The Hilbert pair is required to suppress one of the sidebands that is generated when the filtered input signal is shifted ('transformed') to a higher frequency. The multiply operation carried out after shifting the phase of the input signal over +45° and −45° gives rise to two double-sideband (DSB) signals. In the decoder, these signals appear around a 24-kHz component — the actual frequency depends on the shift used during the encoding, and will be discussed further on.

As shown in Fig. 2b, one of the sidebands disappears when the two DSB signals are added. The mathematics underlying this operation are shown inset in Fig. 4, a drawing reproduced from an earlier article in this magazine on frequency transformation (Ref. 1). The operations shown in Fig. 4 describe largely what happens in the decoder. The equations go to show that there is no way to avoid a Hilbert transform function when one of the sidebands is to be selected without resorting to (very complex) filters. As shown in Figs. 2b and 2c, the upper sideband is removed in the present design.

Multipliers or double-balanced mixers can take a number of practical shapes. Although their design is mostly plain sailing, they do have to be balanced with the aid of adjustments, and may have insufficient linearity for some applications. Good results at a very small outlay, and without the need of adjustments, can be achieved with electronic analogue bilateral switches, e.g., those contained in the 4053 CMOS multiplexer IC. These switches are particularly well suited to use in the decoder where they enable high suppression of the 24 kHz component to be achieved. When this suppression is insufficient, a 1.5-kHz signal (whistle) would readily appear in the decoded spectrum, corresponding to the amount of frequency shift applied. The main disadvantage of the analogue switches is that they generate a frequency spectrum with spurious components centred around odd-numbered harmonics of the 24-kHz switching signal. It will be recalled that switching is the same as multiplying with a rectangular signal. Thus, in terms of the spectrum, switching can be described as a multiplication with the Fourier series

$$\sin(\omega t) - \tfrac{1}{3}\sin(3\omega t) + \tfrac{1}{5}\sin(5\omega t) - \tfrac{1}{7}\sin\ldots$$

The sidebands of the third harmonic, which are visible in Fig. 2c, are removed with the aid of a low-pass filter designed for a steep roll-off at 30 kHz. This is done to prevent the sidebands causing interference in the mixing operation that restores the original frequency band.

The actual decoding process is relatively simple. As shown in Fig. 2d, the encoded signal is subjected to a second multiply operation, this time with a frequency of 22.5 kHz. The equations in Fig. 4 once more prove that the decoding operation works and yields the desired output signal.

Finally, the decoded signal is taken through a low-pass filter to remove spurious components generated by, among others, the switching mixers.

Which frequencies?

The frequency shift of 1.5 kHz used in the decoder is achieved by first shifting the spectrum to 24 kHz. Next, the spectrum is shifted down again with the aid of a signal of 22.5 kHz, or the difference between 24 kHz and 1.5 kHz. This restores the spectrum to the frequency range it has at the input of the encoder (which may be thousands of miles away, or just round the corner). In other words, we have decoded the scrambled signal. Note that it is also possible to shift the spectrum 'direct' by 1.5 kHz, but not when analogue switches are used as mixers.

Even though a special kind of frequency synthesis had to be implemented to ensure the required stability of the frequency transform, the 'third method' is used in the decoder for reasons already mentioned. For example, a stability of ±5 Hz is equal to 0.33% at 1,500 Hz. However, the 1,500 Hz signal is not generated directly, but indirectly as the difference between 24 kHz and 22.5 kHz. At 24 kHz, an error of ±5 Hz is equal to 0.021%, while at 22.5 kHz it equals 0.022%. When these two switching frequencies are generated independently, the accuracy of each of them must be 0.01% to ensure that a total error of ±5 Hz is not exceeded. It is readily seen that 0.01% is a pretty tough requirement as regards stability, particularly when the relevant oscillators are to be designed as free-running types to enable a free choice of the shift frequency. However, it can be shown that if these two frequencies have fixed phase relation, the common (central) oscillator from which they are derived is good enough if it has a relative deviation equal to the maximum permissible error at about 1,500 Hz, which is 0.33%. In the present decoder, this is realized with the aid of a central oscillator in conjunction with two digital dividers. Basically, the first divider is set for a divisor of 15, the second for a divisor of 16. The frequency of the central clock is

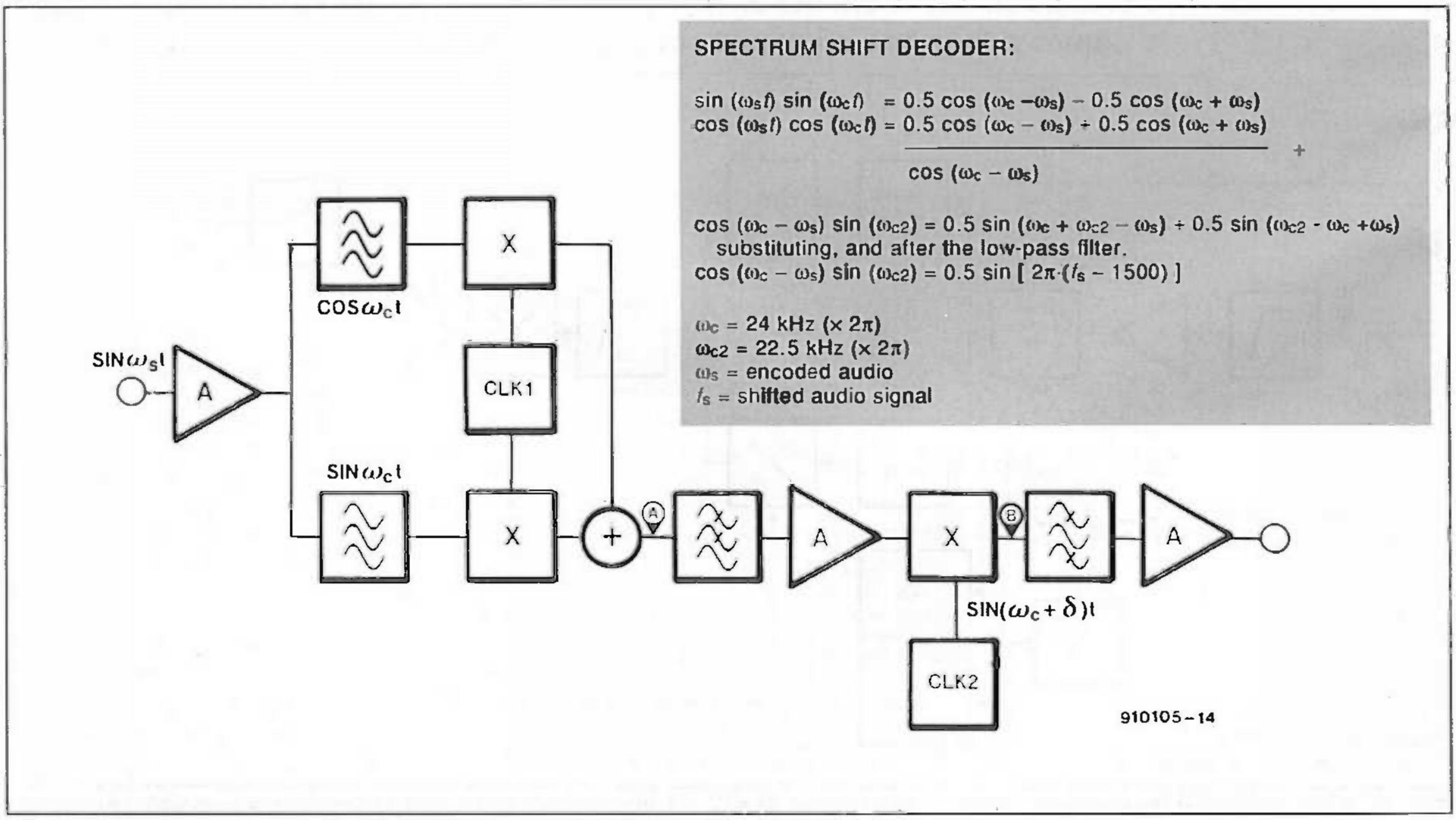

Fig. 4. The 'Feedback killer' (Ref. 1) is a practical realization of a Hilbert transform.