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A sub-nanosecond Synchronized MAC – PHY cross-layer design for Wireless Sensor Networks

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ABSTRACT

In this paper, we present a Wireless Sensor node implementation which aims at solving two major issues in Wireless Sensor Networks. This solution provides nanosecond-scale synchronization between nodes and high data-rate transmission thanks to cross-layer design and the time-domain properties of UltraWide Band (UWB) modulation schemes. The high data rate is achieved through a specific implementation of a IR-UWB physical layer. Specific algorithms are also implanted into the MAC and physical layers and form a cross-layered synchronization protocol for deterministic Wireless Sensor Networks named WiDeCS (Wireless Deterministic Clock Synchronization). This protocol propagates master time reference to nodes of a cluster tree network. WiDeCS Cross layered scheme is possible thanks to flag signals rising in the physical layer. These signals, owing to the UWB time domain properties, capture precise timestamps of transmission and reception. Hardware level simulations show a clock synchronization precision of 2 ns with a 2 GHz bandwidth signal, and an ASIC demonstrator shows 374 ps synchronization precision and 677 ps of standard deviation with the same bandwidth. In this paper, the physical layer implementation is detailed, and the cross-layered WiDeCS scheme is demonstrated.

1. Introduction

Recent research has lead to advances in digital circuits, analog and RF design, Micro ElectroMechanical Systems and sensing technologies. These advances have allowed the fabrication of integrated small form-factor embedded systems. Such systems find their main applications in the field of unobtrusive and remote monitoring when deployed as sensing and communicating networks called Wireless Sensor Networks (WSN).

The applications for these sensor networks vary from health monitoring for dependent persons to real time test and measurement. Most of these applications require the nodes to preserve a synchronized clock information in order to link each measurement to the specific moment it was taken. However this constraint becomes stronger when it comes to study phenomena with fast variations and large effect areas. Structural Health Monitoring (SHM) [1] is one of the main applications that need high data-rate and good synchronization between measurements. Indeed, waves are sent in the structure, and are recorded simultaneously in different points of this structure. Impacts or defects will be detected and located thanks to the echoes and refractions recorded on each node. In order to properly detect and locate defects in the structure, the nodes capturing these waves must be synchronized as precisely as possible to reduce the uncertainty on the default's location.

An other application can also be found in the aerospace industry. During the validation of simulated aerodynamic models, airflow properties are measured during test flights in order to confirm simulations in virtual wind tunnels

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with real captured data. The information concerning pressure over and under the wings is then correlated to deduct airflows. Such signal processing technique, to be accurate, requires sub-microsecond synchronized sensors.

Systems providing solutions to both above examples do exist. However, they are based on a fully wired architecture, and do imply very high deployment costs due to the high amount of cabling, which must be installed throughout the structure. Moreover, these systems often do change the behavior of the monitored structure due to the overweight caused by wires.

For many years, high speed wired computer networks have concentrated a large part of the research about time synchronization. Network Time Protocol (NTP) is the widely spread clock synchronization protocol used for synchronizing computers over the internet. For more precise clock synchronization, IEEE 1588 also known as Precision Time Protocol (PTP) [2] is used in wired networks. However, such protocol does not reach Wireless Sensor Networks' specific needs. New protocols have been developed to take into account the specific needs for usability in Wireless Sensor Networks. The work presented in this article is aiming at solving the problem of synchronized trigger in the context of an instrumentation WSN. The target is to build a network able to take synchronous measurements at different places of a specimen structure, and to gather all of this data at a single end point named gateway. This network is organized around a main concept: determinism. Indeed, such stringent requirements detailed before can be fulfilled with more ease if the entire network architecture provides a reliable information about delays in the different network layers. A deterministic WSN architecture is then constrained in its components by the necessity of knowing every delay involved in a data transmission. The resulting WSN architecture loses in terms of genericity and adaptability to common uses. However, it solves issues related to aeronautic and space applications that did not have any attainable solution with state of the art generic WSN systems.

An overview on related work in physical layers for WSN and clock synchronization schemes is presented in Section 2. In Section 3, the context is detailed along with corresponding assumptions. The cross-layer system is explained, and its block-partitioning is performed in Section 4. The physical layer design and adaptation related to this cross-layer are detailed in Section 5. Section 6 details the Synchronization protocol for deterministic Wireless Sensor Networks along with the related error analysis. Implementation is detailed, and hardware simulation results, as well as ASIC implementation tests are reported in Section 7.

2. Related works

In the vast domain of Wireless Sensor Networks, the most commonly studied applications involve event based data transmission. A large number of sensing nodes are spread over the target area and around monitored objects. In this use case, data transmissions rarely occur. The two main reasons for sending data are an external event, or a timer based trigger. Most of the Medium Access Control (MAC) layers adapted to such networks use contention or demand based protocols as opposed to Time Division Multiple Access (TDMA) or Frequency Division Multiple Access (FDMA) based solutions [3]. In the context of sparsely transmitted data, a TDMA link has high overhead, and forces to form clusters of neighboring nodes. Demand based solutions, in these applications offer more permissive behaviors. MAC protocols targeted for such networks are listed in [4].

However, these contention or demand based solutions do not apply to systems which require a high number of simultaneous and real-time transmitted measurements. Applications including large scale validation tests, as well as Structural Health Monitoring could take an enormous advantage of real time measurement WSNs. Indeed, real time measurement requires a totally different point of view. Such systems require data to be sent continuously over the network, with synchronicity between measurements. The two main issues to solve are then the specific Medium Access Control, and a precise synchronization of nodes in the network.

2.1. IR-UWB physical layer for Wireless Sensor Networks

The channel capacity of such systems has to be high enough to accommodate the continuous transmission of megabits per second of data from each node. This leads to the need for a specific physical (PHY) layer. An ideal physical layer offers short measurable time domain events for synchronization purpose, and a high attainable datarate. Impulse Radio UltraWide Band (IR-UWB) modulations possess both these properties, thanks to the transmission of information through extremely short pulses. IR-UWB suits these constraints and provides other benefits such as low power consumption, reconfigurability, through the wall propagation, multi users scalability, low probability of detection and interception [5]. The main constraint linked to the use of such technique is also the source of its major advantage: the very large bandwidth. Indeed, UWB signals are more affected by multi-paths and do require specifically adapted physical (PHY) layer synchronization techniques. Detecting frames, and avoiding the effects of multi-path is a major goal for such PHY layers. Avoiding the effects of this delay spread, and even taking an advantage out of it has been a hot research topic for the last decade. The transmitted signal is composed, at baseband level, of short pulses, defined by a pulse width and a specific shape depending on the occupied bandwidth. This pulse is then transmitted on the channel, and is received at RX side as a series of secondary pulses caused by multi-paths as illustrated in Fig. 1.

2.2. MAC layers and synchronization schemes

As explained above, TDMA or FDMA MAC layers are more appropriate for continuous transmissions, due to the predictability of the channel occupation. However, when it comes to clock synchronization, a Time Division Multiple Access MAC protocol is based on time to control access to the medium, and then is pre-adapted to capture of Time of Arrival (ToA) events. The induced determinism