Variable Bandwidth Analog Channel Filters for Software Defined Radio

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Abstract— **An important aspect of Software Defined Radio is the ability to define the bandwidth of the filter that selects the desired channel. This paper first explains the importance of channel filtering. Then the advantage of analog channel filtering with a variable bandwidth in a Software Defined Radio is demonstrated. This is done by comparing the requirements of the analog-to-digital converter with and without an analog filter with a variable bandwidth. Then, a technique for channel filtering is described, in which two passive filters are combined to obtain a variable bandwidth. Passive filters have the advantage of high linearity, low noise and inherent energy efficiency. Some limitations of the concept are discussed. Finally, conclusions are drawn and our ideas for further research are presented.**

Keywords— **Software Defined Radio, analog front-end, passive filter, flexibility**

I. Introduction

In recent years, interest for Software Defined Radio has been increasing, as indicated for example by [1]. In a Software Defined Radio, all relevant functions of the radio can be defined (controlled, programmed) by software. This does not however necessarily mean that all functions are implemented in software, as in a Software Radio.

Software Defined Radio can have many advantages. One advantage is the convenience for the user. Having a multi-standard terminal (mobile telephone, laptop with wireless LAN interface) enables global roaming, without carrying an abundance of hardware.

A second advantage is a shorter development time and cost for the manufacturer. Assuming that software can be developed faster than hardware, a Software Defined Radio can be upgraded to a new standard, a new version of the standard or fitted with a better filter much faster than a conventional radio.

A last advantage of Software Defined Radio mentioned here, is its adaptability to a dynamic environment. A Software Defined Radio can dynamically make a trade-off between performance and energy consumption. By minimizing the performance (while still maintaining a required quality of service), battery life can be maximized.

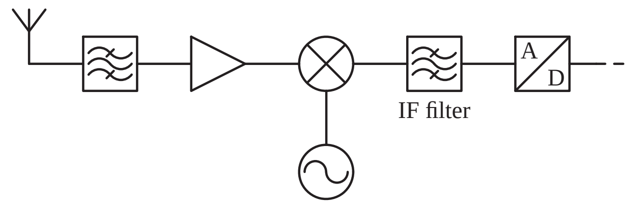


Fig. 1. conventional super heterodyne receiver, with fixed bandwidth IF filter

As stated above, Software Defined Radio implies that important radio characteristics can be defined by software. One important characteristic of every radio receiver is the bandwidth of the filter that selects the desired channel.

Various ways exist for this filtering. In a conventional single-standard receiver, often a passive filter is used in the form of a ceramic, crystal or surface acoustic wave (SAW) filter. These filters are very linear, exhibit low noise, and require no external power.

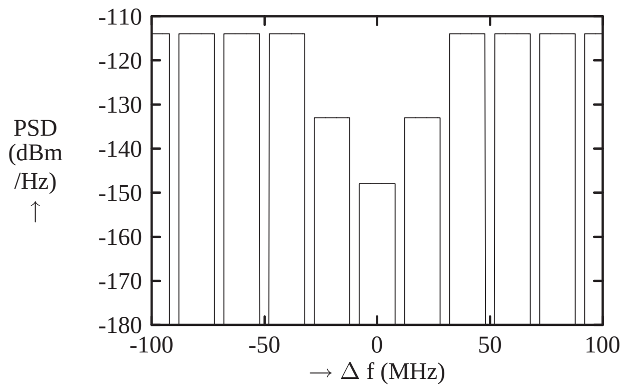
One problem however, is their lack of flexibility. Both center frequency and bandwidth are fixed for one particular device. This is a problem in a multi-standard receiver. Other filtering solutions, like active analog filtering or digital filtering are programmable, but consume power.

This paper describes a concept which uses passive filters, but still gives a programmable bandwidth. The idea itself is not new (see for instance [2]), but its application to software defined radio is.

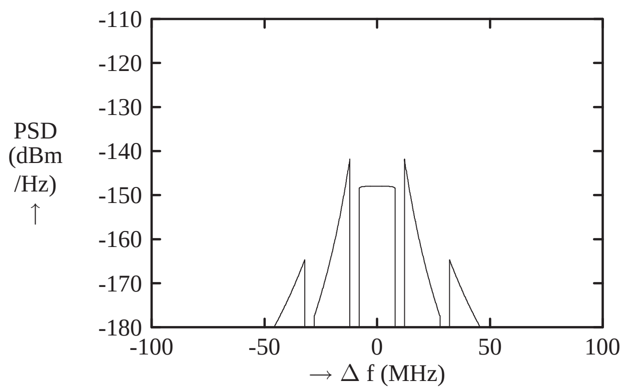
The next section explains why channel filtering with a variable bandwidth is important in a multi-standard receiver. Section III presents a method to achieve this. In section IV limitations of the presented scheme are discussed and finally in section V conclusions are drawn.

II. Effects of Variable Bandwidth Channel Filtering

Every radio receiver has a filter to select the desired channel. This function could be implemented by the IF filter in a normal super heterodyne receiver as depicted in figure 1. As the received power in the adjacent channels



(a) before filtering



(b) after filtering

Fig. 2. Power spectral density (in dBm/Hz) of a HiperLAN/2 signal including adjacent channels, before and after filtering with a 10th order Butterworth bandpass filter.

can be far higher than the power of the wanted signal, and the channel filter suppresses these adjacent channels, dynamic range of the signal is reduced considerably.

An example of this reduction of dynamic range is shown in figure 2. The HiperLAN/2 standard [3] defines the minimum power of the wanted signal, and the maximum power of adjacent channels, at which the receiver must maintain a certain bit error rate (BER). This part of the standard is called the blocking specification. In figure 2(a) the power of these signals are shown, before any filtering has taken place. Figure 2(b) shows the same signal, but after the channel filter. It is clear that this signal has a far lower dynamic range.

Dynamic range of the signal directly relates to the resolution required for subsequent analog-to-digital conversion (ADC). And since the power consumption of an ADC in general depends exponentially on the number of bits [4], it can be concluded that filtering the signal with a bandwidth equal to the signal bandwidth drastically reduces power requirements for the ADC.

In a multi-standard receiver, the standards of interest usually will have a different bandwidth. When for instance a GSM signal with a bandwidth of approximately 200 kHz is passed through the same filter as the HiperLAN/2 signal before, dynamic range will hardly be reduced. This is due to the fact that adjacent channels are much closer in a system with a smaller channel bandwidth.

This means that the bandwidth of the channel filter must be variable in order to minimize ADC requirements. As this will probably result in higher circuit complexity and in higher power consumption, it is interesting to quantify the advantage of a channel filter with a variable bandwidth. This will eventually enable a trade-off between power consumption of the ADC and the filter.

To estimate the advantage of a variable bandwidth filter, consider two receivers, both designed to receive all of the standards GSM[5], DECT[5], Bluetooth[6] and HiperLAN/2[3]. These standards were chosen because they are all quite different with respect to channel bandwidth. A list of these standards can be found in table I.

Standard	Channel BW (Hz)	Impact on ADC Δ DR (dB)	Δ # bits
GSM [5]	200 k	66	11
DECT [5]	1728 k	40	7
Bluetooth [6]	1 M	40	7
Hiperlan 2 [3]	20 M	0	0

TABLE I

VARIOUS WIRELESS STANDARDS, THEIR CHANNEL BANDWIDTH, AND THE EFFECT OF ANALOG CHANNEL FILTERING ON DYNAMIC RANGE AND EQUIVALENT ADC RESOLUTION

One of the two receivers that will be compared has a fixed bandwidth IF filter (as depicted in figure 1), while the other has a variable bandwidth IF filter. Both filters are assumed to have a brickwall type transfer characteristic. Since the largest channel bandwidth of the selected standards is 20 MHz (for Hiperlan), the receiver with the fixed bandwidth will have this bandwidth.

Now, the dynamic ranges of the signals after the IF filter are compared. In the case of the receiver with a fixed 20 MHz bandwidth, more channels than just the wanted channel are entering the ADC. This will result in a higher dynamic range requirement on the ADC. To quantify this increase in dynamic range, the blocking specifications of the standards were examined, and the ratio between the strongest adjacent channel within a 20 MHz bandwidth and the wanted channel was calculated. This equals the increase in dynamic range when using a 20 MHz filter. The results are shown in table I.

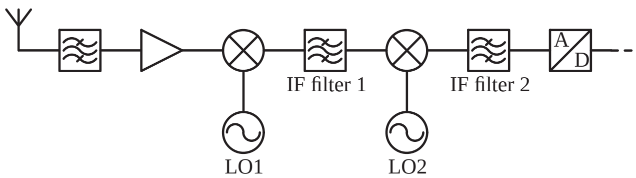


Fig. 3. super heterodyne receiver with variable bandwidth IF filter

Clearly, for Hiperlan the two systems are equivalent, as the filter was chosen to fit this standard. For the other standards, these results show that channel filtering prior to the ADC affects the required resolution for the ADC. And since the power consumption of an ADC is approximately proportional to $2^{\#bits}$ [4], this drastically reduces power requirements for the ADC.

Now that the impact of variable bandwidth channel filtering is clear, the next question will be how to implement such a filter. One way to achieve this, will be shown in the next section.

III. Variable Bandwidth Filtering using Passive Filters

Several solutions for variable bandwidth filtering exist. This section describes one such a system.

The approach is shown in figure 3. This system could be regarded as a standard double super heterodyne receiver, but contrary to a normal implementation, the frequency of the second local oscillator (LO2) can be varied. By doing this, the (band limited) output signal of the first IF filter can be shifted in frequency through the second mixer. This shifted signal is then filtered by the second IF filter. By adjusting the frequency of LO2, a different portion of the signal filtered by the first IF filter can be made to fall within the pass band of the second IF filter. In this way, the bandwidth of the signal at the output of the second IF filter can be varied, from the smaller of the two IF filters' bandwidth, theoretically down to zero (for two filters with infinitely steep skirts).

Figure 4 shows the transfer characteristic of the different filters in this system as a function of (normalized) frequency. The dotted line (labelled 'IF filter 1') is the transfer function of the output of the first IF filter, here modelled as a 14^{th} order Butterworth filter. Assuming an input signal with a white power spectrum, this equals the amplitude spectrum of the output signal of this filter.

The dot-dashed line (labelled 'IF filter 2') is the same signal, after it has been shifted in frequency by the second local oscillator and the mixer. This is the input signal to the second IF filter.

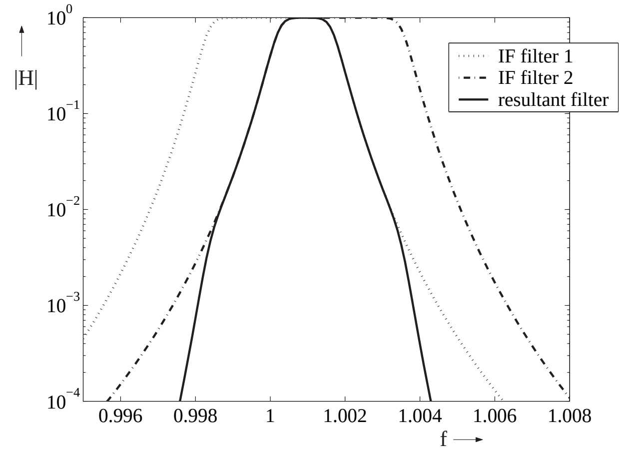


Fig. 4. Transfer characteristic of two 14^{th} order Butterworth bandpass filters, one shifted in frequency, and the resultant filter.

The solid line (labelled 'resultant filter') represents the signal after it has been passed through the second IF filter. As this is the output signal of the whole filter system, and we assumed the input signal to be white, this equals the transfer function of the whole filter system.

The total bandwidth of the system is smaller than that of either of the two passive filters. By raising the frequency of the second local oscillator, the output signal of the mixer will shift in frequency. This results in a smaller portion of the spectrum being passed through the second IF filter, and a narrower system bandwidth.

With this system, the problem of changing filter bandwidth has been transformed into a problem of changing local oscillator frequency. As this is a more frequent problem, solutions have been found and making a local oscillator frequency controllable by software is not a big problem. [7]

IV. Limitations

Nothing is perfect, and the concept described in this paper is no exception. One limitation is the shape of the transfer characteristic of the resultant filter. Usually, a narrower filter has steeper skirts. With this systems however, the slope does not depend on the selected bandwidth. So, when a narrow bandwidth is selected, the filter has a relatively modest roll-off. Also, the transfer function in the pass band is far from flat anymore. This form of linear distortion could have an impact on receiver performance, depending on the modulation scheme and other factors.

Another issue is the insertion loss of passive filters. SAW filters, which are often used for this application, typically have an insertion loss of up to around 20 dB. An amplifier with a gain of 40 dB to compensate for the loss of two of these filters might consume considerable power.

A last point mentioned here is the need for external components. Although research has shown that integrating SAW filters on-chip is feasible [8], standard IC processes do not accommodate this. Consequently, these filters are located off-chip, and have to be connected to the rest of the circuit using bond wires and PCB traces. This may result in more cross talk which degrades filter performance. On a side note, RF MEMS technologies [9] could in the future lead to integrated passive filters.

V. Conclusions

A circuit technique has been described with which a variable bandwidth filter can be achieved using two fixed bandwidth passive filters. It was shown that analog variable bandwidth filtering lowers the required resolution of ADC in a multi-standard receiver.

As mentioned in the introduction, other methods for channel filtering with a programmable bandwidth exist. Therefore, our next step will be to compare the power consumption of the system described in this paper both with that of digital channel filtering and with analog active filtering on a low or zero IF.

VI. Acknowledgement

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