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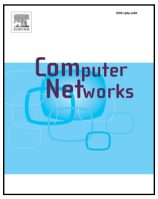

Firefly synchronization with phase rate equalization and its experimental analysis in wireless systems

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ABSTRACT

The convergence and precision of synchronization algorithms based on the theory of pulse-coupled oscillators is evaluated on programmable radios. Measurements in different wireless topologies show that such algorithms reach precisions in the low microsecond range. Based on the observation that phase rate deviation among radios is a limiting factor for the achievable precision, we propose a distributed algorithm for automatic phase rate equalization and show by experiments that an improved precision below one microsecond is possible in the given setups. It is also experimentally demonstrated that the stochastic nature of coupling is a key ingredient for convergence to synchrony. The proposed scheme can be applied in wireless systems for distributed synchronization of transmission slots, or sleep cycles.

1. Introduction

There is a broad spectrum of work on pulse-coupled oscillators (PCO) to model synchronization phenomena in biology, physics, and other sciences (see [1–7] and references therein). A prominent example is swarms of fireflies that synchronize their blinking behavior [8]. The beauty of these synchronization phenomena lies in the fact that system-wide synchrony emerges among the participating entities in a completely distributed, self-organizing manner without any need for central entities. Furthermore, PCO synchronization — sometimes called firefly synchronization — is scalable with respect to the number of entities and robust against full failure of individual entities or appearance of new entities.

Many communication protocols and scheduling techniques, as well as novel approaches such as interference alignment in wireless networks, require synchronization, e.g., [9–12]. Thus, the telecommunications engineering community has been interested to transfer the concepts behind these natural synchronization phenomena to design algorithms for the synchronization of nodes in wireless networks [13]. A one-to-one transfer is, however, infeasible due to the differences between biological and wireless communication systems. Several extensions and modifications are required with respect to delays, noise, and multihop communications, to mention a few (see [13–20]).

Despite the conceptual and theoretical advances in the design of PCO synchronization for wireless systems, real-world performance studies and proofs of concepts are largely missing. There only exist a few implementations on low-cost sensor platforms (see [16,21,22]), whose results are of interest, but whose synchronization precision is limited by restricted hardware capabilities.

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To the best of our knowledge, there is no comprehensive performance analysis of PCO synchronization on programmable radio boards. The paper at hand addresses this issue. We analyze three recently proposed PCO synchronization algorithms by implementing them using field programmable gate-array (FPGA)-based radios and study their performance with respect to the achieved synchronization precision. Besides this experimental contribution, our main conceptual contribution comes from the *lessons learned* during our measurements: we propose an automatic phase rate equalization algorithm, integrate it into PCO synchronization, and show by experiments that this new feature significantly improves the synchronization precision compared to existing PCO algorithms.

The contributions can be summarized as follows:

- Providing a proof-of-concept for three PCO synchronization algorithms on FPGA-based radios.
- Analyzing and comparing the synchronization precision of these algorithms by means of real-world measurements in different network topologies, namely fully connected, star, line, and ring topology with five nodes.
- Showing that the synchronization precisions are in the low μs range in these topologies, and that the key factor preventing better precisions are phase rate deviations among the radios.
- Proposing a new distributed algorithm to additionally synchronize phase rates and showing by measurements that this algorithm used with PCO synchronization achieves precisions below one μs.
- Investigating unreliable or intentionally stochastic communication of synchronization words.

Our work is the most comprehensive experimental performance study of PCO algorithms on programmable radios over real wireless channels. It enables us to state that the following building blocks are essential for PCO synchronization in wireless networks and should be considered by protocol designers: a combination of positive (excitatory) and negative (inhibitory) coupling, unreliable or intentionally stochastic communication of synchronization words, and automatic phase rate equalization.

The remainder of this paper is as follows: Section 2 discusses related work. Section 3 reviews and explains three PCO algorithms for wireless systems. Section 4 addresses the implementation of these algorithms on programmable radios. Section 5 presents an experimental analysis of the algorithms in terms of their convergence and precision. It demonstrates the importance of the stochastic nature in the exchange of synchronization words for convergence and shows that precisions in the order of some ten microseconds are possible. Section 6 proposes and analyzes a distributed phase rate equalization algorithm to further improve the precision. Section 7 presents a performance analysis of synchronization with phase rate equalization and shows that precisions below one microsecond are possible.

In our prior work [23], we have applied phase rate equalization manually by measuring the phase rate of each device and programming static phase rate equalization factors. The paper at hand presents a completely distributed algorithm, which achieves phase rate synchronization among the devices during operation. This is particularly important since phase rates may vary when environmental factors, e.g., temperature, change. Our new algorithm adapts to these changes and hence enables its practical application. Furthermore, the experimental analysis of this paper is much more comprehensive than that of Brandner et al. [23].

2. Related work

Research on PCO synchronization in wireless systems can be divided into conceptual and analytical work (algorithms are proposed and theoretically analyzed) and experimental work (algorithms are implemented in testbeds to evaluate and verify their performance).

2.1. Concepts and analytical work

The mathematical modeling of pulse-coupled biological oscillators, as proposed, e.g., in [1] inspired by Peskin [8], offers a fully distributed and scalable approach for time synchronization with a broad set of applications (see, e.g., [2–7,24–26] and references therein).

The fact that technical limitations hinder a one-to-one transfer of these models to wireless systems led to papers investigating necessary changes for applying these models: Mathar and Mattfeldt [13] present extensions to apply PCO synchronization in TDMA systems. They show, for two oscillators, that synchronization is reached even in the presence of delays. Hong and Scaglione [14] propose a distributed PCO synchronization protocol for wireless networks considering pulse detection and refractory periods. Lucarelli and Wang [15] present synchronization protocols for dense, large-scale sensor networks and show that convergence to a synchronized state is reached even when the communication topology is time varying. Klinglmayr et al. [7] present a PCO synchronization algorithm with inhibitory and excitatory coupling and stochastic pulse emission. They prove that arbitrary networks of pulse-coupled oscillators converge almost surely, i.e., with probability one.

Further manuscripts dealing with the applicability of PCO synchronization in wireless networks are [17,22,27–30].

2.2. Experimental work

Comprehensive experimental performance studies and proofs of concepts of PCO synchronization are largely missing. There only exist a few implementations on low-cost wireless sensor platforms: Werner-Allen et al. [16] implement a PCO synchronization algorithm on TinyOS-based motes. They reach synchronization precisions of about 100 μs. Leidenfrost and Elmenreich [21] implement a PCO synchronization algorithm on ZigBee nodes. The evaluation is performed in terms of time to synchronization and synchronization precision. The 50% quantile of the synchronization precision is at about 700 μs. Pagliari and Scaglione [22] propose and implement a PCO synchronization algorithm on MicaZ nodes. The reported synchronization precision is in the range of a few hundred microseconds.