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Narrowband Digital Filtering With Random Frequency Hopping Spread Spectrum

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Abstract—In digital signal filtering, channels with narrow bandwidth need high order digital filter to be selected without introducing modulation errors. If a carrier randomly switches from a channel to another as in military applications, or some civilian communication standards, it is necessary to detect and estimate these jumps before transposing and analyzing signals in the baseband. This paper presents a real time solution to filter narrow band signals with random frequency hopping spread spectrum. The proposed method is based on three steps. Firstly, the detection of Signal Frequency Hopping (SFH) using the Fast Fourier Transform (FFT), an algorithm to estimate the Dominant Frequency Value (DFV) is developed, it is necessary for better refining the original detection, in particular, with modulated signals. Secondly, the estimated frequency value is scaled and used with a Numerically Controlled Oscillator (NCO) in order shift the interest channel to baseband. Thirdly, the transposed channel in base band is selected using low pass Finite Impulse Response (FIR) filters. Whereas, the multi rate filtering techniques guarantee the high selectivity and low orders of these FIR filters. Each of the following stages is described in detail later in this paper, synthesizing these steps leads to the proposed solution, that is validated by using GSM signals. The algorithms are implemented in Field Programmable Gate Array (FPGA) Altera Cyclone III family.

Index Terms—Frequency hopping, narrow band filtering, GSM modulation, High selectivity, FPGA resources.

I. INTRODUCTION

The spread spectrum technique was restricted for a long time to the military domain, it is now used in more and more non-military applications. It is also proposed as basic techniques for many future digital communication systems [1].

Spread spectrum differs from a classical narrow band or broadband systems in that the signal energy is spread over a much wider frequency range, reducing the power spectral density of the signal and providing several advantages.

Spread spectrum signals are difficult to intercept. A spread-spectrum signal may simply appear as an increase in the background noise to a narrow band receiver. An eavesdropper may have difficulty intercepting a transmission in real time if the random sequence is not known.

Spread-spectrum transmissions can share a frequency band with many types of conventional transmissions with minimal interference. This means the possibility of Code Division Multiple Access (CDMA) operation [2].

Frequency Hopping Spread Spectrum (FHSS) is a method of transmitting radio signals by jumping a carrier among many frequency channels, using a pseudo-random sequence known to both transmitter and receiver.

For example, GSM standard uses FHSS method to transmit radio signal among two or more channels depending on the Base Transceiver Station (BTS) capacity. In some situation, operators need to analyze and control the communication traffic of a given BTS, to attenuate or to eliminate some channels for example. For detection and estimation of FHSS, multiple methods based on FFT have been proposed in the literature [3, 4]. Other methods using wavelet transform and compressive sensing have been discussed in [5, 6]. Each of these methods has its advantages and disadvantages about algorithms speed, precision, FHSS parameters (time to hop, frequency of hop). In the context of real time constraints with limited FPGA resources the most appropriate solution is based on FFT algorithm, because it is easier to implement and it has an acceptable computation time.

Furthermore, controlling NCO needs to have the scaled DFV, for that purpose we merely represent the signal in frequency domain, with an additional algorithm to decide on the presence of a signal according to a given selection criterion. It is also possible to used other FHSS detection techniques, such as wavelet or compressive sensing, to elaborate the proposed solution, nevertheless using these algorithms need additional FPGA resources.

This paper discusses an efficient method for detecting and filtering modulated carriers with FHSS. Firstly, the method is developed for single channel with FHSS, after that, the model is generalized to several channels. An example of 3 channels with FHSS is illustrated in the experimental section.

II. FREQUENCY HOPPING DETECTION AND ESTIMATION

The Fourier transform is a well-established theory, it is not discussed in this work. Nevertheless, it may be useful for us to consider some of the essentials of FFT which is simply an algorithm (i.e. a particular method of performing a series of computations) that can compute the discrete Fourier transform much more rapidly than other available algorithms [7]. Here some FFT parameter definition.

- FFT length :it is the number of samples applied to the algorithm, it is a power-of-two; 1024 points unless otherwise specified. It is noted N_{FFT} .
- Window function :also known as an apodization function or tapering function, is a mathematical function that is zero-valued outside of any chosen interval used to improve FFT performance. It is noted w . Many formulas of window exist, we discuss some of them later in this section.
- Frequency resolution :it is defined as the ratio of frequency sampling (f_s) and the FFT length. It is noted δf such as

$$\delta f = \frac{f_s}{N_{FFT}}. \quad (1)$$

Here,

$$\delta f = \frac{100}{1024} = 0.09765625 \text{ MHz}. \quad (2)$$

According to frequency resolution and window function the FFT result is altered by errors. These errors are around 1 dB (best case) to 4 dB (worst case) as shown in Fig. 1. Note that, for frequencies whose value is multiple of δf ($\delta f = 97.6562$ KHz), errors are zeros.

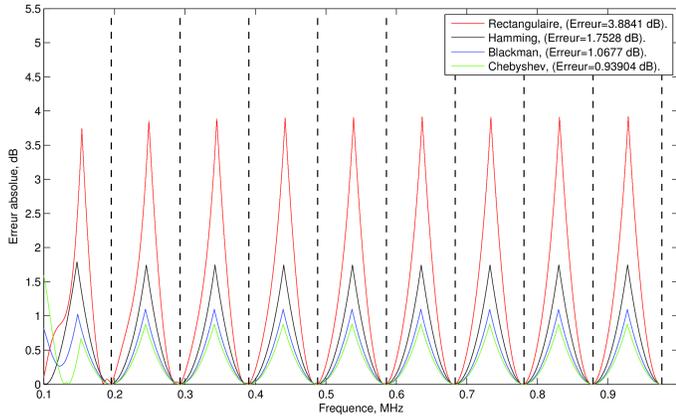


Fig. 1. Estimation of approximation errors with different windows, $N=1024$ points.

Fig. 1 is obtained by sweeping non-modulated carrier frequency from 0.1 MHz to 1 MHz and measuring the difference between the expected maximum of power spectrum density and the actual maximum of PSD. As shown in the legend, mean errors of peaks for rectangular window is the highest (3.8841 dB), while the minimum is given by Chebyshev window (0.9304 dB). For this reason, Chebyshev window will be used.

The incoming signal is digitized with an Analog to Digital Converter (ADC), the digital signal (data) is converted to an analog signal with a Digital to Analog Converter (DAC). Both ADC and DAC have a 16-bit bus width. This allows to detect weak signals (-80 dBm) and high level signals (-10 dBm). Thus the signal magnitude range is 70 dB. This means that the developed method works for far BTS/Mobile Station (MS) and near BTS/MS.

Here, the used FFT algorithm is provided by Altera FFT MegaCore that is configurable with Megawizard. An algorithm called Discretization Algorithm (DA) is developed to be used with FFT for detecting signals, DA refines the obtained to calculate the exact DFV. DA allows to "distinguish" between channels with different powers, even in the presence of frequency overlapping between modulated carriers. The DA uses some knowledge about signal information (channels spacing, neighbor, etc; with GSM for example).

III. FREQUENCY TRANSPOSITION

Once the frequency carrier is estimated using FFT and DA, the signal is transposed to the base band range. In this context, transposing frequency to the base band domain has two main advantages, it allows multi-rate processing (down-sampling, up-sampling) to use merely low pass filters with low order instead of high order band-pass filters. To this end, NCO is used, it offers several advantages over other types of oscillators in terms of agility, accuracy, stability and reliability.

The Altera MegaCore function generates NCOs customized for Altera devices. The IP Toolbench interface is used to implement a variety of NCO architectures, including ROM-based, CORDIC-based, and multiplier-based once.

The generated output frequency, f_{NCO} for a given phase increment, Φ_{inc} is determined by the following equation

$$f_{NCO} = \frac{f_s \Phi_{inc}}{2^B} \text{ Hz}, \quad (3)$$

where B is the accumulator precision and f_s is the frequency sampling.

The frequency accuracy relative to the clock frequency is limited only by the precision of the arithmetic used to compute the phase. The frequency resolution (δf_{NCO}), defined as the smallest possible incremental change in frequency is given by

$$\delta f_{NCO} = \frac{f_s}{2^B} \text{ Hz}. \quad (4)$$

In this work, the following parameters are used $f_s = 100$ MHz and $M = 18$ bits.

The spread spectrum range is 10 MHz (20 to 30 MHz, chosen as an example). Consequently the maximum of baseband range is 10 MHz (if the interest channel is the edge of the spread spectrum, i.e, 20 MHz or 30 MHz), the minimum is 5 MHz (if the interest channel is the middle of the range, i.e, 25 MHz). DA scales the FFT frequencies to NCO phase increment.

The major disadvantages of frequency mixing is the problem of image frequencies that are given by

$$f_{img} = \begin{cases} f + 2f_{NCO}, & f_{NCO} > f \text{ (high side injection)} \\ f - 2f_{NCO}, & f_{NCO} < f \text{ (low side injection)}. \end{cases} \quad (5)$$

In fact, these frequencies image are mixed with the signal when down-sampling.

To suppress these unwanted signals, one of the most known methods is image-rejection (or image-suppress) [8, 9]. These

methods cannot be used in this context because of the randomness of FHSP. Other methods may be used, such as I/Q image rejection [10]. This method has the advantage to suppress image regardless the randomness of FHSS, it is illustrated in Fig. 4.

IV. MULTI-RATE PROCESSING

Transposing frequency to baseband range allows an efficient multi-rate processing. By reducing sampling rate called down-sampling (over-sampling). Finite Impulse Response (FIR) filters with high selectivity (high order) can be realized with fewer FPGA logic elements. Designed FIR with single sampling rate requires significant FPGA resources to have high selectivity.

The multi-rate techniques are used to convert the given sampling rate to the desired sampling rate, and to provide different sampling rates through the system without destroying the signal components of interest. Two discrete signals with different sampling rates can be used to convey the same information [11].

The down-sampling operation with a down-sampling factor M , where M is a positive integer, power-of-two, is implemented by discharging $M - 1$ consecutive samples and retaining every M^{th} sample.

The up-sampling by an integer factor L is performed by inserting $L - 1$ zeros between two consecutive samples, where L is a positive integer, power-of-two.

The drawback of the down-sampling is the aliasing effect, whereas the up-sampling produces the unwanted spectra in the frequency band of interest.

In this work, Spread spectrum W is equal to 10 MHz, theoretically, this means that the down-sampling factor M must be less than 5, because of the Nyquist-Shannon condition

$$\frac{f_s}{M} \leq 2W \Rightarrow M \leq \frac{f_s}{2W} \leq \frac{100}{20} = 5. \quad (6)$$

However, here we allow spectrum overlapping up to the limit of an uncorrupted bandwidth U that must be larger than the half of interest channel bandwidth w .

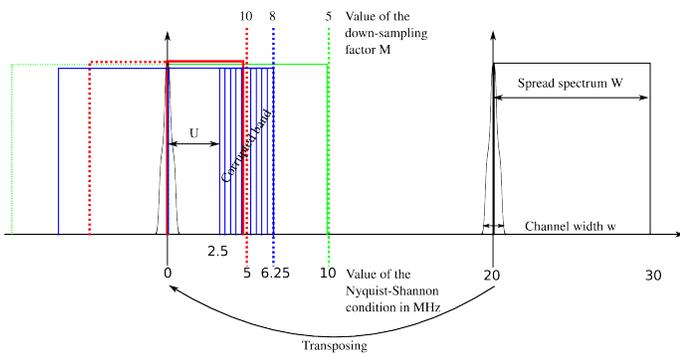


Fig. 2. Transposing a single channel to base band with spectrum overlapping.

In Fig. 2, if :

- $M = 5$, Nyquist-Shannon condition is satisfied; no spectrum overlapping, then $U = W \gg w$.

- $M = 8$, Nyquist-Shannon condition is not satisfied; partial spectrum overlapping, then

$$U = \frac{f_s}{M} - W = \frac{100}{8} - 10 = 2.5 > w. \quad (7)$$

Thus, the interest channel is not corrupted.

- $M = 10$, Nyquist-Shannon condition is not satisfied; full spectrum overlapping, all the bandwidth is corrupted.

Hence, the down-sampling factor M for which the down-sampling is optimum without corrupting the signal is $M = 8$. As mentioned above, up-sampling operation creates aliasing, because of the zeros inserting. These aliases can be removed by the FIR low pass filter. The idea is to up-sampling 2 by 2 instead of 8 in such way that the cascaded FIR filters are clocked by different sampling rates ($f_s/4$, $f_s/2$ and f_s). It is better in hardware implementation because basic operations (multiplication, addition, etc) are done four times, two times faster. Furthermore, FIR filters are low order.

V. MULTI-CHANNEL FILTERING

As explained previously, the solution of narrow band digital filtering with random frequency hopping spread spectrum is the synthesis of three steps. Now, let us explain the mechanism, starting with single path of channel filtering, as shown in Fig. 3.

- (1) Input frequency transposing; intermediate frequency to base band frequency. The FIR filter (low order, $N_{FIR} = 8$) attenuates the unwanted frequency image ($f + f_{NCO}$).
- (2) Down-sampling (by 8 in this example), the Nyquist-Shannon condition is $(100/8)/2 = 6.25$ MHz. Overlapping is allowed without corrupting 0 to 2.5 MHz band, (cf : Fig. 2).
- (3) High selectivity FIR filter with low order. It processes the interest channel (attenuation, amplification).
- (4) Up-sampling 2 by 2 with FIR filters that are clocked at different frequency sampling, for saving FPGA resources.
- (5) Output frequency transposing (baseband to FI), the image is suppressed by I/Q technique.

Cascading these blocks constitutes the filtering path I.

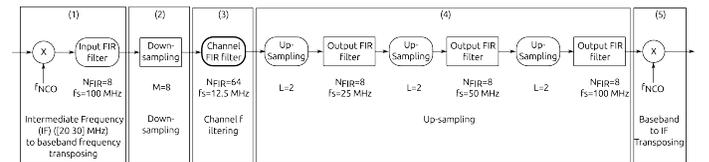


Fig. 3. I path channel filtering.

In Fig. 4, the signal is split to I and Q signal. After filtering, the sum of I and Q signals gives the filtered single signal. The unwanted image frequencies are removed by summing. I and Q paths together form the single channel filter.

In Fig. 5, the parallel adding of several channel filters gives a n-channels filter.

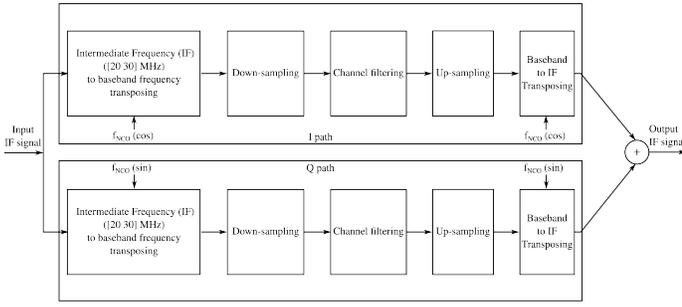


Fig. 4. Single channel filter.

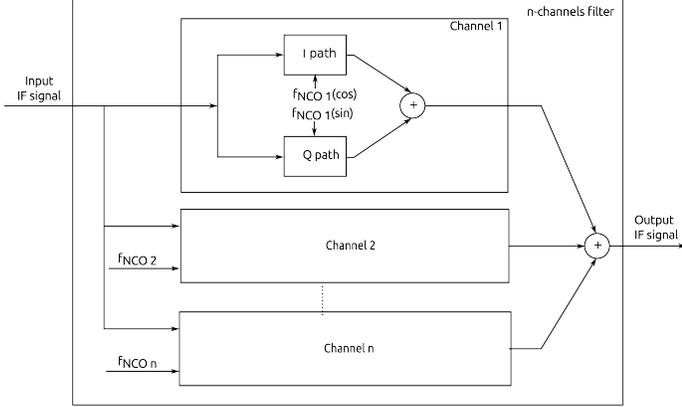


Fig. 5. n-channels filter.

Finally, in Fig. 6, FFT with DA provides Φ_{inc} values to the NCOs block, then NCOs generate corresponding frequencies to shift channels in the n-channels filter.

VI. SELECTIVITY AND EFFICIENCY MEASURES

In this part, the proposed solution has been tested with GSM signal; i.e GMSK modulation with frequency hopping, provided by an Agilent E4438C ESG generator.

This solution remains valid under Time Division Multiple Access (TDMA).

Fig. 7 represents narrow band FIR filter with FHSS, The center frequency of this filter is controlled in real time by the detected frequency. According to this figure, rejections are

- 3.6 dB of rejection at 100 KHz
- 9.9 dB of rejection at 200 KHz.
- 35.9 dB of rejection at 400 KHz.

The FPGA resources to implement this filter are less than 5% of the whole FPGA resources. Without frequency trans-

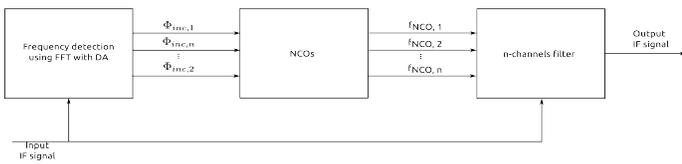


Fig. 6. n channel filtering with FHSS detection.

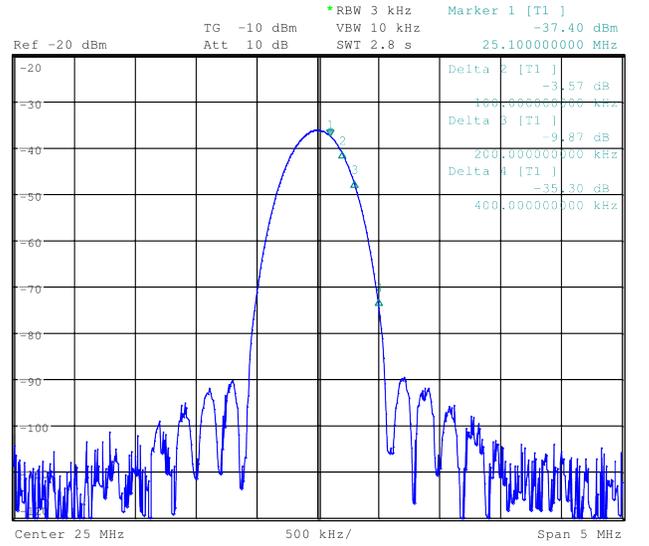


Fig. 7. Single channel FIR filter with FHSS.

position and multi-rate processing, the same filter would have required more than 95% of the whole FPGA resources.

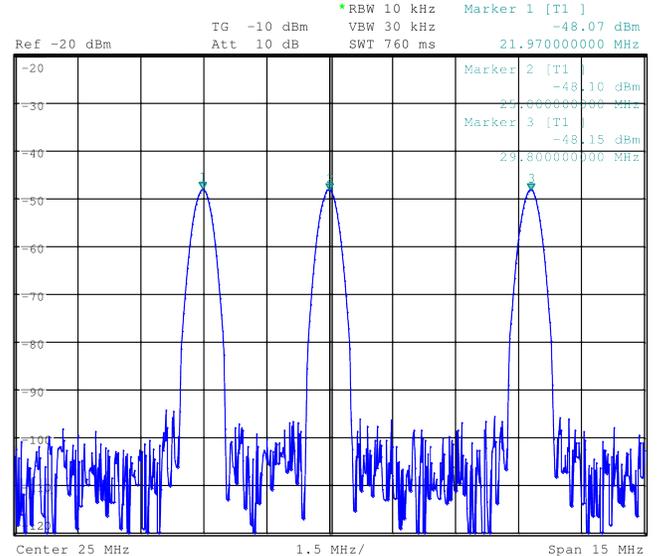


Fig. 8. 3-channels FIR filter with FHSS.

As explained previously, the single channel model can be generalized to several channels. The processing of channel is simultaneously performed. Fig. 8 shows a spectrum scope of 3-channel filter with FHSS. It should be noted that several channel models need an additional FPGA resources. In this example, FPGA resources are about 15%.

Saving FPGA resource percentage $FPGA_{sav}$ is expressed by

$$FPGA_{sav} = +100 \left(\frac{M-1}{M} \right) \%. \quad (8)$$

According to this expression, the higher is the down-

sampling factor M , more the hardware resources are saved. However multi-rate processing would require more FIR filters to eliminate aliasing when up-sampling. A compromise has therefore to be found between multi-rate factors and hardware resources.

VII. CONCLUSION

In this paper, we have proposed a method to select channels under random frequency hopping spread spectrum constraints with high selectivity, by combining three techniques (frequency detection, frequency transposition, multi-rate filtering). Hardware resources are saved by using multi-rate filtering. This method is implemented on a low cost FPGA, the efficiency has been approved with the GSM signal in real time conditions.

This solution can be applied in various fields, for example with GSM signals to filter channels without demodulating, for equalization of power between near and far MS/BTS. It can also be used to eliminate unwanted spurious which may be present in the spread spectrum because of the signal processing operations or interferences.

For both modulated and or non modulated carriers, this technique remains valid. It detects weak signals (-80 dBm) and strong signals (-10 dBm) with speed frequency hopping (0.5 ms) with a single and three channels simultaneously. These

performances can be extended for more channels by using high-quality FPGA.

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