



Digital compensation of lowpass filters imperfection in the Modulated Wideband Converter compressed sensing scheme for radio frequency monitoring

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ABSTRACT

This paper focuses on non-ideal filters in a Modulated Wideband Converter (MWC) scheme. The MWC is a system that can sample a sparse wideband signal at sub-Nyquist rate. Generally, the output of the ideal MWC components will ensure a perfect reconstruction. In practice, the reconstruction should be based on the output of non-ideal components, especially filters. The impact of non-ideal filters will trigger to a bad reconstruction. In this paper, a detailed study on non-ideal lowpass filters imperfection used in compressed sensing MWC scheme is synthesized. A digital post-treatment scheme with amplitude and phase compensation is proposed after real lowpass filtering step in order to have the filtered output as close as the ideal lowpass filter output. At last, reconstruction spectra obtained from different simulated lowpass filters are compared with different parameters of MWC.

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1. Introduction

In the context of wideband spectrum monitoring, efficient sampling has become a critical challenge due to the constraint of analog-to-digital sampling rate. In most of communications applications, the usual analog-to-digital sampling frequency is called Nyquist frequency since it follows the Nyquist–Shannon theorem. This theorem means that a real signal must be sampled at least twice the frequency of its bandwidth in order to be well-reconstructed [1,2]. However in the case of wideband spectrum, the Nyquist frequency will exceed the capability of the conventional analog-to-digital converter (ADC) such as in some spectrum sensing/detection applications. Moreover, the transmitted signals are unknown (blind spectrums) and there are only a few narrow bands presenting behind that wideband spectrum. Hence, the digital conversion of a wideband signal, which respects the Nyquist–Shannon theorem, will lead to an expensive cost, a waste of hardware resource, a high energy consumption and a very high computing cost for spectrum and/or signal reconstruction.

To deal with this critical challenge, uniform interleaved sampling scheme [3] and non-uniform interleaved sampling scheme [4] were introduced to reduce the sampling frequency by M times since they split the input signal to M channels and then sample each channel consecutively at a frequency M times lower with equal spacing delays (“uniform scheme”) or random delay (“non-uniform scheme”). However, the ADC bandwidth of each channel must already be greater or equal to the bandwidth of input signal. These two schemes allow to reduce the sampling frequency but not to overcome the problem of the input wideband signal. Recently, a sub-Nyquist sampling system called Modulated Wideband Converter (MWC) has been proposed in [5], which is based on Compressed Sensing technique [6,7]. This method allows the wideband signal to be converted at a sampling frequency that is much lower than the Nyquist frequency and where the ADC bandwidth is much lower than the input signal bandwidth too.

For wideband signal processing, the MWC system should be considered in two main steps: compressed signal acquisition and signal reconstruction. The compressed signal acquisition step consists firstly of an analog processing and followed by digital conversion. The second step is in charge at least of the input signal spectrum reconstruction or even of the signal itself. In theoretical point of view, all the analog components (mixers, filters, ADCs, etc.) of the MWC scheme are assumed to be ideal [8] for good reconstruction. However, in practice this hypothesis is not true, especially for

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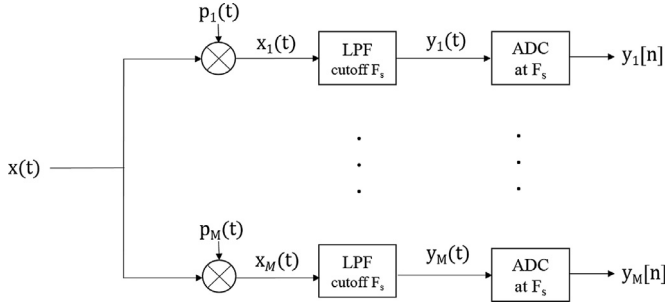


Fig. 1. The Modulated Wideband Converter (MWC) scheme.

filters whose imperfections are the subject of the study presented in this paper. In order to have a filtered output, which is considered to be close to the ideal one, a very high order of filter needs to be deployed. The implementation of such filter is very difficult; even impossible. Moreover, a real filter is neither flat in stopband nor passband. Therefore, its output would produce aliasing information that does not guarantee a perfect reconstruction.

A prototype of compressed sensing based on MWC is currently developed at our laboratory. Before implementing the real components, a study must be done to evaluate the impact of non-ideal filters on reconstruction. This problem has been already addressed in [9,10] and a processing methods based on Finite Impulse Response (FIR) filters have been proposed. The authors in [9] propose to moderately oversample the signal after filtering step. This method is applied in frequency domain, assuming that $H(f)$ is the real filter and $G(f)$ is the FIR filter. The FIR coefficients are obtained by minimizing the function $H(f) \times G(f)$ such that $H(f) \times G(f)$ respects the characteristics of an ideal filter. This paper proposes a method, which can be considered simple to implement in practice, because there is no optimization method to be needed as in [9,10]. It only requires the characterization of filter from spectrum analyzer and low computational cost.

This paper investigates in details the imperfections of low-pass filters which impact on spectrum reconstruction. To solve this problem of the lowpass filter imperfections, a different post-treatment method is proposed after filtering; to provide the output which is considered as close as an ideal filter. Moreover, the performances of the MWC reconstructions with this post-treatment method will be evaluated, based on the probabilities of good reconstruction and false alarms. A comparison between the MWC with post-treatment method and the traditional MWC is demonstrated in order to prove the efficiency of this post-treatment method.

This paper is organized as follows. Section 2 describes the principle of MWC system. In Section 3, some classical filters are compared and the impact of such kinds of filter on MWC output will be examined. Section 4 shows the post-treatment method after filtering step and the results of simulation.

Notations: The following notations are employed throughout the paper.

2. Modulated Wideband Converter

Fig. 1 shows the MWC scheme system with M physical parallel channels, where each channel is composed by one mixer, one lowpass filter (LPF) and one low rate ADC. Firstly, the mathematic equations of the system can be summarized as follows.

The signal $x(t)$ is split into M channels and then multiplied by mixing functions $p_i(t)$, for $1 \leq i \leq M$:

$$x_i(t) = p_i(t)x(t). \quad (1)$$

After that, each mixed signal $x_i(t)$ is filtered by the filter $h(t)$:

$$y_i(t) = (h * x_i)(t). \quad (2)$$

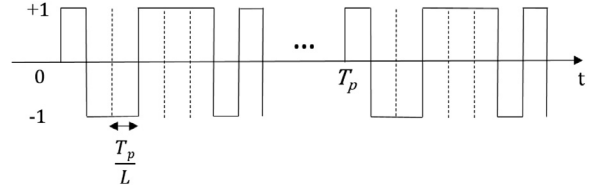


Fig. 2. Mixing function $p_i(t)$.

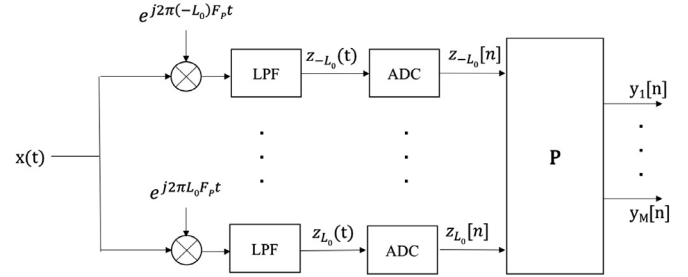


Fig. 3. Equivalent scheme of MWC.

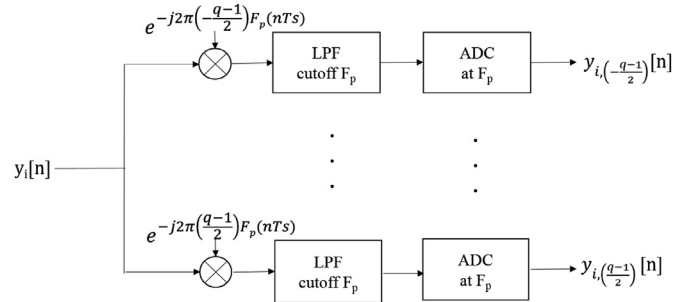


Fig. 4. The extension of number of MWC channels.

At the end, filtered signal $y_i(t)$ is sampled by an ADC at sampling frequency F_s :

$$y_i[n] = y_i(nT_s). \quad (3)$$

Going further in details of each component, at first, suppose that $p_i(t)$ is an arbitrary non periodic function. It leads to an infinite sequence output after mixing that cannot be managed. To solve this problem and make it easier, Mishali and Eldar have chosen $p_i(t)$ to be periodic [5]. With this assumption, there will be a finite output $x_i(t)$ at each channel. Moreover, to simplify, $p_i(t)$ is also set as a piecewise function with values in ± 1 , which is illustrated in Fig. 2.

The mixing function $p_i(t)$ is periodic with period T_p . Let us denote $F_p = 1/T_p$ being the frequency of periodic waveform $p_i(t)$ and L being the periodic mixing sequence length where $L = F_{nyq}/F_p$, which is the ratio between the bandwidth and frequency of mixing function. Under the aforementioned hypothesis, the MWC system can be represented by an equivalent scheme [8,11] as in Fig. 3. Regarding this equivalent scheme, the system equation defined by Eq. (3) can be written in the following way:

$$\bar{y}[n] = \mathbf{P}\bar{z}[n], \quad (4)$$

where $\bar{y}[n]$ is the vector representation of M outputs of MWC system, $\mathbf{P}$ is a $M \times L$ sensing matrix and $\bar{z}[n]$ is the vector representation of L internal channels $z_k[n]$ of the equivalent model. Each internal channel signal $z_k[n]$ with $k \in [-L_0; L_0]$, with $L_0 = \frac{L-1}{2}$, was obtained by firstly shifting the input signal spectrum by a multiple of F_p followed by lowpass filtering and digital conversion at sampling frequency F_s .

This MWC equivalent scheme allows us to simplify the reconstruction step of the signal providing that the sensing matrix $\mathbf{P}$ is

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