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Multi-channel simultaneous data acquisition through a compressive sampling-based approach

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ABSTRACT

Nowadays, a variety of measurement applications require the acquisition and processing of signals coming from many disseminated sensors. To reduce the cost of the overall measurement process, the above-mentioned tasks are typically performed by devices like microcontrollers, low cost data acquisition systems (DASs), field gate programmable arrays (FPGAs), and so on. This is particularly true when smart-sensors or wireless sensor networks are considered. These devices are characterized by some limitations mainly concerning with the reduced internal memory and the use of multiplexing circuits to share the same analog to digital converter (ADC) over different physical channels. The former limitation affects the maximum observation time the devices are able to cover with a single shot acquisition, the latter imposes unwanted phase shifting on the acquired signals. The use of modern acquisition and processing techniques could be of some help. One of the most promising is the compressive sampling (CS), which can assure good signal reconstruction starting from very few acquired samples. To this aim, the paper deals with the definition, implementation and experimental characterization of a CS-based acquisition approach specifically addressed to cost-effective multi-channel DASs, like those characterizing typical 8 or 32-bit microcontrollers. In particular, the paper aims at showing the reliable phase reconstruction capability also in the presence of multiplexed multichannel architectures.

A number of tests conducted both on numerical and actual experiments are carried out to assess the performance of the proposed approach. In particular, the results obtained on real data acquired by means of the considered low-cost platforms shows the efficacy of the adopted approach; phase shift as low as few milliradians are, in fact, experienced.

1. Introduction

Many industrial, medical, life science and user applications nowadays rely on cost-effective smart sensors, usually included in wireless sensor networks (WSNs). Typical application examples refer to the smart metering for energy billing and efficiency [1–4], analysis and assessment of electrical power quality [5–8], survey and control of environmental quantities and pollutants [9–12], control and monitoring of complex production process [13–15], detection of life signs [16–18], to cite a few.

In most of the considered applications, the networks can be thought as the connection of wireless cost-effective and tiny nodes, which have to cooperate in order to

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perform measurement, processing, control and communication tasks. To better appreciate the meaning of concepts as "cost-effective" and "tiny", it has to be considered that the cost of each wireless node, involving sensing, data acquisition system (DAS), processing unit and radio communication blocks, has to be lower than few euros. To this aim, hardware platforms as low-cost microcontrollers, field programmable gate arrays (FPGAs) with a reduced number of gates, or cheap digital signal processors (DSPs) are frequently taken into account. All of them integrate most of the abovementioned blocks in a single chip allowing cost-effective realization of measurement nodes; however, they are generally characterized by limited hardware resources, in terms of internal memory depth and number of available analog-to-digital converters (ADCs). The considered platforms can, in fact, scarcely store more than few tens of kilobytes of data, and typically adopt multiplexers to share different physical channels over the same ADC.

To accomplish the measurement tasks, long time intervals are usually observed and, consequently, acquisition, storage and transmission of a great number of samples is involved; moreover, problems related to time base errors have to be taken into account [19], not to mention EMC issues presented by the acquisition system [20]. Unfortunately, the associated hardware requirements clash with the typical features of the considered platforms as well as with the "cost-effective" and "tiny" issues.

To face the considered problem, new acquisition and processing strategies, capable of reducing hardware requirements of the nodes and allowing reliable measurements to be carried out, have recently been proposed in literature. One of the most promising technique is the compressive sampling (CS) [20–22]. CS is an innovative paradigm of acquisition capable of assuring reliable signals and images reconstruction from a reduced and apparently insufficient number of samples. The innovative idea underlying the CS is the simultaneous execution both of acquisition and compression stages, thanks to the in-line acquisition of a reduced number of samples lower than that required by applying the Nyquist–Shannon rule. Thanks to its some attractive features, CS overcomes the limitation of the sampling theorem, without requiring no information about the signal of interest but its sparsity in a suitable orthonormal basis. This way, the application of CS drastically reduces the number of acquired, stored, processed and transmitted information data, making it reliable the adoption of the considered low-cost hardware platforms for the above-mentioned applications. CS is rapidly attracting interest in medical imaging research, with special regard to the Magnetic Resonance Imaging (MRI) and Computed Tomography (CT). MRI is an essential medical imaging tool with an inherently slow data acquisition process. As a matter that speed at which data can be collected is fundamentally limited by physical and physiological constraints. Therefore, many researches are seeking for methods to reduce the amount of acquired data without degrading the image quality [23]. Applying CS approach to medical imaging obtains scan time reductions with benefit for patient and increases reliability and rapidity of diagnosis.

However, it is often required that the measurement node simultaneously acquires a number of quantities (e.g. voltage and current acquisition for smart metering applications). This requirement cannot be met on most of the considered platforms, since, as stated above, they multiplex input physical channels to reduce the cost of the ADC section (i.e. one of the most expensive), thus allowing only sequential data acquisition to be performed. As a consequence, overall measurement performance is limited, because an unwanted phase displacement turns out to be imposed on the acquired signals. This phase shift is mainly due to the inter-channel delay the multiplexer spends to acquire two samples on different channels, and proves to be a deep constraint that typically reduces the applicability of low-cost measurement nodes.

Although many studies can be found in scientific literature concerning with the application of CS to measurement applications (in particular, to WSNs), the attention has been generally paid to aspect as memory management, energy consumption, and communication optimizations [24,25] or single channel implementation of acquisition strategies [26,27]. Examples of multi-channel DASs based on CS are also present in the literature [28]; however, most of them requires hardware modifications to be implemented. Finally, the effect of the CS on the phase shift of the acquired signals due to the inter-channel delay in multichannel platforms has to be yet deeply investigated.

Starting from their previous experience on data acquisition devices [12,29,30], cost-effective measurement systems, microcontroller based measurement systems and CS [31–33], the authors propose a novel acquisition approach, based on CS, capable of carrying out multichannel simultaneous data acquisition also through inherently sequential DASs. To this aim, the approach exploits a unique time-basis for all the input channels adopted, along with a compressive random sampling, in order to assure the reconstruction of desired signals without any artefact due to the inter-channel delay and/or sequential acquisition scheme.

In the following after a brief theoretical description of the CS technique, the architecture of the proposed CS-based acquisition approach is presented. Then, after some numerical results describing the inherent performance of the approach some experimental results on different hardware acquisition devices are proposed and discussed. Conclusions are finally drawn.

2. Theoretical background

In the following, some notes regarding sampling and compression theory as well as CS are given.

2.1. Fundamental of sampling and compression theory

Traditional sampling paradigm is based on the Nyquist–Shannon theorem to reliably recover a signal, an image or a video. In particular, to reconstruct a signal from a sequence of acquired samples, it is necessary that the signal is characterized by a finite bandwidth and it must be sampled with a frequency at least twice its bandwidth: