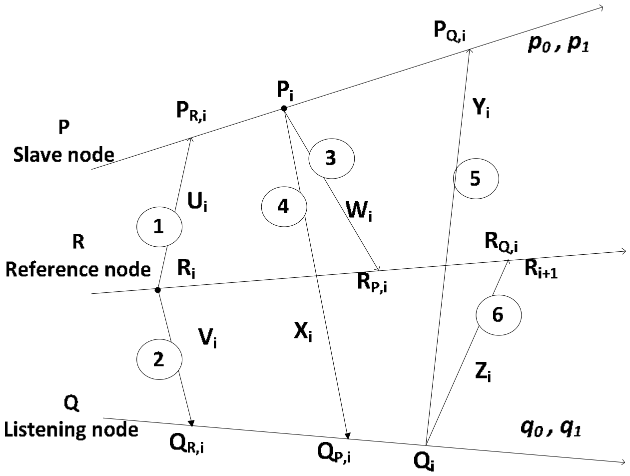

**Figure 1:** Three-way message exchanges among a group of three nodes *R*, *P* and *Q*

The operation of three-way message exchange is the following. The synchronization process for the *i*th round begins with a time stamp $R_i$, originated from the reference node, being broadcast to nodes *P* and *Q*. A time stamp is a packet containing a local time at the transmitting node. Nodes *P* and *Q* receive the time stamp at time $P_{R,i}$ and $Q_{R,i}$, respectively. All reception times are the local times at the receiving nodes. Subsequently, node *P* sends its time stamp $P_i$ to nodes *R* and *Q*, which receive the timing message at local times $R_{P,i}$ and $Q_{P,i}$, respectively. The process is completed with node *Q* sending its time stamp $Q_i$ to nodes *R* and *P* in order to finalize reception of timing messages at time $R_{Q,i}$ and $P_{Q,i}$, respectively. The $i^{th}$ round of message exchange generates the time measurements $(P_{Ri}, P_{Qi}, Q_{Ri}, Q_{Pi}, R_{P,i}, R_{Qi})$, which will be used to synchronize the nodal clocks.

The time measurements $(P_{Ri}, P_{Qi}, Q_{Ri}, Q_{Pi}, R_{P,i}, R_{Qi})$ depend on the clock offsets, clock skews, as well as transmission and processing delays, according to the following equations:

$$P_{R,i} = p_1 R_i + p_o + p_1 U_i \tag{1}$$

$$Q_{R,i} = q_1 R_i + q_o + q_1 V_i \tag{2}$$

$$R_{P,i} = \frac{P_i}{p_1} - \frac{p_o}{p_1} + W_i \tag{3}$$

$$Q_{P,i} = \frac{q_1}{p_1} P_i + \left(q_o - \frac{q_1}{p_1} p_o\right) + q_1 X_i \tag{4}$$

$$P_{Q,i} = \frac{p_1}{q_1} Q_i + \left(p_o - \frac{p_1}{q_1} q_o\right) + p_1 Y_i \tag{5}$$

$$R_{Q,i} = \frac{Q_i}{q_1} - \frac{q_o}{q_1} + Z_i \tag{6}$$

Here, $p_o$ and $p_1$ are clock offset and clock skew, respectively, of node *P* with respect to node *R*; $q_o$ and $q_1$ are clock offset and clock skew, respectively, of node *Q* with respect to node *R*; and each of $U_i, V_i, W_i, X_i, Y_i, Z_i$ is a random variable, representing a sum of transmission and processing delays between the respective nodes as shown in Figure 1. These random variables are considered to be independent Gaussian random variables, with mean $\tau$ and standard deviation $\sigma$.

The problem statement is the following. Given message arrival times $(P_{R,i}, P_{Q,i}, Q_{R,i}, Q_{P,i}, R_{P,i}, R_{Q,i})$ and time-stamps $R_i, P_i, Q_i$, for *i*=1, 2, 3, …, *n*, we shall estimate the deterministic but unknown parameters $(p_o, p_1, q_o, q_1, \tau, \sigma)$, where $p_o, q_o$ are real numbers and $p_1, q_1, \tau, \sigma$ are non-negative real numbers.

2. **The estimators.** In this step, we derive the log-likelihood function and the maximum likelihood estimators.

### *Log- Likelihood Function*

By using Gaussian distributions and applying equations (1)-(6), we can show after some algebra that the log-likelihood function equals

$$L = -3n\ln(2\pi) - 2n\ln(p_1) - 2n\ln(q_1) - 6n\ln(\sigma) - \frac{1}{2p_1^2\sigma^2}\sum_{i=1}^{n}\left(P_{R,i} - p_1R_i - p_0 - p_1\tau\right)^2 - \frac{1}{2q_1^2\sigma^2}\sum_{i=1}^{n}\left(Q_{R,i} - q_1R_i -\right.$$

$$q0-q1\tau2-12p12\sigma2i=1np1Rp,i-Pi+p0-p1\tau2-12q12\sigma2i=1nq1RQ,i$$
$$-Qi+q0-q1\tau2-12p12q12\sigma2i=1np1QP,i-q1Pi-q0p1+q1p0-p1q1\tau$$
$$2-12p12q12\sigma2i=1nq1PQ,i-p1Qi-p0q1+p1q0-p1q1\tau2.$$

By the principle of MLE, the estimators are solutions to a constrained optimization in six variables:

$$(\widehat{p_0},\widehat{p_1},\widehat{q_0},\widehat{q_1},\hat{\tau},\hat{\sigma}) = \arg\max_{\substack{p_0\,\epsilon\,\mathbb{R},p_1\geq 0\\ q_0\,\epsilon\,\mathbb{R},q_1\geq 0\\ \sigma\geq 0,\tau\geq 0}} L\left(P_{R,i},P_{Q,i},Q_{R,i},Q_{P,i},R_{P,i},R_{Q,i} \mid p_0,p_1,q_0,q_1,\tau,\sigma\right)$$

Here, a parameter with a hat on top denotes an estimate of that parameter. We will solve the above optimization analytically and numerically, by a technical called block optimization. Using this technique, we optimize one variable at a time and treat the other variables as constants.

### *Maximum Likelihood Estimator of $\boldsymbol{\tau}$*

We optimize $\tau$ while treating $p_0$,$p_1$,$q_0$, $q_1$ and $\sigma$ as given constants. The maximum likelihood estimator of $\tau$ is given by an optimization in one variable:

$$\hat{\tau}(\,p_0,p_1,q_0,q_1,\sigma) = \arg\max_{\tau\,\geq 0} L\left(P_{R,i},P_{Q,i},Q_{R,i},Q_{P,i},R_{P,i},R_{Q,i} \mid p_0,p_1,q_0,q_1,\tau,\sigma\right)$$

To optimize, we take the derivative of the objective function with respect to $\tau$, solve for the zeros of the first derivative, and verify from the second derivative that we have a maximizer. This procedure gives us a maximum likelihood estimator, as a function of $p_1$ and $q_1$:

$$\hat{\tau}(p_1, q_1) = \frac{1}{6n}\left[\frac{1}{p_1}\sum_{i=1}^{n}\left(P_{Q,i} + P_{R,i} - 2P_i\right) + \frac{1}{q_1}\sum_{i=1}^{n}\left(Q_{P,i} + Q_{R,i} - 2\,Q_i\right) + \sum_{i=1}^{n}\left(R_{P,i} + R_{Q,i} - 2Q_i\right)\right]^{+}$$

The symbol $[x]^{+}$ is the maximum between 0 and *x*. Next, we substitute $\tau$ in the log-likelihood function with the estimate $\hat{\tau}(p_1, q_1)$, thereby reducing the number of variables from six to five. The variable $\tau$ is now eliminated from the objective function. It remains to optimize over the remaining five variables.

*Maximum Likelihood Estimators of $p_0$, $q_0$, and $\sigma$*

To estimate each one of the three parameters $p_0$, $q_0$, and $\sigma$, we follow the same approach as that for $\tau$: specify the optimization, solve for the zeros of the first derivative, and verify from the second derivative that we have the maximizer. After some algebra, the procedure gives us the following maximum likelihood estimators, as a function of $p_1$ and $q_1$:

$$\widehat{p_0}(p_1, q_1) = \frac{1}{6n}\left[\sum_{i=1}^{n}\left(P_{Q,i} + 2P_{R,i} + 3P_i\right) - p_1\sum_{i=1}^{n}\left(R_{Q,i} + 2R_{P,i} + 3R_i\right) + \frac{p_1}{q_1}\sum_{i=1}^{n}\left(Q_{R,i} - Q_{P,i}\right)\right]$$

$$\widehat{q_0}\,(p_1, q_1) = \frac{1}{6n}\left[\sum_{i=1}^{n}\left(Q_{P,i} + 2Q_{R,i} + 3Q_i\right) - q_1\sum_{i=1}^{n}\left(R_{P,i} + 2R_{Q,i} + 3R_i\right) + \frac{q_1}{p_1}\sum_{i=1}^{n}\left(P_{R,i} - P_{Q,i}\right)\right]$$

$$\hat{\sigma}(p_1, q_1) = \begin{cases} \sqrt{\dfrac{-D_0}{3n}} & if\ A \geq 0 \\ \sqrt{\dfrac{-D_1}{3n}} & if\ A < 0 \end{cases}$$

Here, $A$ is the term inside square brackets in the expression of $\hat{\tau}(p_1, q_1)$, and $D_0$ and $D_1$ are explicit expressions of $p_1$, $q_1$, and the time measurements. For brevity, we did not include the expressions of $D_0$ and $D_1$ here.

*Maximum Likelihood Estimators of $p_1$ and $q_1$*

To optimize over the clock-skew variables, we substitute $\tau$, $p_0$, $q_0$, and $\sigma$, in the log-likelihood function, with their respective estimates $\hat{\tau}(p_1, q_1)$, $\widehat{p_0}(p_1, q_1)$, $\widehat{q_0}(p_1, q_1)$, and $\hat{\sigma}(p_1, q_1)$. As a result, the objective function is a function of two variables, $p_1$ and $q_1$ , as shown in Figure 2 as an example. Then, we optimize the objective function numerically by an exhaustive search over the feasible space of $p_1$ and $q_1$ . The numerical approach is needed here since, in this case, zeros of first derivatives are prohibitively difficult to obtain.

Optimization in variables $p_1$ and $q_1$ provides the maximum-likelihood estimates of all parameters. The estimates of clock skews $p_1$ and $q_1$ are the numerical values $\widehat{p_1}$ and $\widehat{q_1}$, respectively, that jointly maximize the objective function. The estimate of the fixed portion $\tau$ of delays is $\hat{\tau}(\widehat{p_1}, \widehat{q_1})$, which equals $\hat{\tau}(p_1, q_1)$ where $p_1$ and $q_1$ are substituted with $\widehat{p_1}$ and $\widehat{q_1}$, respectively. The maximum likelihood estimates of the clock offsets $p_0$ and $q_0$, and the standard deviation $\boldsymbol{\sigma}$ of delays are $\widehat{p_0}(\widehat{p_1}, \widehat{q_1})$, $\widehat{q_0}(\widehat{p_1}, \widehat{q_1})$, and $\hat{\sigma}(\widehat{p_1}, \widehat{q_1})$, respectively. The maximum likelihood estimates of the remaining parameters come as a consequence of the available estimates $\widehat{p_1}$ and $\widehat{q_1}$.

3. **Performance evaluation.** To evaluate performance of three-way message exchange, we simulate the time-stamps using the following parameters: clock offsets $p_0 = 0.2\ sec$ and $q_0 = 0.1\ sec$, clock skews $p_1 = 1.1$ and $q_1 = 0.9$, the mean of random delays $\tau = 2\ sec$, and the standard deviation of random delays $\sigma = 0.1\ sec$. The choice of parameter values is for illustration and may vary to suit the applications at hand.

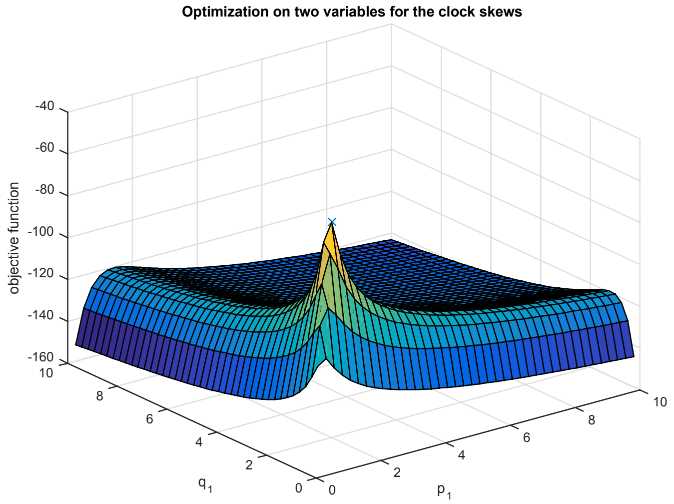

**Figure 2:** Estimating clock skews from the objective function of two variables

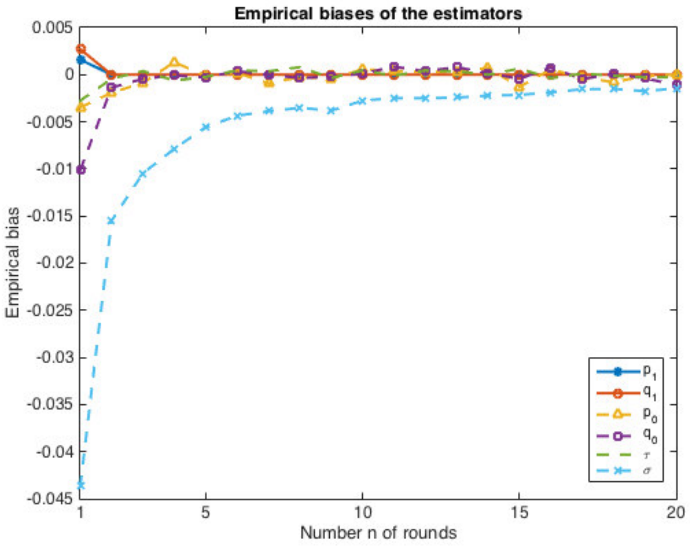

**Figure 3:** Biases of the estimators for clock skews and clock offsets

Figure 3 shows the empirical values of biases as a function of the number *n* of rounds in message exchanges. Each point in the figure is an average of 1000 empirical values of the bias. The value 1000 is large enough to guarantee convergence in numerical simulation. Six curves in the figure are biases for clock offsets $p_0$ and $q_0$, clock skews $p_1$ and $q_1$, as well as biases for mean $\tau$ and standard deviation $\sigma$. A bias that is close to zero indicates accuracy of the estimator.

The number of exchanging rounds affect biases of the estimators. As the number of exchanging rounds increases, the biases of all clock estimators $\widehat{p_0}$, $\widehat{q_0}$, $\widehat{p_1}$, $\widehat{q_1}$, $\hat{\tau}$ and $\hat{\sigma}$ tend to decrease until reaching values close to zero. In other words, the more rounds, the more accurate the estimates of clock parameters. This finding indicates that three way-message exchange accurately estimates the clock parameters as the number of rounds increases.

## Conclusion and Discussion

This research proposes a method, called three-way message exchange, to synchronize WSNs. The process of synchronization reduces essentially to the task of estimating clock offsets, clock skews, as well as the mean and standard deviation of random delays. Three-way message exchange synchronizes three sensor nodes at a time. The key idea is to use a complete round of information exchange, resulting in each node sends and receives time-stamps to and from the other nodes. The time-stamps are used as the input to estimate the clock and delay parameters. In this framework, every transmission is fully utilized in synchronizing the clocks.

The method of estimation relies on the principle of maximum likelihood estimation. In other words, the estimates are derived from the variables that maximize the likelihood function. Among the six parameters, the clock skews are the first to be estimated, using a numerical method such as an exhaustive search. The other four parameters are estimated using closed-form expressions that depend explicitly on the clock skews. The method of estimation is simple to implement in sensor nodes and requires just one numerical step in maximizing the objective function in two variables.

According to simulation, three-way message exchange performs well in synchronizing a WSN. Three-way message exchange estimates the clock offsets and clock skews with great precision by increasing the number of exchanging rounds. Three-way message exchange can achieve a reasonable level of synchronization accuracy within a few rounds, making it suitable for energy-conscious sensor nodes. Future work includes finding analytical solution to the optimization for clock skews, comparing the proposed estimators to existing ones in terms of biases and mean square errors, and deriving the Cramer-Rao lower bound for an ultimate performance.

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