Distributed Synchronization in Wireless Networks
Pulse-coupled clocks

PAPER SUMMARY

(700.460) Sensor Networks

UNIVERSITY OF KLAGENFURT

Authors
Andreas Eberdorfer
Marcus Schef

Klagenfurt, June 12, 2023

1. Introduction

This article focuses on synchronization in wireless networks, particularly decentralized structures like ad hoc and sensor networks. It explores different synchronization schemes to overcome challenges posed by inaccurate clocks and propagation/processing delays. Advancements in telegraphy and wireless transmission allowed synchronization of distant clocks, leading to applications in transportation and geodesy. The coordination of clocks through electromagnetic signals played a crucial role in synchronization.

2. Distributed Synchronization in wireless networks

Wireless networks have primarily focused on synchronization in cellular telephony, using a master-slave structure. Base stations broadcast signals for mobile station synchronization. However, there is a growing interest in distributed synchronization for decentralized networks like ad hoc, sensor, and vehicular networks. These networks benefit from synchronized local oscillators, enabling unique functionalities across different protocol layers. Some examples are Signal processing applications, Spectral and energy-efficient networking, Cooperative transmission. The article discusses network synchronization methods in various scenarios. It explores beacon and satellite-based synchronization but focuses on fully distributed scenarios. Mutual synchronization in wireless networks relies on exchanging local time information and faces challenges such as signal delays and hardware inaccuracies. Achieving distributed synchronization presents additional unique challenges like, Energy efficiency, Scalability and Application specificity.
System analysis involves studying the dynamic behavior of coupled oscillators. It requires stability analysis of linear or nonlinear equations, which can be complex, especially when dealing with deterministic or random nuisance parameters.

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

This article primarily focuses on time synchronization in distributed wireless networks and explores various synchronization techniques. It discusses the concept of clocks ticking asynchronously and the possibility of achieving synchronization by exchanging time offset information between nodes. The synchronization techniques are categorized based on how local time differences are computed and processed within the network.
Traditional packet-based techniques involve periodic packet exchanges containing time stamps, but they are susceptible to errors and random delays. The article highlights the challenges and approaches to mitigate these factors.Packet-based synchronization methods in wireless networks have limitations in terms of complexity, energy consumption, and scalability. To overcome these drawbacks, physical layer-based schemes encode timing information directly into waveform transmission times. This approach improves accuracy and involves nodes radiating periodic waveforms based on their local clocks. Figure 3 provides a visual representation of this concept.

4. Clocks and synchronization

This section explores interconnected clocks in wireless networks. Clocks are defined as objects with periodic phases and consist of oscillators and accumulators. The section covers both uncoupled clocks and mutual synchronization through clock coupling.

UNCOUPLED CLOCKS: Uncoupled clocks refer to a set of clocks that operate independently without any interaction or synchronization between them. Each clock has its own oscillator and accumulates time independently, resulting in asynchronous behavior. Uncoupled clocks do not achieve synchronization and may exhibit variations in their periods and phases due to hardware imperfections and random factors. ANALOG CLOCKS: Analog clocks in wireless networks have oscillators with a nominal period T_{nom} and random offsets ΔT_i caused by hardware imperfections. Phase noise is represented by a nonstationary random process ξ. The clocks are initialized at $t = 0$ with an initial phase $\Phi_i(0)$ of 0 for $t < 0$. Frequency drifts are not considered in this article. DISCRETE-TIME CLOCKS: Discrete-time clocks, represented as sequences of significant time instants, are derived from analog clocks. Uncoupled discrete-time clocks, without synchronization, exhibit asynchronous behavior.

COUPLED CLOCKS: Clock coupling is a mechanism to achieve synchronization among clocks. It involves formalizing synchronized states for both analog and discrete time clocks. We have several important conditions, Frequency synchronization, Full (frequency and phase) synchronicity, Frequency synchronicity and Full (frequency and phase) synchronicity. The article discusses diffusion protocols for exchanging local time information to achieve synchronization. Nodes transmit their time to neighboring nodes using packet-coupling or pulse coupling methods. The goal is to measure and adjust the phase or time differences between clocks while accounting for propagation delays.

5. Continuously Coupled Analog Clocks

Continuously Coupled Analog Clocks are interesting for applications such as cooperative beamforming or frequency division multiple access (FDMA) in ad hoc networks. To achieve distributed synchronization of the nodes, on the one hand, each node continuously transmits a signal representing its own local oscillator. On the other hand, each node updates its phase according to the signals received from other nodes. This requires the nodes to send and receive signals continuously and simultaneously, which is why full duplex capability is necessary. However, it is difficult to realize full-duplex transmissions in wireless networks.

6. Pulse-Coupled Integrate-and-Fire Oscillators

Pulse-Coupled Integrate-and-Fire Oscillators is a concept for synchronizing nodes with discrete time clocks. For this method it is assumed that all nodes run in frequency synchronicity, hence that there is only a difference in the phase of the nodes. The oscillator of a node is represented by a state variable increasing from 0 to 1 monotonically. After reaching the maximum value 1 the node "fires", i.e., transmits a pulse, and resets its value to 0. However, when a node receives a pulse from another node, it adds a predefined value to its own state variable to get closer to the clock of the other node. Through the mutual exchange of pulses, the nodes could eventually achieve synchronicity. One disadvantage of the ”integrate and fire” approach is the difficulty in analyzing the impact of real-world constraints such as inaccurate clocks, propagation delays or time-varying channels. Moreover, the system design is rather inflexible in terms of trade-offs between complexity and accuracy, safety, etc.

7. Pulse-Coupled Discrete-Time PLLs Oscillators

Pulse-Coupled Discrete-Time PLLs is an alternative method for pulse-coupled clocks. Standard tools from algebraic graph theory and signal processing can be utilized for analysis and a more flexible system design. The nodes send signals according to their local voltage controlled clock (VCC). The adjacent nodes will receive the signal and utilize the signal to improve synchronicity with the other nodes. Each node calculates a convex combination of time differences according to the received signals from the other nodes and the output of its own VCC. This is done by utilizing a time difference detector (TD). The result of the TD is passed forward to a loop filter and afterwards fed into the VCC to adjust the output of the VCC.

8. Impact of Topology and Small-World Effects of Shadowing

The convergence of distributed synchronization in wireless networks depends on the topology of the network. Simeone et al. show that the convergence speed and asymptotic phase error of the system of distributed PLLs can be improved by rising the level of shadowing. This is because the graph possesses features of a small-world network when shadowing is introduced. Small-world networks have short paths (small number of hops) between arbitrary nodes in the network. Through shadowing some of the short connections are no longer available and a few long links are created. These features of small-world networks improve the capability of distributed agreement.

9. Signal Processing Aspects of Distributed Time Synchronization

Accuracy vs. Complexity:

Signal processing aspects play an important role in the system design pulse-coupled discrete-time PLLs for distributed time synchronization and the tradeoffs between accuracy and complexity. One major aspect is the refractory time, i.e., the time switching from the transmission to the reception mode. This time depends on the used hardware. In addition, the synchronization process could be improved by oversampling. However, this requires a higher computational effort as well as better hardware. Moreover, using a pole in the loop filter could improve performance, but this would in turn increase computing power.

Fault-Tolerance and Security:

In real-world scenarios faulty and malicious nodes can drastically impact the distributed synchronization of nodes. Therefore, a robust design is required that uses simple signal processing techniques to achieve synchronization even in the presence of disturbance. Simeone et al. highlight a concept to evaluate the dispersion of clock errors around the average by calculating the variance. Afterwards only the clock differences within a certain range from the average are used to update the local clock of a node. This leads to a significant improvement in the presence of faulty or malicious nodes.

The Impact of Propagation and Processing Delays and Phase Noise:

Propagation delays can be seen as an equivalent frequency offset between the clocks of the nodes. In the presence of phase noise, the clocks of the nodes do not converge, but the average of the relative deviation of the clocks converges.

10. Conclusion

Simeone et al. gave an overview of important concepts and open research questions in distributed synchronization for distributed wireless networks. The authors especially highlighted the signal processing aspect of time synchronization in distributed wireless networks and the challenges and tradeoffs that are connected to this field. Insights were also provided on distributed synchronization-based signal processing and control applications such as distributed consensus for multi-agent coordination or distributed estimation/detection in wireless sensor networks.

References

”Pulse-Coupled Clocks”, Simeone et al. Distributed Synchronization in Wireless Networks. Signal Processing Magazine, 2008