Chapter 56
Long–Term Synchronization of Hybrid Sensors Networks

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ABSTRACT
This article presents synchronization of a hybrid distributed sensor network with wired and wireless sensors. Authors present an implementation of a sleep monitoring system as a hybrid sensor network that combines wireless inertial sensors controlled by a custom smartphone application as an extension of the polysomnographic (PSG) monitor to improve user’s comfort. The authors developed an original method of synchronization of wireless sensor data with the PSG records using an auxiliary audio synchronization signal generated by the smartphone. The timestamps on the smartphone are synchronized with the timestamps from inertial sensors, and time of generated synchronization pulses recorded by the PSG. The individual data streams were synchronized using the Dynamic Time Warping (DTW) mechanism. Authors present the system organization and the results of analysis of the whole night monitoring, including the analysis of channel reliability and clock drift. Clock drift has been reduced from 10-30 seconds to 5.1±3 milliseconds which is with an improved accuracy as compare to existing methods.

1. INTRODUCTION
Wireless Sensor Networks (WSNs) are spatially distributed sensors systems that represent architecture of choice for distributed monitoring due to the ease of deployment and configuration. This is an active and emerging research area with applications in military, environmental monitoring, industrial control, home automation, health monitoring, and other applications. It is a promising technology for ubiquitous health monitoring and management, and monitoring of activities of daily living (Jovanov, Poon, Yang & Zhang, 2009; Jovanov & Milenkovic, 2011; Milenković, Otto, & Jovanov, 2006). In most of the applications, sensor nodes are deployed in harsh or changing environmental conditions (Chand Gautam &
Chand Kaushal, 2014). In most of the WSN, sensor nodes cooperatively send data to a central device, such as smartphone gateway, that can be used to control and configure the network (Jovanov, Milenkovic, Otto, & de Groen, 2005).

WSNs sense and collect data that must be time synchronized to enable essential functions such as sleep scheduling of the nodes, localization, data fusion, coordination among nodes etc. In WSN, it is required to maintain a common notion of time among the sensor nodes (Huang, Zomaya, Delicato, & Pires, 2014). In a centralized wired system, the need for synchronized time is less stringent because of the lower latencies (Chand Gautam & Chand Kaushal, 2014). A combination of a wired system with wireless distributed monitoring system forms a Hybrid Sensor Network (HSN). Each sensor node (wired or wireless) in the network has its own local clock and they certainly have clock drift caused by environmental changes, such as pressure, temperature, and battery voltage (Sundararaman, Buy, & Kshemkalyani, 2005).

The sleep and user’s activity monitoring, using small wearable sensors and a smartphone, has been increasingly used in many applications. Approaches for automatic sleep activity monitoring used by researchers vary in number, type, and placement of utilized sensors, as well as in processing of recorded signals. It has been demonstrated that smartphone sensing and processing can be used to monitor movement of chest and abdomen caused by breathing (Nandakumar, Gollakota, & Watson, 2015). iSleep uses a smartphone’s microphone to monitor snoring and body movements and infer quantitative measures of sleep quality (Hao, Xing, & Zhou, 2013). Smartphone applications frequently include sleep diary (eDiary) for sleep related questionnaire and assessment (Yousaf, Hamida, & Ahmed, 2014).

In recent years, several sleep monitoring systems have been developed (Hamida, Hamida, & Ahmed, 2015) that are highly automated, and portable for use at home. However, the entire setup integrates a number of devices, sensors, and wires that has been proven to significantly disturb sleep of users, particularly during the first night of monitoring (McCall & McCall, 2012). Moreover, wired sensors and electrodes are not only inconvenient and uncomfortable but also affect the subject’s health and mood (Hamida et al., 2015). Hence introducing wireless sensor technology in sleep monitoring would significantly improve the comfort of users and the quality of monitoring. In the new era of sleep monitoring, wearable sensors, advanced sensing and wireless technology should be utilized to significantly improve the diagnosis and treatment of sleep related problems.

We developed a hybrid monitoring system to facilitate sleep studies using wireless inertial monitoring sensors (SP-10C) (Sensoplex, 2014) and a smartphone with a standard Polysomnography (PSG) sleep monitoring system. Smartphone has been used to facilitate time synchronization between wireless inertial sensors and the PSG system. Since standard PSG monitors use wired sensors for monitoring of sleep activities and Periodic Leg Movement (PLM), which is inconvenient to the users, we developed our system to monitor PLMs wirelessly to improve user’s convenience.

We describe our sleep monitoring system briefly in a previously published paper (Madhushri, Ahmed, Penzel, & Jovanov, 2015). That paper was mainly focused on the test experiments and signal processing performed to detect PLMs using inertial sensors. The current paper is an extension of previous paper which describes the whole system in detail. This elaborates each and every component of the sleep monitoring system and mainly focused on time synchronization of HSN including detailed analysis on Bluetooth communication channel reliability. The main contributions of the current paper are the implementation of HSN for sleep monitoring which facilitates PLM monitoring with improved user’s convenience and comfort, the assessment of reliability and usability of the system for whole night monitoring and the implementation of time synchronization algorithm using pulse Dynamic Time Warping (DTW) method.
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