Techniques for Digital Implementation of Multi-mode Radio Receivers

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Abstract: There is an increasing demand for radio applications in mobile devices. In the future, terminals will require a combination of broadcast, cellular, wireless connectivity and positioning functionality in a single device. In order to achieve this, radios are increasingly being implemented in the digital domain. The usual advantages of digitisation are well known and include robustness against process variation, design reuse and adaptability, the last of which is of most interest in the context of multi-mode radio. This paper describes two techniques that can be used to improve the performance of the radio in the digital domain: signal path error correction and pre-emphasis of radio spectrum. Signal path error correction is used to compensate for the poorer accuracy of the analogue radio components and pre-emphasis is used to reduce the dynamic range requirement, and hence power consumption, of the analogue to digital converter (ADC).

1. Introduction.

This paper describes work in the field of radio receiver digitisation. The main motivation for the work is the "convergence" of applications in mobile terminals. As illustrated in Figure 1, users of future multi-media terminals will demand a combination of broadcast, cellular, wireless connectivity and positioning functionality in a single device.

Figure 1: Convergence of Radio Systems

The standards that will be required to implement such systems include GSM, EDGE, UMTS, the IEEE 802.11 family of WLAN standards, DVB-H for mobile TV and GPS for positioning. When many of these standards are required in a single terminal, it is no longer practicable to have a radio for each system and a multi-mode radio, capable of implementing many or all of the systems above, is required.

2. Digital Implementation of Radio Receivers.

Methods for digital implementation of radio receiver have been described in the literature [1]. The basic idea is shown in the diagram below:

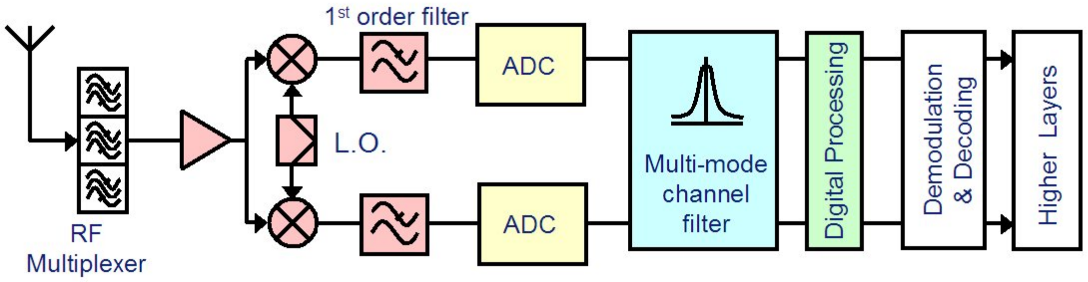

Figure 2: Digitally Implemented Radio Receiver

The receiver consists of an RF multiplexer that presents the appropriate RF signal to a low noise amplifier, followed by a single down conversion to a low or zero intermediate frequency. The signal is then filtered and converted to the digital domain, where further processing including demodulation occurs. In order to minimise power consumption, the ADC is of the sigma-delta type, as described in [2]. The main difference between the radio architecture shown in the diagram above and a more conventional analogue receiver is that the channel filter is implemented largely in the digital domain. In an ideal world, the channel filter would be completely digitally implemented and could be reprogrammed to perform any of a number of radio requirements. In practise, it turns out to be beneficial to implement a 1st order filter before the ADC, the purpose of which is to prevent large unwanted signals that are well separated in frequency from the wanted signal from reaching the ADC. This reduces the dynamic range required of the ADC and hence reduces its power consumption.

The usual advantages of digitisation are well known and include robustness against process variation, design reuse and adaptability, which is of most interest in the context of multi-mode radio. The remainder of this paper describes two less obvious techniques for digital correction of the signal that are possible and practicable once the signal is in the digital domain.

3. Signal Path Error Correction.

One advantage to digital implementation is the ability to perform signal error correction. Once in the digital domain, corrections for analogue imperfections can be made. For example, if the I and Q paths of the radio system are not matched in amplitude, this can be corrected by amplification of one of these paths appropriately. DC offsets and phase imbalance can also easily be corrected. The principle of the phase correction technique is shown in Figure 3 below:

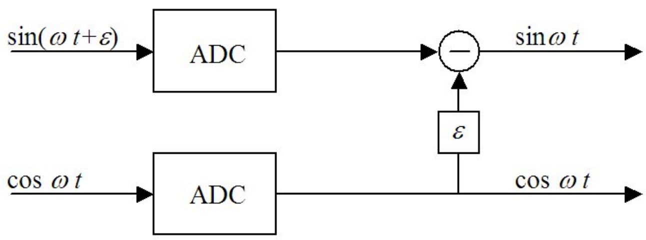

Figure 3: Phase Correction of Digitised Signal

A phase error of ε in one path is eliminated by subtraction of a certain amount of the other path. This works because:

$$\sin(\omega t+\varepsilon) \quad = \quad \sin\omega t\cos\varepsilon + \sin\varepsilon\cos\omega t \approx \sin\omega t + \varepsilon\cos\omega t$$

The correction of phase, amplitude and DC errors leads to the improvement of various aspects of radio receiver performance, including image rejection. These kinds of techniques were originally proposed for use with analogue correction circuits as patented in reference [3]. However, they have become more practicable now the signal is in the digital domain, and another patent has been awarded [4].

4. Pre-emphasis of Radio Spectrum.

One problem with the first order pre-filter described above is that as well as filtering the unwanted interferer, it will to some extent filter the wanted signal. The output of the pre-filter may be as shown in Figure 4 below: before filtering, the spectrum of the wanted signal was white (i.e. rectangular), but after filtering its high frequencies are attenuated. This filtering of the wanted signal may introduce problems in demodulation. This problem is particularly severe when the interferer is very close to the wanted signal, as in CDMA2000 where a 900 kHz interferer is specified and the wanted signal has a bandwidth of 1.2 MHz (half-bandwidth 600 kHz).

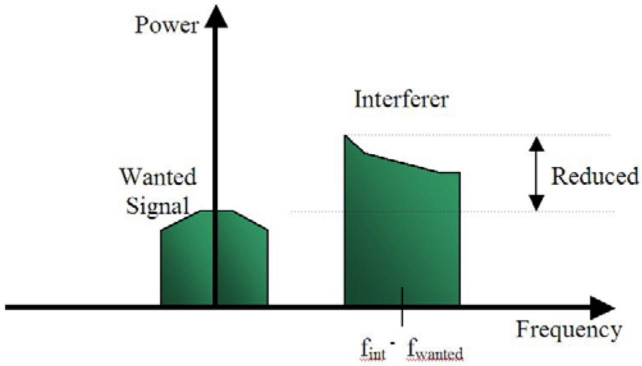

Figure 4: Output of First-order Pre-filter

Therefore, one technique that can be implemented in the digital domain is the reconstruction of the wanted signal. The low pass filtering operation is essentially reversed in the digital domain once the ADC bottleneck is passed. In this case, the overall process involving the low-pass filter and the reconstruction operation is very similar to techniques known as “pre-emphasis” which have been widely used in electronics, for example the RIAA equalisation process used for the recording of vinyl records, and a similar process used in the transmission of FM radio. The only difference is that these two cases the higher frequencies were boosted, whereas in the present application the higher frequencies are being attenuated.

A possible reconstruction filter is shown in the diagram below:

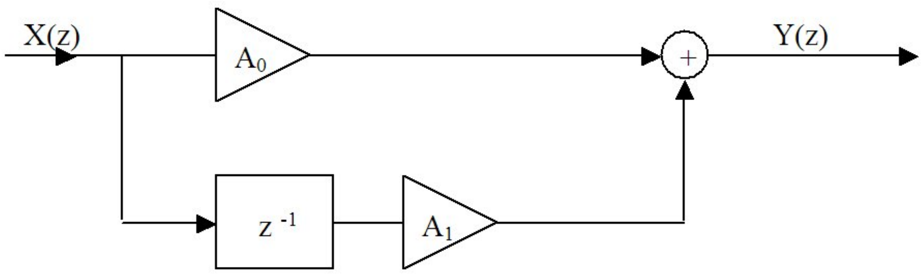

Figure 5: Digital Reconstruction Filter

The frequency response of the analogue low-pass filter may be given by:

$$H(\omega) = \frac{1}{1 + j\omega T}$$

The frequency response of the digital reconstruction filter is given by (T_S is the sampling period in the digital domain):

$$A_0 + A_1 \cos(\omega T_S) - j A_1 \sin(\omega T_S)$$

This is to be equated to the inverse of the pre-filter characteristic, $1 + j\omega T$. A little maths shows that this occurs when $A_1 = -T/T_S$ and $A_0 = 1 + T/T_S$.

This system was simulated for a CDMA2000 application with a 900kHz blocking signal and 1.2 MHz bandwidth wanted signal. Comparison was made with a more conventional digitally implemented radio with a 3rd order Chebychev pre-filter. The results for sensitivity are given in Table 1 below:

Signal level (dBm)	-108	-106	-104	-102	-100
3rd Order Chebychev	0.164	0.121	0.0828	0.0519	0.0286
1st Order Pre-emphasis	0.159	0.113	0.0703	0.0403	0.0227

Table 1: Sensitivity Performance

The results for the pre-emphasised system are a little better than those for the Chebychev filter, where the filtering of the wanted signal is not corrected in the digital domain. The blocking performance was as follows:

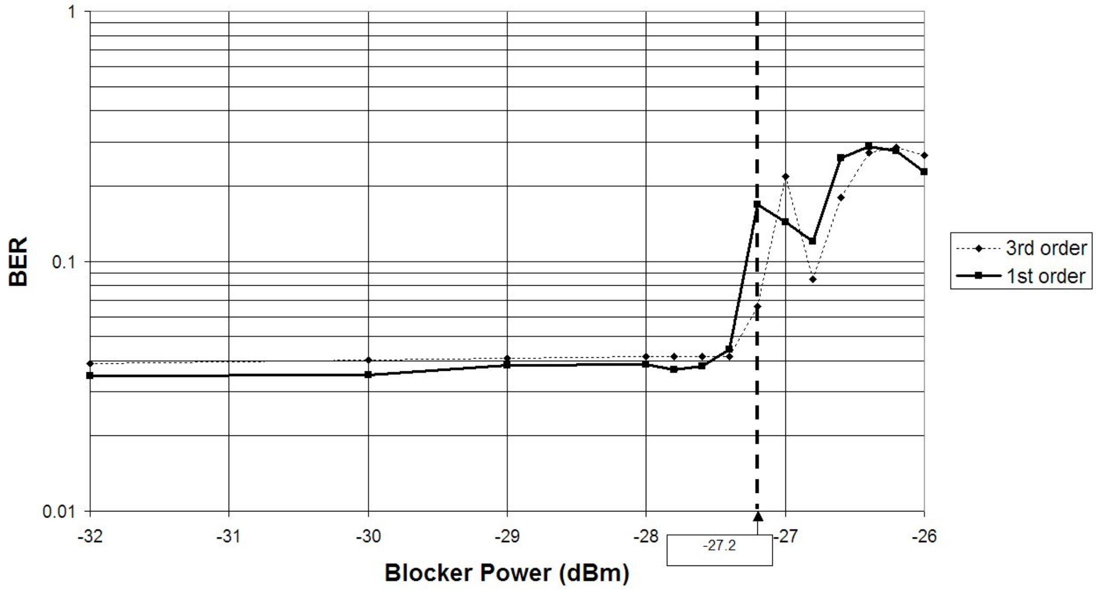

Figure 6: Blocking Performance

The graph above shows that a 30 dBm blocker is handled better by the 1st order system than by the Chebychev filter based system, and the device meets the required specification. Thus a 3rd order Chebychev filter specifically designed for the CDMA application can be replaced with a first order filter, which can more easily made adaptable and used for other applications. The first order filter does however fail to meet the required bit error rate at a slightly lower blocker power (-27.2 dBm cf. –27.0 dBm).

5. Conclusions.

This paper has described two techniques that are being used to improve the performance of the radio in the digital domain: signal path error correction and pre-emphasis of radio spectrum. It has been shown that the pre-emphasis technique can be used to replace a 3rd order Chebychev filter specifically designed for CDMA2000 with a more adaptable first order filter.

6. References.

[1] Minnis, BJ and Moore, PA “A highly digitised multimode receiver architecture for 3G mobiles”, IEEE Transactions on Vehicular Technology, Vol. 53, Issue 3, May 2003

[2] Veldhoven, R van, “A Tri-mode Continuous-time sigma-delta Modulator with Switched Capacitor Feedback DAC for a GSM-EDGE/CDMA2000/UMTS Receiver”, IEEE International Solid-State Circuits Conference, February 2003, p.60.

[3] Cheer, AP and Barber, AB (Plessey Company plc) “Apparatus for the correction of frequency independent errors in quadrature zero I.F. radio architectures”, UK patent GB 2,215,544 A, September 1989.

[4] Jasper, SC (Motorola, Inc.) “Method and apparatus for compensation of imbalance in zero I.F. downconverters”, US patent 5,263,196, November 1993.