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Compressed Sensing Based Direct Conversion Receiver With Interference Reducing Sampling

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Abstract—This paper describes a direct conversion receiver applying compressed sensing with the objective to relax the analog filtering requirements seen in the traditional architecture. The analog filter is cumbersome in an Integrated Circuit (IC) design and relaxing its requirements is an advantage in terms of die area, performance and robustness of the receiver. The objective is met by a selection of sampling pattern matched to the prior knowledge of the frequency placement of the desired and interfering signals. A simple numerical example demonstrates the principle. The work is part of an ongoing research effort and the different project phases are explained.

I. INTRODUCTION

The Direct Conversion Receiver (DCR) architecture is the most widely used receiver architecture in mobile communication devices [1]. This is caused by a small analog part as well as reduced analog high quality filtering that causes financially expensive and power and area inefficient off-chip interconnects. Thus the DCR is suitable for IC implementation. Nevertheless, there is a trend in the development of mobile receivers to digitize even more of the receiver [1]. DCRs are normally implemented in Complementary Metal–Oxide Semiconductor (CMOS) which is excellent for digital designs but problematic for analog designs due to high substrate losses and tolerances making high-quality filtering very difficult if not impossible. Therefore, it is generally preferred to have architectures with reduced filtering demands and higher demands on the digital signal processing.

In a DCR the baseband signal(s) must be analog low-pass filtered due to possible adjacent channel interference signals and to avoid aliasing in the following Analog-to-Digital Conversion (ADC). The filter may also serve as partial channel selection filter jointly with a digital filter. If the analog filter does not significantly reduce the adjacent interfering signal it adds to the requirement of dynamic range and/or the sampling frequency of the ADC [2]. One possible solution to reducing the analog filtering requirements is to use the principles of compressed sensing [4] which allows signal acquisition with a sampling frequency lower that the Nyquist frequency of a signal and also allows usage of prior knowledge in the signal reconstruction. In this receiver case we may apply prior knowledge of the frequency location of the desired and adjacent interfering signals.

In [3] the authors of the present paper proposed a compressed sensing based DCR which uses e.g. prior knowledge in the signal reconstruction used in compressed sensing to relax the filtering requirements without significant increase in sampling frequency. The following sections present further work on this idea.

II. IRfDUCS PROJECT

Interference Reduction for Direct conversion receiver Using the Compressed Sensing (IRfDUCS) is a 3 year research project carried out at Aalborg University, Denmark.1 As illustrated in Fig. 2 the project consists of three phases: 1) numerical simulation; 2) hardware implementation; and 3) integrated circuit design.

Currently, the project is in the phase of numerical simulations. Two software packages are being developed during this phase:

1More information at: http://www.sparsesampling.com/interference2/pates.
The clock frequency can be lower than the Nyquist frequency by an amplifier, and sampled by a uniformly clocked ADC. The reconstructed signal is then given to a demodulation module as seen from Fig. 3. The proposed architecture allows for using relaxed lowpass filter requirements compared to a traditional DCR, without using a fast-clocked ADC. Unlike the previously proposed solution [3], the ADC is clocked uniformly. The requirements for the dynamic range of the ADC are relaxed – hence there is some tolerance for saturation of the signal. Instead, the architecture includes an AGC enabled amplifier combined with the compressed sensing signal reconstruction.

**RxCS**: Receiver simulation with emphasis on Compressed Sensing. This is a software system with a selection of radio signal generators, acquisition subsystems, signal reconstruction techniques and evaluation modules. The software is able to simulate receiver systems and compressed sensing systems based on behavioral models. It is the main tool used for numerical simulations in the project.

**PaTeS**: Patterns Testing System. This software is dedicated to generate and analyze sampling patterns. The most important part of the software performs a quality assessment of the compressed sensing reconstruction when using different sampling patterns.

The second phase of the project targets hardware implementation of the proposed architecture using Commercial Off-The Shelf (COTS) components. Programmable development platforms equipped with Field Programmable Gate Arrays (FPGAs) and Reduced Instruction Set Computing (RISC) devices are to be used in this phase.

In the third and last phase the developed system is planned to be designed as an IC using a dedicated development tool. The design is to be performed on schematic and layout level.

### III. System architecture

The proposed system architecture is presented in Fig. 3. The received radio signal is filtered by a relatively wide bandpass filter allowing passage of all relevant channels. Next, this signal is mixed with an Local Oscillator (LO) signal to form a down-converted signal and whatever undesired interfering signals that are also present after the bandpass filter. Normally a quadrature down-converter (quadrature-mixer) is used to extract in-phase and quadrature-phase signal components – in the presented architecture in Fig. 3 the signal extraction is done in the signal processing part. As seen from Fig. 4, the down-converted signal consists of a wanted signal (green band) and unwanted interfering signals which must be removed or at least significantly reduced (red bands). The signal is then filtered by a low-pass filter which only partially removes the interfering signals. The loosely-filtered baseband signal is then processed by an amplifier, and sampled by a uniformly clocked ADC. The clock frequency can be lower than the Nyquist frequency of the baseband signal. The amplification stage has Automatic Gain Control (AGC) functionality for signal conditioning.

The precise sampling scheme used in the compressed sensing signal reconstruction depends on several factors such as frequency band of the desired signal, frequencies of the interferers, sampling frequency etc. All this is pre-computed by the PaTeS software which makes the extensive signal condition analysis to allow the real-time processing to use the best possible sampling scheme. It is possible to adapt the scheme to Software Defined Radio (SDR) [5] compliance by having PaTeS run offline and downloading new data for the sampling scheme in case for example the bandwidth of the desired signal changes or similar. However, normally it is possible to pre-compute many scenarios but there is the possibility to update in case there are some special use-cases that are typical or to handle special situations. This updating is thus optional and provides an added bonus in case it is used.

The PaTeS software is able to define which strategy to apply in certain situations – for example if a sample should be removed if it allows decreasing the risk of ADC saturation or keep the sample if the signal reconstruction improves significantly by that. This is part of the compressed sensing technique where loosing a limited number of samples may be possible without severe effects on the reconstructed signal. The PaTeS system thus analyzes the conditions for the received signal and seeks to jointly optimise the reconstruction quality of the desired signal while relaxing the lowpass filter requirements. The reconstructed signal is then given to a demodulation module as seen from Fig. 3.

A numerical experiment was conducted to demonstrate the idea of the project. In the experiment a sampling pattern was

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**Fig. 2: Conducted experiment.**

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designed for a given desired and interfering signal constellation. A very simple case of a single tone was used for both the desired and the interfering signal. The frequencies were initially chosen as shown in Fig. 2 with \( f_B = 20 \) kHz. The sampling pattern was designed according to the setup shown in Fig. 2. Both frequencies were varied in increments of 5 kHz to see the effect of frequency changes. During the simulation the frequency of the desired frequency was swept from 5 kHz to 95 kHz – thus significantly above the maximum frequency for which the sampling pattern was generated. The purpose was to see the effect of violating the design constraint. The power spectral density of the signals is illustrated in Fig. 4.

Fig. 5 shows the probability of successful signal reconstruction of the wanted signal versus the frequency of the desired signal. As seen the signal is perfectly reconstructed for all frequencies up to the maximum design frequency of 20 kHz. When the frequency of the desired signal increases above the design frequency of 20 kHz the probability of correct signal reconstruction reduces as expected and above 55 kHz it is impossible to obtain correct reconstruction. This shows that the principle works and that the interference signal can be handled within the design constraint of the sampling pattern.

V. CONCLUSIONS

A modified DCR architecture allowing relaxed filtering requirements compared to a standard DCR has been presented. The proposed architecture was based on adapting the compressed sensing technique to utilize two aspects: 1) prior knowledge of frequency placement of the desired and interfering signals; and 2) selecting the sampling patterns according to the placement of the interfering signals. Combined the concepts allowed a compressed sensing formulation which was tailored to relax the analog filtering requirements while meeting the quality metrics for the reconstructed in-phase and quadrature-phase signals. A proof of concept has been demonstrated in a simple configuration and research is ongoing to further advance the technique.

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