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Firefly-inspired and robust time synchronization for cognitive radio ad hoc networks

Nadine Lipa, Elisa Mannes, Aldri Santos, Michele Nogueira*

Department of Informatics, Federal University of Paraná, Brazil

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ABSTRACT

Harnessing the full power of the paradigm-shifting cognitive radio ad hoc networks (CRAHNs) hinges on solving the problem of time synchronization between the radios on the different stages of the cognitive radio cycle. The dynamic network topology, the temporal and spatial variations in spectrum availability, and the distributed multi-hop architecture of CRAHNs mandate novel solutions to achieve time synchronization and efficiently support spectrum sensing, access, decision and mobility. In this article, we advance this research agenda by proposing the novel Bio-inspired time SynChronization protocol for CRAHNs (BSynC). The protocol draws on the spontaneous firefly synchronization observed in parts of Southeast Asia. The significance of BSynC lies in its capability of promoting symmetric time synchronization between pairs of network nodes independent of the network topology or a predefined sequence for synchronization. It enables the nodes in CRAHNs to efficiently synchronize in a decentralized manner, and it is also reliable to changes, faults and attacks. The findings suggest that BSynC improves convergence time, thereby favoring deployment in dynamic network scenarios.

1. Introduction

Cognitive radio ad hoc networks (CRAHNs) are promising candidates for effective spectrum management in a system comprising licensed primary users (PUs) and distributed unlicensed secondary users (SUs). The SUs communicate with one another in a multi-hop way by opportunistically accessing spectrum holes, portions of the licensed spectrum not been used by PUs for a period of time. However, leveraging the full potential of CRAHNs depends on time synchronization for SUs during the stages of the dynamic spectrum management, such as spectrum sensing, decision, sharing, and mobility [1,2].

Further, effective time synchronization assists in overcoming artifacts of wireless channels, such as shadow fading that impedes user-coordination, and also in avoiding interfering with the PUs [3]. The asynchronous nature of the distributed SUs, especially in mobile conditions, where they move at different speeds and along different directions makes time synchronization very challenging [4]. SUs will have different values for transmission times, sample and carrier frequencies inducing offsets in transmission times and sample frequencies in non-coherent communication systems, and divergent carrier frequencies in coherent communications.

In this article, the novel Bio-inspired SynChronization (BSynC) protocol has been proposed for CRAHNs, mainly aimed at mitigating the effects of the aforementioned issues and the impact of security vulnerabilities. These characteristics mainly differentiate this work from our previously published on [5], in which the presented proposal did not consider security issues, such as those security vulnerabilities emphasized by [6]. BSynC synchronizes pairs of nodes "on the fly" and when compared to one of the popular synchronization protocols for wireless ad hoc networks, the timing-sync protocol in sensor network (TPSN) [7], it outperforms the traditional sender–receiver based synchronization in terms of the speed of achieving network-wide synchronization, and resiliency to link disruptions owing to node mobility.

Bio-inspired techniques have been applied to solve key problems in communication technologies [8]. More specifically, the phenomenon of synchronization has been investigated in large biological systems [8]. Fireflies provide one of the most spectacular examples of synchronization in nature. At night in certain parts of southeast Asia thousands of male fireflies of some species congregate in trees and flash in synchrony [9]. Mirollo and Strogatz have characterized the fireflies synchronization behavior [10] and we employ their model to design the BSynC protocol, supporting the synchronization between pairs of SUs (nodes) irrespective of the network topology. In addition,

* Corresponding author: Tel.: +55 41 3361 3412; fax: +55 41 3361 3205.
E-mail addresses: nadine.lipa@gmail.com (N. Lipa), elisam@inf.ufpr.br (E. Mannes), aldri@inf.ufpr.br (A. Santos), michele@inf.ufpr.br (M. Nogueira).

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the BSynC protocol intends to offer reliability and security to the time synchronization in CRAHNs.

We assume a CRAHN comprising very few nodes with access to a global time reference, i.e., the time used by the Internet, e.g., coordinated universal time (UTC). They serve as “master” nodes for the other nodes by periodically broadcasting their *timestamps*. Master nodes are not elected or selected. They are master node by the fact that they own a device allowing to access a global rime reference, such as a Global Position System (GPS) device. The other nodes infer their timing from the timestamps broadcast by the master node. It is remarked that this assumption is valid from a real-world implementation stand-point as enabling each node with global time reference capabilities will prove to be less efficient and more expensive. Upon receiving the broadcast from the master node, the neighboring nodes adjust their clocks to ensure that the offsets are minimized. This iterative process occurs in the network until the nodes are synchronized, following Mirollo and Strogatz’s synchronization model.

The performance and security of BSynC is assessed by simulations under static and mobile scenarios, and also in face of two kinds of easy to launch and harmful attacks, the **lack of cooperation** and **pulse-delay** attacks. Simulation results show that the convergence time of BSynC is smaller than the convergence time of TPSN. Furthermore, our findings suggest that BSynC outperforms TPSN in dynamic scenarios, managing efficiently changes in the network topology caused by spectrum handoffs, failures and others. BSynC presented satisfactory results independent of the number of master nodes and also a high tolerance against both attacks. We emphasize that these results are original and they have not been published anywhere, complementing and improving significantly our previously published work [5].

This article proceeds as follows. Section 2 presents the related work. Section 3 describes the analytical model developed by Mirollo–Strogatz model and inspired by firefly synchronization, as well as assumptions and general definitions. Section 4 describes the novel BSynC protocol, and Section 5 presents the performance and security evaluation of the protocol and analyzes our findings. Finally, conclusions and some directions for future research are presented in Section 6.

2. Related work

The state-of-the-art in network-wide time synchronization is based on identifying a common global time reference. Solutions to time synchronization in decentralized wireless networks, such as sensor networks and mobile ad hoc networks, have been studied by the authors of [11] (and the references within). In general, perfect time synchronization in massively distributed systems is a complex issue and difficult to solve [12], and most of these solutions cannot be directly applied to CRAHNs due to channel handoffs and their self-adaptive features. With this in mind, we briefly review previous work, which are most closely related to our proposed protocol.

To the best of our knowledge, cognitive radio (CR)-Sync is the only synchronization protocol designed to take into account cognitive radio networks characteristics [4]. CR-Sync is based on the very popular timing-sync protocol in sensor network (TPSN) [13] that also creates a tree structure with several levels and carries out a procedure for synchronization of time between a parent and its children. The synchronization is typically achieved by exchanging periodic messages containing a timestamp and a delay. TPSN has as main disadvantage the fact that the higher the level of a node in the tree, the clock offset relative to the root of the tree (a node in possession of the global time reference) may also increase. Since this protocol was designed for wireless sensor networks, it does not take into account mobility aspects, not having self-adaptation or fault tolerance priorities for the protocol.

Some researchers have observed that synchronicity is a useful abstraction in many contexts and applications [14–16]. Also, few existing synchronization protocols have taken advantage of bio-inspired models [8,12]. These protocols have been inspired by the first biological experiments carried out by Richmond, who developed mathematical models of synchronization. Mirollo and Strogatz used as reference pulses from the study of coupled-oscillators in order to provide an analysis of synchronization between fireflies and developed a model [10]. Werner et al. present an algorithm for synchronous wireless sensor networks, called the reach-back firefly algorithm (RFA) [12]. The RFA is an algorithm implemented for TinyOS synchronicity. It is based on Mirollo and Strogatz model and on a mathematical model that describes how neurons spontaneously synchronize. The RFA considers realistic effects in the communications networks of sensors.

Our contribution to this emerging area is the design of the BSynC protocol, proposed to combat frequent switches of used channel by SUs on CRAHNs. Based on the Mirollo and Strogatz model, BSynC achieves temporal synchronicity between nodes in a flexible, self-adaptive, and fault-tolerant way.

3. Models, assumptions and general definitions

In the current section full description of the models, assumptions and all definitions that are followed throughout this article is given. It starts with an overview about the firefly synchronization model applied to develop the BSynC protocol. Next, it provides detail of the network environment considered. Along the next subsections, assumptions and definitions are explained and justified.

3.1. Firefly synchronization model

Considering the characteristics required for CRAHNs solutions, such as decentralization, flexibility and node autonomy, the proposed protocol has as reference the synchronization model inspired by fireflies developed by Mirollo and Strogatz [10,17]. In this model fireflies are represented by pulse coupled oscillators, which are assumed to interact with each other at discrete times. The coupling can be described as an effect usually captured as a phase response curve (PRC). This formulation allows the time evolution of the coupling to be described by a map from one cycle to the next. PRC illustrates the transient change in the cycle period of an oscillation induced by a perturbation as a function of the phase (ϕ) at which it is received. PRCs are used in various fields; examples of biological oscillations are the heartbeat, circadian rhythms, and the regular, repetitive firing observed in some neurons in the absence of noise.

The reference model was built based on observations of spontaneous synchronization phenomena derived from the theoretical framework of *pulse coupled oscillators* for the synchronicity convergence. In the model, an oscillator owns a fixed period T, a frequency and a phase ϕ. Each oscillator has an internal timer t, a variable that controls its cycle, and consequently its frequency. The values for t continuously vary from 0 up to the threshold T. When $t = T$, the oscillator resets its internal timer t to zero and emits a *pulse*, simulating fireflies flashing. Observing the pulses of others, a given oscillator slightly adjusts its own internal timer. Although a gross approximation, this model has been of heuristic value to neurobiology and through this process, it is possible to observe that the oscillators are aligned, achieving synchronicity.

At the initial state, the oscillators’ internal timers are not synchronized because they can start the synchronization procedure at different moments, however it is assumed that all oscillators own initially the same frequency but it can be easily affected by messages delay and drops. Hence, when an oscillator pulses, another in its neighborhood responds to this stimulus, slightly increasing its internal timer t and hence its frequency. Guided by the PRC, the variable t is a function