Baseband tuning of Cartesian delta–sigma RF upconverters

S. Sirmayanti, V. Bassoo, H. King and M. Faulkner

Many digital delta–sigma radio frequency (RF) upconverters exhibit poor performance when the carrier frequency is tuned away from the centre of the band. The offsetting of signals from the nominal carrier frequency position generates unwanted distortion products which are dominated by the image and third harmonics. It is shown that these products can be moved out of the band by the correct choice of intermediate frequency. A novel technique for shifting both the signal and the noise null to the new frequency position is described.

Introduction: Advances in the speed of digital logic have opened the possibility of directly generating modulated radio frequency (RF) signals from a single bit stream. Pulse width and pulse position (PWM/PPM) techniques are used to control the amplitude and phase of an RF carrier. However, the rectangular nature of the output pulse generates a number of unwanted harmonics and distortion products. In addition, quantisation noise is generated when the pulse edges are synchronised to the timing grid of the digital clock. The management of distortion and noise is a key design challenge as is the requirement for tunability. Delta–sigma ($\Delta\Sigma$) techniques can shape the noise away from the carrier band for subsequent removal in a bandpass filter (Fig. 1) [1], but tunability remains a problem.
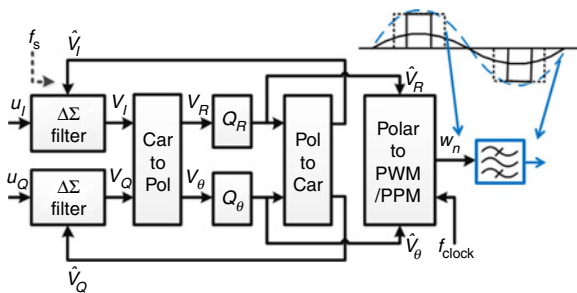

Fig. 1 *Cartesian $\Delta\Sigma$ upconverter [2]*

Wireless systems generally require the carrier frequency to be tunable to any channel position within the band of operation. Ideally, the $\Delta\Sigma$ noise null should span the whole band to avoid the need for a tunable RF bandpass filter at the output. There are two tuning possibilities: first, by changing the clock frequency of the upconverter circuit, which implies the use of a synthesised clock, with an appropriate fine frequency resolution; secondly, by frequency offsetting the input signal within the existing noise null. The latter is easily achieved by rotating the input baseband components. Unfortunately, a number of distortion products (spurious signals) become apparent when the carrier frequency is offset. Harmonics from the square pulse nature of the output signal fold in-band and become a potential source of interference to adjacent and nearby channels. The most dominant of these harmonics are the image and low-order harmonic components which occur in most PWM and $\Delta\Sigma$-like structures [3]. These distortions reduce the dynamic range, making it difficult to meet the spectrum mask requirements within the operating band.

In this Letter, we describe a method of tuning which is particularly suitable for schemes with high-resolution polar quantisers, such as the waveform PWM-mode Cartesian $\Delta\Sigma$ [2–4]. The proposed scheme recovers much of the dynamic range over the operating band.

Cartesian $\Delta\Sigma$: The Cartesian $\Delta\Sigma$ scheme operates in the baseband and avoids bandwidth expansion using a polar quantiser in a Cartesian structure. The magnitude and phase quantisers, Q_R and Q_θ, are sandwiched between Cartesian to Polar and Polar to Cartesian converters (Fig. 1). The quantised polar output $[\hat{V}_R, \hat{V}_\theta]$ selects an appropriate bit stream (w_n), from the 'Polar to PWM/PPM' block, having the desired PWM/PPM for the specified quantised value. The bit stream repeats in every RF carrier period. The number of clock periods, N (even), per nominal RF carrier period sets the number of available quantisation points; the number of pulse widths or quantisation levels is $N_a = [1 + (N/4)]$, and the number of pulse positions or quantisation phases is

$N_p = N$, where $N = f_{clock}/f_c$ and f_c is the nominal carrier frequency. An improved quantiser fidelity implies a higher digital clock frequency. The width and position of the pulse train are updated after K periods of the RF carrier ($K \geq 1$) giving a fixed relationship between the $\Delta\Sigma$ sample frequency, f_s, and the nominal carrier frequency f_c: $K = f_c/f_s$. See [4] for further details. In the simulations, the $\Delta\Sigma$ filters are second order (MOD 2) [1], the nominal carrier frequency $f_c = 512$ MHz, $K = 1$ and $N = 32$. The clock frequency, f_{clock}, is therefore 16 GHz, which is within the limits of the current digital technology [5, 6].

Baseband tuning: We consider a $BW_b = 70$ MHz band with $BW_{ch} = 10$ MHz channelisation (normalised bandwidths of 0.137 and 0.02, respectively). A complex phase rotation applied on the input baseband signal, s, will frequency offset the output signal to the desired channel position

$$u = \exp\left(j \times \frac{2\pi}{f_s} \times f_{offset} \times n\right) \times s \qquad (1)$$

where $u = (u_I + ju_Q)$, $s = (s_I + js_Q)$ and n is the sample number. Channel 4 ($f_{offset} = 0$) shows only small distortion skirts some 56 dB below the carrier affecting the two nearest adjacent channel positions (Fig. 2). However, offsetting the frequency by 10 MHz to the next channel (Channel 3) enables the identification of a number of large distortion components; the image in Channel 5, the −3rd order in Channel 7 and the +3rd order in Channel 1. The +3rd order distortion produces the worst-case in-band spurious some 41 dB below the carrier, which is 14 dB more than that produced by Channel 4. As the offset frequency increases so does the magnitude of the spurious outputs. Channel 1, at the band edge, generates the largest spurious components, of which the image in Channel 7, some 35.5 dB below the carrier, is the most problematic. The distortion components destroy the good in-band noise-shaping performance of the $\Delta\Sigma$ filters.
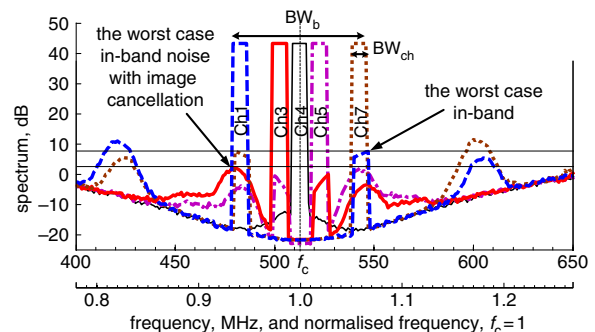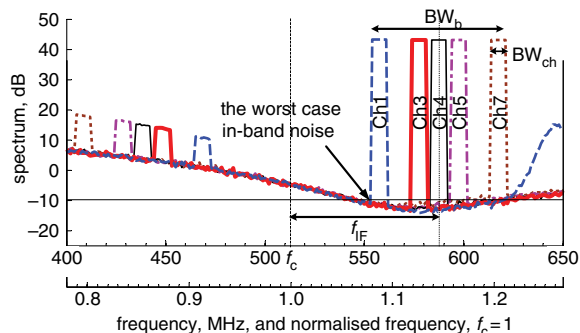

Fig. 2 *Simulated output spectrum for different channel positions*

Spurious removal: We exploit the fact that as the frequency offset increases, the distortion products actually move out-of-band and can be potentially filtered out using the RF bandpass filter. If the whole band is shifted by an intermediate frequency, $f_{IF} > BW_b/2$, then all the channels will be on one side of the nominal centre frequency, f_c, and all the spurious images will fall on the other side of f_c and are hence out of band. If the intermediate frequency is shifted by $f_{IF} > BW_b$ then all the +3rd distortion components will be out-of-band (since they are shifted by three times as much). In practice, the distortion energy of the 3rd's spans three or more channels and so some energy still leaks in-band, a further shift of 0.5 channels is required giving

$$f_{IF} = BW_b + \frac{BW_c}{2} \qquad (2)$$

which in this case is a shift of $70 + 5 = 75$ MHz as shown in Fig. 3. The third-order product of Channel 1 just misses the upper band edge.

Fig. 3 *Simulated output spectrum at f_{IF} = 75 MHz*

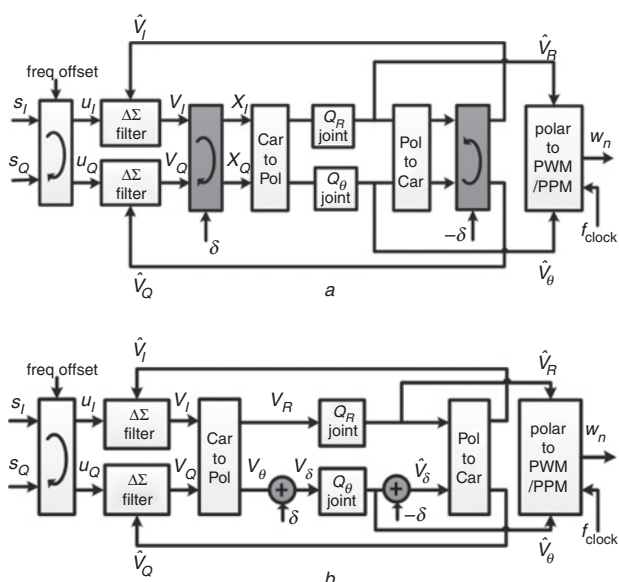Distortion products are moved away from band of interest

Although the distortion has been removed, the band of interest is no longer in the $\Delta\Sigma$ noise null. To solve this problem, we shift the noise null to the new frequency. One way to do this is to use $\Delta\Sigma$ filters with complex coefficients, to shift the noise transfer function zeros around the unit circle to the new f_{IF} frequency [7]. However, here we describe an alternate method that tunes both the noise and the input baseband signal to the new intermediate frequency. The proposed scheme involves applying a frequency rotation of f_{IF} at the input to the quantiser and then reversing the rotation in the feedback path (Fig. 4a). The phase rotation is given by

$$X = \exp(\mathrm{j}\delta) \times V \qquad (3)$$

and

$$\delta = \frac{f_{IF} \times 2\pi}{f_s} \times n \quad : \quad \mathrm{Mod}\,2\pi \in [-\pi,\ \pi) \qquad (4)$$

where $X = (X_I + \mathrm{j}X_Q)$ and $V = (V_I + \mathrm{j}V_Q)$ are in the Cartesian form. In this way, the output signal is frequency shifted yet the $\Delta\Sigma$ filters still see the same baseband signal and therefore have no need for complex coefficients. The structure can be applied to IQ-based quantisers such as in [8], but is particularly suitable for polar quantisation as shown in Fig. 4b, where the complex multiplication can be replaced by a simple addition (or subtraction) of the phase component ($V_\delta = V_\theta + \delta$).

Fig. 4 *Proposed Cartesian $\Delta\Sigma$ upconverters with applied phase rotation and derotation*

a Cartesian
b Polar

With the distortion products removed, the overall performance is determined by the noise null, which is not as deep as the baseband signal would suggest due to other noises folding into the band from the image [7] and distortion products. Even so, the noise is at least 52 dB below the carrier for all channel positions. An improvement in all the channel positions, except the zero offset channel (Channel 4) of the original baseband is shown in the scheme of Fig. 3.

Conclusion: All digital $\Delta\Sigma$ transmitters suffer from image and distortion products that generate adjacent channel interferences when the transmission is tuned away from the natural carrier frequency. We show that introducing a deliberate intermediate frequency shift equal to the transmission band bandwidth plus half of a channel bandwidth will move all the distortion products out of band. A new frequency shift method involving phase rotators before and after the quantiser is described.

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