# Front-End Filters for Software Radio Receivers Employing Bandpass Sampling

M. Patel and Dr. I. Darwazeh

University College London

**Abstract:** Bandpass sampling holds much promise for the realisation of software radio receivers, particularly for mobile devices. Sampling at reduced rates eases many of the ADC requirements, and decreases power consumption, thus increasing battery lifetime, and overall receiver size. The need for very high performance programmable devices is also reduced. This paper demonstrates the importance of the bandpass filter at the front-end of bandpass sampling receivers, and investigates the bandpass filter requirements for QPSK, and π/4-DQPSK modulation schemes. Also considered is a practical software radio receiver where channel selection occurs at baseband.

## 1 Introduction.

Mobile communications continues to develop at a rapid pace. Heterogeneous networks will be required to operate in synergy, providing seamless access to a variety of mobile and fixed wireless terminals. Software radio is an enabling technology that allows mobile terminals or base stations to be reconfigured so that they can operate within a number of different environments or systems.

The main characteristics desired in a software radio terminal are programmable devices, such as DSPs, or FPGAs on to which radio functionality can be downloaded; a wideband front-end, including wideband ADC; digitisation occurring as close to the antenna as possible in order to encapsulate as many radio functions in the digital domain and hence defined in software [1]. Ideally the front-end would be as linear as possible and digitisation would take place at RF. However, this is severely limited by the characteristics of wideband RF components such as amplifiers, which require linearisation techniques to obtain the linearity required [2]. The carrier frequency at which digitisation can take place is limited by the input analogue bandwidth of ADCs and also aperture jitter.

Bandpass sampling holds much promise for the realisation of software radio [3]. It allows sampling of a received signal at RF or IF but with significantly reduced sampling rates.

This paper compares the performance, in additive noise, of bandpass sampling receivers with an ideal direct conversion receiver for QPSK, and π/4-DQPSK modulation schemes. The importance of a front-end bandpass filter is demonstrated and the optimum bandpass filter is determined for the different modulation schemes.

A practical software radio receiver architecture is considered where channel selection is implemented at low-IF, or baseband and compared to a single channel bandpass sampling receiver.

## 2. Bandpass Sampling.

Conventional sampling theorem requires a sampling rate that is at least twice the maximum signal bearing frequency. However, if sampling takes place at higher carrier frequencies, as opposed to at baseband, the sampling rate can become very high, and therefore impractical for processing the signal using commercially available DSPs. If, on the other hand, the signal is treated as a bandpass signal, and the sampling rate is at least twice the information bandwidth, significantly lower sampling rates can be achieved. The intentional aliasing that occurs when sampling below the Nyquist rate, results in an inherent down conversion property, shifting the received signal down to a low-IF, or even baseband if the sampling frequency is chosen correctly. However, to preserve phase information when aliasing down to baseband, two ADCs are required operating in quadrature.

Bandpass sampling requires careful selection of the sampling frequency if folding of the signal spectrum on top of itself is to be prevented. A number of expressions are available to assist in choosing a sampling frequency, and are dependent on the upper and lower frequencies of the information signal, and hence the signal bandwidth [4]. The IF that the signal is aliased down to depends on the carrier frequency, and sampling rate.

Bandpass sampling offers the advantage of downconversion without the use of mixers. This is due to the inherent frequency translation property of the intentional aliasing. The use of digital mixers and NCO to translate the signal from low IF to baseband can also be eliminated, and replaced by simple logic circuits if the sampling rate is chosen to be an optimum frequency as described by [5].

Bandpass sampling is limited by requirement of a high analogue input bandwidth for the ADC, and frequency limitations due to jitter [6]. Therefore for a practical software radio receiver, bandpass sampling can only be employed at IF, until advances are made in ADC technology. Also required at the front-end of the receiver, prior to sampling is a sharp roll-off filter to limit out-of-band interference. This filter may be difficult to implement at higher frequencies.

## 3. Bandpass filters.

The bandpass filter prior to the sampling process band limits the signal and attenuates out-of-band interference. A narrow passband with steep roll-off is desirable, but this may be difficult to achieve, especially at higher frequencies. However, a trade-off exists, whereby the filter needs to be narrow enough to restrict the amount of noise aliased down to baseband, but if the signal bandwidth is restricted too much, ISI occurs, thus reducing performance.

For the purposes of this research, the following system parameters are used. The transmitted bit rate is 1Mbit/s which when modulated using QPSK results in a 1MHz bandwidth centred on the carrier frequency. The carrier is chosen to be 100MHz, which could represent an IF which the received signal is heterodyned down to.

The optimum bandpass filter is determined by considering the performance of the receiver in AWGN, where $E_b/N_o$ is approximately 8dB, using different filter types and filter orders. The filters considered are Butterworth, Bessel, and Chebyshev approximations, readily available in the ADS libraries, and their frequency responses shown below in Figure 1. The Bessel filters are included since they possess a more constant group delay in the filter passband compared to the other filters. Filters with pass bandwidths of 1MHz and 2MHz are considered. Root raised cosine filters are implemented in the transmitter and receiver, which have 50% excess bandwidth. Thus the narrow bandpass filters, may cause more ISI.

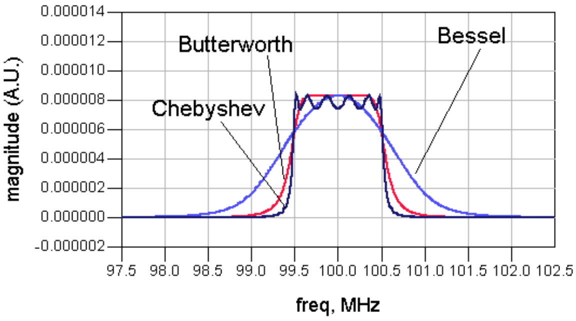



**Figure 1: Frequency responses of bandpass filters**

## 4. Simulation results

In this section, results from simulations using the ADS simulation environment are presented. Modulation schemes based on Quadrature Phase Shift Keying are modelled. These schemes are conventional QPSK, and rotated DQPSK ($\pi/4$ DQPSK). Their constellations are presented below as trajectory diagrams in Figure 2. $\pi/4$ DQPSK has the advantage of no zero-crossings, which is more suitable for non-linear systems. Linearity is difficult to achieve, especially for wideband receivers.

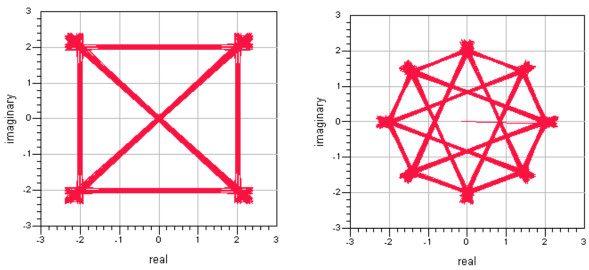



**Figure 2: trajectories of QPSK and π/4 DQPSK modulation schemes**

Figure 3 shows the BER estimation for the performance of the ideal demodulation of QPSK and $\pi/4$ DQPSK and the performance of the bandpass sampling receivers in AWGN. The ideal demodulation does not have a front-end bandpass filter (BPF), and the BPF for the bandpass sampling receiver is an 8$^{th}$ order Butterworth filter. QPSK performs better than $\pi/4$ DQPSK as expected, and the performance of the bandpass sampling receivers are significantly worse than their ideal counterparts.

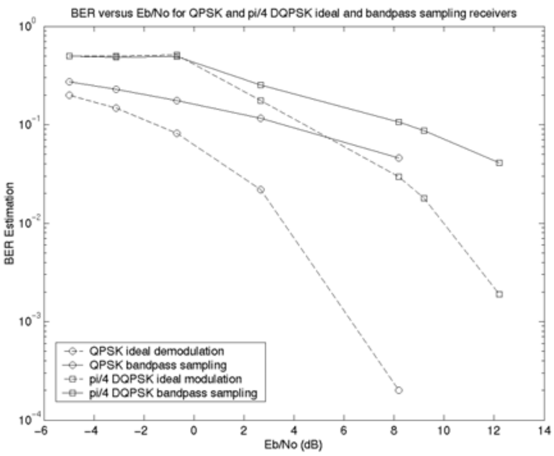
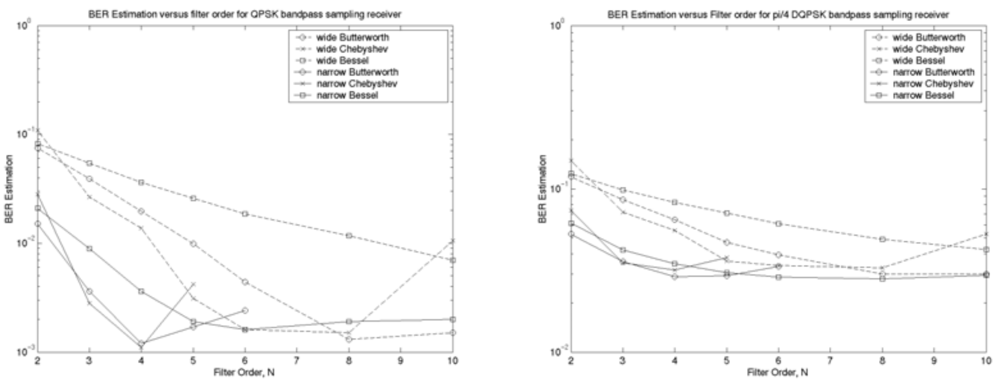



**Figure 3: Performance in AWGN of ideal and bandpass sampling demodulation**

The optimum front end filter for each of the two modulation schemes is determined. Butterworth, Chebyshev, and Bessel filters with different orders were implemented, and the bandpass sampling receiver was simulated for BER performance. The input $E_b/N_o$ was 8dB as mentioned before. The results are presented as graphs of BER versus filter order as shown in Figure 4. These results show that a narrow bandwidth (1MHz) $4^{th}$ order Butterworth and Chebyshev filters will give the best performance for both QPSK and π/4 DQPSK bandpass sampling receivers. The $6^{th}$ order Bessel filter also demonstrates good performance. It is desirable that the same filter is most suitable for a variety of modulation schemes or systems, since it reduces the front-end complexity of the bandpass sampling receiver, particularly if implemented as a software radio. Although the Bessel filter exhibits a less sharp roll-off, it has a more constant group delay compared to the other filters, thus reducing signal distortion. The $4^{th}$ order Butterworth and Chebyshev filters have narrow transition widths thus reducing out-of-band interference.




(a) (b)

**Figure 4: BER versus filter order for (a) QPSK and (b) π/4 DQPSK bandpass sampling receiver**

## 5. Wideband approach

The single channel selection at RF/IF is fine for demonstrating the importance of filtering prior to the bandpass sampling process. However, when considering a practical software radio employing bandpass sampling, the most efficient method of performing channel selection is at baseband. This requires a wider bandpass filter that can accommodate the entire system operating band, and not just a single channel. The wideband filter at the receiver front-end now carries out band selection. The bandpass sampling process, samples and downconverts the entire band to a low-IF. At this stage, channel selection can occur by configuring an NCO to the frequency of the desired channel centre frequency to convert the desired channel to baseband, or using the low-IF principle architecture. The low-IF method requires additional image cancellation techniques, since the desired channel may not necessarily reside at the band centre

In the paper we consider the simple case of channel selection at IF. Although this scheme reduces flexibility of the receiver, since a highly tuneable NCO is required, it indicates the effects of using a wideband front-end as preferred in a software radio implementation. A channel is located at the centre of the band, implemented for ease of modelling. The channel bandwidth is 1MHz, as before, and the system band is 10MHz wide. Both the ideal downconversion, which converted the band to baseband, with the received channel at the centre of the band, and the bandpass sampling receiver employ a 6th, order Butterworth filter at the front-end. The sampling rate for the bandpass sampling receiver is 80MHz. This is 8 times the system bandwidth. In real systems, oversampling is often employed to reduce in-band quantisation noise. Figure 5 shows the performance of the ideal wideband receiver, compared to the performance of the bandpass sampling receiver in additive noise. Again, the bandpass sampling receiver performs significantly worse. When compared to the narrowband performance shown in Figure 3, the wideband bandpass sampling receiver has worse performance. This is due to more out-of-band interference folded into the passband due to the sampling process.

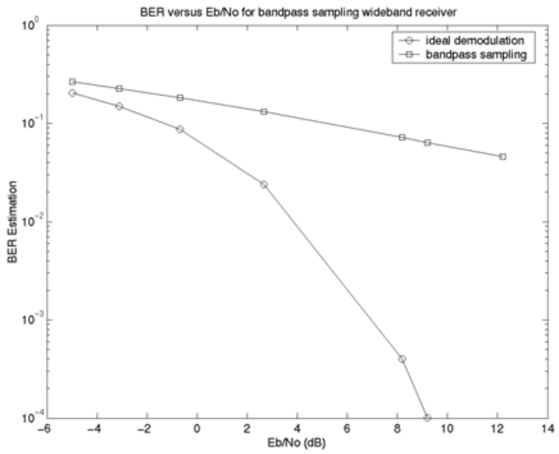



**Figure 5: BER versus Eb/No for wideband QPSK receiver**

## 7. Conclusions.

Bandpass sampling for software radios has been described, with discussion of the importance of the front-end bandpass filter. The performance of a simple bandpass sampling receiver, which selects the desired channel before downconversion to IF, or baseband, was demonstrated. It was shown that when compared to an ideal downconversion architecture, both QPSK and π/4 DQPSK bandpass sampling receivers performed significantly worse. This is due to the aliasing of out-of-band interference in to the passband as a result of the inherent dwonconversion due to aliasing during the sampling process. This also demonstrates the need for a high performance bandpass filter to reduce out-of-band interference. It was determined that a $4^{th}$ order Butterworth or Chebyshev filter, or a $6^{th}$ order Bessel filter has the best performance in AWGN for QPSK and π/4 DQPSK narrowband receivers employing bandpass sampling. The Butterworth filter would be the simplest to implement, however, the Bessel filter is more linear in phase. A simple wideband approach was discussed and its suitability to software radio implementation. Performance of the wideband bandpass sampling receiver was found to be worse than that of a narrowband receiver. Further work will model the performance of bandpass sampling receivers in ACI, and concentrate on the wideband approach.

## References.


[1] J. Mitola, “The software radio architecture,” IEEE Communications magazine, Vol. 33, no. 5, May 1995,pp. 26-38.

[2] P. B. Kenington, “Linearized transmitters: an enabling technology for software defined radio”, IEEE Communications Magazine , Volume: 40 Issue: 2 , Feb. 2002 Page(s): 156 –162

[3] J. A. Wepman, “Analog-to-digital converters and their applications in software radio receivers,” IEEE Communications magazine, Vol. 33, no. 5, May 1995,pp. 39-45.

[4] R. G. Vaughan, N. L. Scott, D. R. White, “The theory of bandpass sampling,” IEEE Transactions on Signal Processing, vol. 39, No. 9, September 1991, pp. 1973-1984.

[5] G. Guirong, Z. Zhaowen, W. Feixue, “Mixer-free all digital quadrature demodulation,” International Conference on Signal Processing, ICSP, 1998, vol. 2, pp. 1704-1707.

[6] M. Patel, I. Darwazeh, “Bandpass sampling for software radio receivers, and the effect of oversampling in aperture jitter,” IEEE 55th Vehicular Technology Conference Spring 2002, Vol. 4, pp 1901-1905.

[7] H. Tsurumi, H. Yoshida, S. Otaka, H. Tanimoto, “Braodband and flexible receiver architecture for software radio terminal using direct conversion and low-IF principle,” IEICE Trans. Communications, Vol. £83-B, No. 6, June 2000, pp 1246-1253.