Distributed Synchronization in Wireless Networks – Pulse-coupled clocks

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Introduction

- This article focuses on synchronization and wireless networks, particularly in decentralized structures like ad hoc and sensor networks
- Synchronization involves coordinating independent local clocks through exchanging and processing time information
- Wireless communication enables time information exchange between synchronized clocks, supporting signal processing and communication applications
- The article explores synchronization schemes to address challenges from inaccurate clocks and propagation/processing delays.

Introduction

- In the late 19th century, telegraphy and wireless transmission enabled synchronization of distant clocks, benefiting transportation and geodesy
- Synchronization involves estimating time offsets considering propagation delays and hardware imperfections
- Synchronized time sparked debates in physics and philosophy and contributed to Einstein's theory of relativity
- Clock coordination through electromagnetic signals and accounting for signal transit time are crucial in synchronization

Distributed Synchronization in wireless networks

- Cellular telephony has been the main focus in wireless network research, utilizing a master-slave structure for synchronization
- In this structure, the base station broadcasts a beacon or training signal to synchronize mobile stations
- However, in distributed wireless networks like ad hoc, sensor, or vehicular networks, there is a growing interest in distributed synchronization

Distributed Synchronization in wireless networks

- Distributed synchronization allows for a common time scale or synchronized local oscillators in these networks
- Synchronization enables unique functionalities across different protocol stack layers in distributed wireless networks
- Some of these examples are: Signal processing applications, Spectral and energy-efficient networking, Cooperative transmission

Distributed Synchronization in wireless networks

Let’s have a look at these functionalities

Signal processing applications

- Data fusion of time-sensitive measurements in distributed estimation and tracking for monitoring or surveillance based on sensor networks.

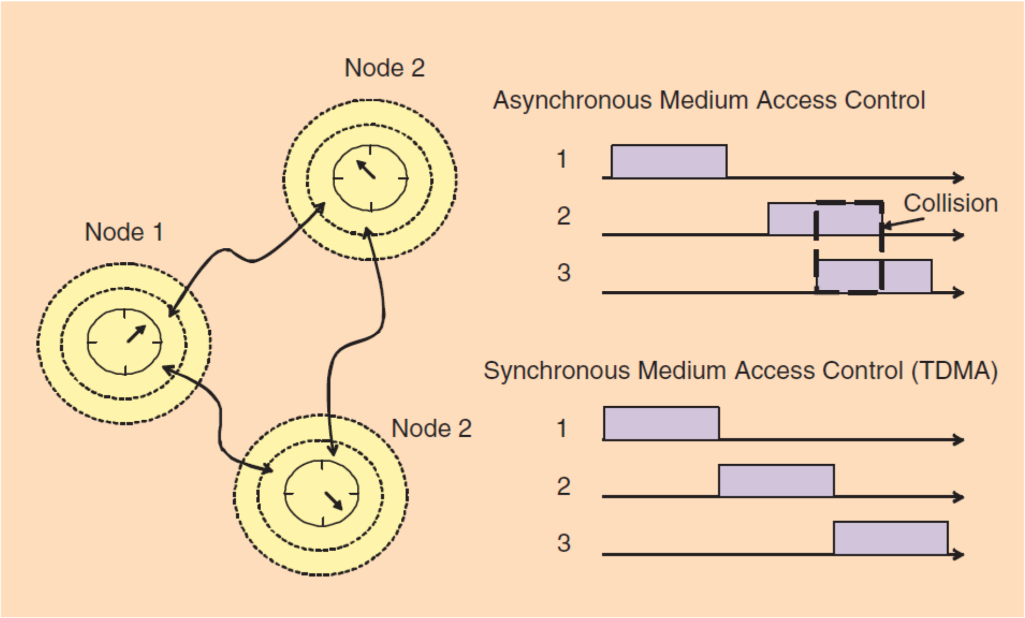
Cooperative transmission

- Collaborative transmission through space-time coding, which requires mutual time synchronization or distributed beamforming, which demands mutual carrier synchronization.

Distributed Synchronization in wireless networks

Spectral and energy-efficient networking:

- Coordinated MAC schemes such as time division multiple access or variants, which overcome the shortcomings of collision-based schemes in terms of bandwidth efficiency.



Distributed Synchronization in wireless networks

- Network synchronization can be achieved by broadcasting a beacon timing signal from a fixed or mobile access point
- IEEE 802.15.4 standards facilitate beacon-based synchronization in sensor networks
- Satellite-based synchronization can be used in outdoor environments with flexible energy constraints
- This article focuses on fully distributed scenarios where these options are not available, necessitating distributed synchronization

Distributed Synchronization in wireless networks

- Mutual synchronization in distributed wireless networks relies on the exchange of local time information between nodes
- Challenges include random delays, propagation and processing latency, hardware and clock inaccuracies
- Achieving distributed synchronization in wireless networks requires the use of signal processing, automatic control, and algebraic graph theory
- Designing mutual synchronization in wireless networks needs to address specific issues

Distributed Synchronization in wireless networks

These issues are:

- *Energy efficiency*: In the presence of battery-powered nodes, the trade-off between energy consumption and network performance becomes an essential merit criterion

- *Scalability*: Certain distributed networks, such as microsensor networks, are envisaged to be composed of a large number of nodes, in which case well-behaved scaling performance of synchronization is a critical issue

- *Application specificity*: In sensor networks, performance is defined in terms of application-specific criteria, thus rendering the design of mutual synchronization and the given signal processing functionality thoroughly intertwined

Distributed Synchronization in wireless networks

- System analysis involves studying the dynamic behavior of coupled oscillators
- Coupled oscillators can form a large set, requiring stability analysis
- Stability analysis involves examining the system of coupled linear or nonlinear equations

Distributed Synchronization in wireless networks

- Analyzing a system of coupled oscillators is often a complex task
- Deterministic or random nuisance parameters further complicate the analysis process

Packet-coupling vs pulse-coupling for mutual synchronization in wireless networks

Packet-coupling:

- Packet-coupling is a synchronization technique used in wireless networks
- It involves the periodic exchange of packets containing time stamps between nodes
- The packets carry local time information and are transmitted through point-to-point or broadcast connections

Packet-coupling vs pulse-coupling for mutual synchronization in wireless networks

- Packet-coupling aims to achieve mutual synchronization among nodes in the network
- However, it is susceptible to errors caused by random delays during packet transmission and reception
- Various techniques have been developed to mitigate the impact of these random factors on synchronization accuracy

Packet-coupling vs pulse-coupling for mutual synchronization in wireless networks

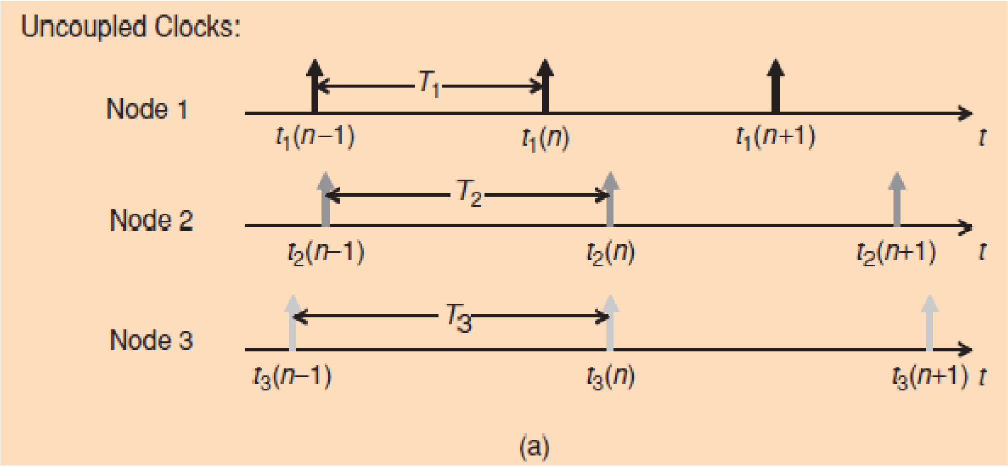
Pulse-coupling:

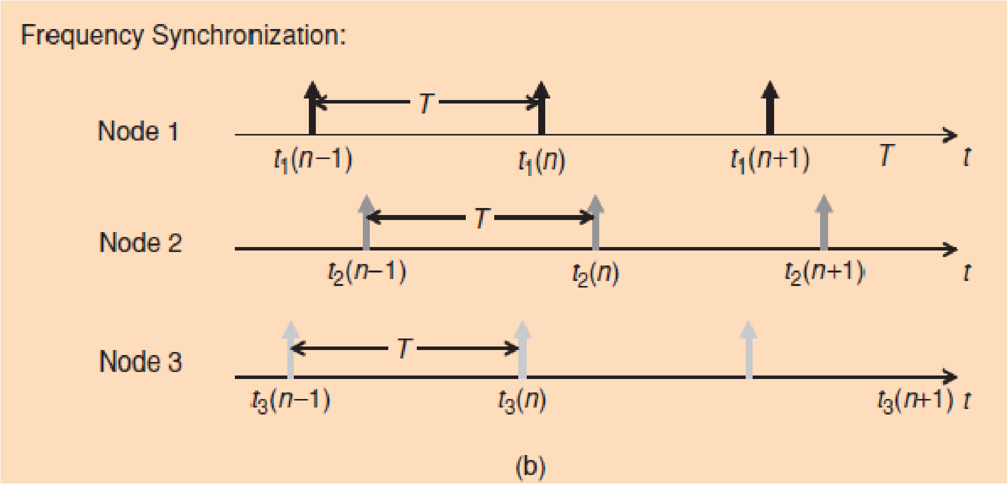
- Pulse-coupling is also a synchronization technique used for mutual synchronization
- It involves encoding local timing information into the transmission times of specific waveforms
- Each node radiates a periodic train of waveforms according to its local clock

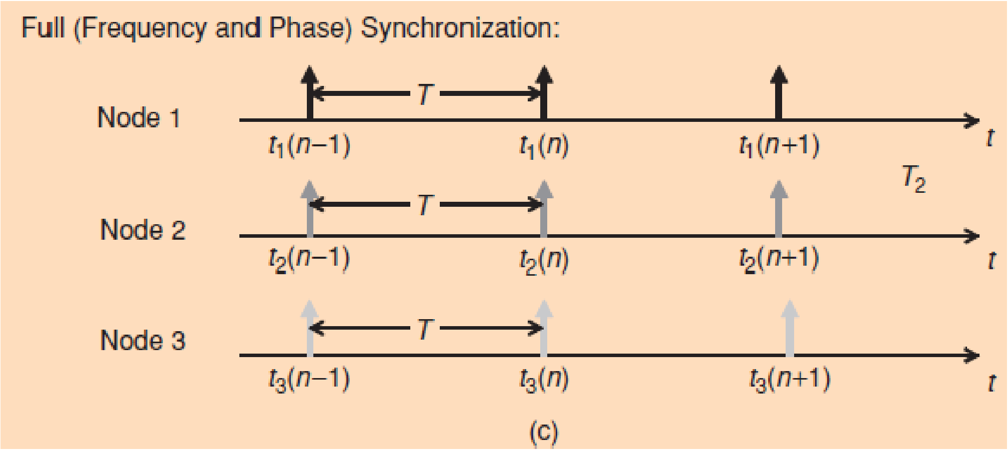
Packet-coupling vs pulse-coupling for mutual synchronization in wireless networks

- Pulse-coupling can be used for both analog and discrete-time clocks
- It aims to overcome the limitations of packet-based techniques, such as computational complexity and limited scalability
- By exchanging and processing the timing information carried by the waveforms, nodes can achieve mutual synchronization
- Pulse-coupling is a promising approach for achieving accurate and scalable synchronization in wireless networks

Packet-coupling vs pulse-coupling for mutual synchronization in wireless networks

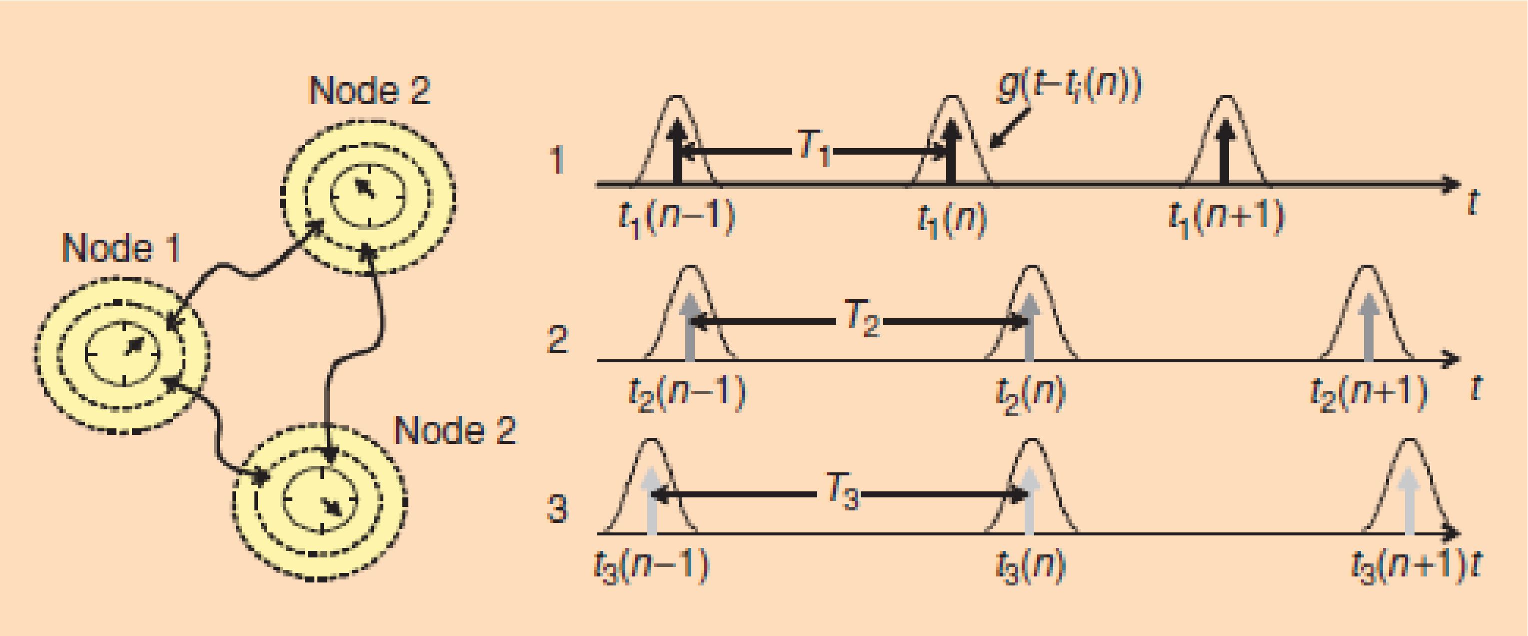






- (a) Uncoupled clocks
- (b) Frequency sync.
- (c) Frequency and phase sync.

Packet-coupling vs pulse-coupling for mutual synchronization in wireless networks



- N = 3 Nodes, for pulse coupled clocks
- Each node sends a train of waveforms g(t) for every tick of the local clock

Packet-coupling vs pulse-coupling for mutual synchronization in wireless networks

- Physical layer-based schemes update local clocks by processing the received signal
- Waveforms transmitted by nearby nodes are used for synchronization
- Different processing techniques, like time-of-arrival estimators, can be applied
- Efficient synchronization techniques can be designed without relying on explicit operations

Clocks and synchronization

- A clock refers to an object that undergoes identical phases periodically
- The principle of sufficient reason suggests that events within one period are identical to those in any other period
- Clocks consist of an oscillator and an accumulator, serving as time measurement devices
- Both analog and discrete time clocks follow this principle

Clocks and synchronization

Uncoupled clocks:

- Uncoupled clocks operate independently without synchronization or interaction
- Each clock has its own oscillator and accumulates time independently
- Uncoupled clocks exhibit asynchronous behavior and lack synchronization
- Variations in periods and phases can occur in uncoupled clocks due to hardware imperfections and random factors.

Clocks and synchronization

Coupled clocks:

- Coupled clocks interact with each other and exchange information to align their time measurements
- The synchronization of coupled clocks reduces variations in their periods and phases, resulting in coordinated behavior
- Synchronized states are formalized for analog and discrete time clocks.

Clocks and synchronization

Coupled clocks:

- Conditions for synchronization include frequency synchronization and full synchronicity
- Diffusion protocols are used to exchange local time information for synchronization
- The synchronization of coupled clocks reduces variations in their periods and phases, resulting in coordinated behavior
- The objective is to measure and adjust phase or time differences between clocks while considering propagation delays

Continuously Coupled Analog Clocks

- Nodes transmit signals proportional to their local oscillators
- Update phase based on received signal from other nodes
- Continuous transmission and reception
- Full duplex required
- Not suitable for wireless sensor networks

Pulse-Coupled Discrete Time Clocks

Integrate-and-Fire Oscillators

- Monotonically increasing
- Upon reaching maximum value
  → Reset to 0
  → "Fire event"
- Upon pulse reception
  → Phase adjustment

$$x_i(t_j(n)^+) = \begin{cases} x_i(t_j(n)^-) + \varepsilon & \text{if } x_i(t_j(n)^-) + \varepsilon < 1 \\ 0 & \text{otherwise} \end{cases}$$

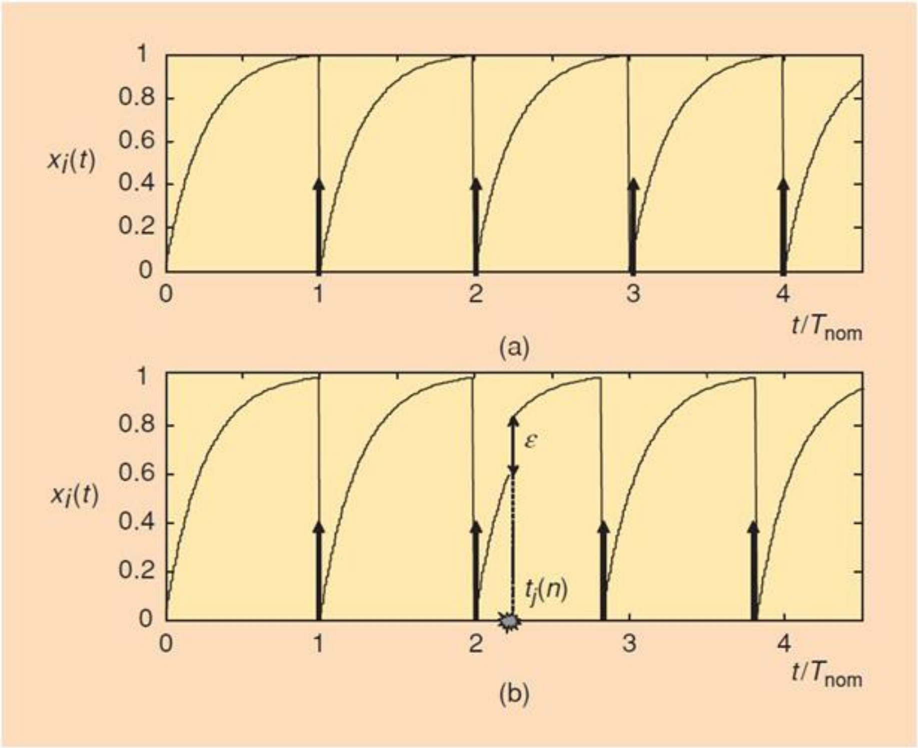


Figure: Pulse-coupled integrate-and-fire clocks. [1]

Pulse-Coupled Discrete Time Clocks

Discrete Time PLLs

- Control system with feedback
- Standard tools can be used for analysis
  - Algebraic graph theory
  - Signal processing
- More flexible system design

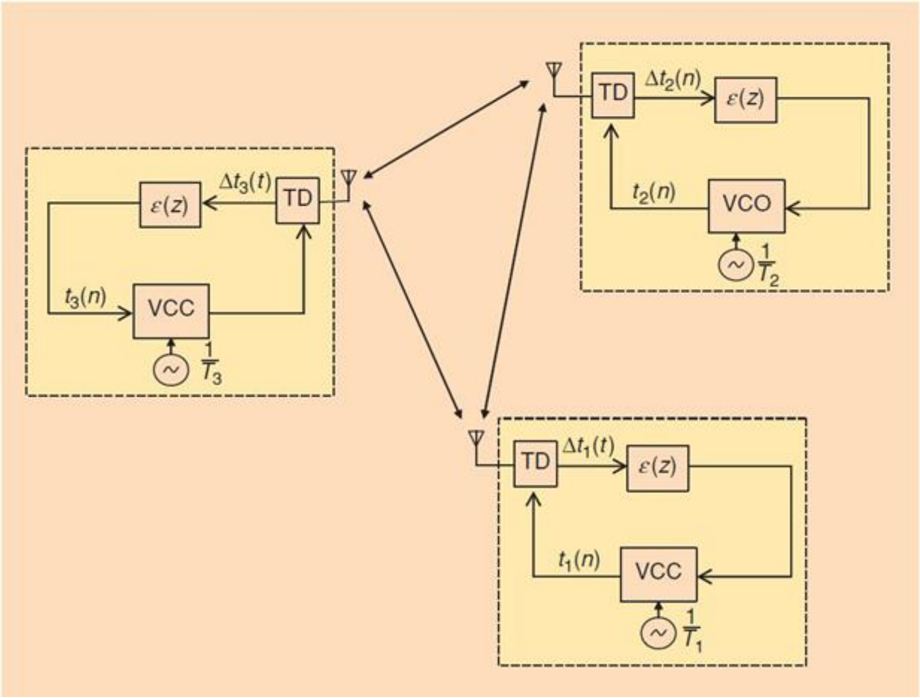


Figure: pulse-coupled discrete-time PLLs. [1]

Impact of Topology and Small-World Effects of Shadowing

- Convergence depends on network topology
- Shadowing introduces small-world network features
- Improved synchronization for more severe shadowing

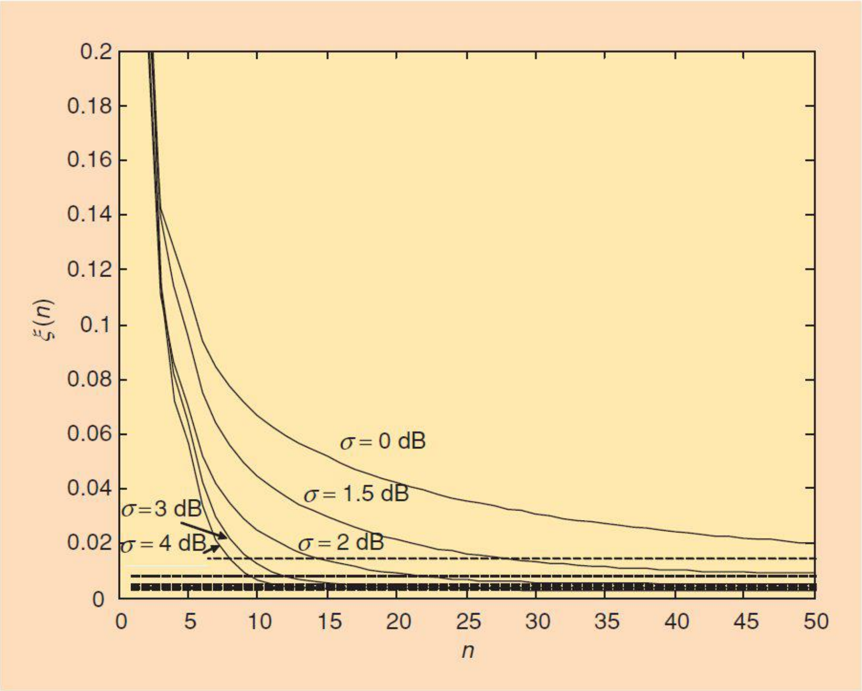


Figure: Small-world effects of shadowing. [1]

Signal Processing Aspects of Distributed Time Synchronization

Accuracy vs. Complexity	Fault-Tolerance and Security
Propagation and Processing Delays	Phase Noise

Summary

- Analog $\leftrightarrow$ Discrete
- Packet $\leftrightarrow$ Pulse
- Signal processing plays a key role in distributed synchronization
- Many challenges and open research questions remaining
- Applications:
  - Distributed consensus for multi-agent coordination
  - Distributed estimation/detection in wireless sensor networks

Thank you for your attention!

References

[1] O. Simeone, U. Spagnolini, Y. Bar-Ness and S. H. Strogatz, "Distributed synchronization in wireless networks," in IEEE Signal Processing Magazine, vol. 25, no. 5, pp. 81-97, September 2008, doi: 10.1109/MSP.2008.926661.