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Polyphase Channelizer as Bandpass Filters in Multi-Standard Software Defined Radios

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***Abstract*—The aim of this work is to design efficient bandpass filters for multistandard software defined radios. Software Defined Radio (SDR) based applications which demand high sampling rate to eleminate the most of the analog components require high-performance technology and digital signal processing methods to handle and process the high sample rate data. State of the art technology such as FPGAs can support several hundred MHz of I/O data transfer rate. The internal hardware architecture, however, would limit the maximum operating frequency of the design. An alternative is therefore to use advanced DSP methods to overcome this bottleneck. Polyphase channelizers having spectral shifter to move the filter position are used in a scenario of dual standard (WLAN and UMTS) SDR receiver for the bandpass filtering. It will not only split the data in multiple paths to reduce the per arm data rate but the filter also operates at lower rate than the input sample frequency. Furthermore it can also eleminate the need of IQ demodulator.**

I. Introduction

A Software-Defined Radio (SDR) system is a wireless communication system which ideally can tune to any frequency band and receive any modulation scheme by means of various functionalities implemented in software and/or programmable hardware. SDR is an enabling technology for future radio transceivers, allowing the realisation of multi-mode, multi-band, and reconfigurable base stations and terminals. However, considerable research efforts and breakthroughs in technology are required before the ideal software radio can be realised. An ideal software radio (ISR) samples the signal at Radio Frequency (RF), just after the antenna, whereas the realizable version of the software radio is the one where the analog to digital conversion takes place after the first intermediate frequency (IF).

Recent developments and increasing trends toward a single device integrating several features and capabilities encourage the companies and research centers to develop portable multi-standard multi-mode "all-in-one" front-ends. High level of integration and small size are precedence objectives in these types of mobile applications. In order to acheive those objectives it is feasible to move most of the data processing to the digital domain through shifting the analog to digital converter (ADC) as close to the antenna as possible [1]. This imposes more stringent performance requirements on the analog-to-digital (A/D) conversion, where a high dynamic range must be combined with a high sampling rate [2].

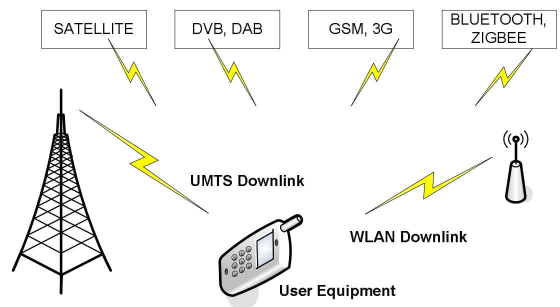

Fig. 1. A scenario of multi-standard "all-in-one" front-ends user equipment. It highlights the user equipment capable of receiving two standards i.e.UMTS and WLAN.

A scenario of a general multi-standard is shown in Fig. 1. This scenario in our work has been scaled down to the UMTS and WLAN standards [1] which actually fits to the mobile application. The RF spectral location for UMTS and WLAN standards are shown in Fig. 2. UMTS has a bandwidth of 60MHz for downlink with 12 channels and WLAN has 84.5MHz of bandwidth with 3 non-overlapped channels. It is required to down-sample and down-convert these channels to baseband.

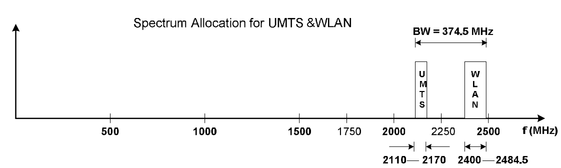

Fig. 2. Spectrum allocation for UMTS and WLAN standards. UMTS has a bandwidth of 60MHz for downlink having 12 channels and WLAN has a 84.5MHz of bandwidth having 3 non-overlapped channels.

Bandpass sampling and direct conversion are the two receiver architectures that are suitable for the software radios [6]. The sampling of bandpass signals can be carried out at rates significantly lower than the conventional lowpass Nyquist sampling, causing intentional aliasing of the signal. Bandpass sampling can allow received signals to be digitized closer to the antenna using manageable sampling rates and hence could be favourable for down-conversion in the software radios.

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II. System Design

The combined band of WLAN and UMTS is under-sampled at 630MHz which results in overlapped aliases, but the individual bands of UMTS and WLAN are non-overlapped. WLAN band aliases to 36-120MHz and UMTS aliases to 220-280MHz in the Nyquist zone. WLAN band is spectrally inverted. Bandpass sampling aliases are shown in Fig 3.

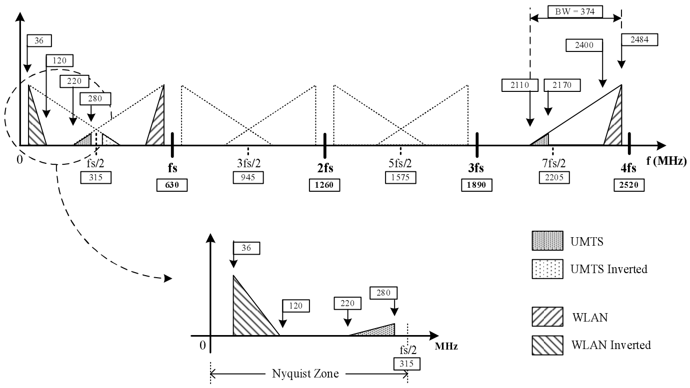

Fig. 3. The combined band of UMTS and WLAN is undersampled at 630MHz, and the aliased signals are shown in the Nyquist zones. The aliases are overlapped but individual UMTS and WLAN bands are non-overlapped. WLAN alias is spectrally inverted in the Nyquist zone.

In order to extract the individual channels of UMTS and WLAN standards to baseband with the desired output sample rate, channelizers are required. There are different types of channelizers being per-channel approachws, pipeline frequency transforms and polyphase channelizers [4]. Polyphase channelizers are the most efficient interms of computations and required hardware resources as compared to the other channelizers [4]. Based on the unique features of the polyphase channelizer, we have choosen this concept to implement the system design. The relation between the sampling frequency, channel spacing and number of channels for the polyphase channelizer is [7]:

$$f_s = N \cdot \Delta f \tag{1}$$

where f_s is the input sampling frequency, N is the number of channels (i.e., transform size) and Δf is the inter-channel spacing. There are two constraints that have to be met; one is that N should be an integer, and the second is that the channels to be down-sampled and down-converted to baseband should be centered onto the multiples of the channel spacing.

The block diagram of the system design [5] having a sampling frequency of 630MHz is shown in Fig. 4. The selection of the sampling frequency is an iterative process that requires the conditions of non-overlap aliases and polyphase channelizer constraints to be fulfilled. The block diagram shows a dual-standard system, sampling at 630MHz and using bandpass filters to separate the two standards before channelization. In order to reduce the computational workload of the polyphase filters, the incoming complex signals from the bandpass filters are down-sampled by possible large factors such that the sampling frequency of the re-sampled signals is above the signal's bandwidth.

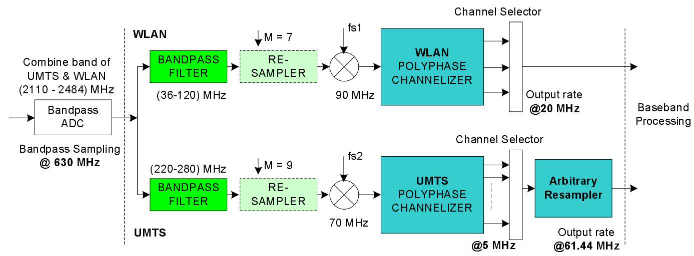

Fig. 4. System block diagram having spectrum translation prior to UMTS and WLAN channelizers. UMTS channelizer is followed by Arbitrary Resampler to achive the target rate of 61.44MHz [5].

In an SDR receiver chain, after the ADC we need to have IQ demodulators to have quadrature signals needed to perform the filtering task on complex data. The well known methods for IQ demodulations are quadrature mixer which is known as Digital Down Converter (DDC), complex filtering and hilbert transform methods [10]. Irrespective of their performance characteristics, in all of these cases multipliers operate and deliver the output at the same rate as the input. SDR based applications demand high sampling rates to eleminate most of the analog components. It will require not only the technology advancements but especially the advanced signal processing methods to handle and efficiently process the high sample rate data with the current technology.

This paper will focus on the bandpass filters used in a multi-standard system design [5]. High sampling rate at the input leads to the problems of complicated ADC-FPGA interfaces, and the design of bandpass filters which should operate at high rate. These problems can be solved by splitting the data stream in multiple paths and feeding the data to the polyphase channelizer. The splitted data drives the commutator (a rotatary switch distributing the data among the various arm (sub-filter) in the polyphase filter) of the polyphase channelizer [9] and reduces the per-arm data rate. The next task is to design the polyphase prototype filter to extract the band of channels (standards) rather than single channels. It will be helpful in two folds. First, we do not need to have an IQ demodulator at the input which is the high frequency end. Second, the bandpass filter operates at a low frequency due to the down-sampling at the commutator which further can be configured to deliver the required output sample rate by using embedded resampling (an efficient technique to resample the data in the polyphase arms rather than using separate P/Q resamplers).

A channelizer described in [8] gives a proof-of-concept implementation, operating at a 1.6GHz input signal. The input signal is splitted in parallel paths, lowering the per-arm frequency and then fed to the polyphase channelizer. The high speed demands of 1.6GHz channelizer are efficiently satisfied using the Xilinx Virtex-4 FPGA by using the DSP48 blocks capable of operating at 500MHz [11]. The input signal is quickly fanned-out to 16 synchronized and parallel paths, effectively reducing the individual path rates. In this case the polyphase channelizer is efficiently used at the high input sampling rate, extracting the individual channels. We will extend its use to act as bandpass filter having the same characteristics in terms of the low operating frequency and splitted data paths. Refering to the multi-standard system design whose block diagram is shown in Fig. 4. The system uses the undersampling technique and aliases down the combined spectrum of UMTS and WLAN, resulting in overlapped aliases but the individual bands of UMTS and WLAN are still non-overlapped. The channel bandwidth of both standards is different thus requiring separate channelizers. Therefore it requires bandpass filters to separate the standards before the channelizers as shown in Fig. 4.

For a polyphase channelizer to act as a bandpass filter, we follow the same proceedure, i.e., split the frequency spectrum in equal spectral bins and try to choose a factor N that meets the $fs = N \cdot \Delta f$ requirements in terms of the channel spectral allocation and non-overlapped channels. Furthermore, the polyphase channelizer can be used in its variant mode where the channels' bin can be shifted by multiples of quarter of the channel spacing [9] in order to have a better channel filtering operation. The filter requirements for UMTS and WLAN standards are shown in Fig. 5.

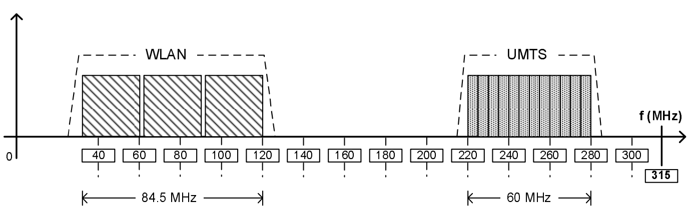

Fig. 5. Bands of WLAN and UMTS having 3 and 12 channels respectively. WLAN and UMTS bands are (36-120)MHz and (220-260)MHz respectively.

Designing the prototype filter for the polyphase channelizer to act as a bandpass filter is an iterative task which needs to satisfy both the standard's channel widths. Case A: In the standard polyphase channelizer the prototype baseband filter can not comply to the requirements because no value of N delivers the appropriate spectral bins for UMTS and WLAN channel bandwidths. Case B: The variant of the polyphase channelizer [9] which accomodates the spectral shift of multiples of quarter of the channel spacing, may result in a useful solution. The variant polyphase channelizer can also accomodate the spectral shifts other than the multiples of quarter of the channel spacing, but it results in complex multiplier operations in the sub-filters and therefore demands more resources. The prototype filter designed for WLAN can also cover the specifications of UMTS because the bandwidth of 84MHz can accomodate the bandwidth of 60MHz. Now, aiming at meeting the constraint of Eq. 1, Δf is choosen as 90MHz which will cover both 84MHz and 60MHz bandwidths and satisfy the N which turns out to be 7. The filter spectral locations are shown in Fig. 6

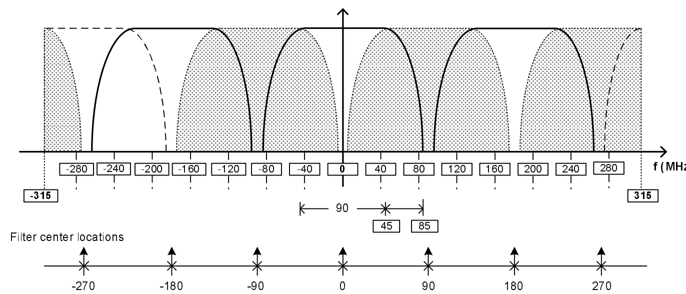

Fig. 6. Prototype baseband filter for the polyphase channelizer illustrating its spectral location in other channels' bin.

The prototype filter is designed with the 'firls' method (in MatLab) having the transition widths as [0 45 85 315] as shown in Fig. 6. The passband ripples and stopband attenuation are 0.1 dB and 60 dB respectively. It results in a 42 taps prototype filter which are partitioned into 7 sub-filters (6 taps per sub-filter). The filter is designed for the larger transition band to have overlapped filter response to minimize the filter coefficients. The spectral position of the filter bins are shown in Fig. 7.

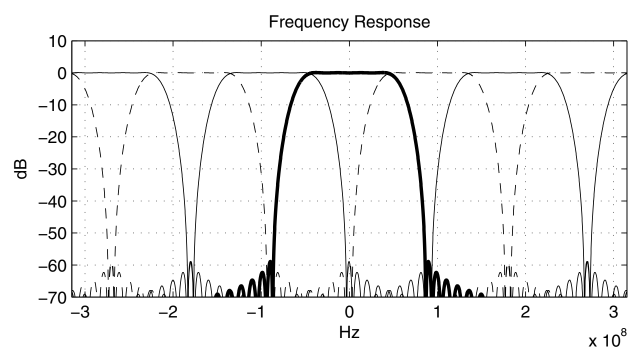

Fig. 7. Spectral locations of prototype filter in different channels' bin (N=7)

It can be seen by comparing the spectral location of the filter in Fig. 6 or Fig. 7 with the required channels in Fig. 5 that the filter's spectral location does not cover the channels bandwith. Next, we therefore experiment the variant polyphase channelizer having the spectral shifts of quarter of the channel spacing in order to achieve a working solution. The shifted versions in terms of multiples of quarter of the channel spacing (90MHz) are shown in Fig. 8, 9, 10. The first case (case 0) where the shift is zero (s=0) is the same as shown in Fig. 7. In these figures, different cases for the filter spectral position are illustrated having the spectral shift of multiples of quarter of the channel spacing. Now, again by comparing the spectral location of the filters in Fig. 7 to Fig. 10 with the required channels in Fig. 5, it is seen that the filter's spectral location in Fig. 10 provides a solution

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satisfying the requirements for both of the standards. It will be more clearly shown in the simulation section.

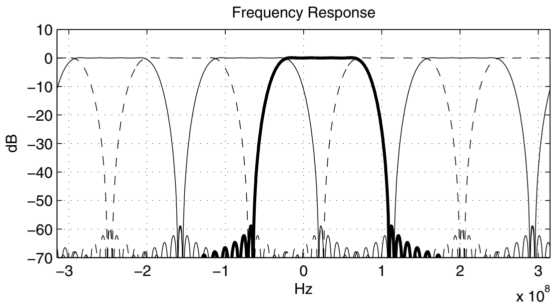

Fig. 8. Case 1: Spectral locations of prototype filter in different channels' bin (N=7) with a spectral shift s=1 ('s' is the multiple of the quarter of the channel spacing).

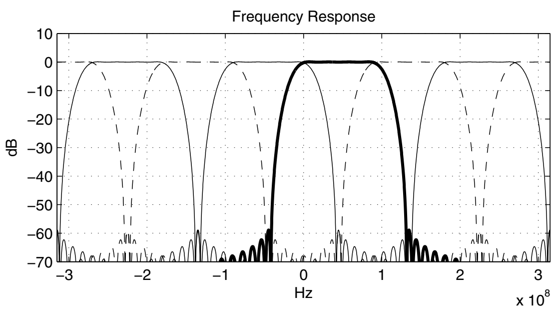

Fig. 9. Case 2: Spectral locations of prototype filter in different channels' bin (N=7) with a spectral shift s=2 ('s' is the multiple of the quarter of the channel spacing).

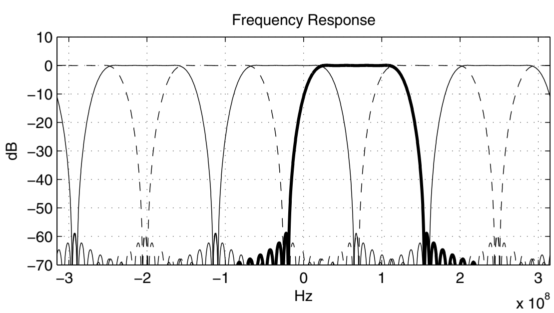

Fig. 10. Case 3: Spectral locations of prototype filter in different channels' bin (N=7) with a spectral shift s=3 ('s' is the multiple of the quarter of the channel spacing).

If even by these two solutions (case A & B), the filter requirements of both standards are not met, then variant polyphase channelizer having spectral shifts other than multiples of the quarter of the channel spacing can be employed. As explain earlier, that it will increase to the required resource utilization but the design will have characteristics of low operating frequency and multiple path input data which is the most important while working with the high frequency input data.

III. Simulations

In order to simulate the working of the design, we have generated a composite test signal at the spectral locations of WLAN and UMTS standards which is shown in Fig. 11.

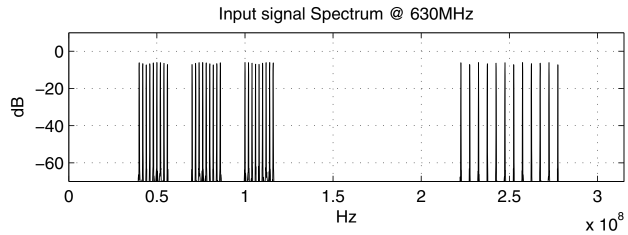

Fig. 11. A composite test signal generated at the spectral locations of WLAN and UMTS standards. WLAN has 3 non-overlapped channels whereas UMTS has 12 channels.

This test signal is applied to the variant polyphase channelizer having $s = 3$ as shown above, which delivers the required UMTS and WLAN bands at the output. The input signal's spectrum overlaid with the filter's spectral positions for the variant polyphase channelizer with $s = 3$ which gives a solution in this case as shown in Fig. 12. It can be seen that UMTS and WLAN bands are well occupied by the filter's passband only in channel 1 and 3.

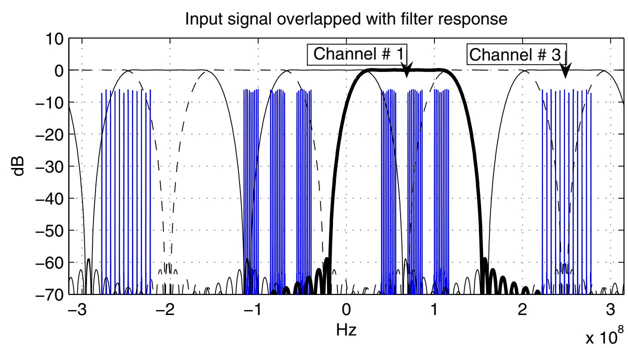

Fig. 12. The input signal spectrum is overlaid with the filter's spectral positions for variant polyphase channelizer with $s = 3$.

All 7 channel outputs of the channelizers are shown in Fig. 13. It can be seen that only outputs from channel 1 and 3 delivers the required outputs as bandpass filters for UMTS and WLAN standards. The remaining outputs are garbage being mixtures of both the standards. The outputs have sample rate of 90MHz which is due to down-sampling by 7 in the commutator. Furthermore the outputs from the variant polyphase channelizer are complex which therefore eleminate the need of IQ demodulators in this case. WLAN and UMTS bandpass signals are spectrally shifted by Π and $\Pi/2$ rotators respectively to have a clear view of bandpass outputs as shown in Fig. 14. These shifting will not require any real multiplication operation as Π and $\Pi/2$ rotators result only in sign change operation. So we have efficiently bandpass filtered UMTS and WLAN standards at input sampling rate of 630MHz and delivering the outputs at 90MHz.

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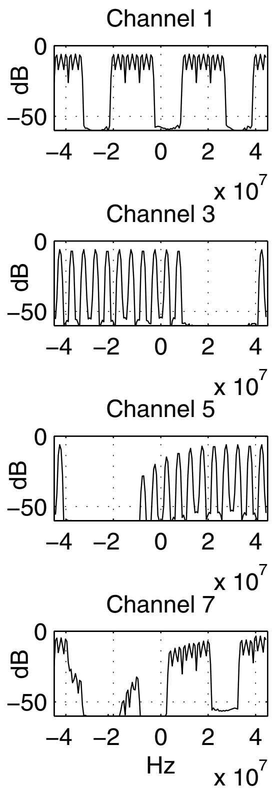

Fig. 13. All 7 Channel outputs of the channelizers. It can be seen that only outputs from the channel 1 and 3 deliver the required outputs as bandpass filters for the UMTS and WLAN standards.

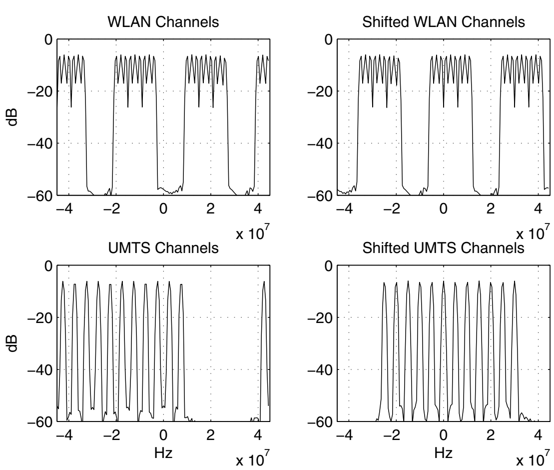

Fig. 14. WLAN and UMTS bandpass signals are spectrally shifted by Π and $\Pi/2$ rotators to have a more clear view of the bandpass signals. These shifting will not require any multiplication operation.

IV. Conclusion

A dual-standard (UMTS & WLAN) software radio receiver architecture is presented with the focus on high performance bandpass filters. It is required to have bandpass filters to separate out the standards before channelization such that they can handle the high input data stream and can operate on the current technology platforms as well. It is seen that the polyphase channelizer or its variant can be used with their unique and extraordinary features of multiple paths and spectral translation, to act as a high performance bandpass filter which can also eleminate the need for IQ demodulators. The final system block diagram is shown in Fig. 15 where the previous bandpass filters for UMTS and WLAN standards in Fig. 4 are removed by a single polyphase channelizer, making the architecture more compact and resource efficient. The initial estimates for resource utilization result in approx. 32% of reduction compared to the solution with separate bandpass filters implemented in polyphase fashion as well.

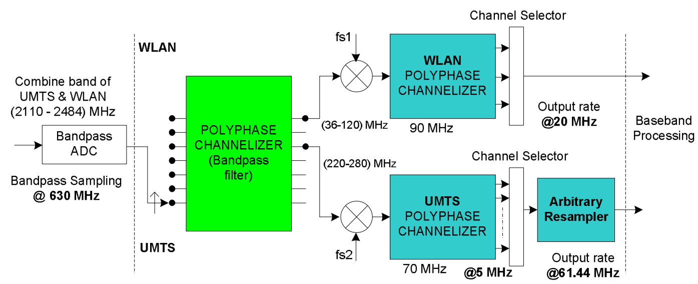

Fig. 15. Final system block diagram where the previous bandpass filters for UMTS and WLAN standards are removed by a single polyphase channelizer.

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