Clock synchronization in WSNs: maximum consensus-based approach

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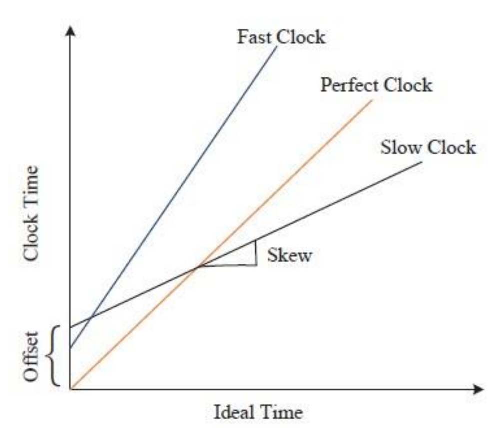
Background

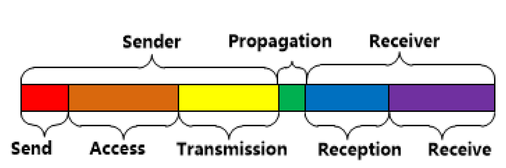
- **What is time synchronization?**
  - Common clock skew (clock speed)
  - Common clock offset (instantaneous clock difference)

    Getting all devices in network to the same time (clock offset) at exactly the same rate (clock skew)



- **Why do we need time synchronization in WSNs?**
  - Fundamental requirement of applications
  - Precondition of sensors coordination
  - Save sensors energy
- **How is time-synch in WSNs different from traditional networks ?**
  - Energy Utilization
  - Single hop vs. multi hop
  - Infrastructure-Supported vs. Ad-hoc
  - Static topology vs. Dynamic Topology
  - Connected vs. Disconnected
  - Dynamic time sync. requirements, depending on the application
- **What are the challenges in WSNs?**
  - Difference noises are inevitable in network
  - Time-varying clock speed
  - Distributed requirement
  - … … …

  i.e., simple problem but hard to be solved



Motivation

- **Disadvantages for traditional protocol [1-2]**
  - Need a root or a reference node
  - Tree-topology based
  - Inaccurate synchronization
  - Lack theoretical support
- **Advantages of consensus-based protocol [3-4]**
  - Fully distributed
  - Strong robustness and scalability
  - Highly accurate synchronization
  - Compensate both skew and offset
  - Exponential convergence speed
- **Improvements of our protocol [5-7]**
  - Finite-time convergence
  - Solve the communication delay
  - Lower complexity
  - Compensate simultaneously
  - Theoretical support

Clock Model

- **Hardware clock: linear model**

$$\tau_i(t) = a_i t + b_i$$

- **Relative clock between nodes**

$$\tau_i(t) = \frac{a_i}{a_j}\tau_j(t) + b_i - \frac{a_i}{a_j}b_j$$

- **Software clock: linear function**

$$L_i(t) = \hat{a}_i \tau_i(t) + \hat{b}_i$$

Objective

- **Designed synchronization protocol, such that**

$$\begin{cases} \lim\limits_{k\to\infty} \hat{a}_i(k) a_i = a_c \\ \lim\limits_{k\to\infty} [\hat{a}_i(k) b_i + \hat{b}_i(k)] = b_c \end{cases}$$

i.e., have the same logical clock

Main Approaches

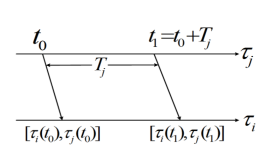
- **Maximum consensuses-based approach**
  - maximum consensus-based for fast convergence

    i.e., always select the fastest clock as the reference clock
- **Stochastic approximation approach**
  - make an average of all time of estimation to achieve accurate relative skew
- **Hops-based weight design and reference node number mark**
  - design hops-based weight and mark the reference node for preventing clock drift

Relative Clock

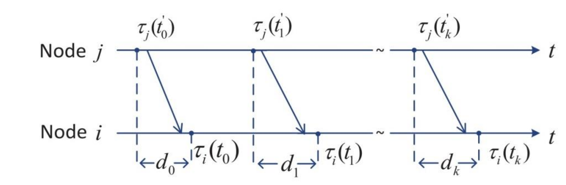
- **Noise free**

$$a_{ij} = \frac{\tau_j(t_1) - \tau_j(t_0)}{\tau_i(t_1) - \tau_i(t_0)} = \frac{a_j}{a_i}$$



- **Random noise**

$$a_{ij}(k) = \frac{\frac{\tau_j(t'_k) - \tau_j(t'_{k-1})}{\tau_i(t_k) - \tau_i(t_{k-1})} + (k-1) a_{ij}(k-1)}{k}$$



Algorithms

- **MTS**

$$\begin{cases} \hat{a}_i(k+1) = a_{ij}(k)\hat{a}_j(k) \\ \hat{b}_i(k+1) = \hat{a}_j(k)\tau_j(k) + \hat{b}_j(k) - \hat{a}_i(k+1)\tau_i(k) \end{cases}$$

$$\hat{b}_i(k+1) = \max_{x=i,j}[\hat{a}_x(k)\tau_x(k) + \hat{b}_x(k)] - \hat{a}_i(k)\tau_i(k)$$

- **WMTS**

$$w_i = w_j + 1 \qquad r_i = r_j$$

$$\begin{cases} \hat{a}_i(k+1) = a_{ij}(k)\hat{a}_j(k) \\ \hat{b}_i(k+1) = \hat{a}_j(k)\tau_j(k) + \hat{b}_j(k) - \hat{a}_i(k+1)\tau_i(k) \end{cases}$$

$$\hat{b}_i(k+1) = L_j(k) - \hat{a}_i(k)\tau_i(k)$$

Main Results

- **Convergence of MTS**
  - **Theorem 1: asymptotic convergence of MTS**

    Considering a connected network, by MTS, the skew and offset converge and satisfy

$$\begin{cases} \lim\limits_{k\to\infty} \hat{a}_i(k) a_i = a_{\max} \\ \lim\limits_{k\to\infty} \hat{a}_i(k) b_i + \hat{b}_i(k) = b_{\max} \end{cases}$$

  - **Theorem 2: finite-time convergence of MTS**

    Considering a connected network, by using MTS, the convergence time satisfy

$$T_{con} \le B(N-1)$$

- **Convergence of WMTS**
  - **Theorem 3: mean-square convergence of relative skew estimation**

$$E\{a_{ij}(k)\} = \frac{a_j}{a_i}, k \in N^+$$

  - **Theorem 4: finite-time converge in expectation of WMTS**

    Considering a connected network, by WMTS, the converge in expectation

$$E\{\hat{a}_i(t) a_i\} = a_{\max}, i \in V, t \ge B(n-1) \qquad E\{L_i(t)\} = a_{\max} t + b_{\max} - w_i(t) a_{\max}\mu, i \in V, t \ge B(n-1)$$

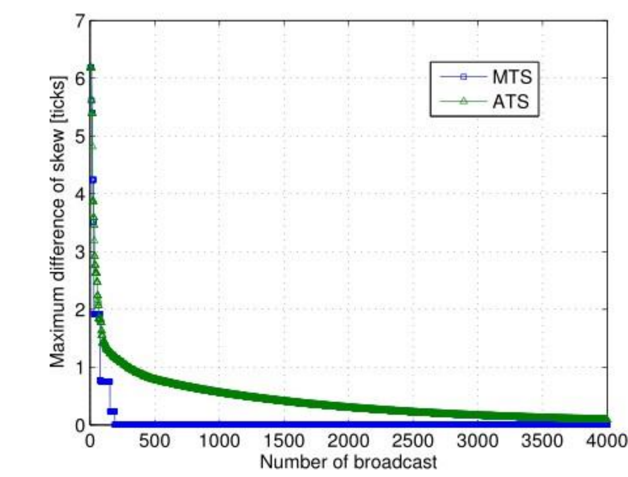
  - **Theorem 5: mean-square convergence of WMTS**

    Considering a fixed connected network, by WMTS, we have

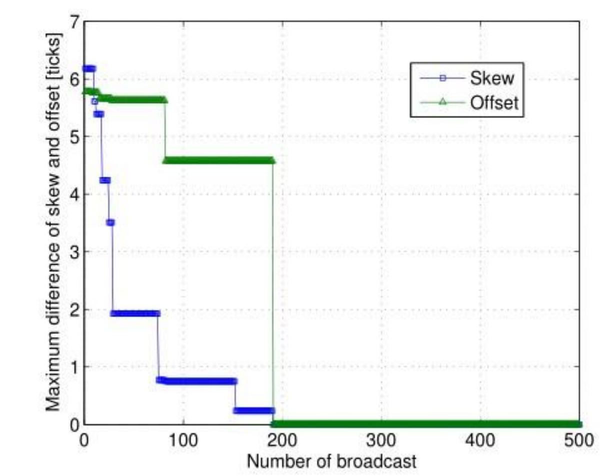
$$E\{\hat{a}_i(k) a_i - \hat{a}_j(k) a_j\} = 0 \qquad \lim_{k\to\infty} Var\{\hat{a}_i(k) a_i - \hat{a}_j(k) a_j\} = 0$$

Evaluation

- **Noise free**

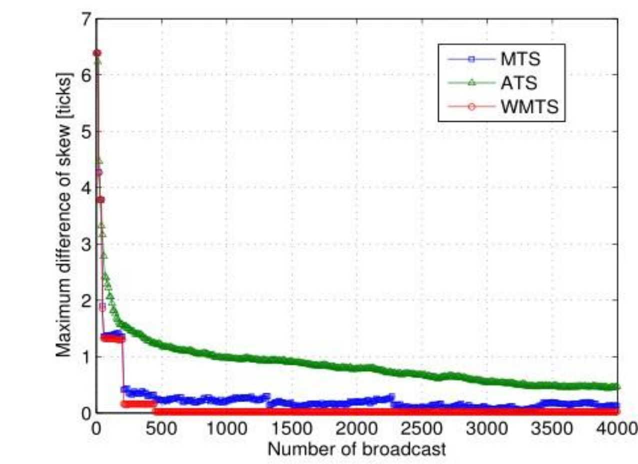


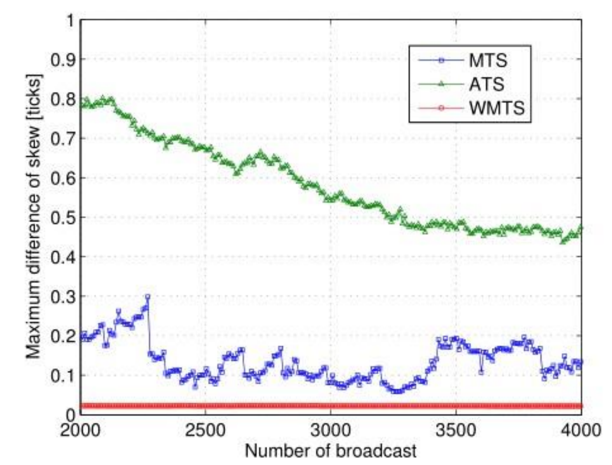
much faster convergence speed

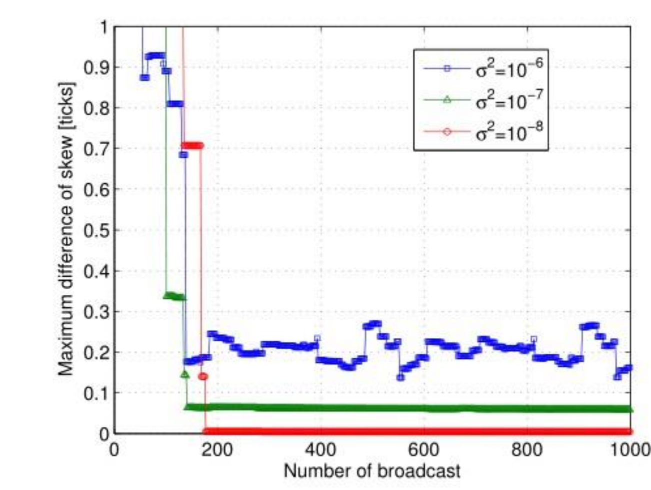


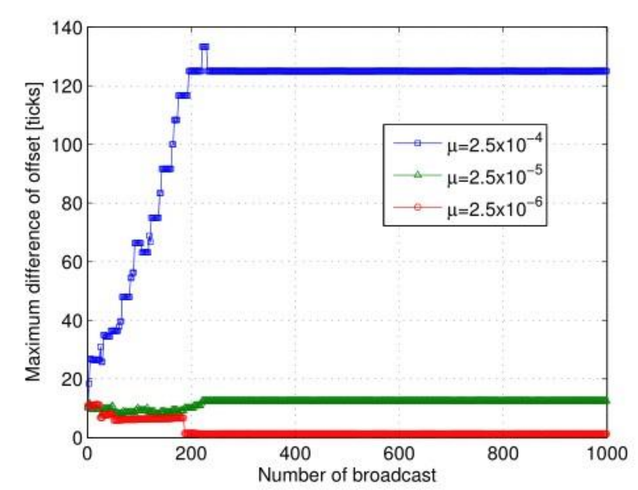
compensate simultaneously

- **Random noise**









higher synchronization accuracy and robust against to random noise

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