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Cover page

Title: Synchronization of wireless sensors : review of methodologies. Experience feedback of the very precise GPS solution

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ABSTRACT

Measuring numerous or various physical parameters all along a structure often implies that collected data should be compared or correlated by a central process unit (that ensures the structure assessing or controlling). That typical configuration of a sensors' distribution and particularly wireless sensors network, underlines the need of precise relative or absolute time stamping of each measurement.

Unfortunately, each sensor of a network is an electronic entity whose time-base varies because of many factors (its own quartz drift, temperature influence, age, etc.). Thus, a synchronization mechanism is needed to reach a time stamping that suits the required precision. The level of precision in sensor synchronization is directly determined by the SHM need (from few seconds for temperature to micro-seconds for acoustic wave propagation).

Many topologies could be considered but a review of the appropriate and case-dependent methodologies is proposed. The simplest case where each sensor directly measures and transmits data to a supervisor that ensures the final time-stamping is limited because this supposed a determinist knowledge of the delay due to acquisition and the RF transmission (moreover, this configuration excludes local signal processing like those embedded in smart sensors). Two other topologies are analyzed. First, the topology where a supervisor performs and distributes a synchronization mechanism through the sensor network. This could be achieved by means of appropriate network time protocols or by the exchange of specific packets for sensor time-base reset or synchronization. Another topology consists in an embedded synchronization mechanism; each sensor manages its own and absolute time-base.

LCPC has integrated such a mechanism in its smart and wireless sensor platform by means of low-cost, low-power consumption and very integrated GPS module. Smart sensors are based on a DSP processor to which the PPS signal of the GPS module is input. By an appropriate algorithm using timer counter, interruption, frame decoding and the guarantee of a PPS signal precision of $1\text{ s} \pm 50\text{ ns}$, each sensor is able to ensure an absolute time-base with a precision of $1\mu\text{s}$.

INTRODUCTION

Recent evolutions in wireless sensors that include from power harvesting to size reduction including their ability to run algorithms make more and more viable the idea of a world where wireless sensors dissemination could be an easy action consecutively to the decision of a structure instrumentation. Unfortunately, numerous overviews of Wireless Sensors Networks (WSN) [1] demonstrate that no single generic solution emerges in this domain [2].

Even if remarkable works try to converge to a generic approach of wireless sensors such as WINS platform [3] that provides a distributed network and Internet access to sensors or the TinyOS virtual system that aims at proposing a hardware abstraction level to implement an OS on 'any' wireless embedded sensor networks like done in [4], the first postulate of this article is to admit that most of WSN designs are, at this time, target application dependent.

The two main reasons that explain this situation are, first, the wide diversity of application fields (monitoring space, military application, traffic control, SHM, etc.) and the second is a structural reason: available and enabled technologies to design WSN are not enough mature to cover all monitoring needs in only one reproducible model.

Various parameters make a WSN more or less able to ensure the wished monitoring. The most often cited parameters whose influences are crucial in WSN design are: power consuming, ability to 'smart' processing, scalability, static or dynamic topology, synchronization, accuracy, lifetime, scope and range, cost and size.

On the basis of this remark, the goal of this article is to focus on a specific parameter: the need of time synchronization for wireless sensors nodes. From two examples that underline that synchronization need, a non-exhaustive review of typical solutions is presented, then our experience feedback about GPS solution is presented.

W.S.N. PARAMETERS - NEED OF SYNCHRONIZATION

Introduction

Another postulate could be: in SHM, the way instrumentation has to be designed is dictated by the structure itself. Well analyzing the needs and waited accuracy, the criticality of each parameter (ex.: distances between nodes) specify the design WSN solution.

If power consuming obviously appears as the most influential parameter, time synchronization parameter reveals new requirements that were forgiven in wired worlds. Structural Health Monitoring often implies measurements of numerous and various physical parameters from sensors on structures: vibration, temperature,

displacement, strain, localization, etc. Algorithms that ensure the health monitoring traditionally use the heterogeneous and numerous samples collected as inputs to detect or localize a default, an undesired event, dangerous tendencies, to fill statistical databases, etc. Thus, most of configurations require data to be compared and correlated. This need is much more obvious in cases where instrumentation is used for distributed task amongst sensor nodes or for control algorithms.

Example 1 : real-time Monitoring of cable anchoring



Figure 1. (A) Real-time monitoring of cable anchoring. (B) Distribution of 4 wireless sensors

In this SHM system, cable movements could approach a frequency of 30 Hz. Whished accuracy to make this system able to evaluate cable displacements impose each sensor a sampling frequency of 300 Hz. Then, at any moment “t”, each couple of wireless sensors “Si and Sj”, must has a time base such as $\| T_i - T_j \| \leq 3,3 \text{ ms}$.

Example 2 : wire-breaks in cable monitoring

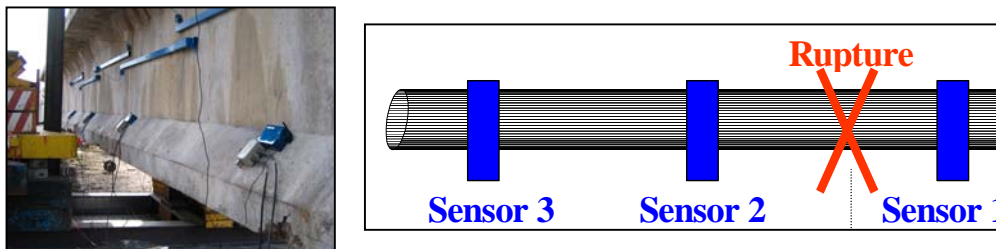


Figure 2. (A) Distribution of a WSN on a prestressed beam. (B) Synoptic

As detailed in [5], this SHM system localizes wire-breaks in cables by means of a WSN distribution that detect and record the acoustic wave caused by the rupture. Typical velocity of acoustic wave in steel cable is around 5000 m.s^{-1} . The whished precision to localize acoustic events is set at $\pm 0.15\text{m}$. This implies that each couple of sensor “Si and Sj”, must has a time base such as $\| T_i - T_j \| \leq 30 \mu\text{s}$!

REVIEW OF SOLUTIONS FOR W.S.N. SYNCHRONIZATION

The two examples above demonstrate, first, the need of synchronizing nodes in typical SHM configurations and how precise it could be ($1 \mu\text{s}$). If synchronization is a crucial aspect for wireless sensors design, this is because it is a very new challenge compared to the wired topologies where the philosophy is: at least one wire could be used to transmit a synchronization signal (for example, a server can sends a

periodical Dirac signal to all connected sensors). In wireless world, many approaches are evaluated and solutions are case-dependent. Synchronization methodologies can be sorted by 3 categories: Distributed synchronization, “Post-facto” synchronization and Sensor self synchronization.

Network topologies influence

Network topology is a consequence of the nodes and tasks distribution on the structure. But more than a simple organization, network topology has drastic consequences on synchronization. A description of typical network topologies are detailed in [1] and some are listed below:

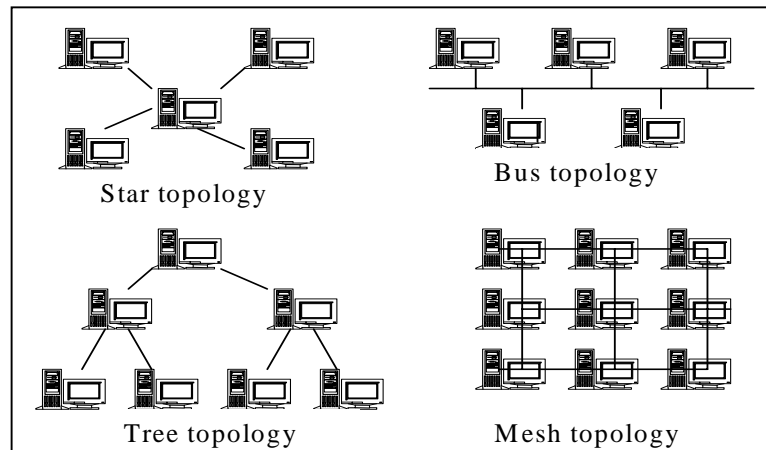


Figure 3. Four typical network topologies

There is no better way to save energy that wireless sensors spend most of their time in a sleep mode (from R.F. point of view). Figure 3 shows how influent the network topology is. In Star or Bus topologies, distributed synchronization is easiest to solve than in Tree or Mesh topologies where many nodes have to “wake up” at the same moment.

Distributed Synchronization

Distributed synchronization is the domain where most of approaches are developed or under review. They are more or less precise depending on their ability to take into account the drift of each node, latency time in the WSN, power efficiency.

The standard Network Time Protocol NTP [6] has been made for Internet network synchronization. It is based on the assumption that a precise master clock, hosted on a server (possibly connected to a GPS receiver), is distributed trough the network and it encapsulates appropriate exchanges. This protocol offers a synchronization that can reach $1 \mu\text{s}$ but, more a node is far located from the master clock and poorly synchronized the node will be; that is often the case in SHM. However, this protocol has been implemented on a WSN by J. Elson [7] and proved the efficiency of this protocol for Internet WSN. Accuracy up to $1 \mu\text{s}$ has been obtained for 10 close nodes. Even if many works –like those of Adam Dunkels - try to make the useful TCP/IP protocol viable for WSN [9], NTP must be precluded for

accurate wireless synchronization like detailed in [8] and [10]. Because of the energy constraint, NTP violates too many WSN assumptions: large use of CPU at each node, many transmissions and often listening to the network, need a continuous ability to transmit packets (no possible sleep-mode), the master clock must ‘see’ each node to maintain a synchronized system clock.

Reference-Broadcast Synchronization RBS [13] : when not synchronizing at application layer (ex.: NTP), but at physical (ex.: MAC) layers, RBS could be considered as the most representative in terms of mechanisms. It aims at providing instantaneous synchronization among a set of receivers that are within the reference broadcast of a transmitter perfectly time stamped. Nodes periodically send beacon messages to their neighbors using the networks physical-layer broadcast. RBS can provide [11] multi-hop synchronization between different broadcast domains. RBS provides a natural and precise way to synchronize a network with an external timescale. These techniques are widely applicable for a wide range of applications in both wired and wireless networks where a broadcast domain exists and higher-precision or lower energy synchronization is required. However, errors and delays as well as energy dissipation need to be studied and RBS requires a network with a physical broadcast channel.

Timing-sync Protocol for Sensor Networks TPSN [11]. This laboratory protocol aims at providing synchronization between two nodes at the moment packets are sent, at MAC layer. It has been implemented and tested on a small network of MOTES. If TPSN synchronizes a pair of nodes with an average accuracy of less than 20 μ s in the best case, it is based on similar methodology as NTP, where nodes are organized into multiple levels and synchronized to the root node of the hierarchy. But root node and nodes at different levels responsible for synchronization may fail often, which may cause synchronization problems. So this averaging method is probably not enough robust for long period and long distances of SHM configurations.

Time-Diffusion Protocol TDP [12]. TDP also belongs to the family of “broadcast protocols”. It allows the sensor network to reach an equilibrium time and maintains a small time deviation tolerance from the equilibrium time. TDP enables time in the network to converge. TDP can be used to provide timing precision that is gated by the round trip delays among neighbor nodes. The convergence to the equilibrium time depends heavily on the rate of timing information message diffusion. This allows the designer to trade-off between convergence time and energy consumption. By choosing different values for time parameters, accuracy can be fitted to the application accuracy. Precision in the order of ms can be obtained.

“Post-facto” Synchronization

Those methods are based -like described in [7] or [15]- on the principle: instead of trying to optimize the equilibrium between broadcasting periodical beacon in the network while keeping most of nodes turned off most of the time, this method voluntarily lets node clocks normally unsynchronized. When an event occurs, node records its local time, then it immediately listens to a “third party” node -acting as a beacon- that broadcasts a synchronization pulse to all nodes. Nodes that receive this

pulse use it as an instantaneous time reference and can normalize their stimulus timestamps with respect to that reference. This synchronization is dependent of the network topology (sensors must be in the scope of the beacon). The synchronization pulse is received through a non-deterministic channel that makes it inappropriate for long distances applications or for very accurate synchronization. However, its implementation could provide good results for accuracy in the order of ms.

SENSOR SELF SYNCHRONIZATION – FEEDBACK FROM THE ACCURATE GPS SOLUTION

A self-synchronized sensor is a node whose time-base is not provided by another node or server in the network. The most known method consists in using a GPS receiver at each node. Without use of GPS, considered solutions using specific transmitters and receivers face similar problems that those of distributed synchronization.

The main restriction is that GPS is not available inside buildings, under water or on mars. But, within the SHM scope, sensors able to receive GPS signals cover a sufficient range to be studied. GPS solutions are often forgotten for three main reasons [8] [10]: GPS receiver is often supposed to be an energy-hungry equipment, too much sized and too expensive. We argue that those three constraints are actually subject to very positive evolutions that force designers to reconsider integration of GPS receivers into sensors in many cases. As an example, the type of receiver we chose [14] for our platform has the following characteristics:

Low power : less than 86 mW (27 mA under 3.3 V)
Very little dimensions : 26 mm W * 26 mm L * 6 mm H
Less than 35\$ per unit (much less for large quantity)

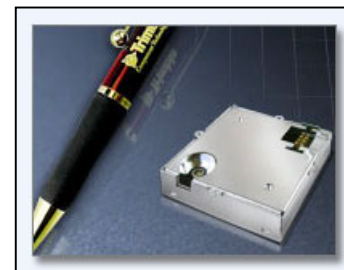


Figure 4. Characteristics of the chosen GPS receiver [14]

Implementation of the GPS synchronization

The solution is based on the property that each standard GPS receiver provides two interesting numerical information: a customizable sequence of bytes containing absolute time, localization and some other parameters, and, a synchronization TTL signal (i.e. a 0 or 1 signal) named PPS (Pulse Per Second) that has a period of 1s with a guaranteed accuracy of +/- 50 nanoseconds.

The solution consists in connecting the PPS signal to an input of the node processor that immediately interrupts its processes on PPS rising edge. On this high-level interruption, each processor node resets its time base counter.

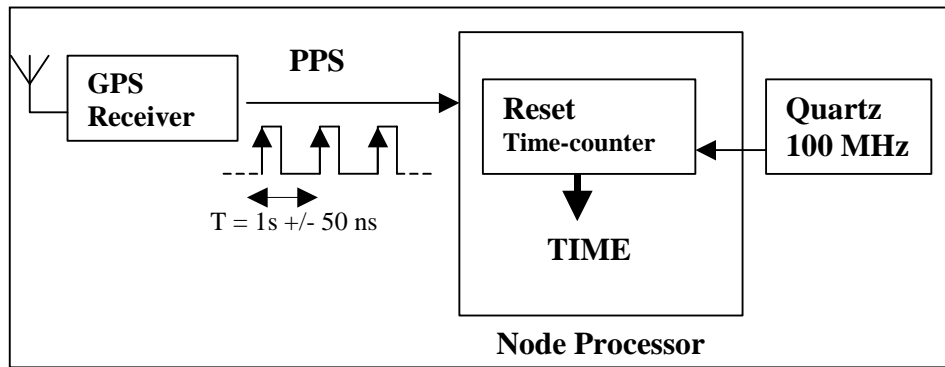


Figure 5. Synoptic of the GPS synchronization mode

Microprocessors time-base counter usually use the quartz as sequencer. As it is precisely reseted every 1 second, time counter is only affected by quartz drift (due to native design, age, temperature) during 1 second.

Results:

We chose a typical 100 MHz quartz whose drift is guaranteed to be less than 10 Parts Per Million (PPM). This means that if an event occurs just before 1 second, counter value could be equals to 100 000 000 quartz cycles +/-1000 quartz cycles so, in the worst case, time-stamping error is less that 10 μ s. Short term variations of quartzes during 1 second are negligible. In other words, a PPS synchronization cancels long dynamic effects such as temperature or age. Then, by precisely measuring the native quartz drift at design step and by setting this value as a parameter in time evaluation: sensor is able to correct time drift by itself.

In our case, for the 5 wireless sensors we designed, the same quartz drift has been measured as the 5 quartzes were produced in the same silicium series. This average value is equals to: 9700 quartz cycles for 100 000 000 quartz cycles. Then for any event "Ev" that occurs at a counter value "Ti", the real time stamping is programmed in the processor itself as follow :

$$Ti' = Ti * \frac{100000000}{100009700} \quad (1)$$

This simple correction provides a very good accuracy. In our WSN, each couple of sensor "Si and Sj", ensure a time stamping such that $\| Ti - Tj \| \leq 4 \mu$ s.

An SHM application:

Such a GPS synchronization mechanism has been deployed in our SHM application (cf. example n°2 above) made for wire-breaks localization in cable. The precision of 30 μ s was crucial to ensure a good localization and this application was successful enough to be subject to industrial transfers.

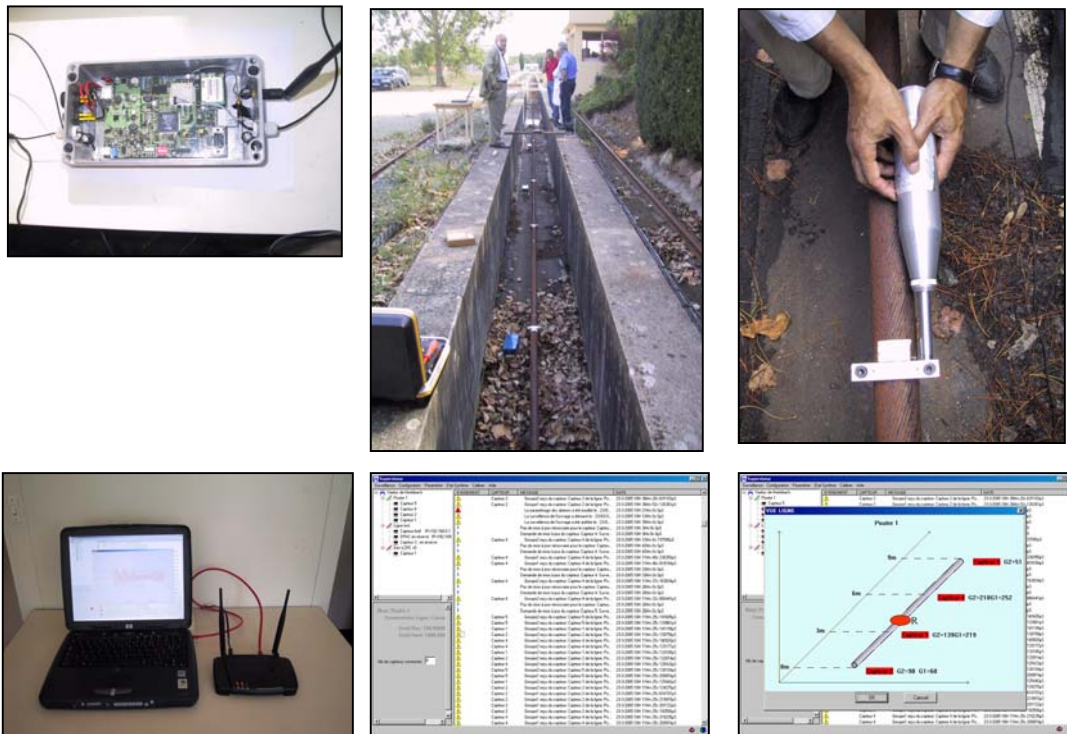


Figure 6. A) wireless sensor including GPS B) Installation on a real cable C) Rupture simulations D) Wireless supervision E) Software supervisor F) Accurate localizations

CONCLUSION :

This article gives a sensibilization to the wide diversity of problems in the new domain of Wireless Sensor Network that are as unlimited as SHM is. If power consuming seems to be the biggest challenge to solve, two SHM applications underline how the ability of time synchronization is a crucial parameter for an efficient design. Those examples and references below demonstrate that accuracy of $1\mu s$ between two nodes is often necessary.

If no generic WSN platform exists yet for each parameter (energy, size, cost, etc.) it is because no optimal solution emerges, at least, for time synchronization. It has been proven how this parameter depends on the network topology and how it could be influent on power consuming.

After a short review of typical network topologies, distributed synchronisation methods appears as the way where numerous development are done. In particular TPSN and TDP protocols open a tendency to a kind of promising synchronization where an equilibrium has to be find between accuracy and power-consuming.

Our solution consists in reconsidering the use of GPS in sensor because, thanks to recent evolutions (cost, size, power), this method is very accurate ($1\mu s$) and offers other advantages such as : independence from the network topology, density, states of neighbors nor other nodes failures. The complete time independence between two GPS-synchronized sensors means that the geographic span of nodes can be nearly infinite; contrary to distributed synchronizations where accuracy is linked to the

network area size. GPS also provide a precise sensor localization that can be useful in case of mobile instrumentations.

Future works will consist in optimizing time synchronization and energy consumption by adjusting the GPS module wake-up period to the the application needed accuracy. Because quartzes drift is negligible during short period, GPS module should be sleeping most of the time and provides a counter reset as seldom as possible. Moreover, this parameter could be modified dynamically during the monitoring phase, as a parameter sent by the supervisor.

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