CARRIER RECOVERY FOR 49 QUADRATURE PARTIAL RESPONSE SIGNALS

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ABSTRACT

A reference carrier signal should be regenerated from a received partial response (PR) signal in order to facilitate optimal demodulation of the received signal. This paper describes the development and evaluation of such a carrier recovery system using DSP techniques.

The relative phase of a free-running local oscillator at the receiver is synchronized with the carrier signal of a received 49 quadrature partial response signal (49QPRS). Synchronization is achieved and maintained by means of a process of cross-correlation.

Key words: QPRS, carrier recovery, correlation, synchronization.

1. INTRODUCTION

When data is transmitted from one location to another, successful receiving of the data is, amongst other things, dependent on the ability of the data receiver to reconstruct the time base of the transmitter. Both the phase and frequency of the receiver carrier oscillator should be aligned with that of the transmitter if the bit stream is to be demodulated successfully.

This paper describes a carrier synchronization scheme developed for an experimental low-frequency 49QPRS data transmission system. A data rate of 9600 bits per second was used, with data encoded into two 7PRS channels. These channels were modulated in quadrature on a carrier frequency of 3600 Hz with a symbol rate of 2400 Hz.

The system as described was implemented using two SIG-56 DSP development boards, fitted into the expansion slots of two personal computers.

2. CARRIER RECOVERY

To successfully recover the carrier signal of a data transmitter, both the frequency and phase of the transmitter carrier signal should be tracked accurately by the receiver. Several causes can introduce fluctuations in these parameters of the received signal and in order to successfully demodulate the received signal, these fluctuations should be replicated on the locally generated carrier.

The detection process is described as follows in [1]:

Assume the presence of a small frequency error.Aw, and a phase error, *K,* in the recovered carrier signal at the receiver. During demodulation, the receiver then forms the product,

$$
\begin{aligned}
b(t) &= a(t)\cos\omega_c t\cos[(\omega_c + \Delta\omega)t + \theta_o] \qquad (1)\\
&= \tfrac{1}{2}a(t)\cos[(\Delta\omega)t + \theta_o]\\
&+ \tfrac{1}{2}a(t)\cos[(2\omega_c + \Delta\omega)t + \theta_o]
\end{aligned}
$$

where:

mo = modulating signal
«>, =carrierfrequency
•w = frequency error
o, = phase error

The second term in the bottom line of (1) is centered at twice the carrier frequency and can be filtered out by a low-pass filter. The output of this filter is then:

c(O = ^(Ocos[(A(u)f+0J (2)

The output is therefore the modulating voltage, as well as an error signal as a function of any frequency or phase error present. Now consider the case where there is no frequency error, so that there is only phase error. The filter output can now be simplified to:

$$c(t) = \tfrac{1}{2}a(t)\cos\theta_o \qquad (3)$$

Thus, the phase error in the local oscillator causes a variable gain factor in the output signal that is proportional to the cosine of the phase error. For small, fixed errors, this is tolerable, but for errors approaching 90 degrees the signal disappears. Hence, under these conditions, there is no evidence in the output of the phase error. Obviously a randomly varying phase error results in unacceptable performance. However, if the phase error can be kept relatively constant and below say, 10 degrees, the variation in gain of the output will not be in excess of 1.5%-with a limited negative effect on the output signal.

If there is only a frequency error, (2) simplifies to:

c{t) -- ±a(t)cos(A(o)t (4)

Hence, instead of recovering the modulating signal successfully, the output now consists of the modulating signal, multiplied by a low frequency sinusoid. This multiplying frequency equals the error frequency as a consequence of the imperfect transmission of the transmitted signal. Obviously this results in unacceptable distortion and a loss of coherent reception.

From the above it is obvious that accurate recovery of both the frequency and phase of the locally generated carrier is imperative for good recovery of the modulated signal. Therefore, the function of the carrier recovery circuit in the receiver can be described as follows [2]:

- To generate a local frequency equal to that of the carrier oscillator in the transmitter.
- To estimate the phase difference between the outputs of the transmitter carrier frequency generator and the local carrierfrequency generator.
- To adjust the phase of the receiver oscillator to correspond with that of the transmitter.

A 1982/1983 survey of the USA telephone network revealed a shift of 2 Hz on only 0.2% of all connections [3]. Modern techniques are capable of producing oscillators with exceptional stability and stability performance levels better than 10-7 is preferred [4].

A number of different techniques have been developed to enable the successful recovery of carrier signals. One of these entails transmission of a pilot tone, from which the desired frequency is derived.

3. PILOT CARRIER SYNCHRONIZATION

A residual carrier signal is available for synchronization purposes in a double-sideband amplitude-modulated system. Isolation of the unmodulated carrier from the composite frequency spectrum can be realized by the use of suitable bandpass filtering. In the case under consideration, with a double-sideband suppressed carrier (DSBSC) signal, no carrier is transmitted. However, a pilot carrier signal can be transmitted for synchronization purposes. This technique was utilized in the system as developed.

The spectral composition of the modulated 49QPRS system as defined above has a spectral null at a frequency of 1200 Hz. Since this is equal to a third of the carrier frequency, it is a suitable position for a pilot tone. Figure 1 shows the frequency contents of the modulated signal with the pilot tone included.

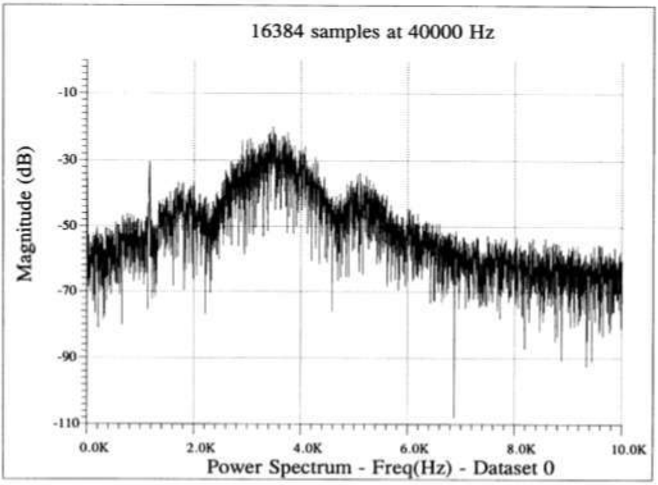

Figure 1: Frequency composition of modulated 49QPRS signal -with a pilot tone at one-third of the carrier frequency.

Due to the following reasons it was decided to implement carrier synchronization using a pilot tone:

- Ease of implementation in a discrete-time system.
- A desire to evaluate the performance of a correlation calculating technique of acquiring and maintaining carriersynchronization.
- The suitability of the frequency spectrum of the 49QPRS signal for such an approach to the regeneration of the carriersignal.

The operation of the clock recovery circuit can be described as follows:

The received signal is sampled at a frequency of 19200 Hz. The pilot tone is extracted from the sampled, composite 49QPRS signal using bandpass filtering at 1200 Hz. Using digital signal processing (DSP) techniques, this signal is converted to a frequency of 3600 Hz and again bandpass filtered. This signal is at the correct frequency, but may be noisy and of varying amplitude. In order to derive a noise-free signal at the correct phase - as well as the quadrature equivalent thereof for the reception of the quadrature data component - this signal is correlated with a built-in sinetable in the DSP processor. Deriving the carrier output signal from the sinetable has the added advantage that a constant amplitude signal is obtained.

The correlation process takes place every eleventh sample, and, if necessary, is accompanied by a phase adjustment in the recovered signal.

Twelve samples of the received signal are used for the correlation calculations. At the stipulated sampling rate, this corresponds to a correlation/phase adjustment once every 2.0625 cycles of the 3600 Hz carrier wave. The position on the sinetable, corresponding to the maximum correlation value, is determined and used as reference for the duration of the next eleven samples. Since both sine and cosine values are read from the built-in sinetable, this output can be used for demodulation of both the in-phase and quadrature data channels of the received signal.

Since the built-in sinetable has 256 values, the phase adjustment is done with a resolution of less than 1.41 degrees. It is realized that a correlation length of slightly more than two cycles is substantially less than the generally accepted minimum value of five cycles [5]. However, a compromise had to be arrived at regarding the correlation length between (1) the possible improved accuracy of a longer length, and (2) the additional processing time required for longer sequences. Considering that the aim of the correlation procedure is not to determine the relative wave shapes of two signals, but rather only to determine the relative phase of the received signal, the correlation length as specified was decided on. This decision proved to be correct during the eventual evaluation of the recovery scheme.

The process of cross-correlation between the recovered signal, $g_r(f)$, and the signal, $g, (t)$ read from the sinetable, can be described as [6]:

$$R_{12}(\tau) = \frac{1}{T_c} \int_{-T_c/2}^{T_c/2} g_r(t) g_s^*(t-\tau) dt \qquad (4)$$

Where:

T_c =the period of the recovered frequency

The resulting cross-correlation value is also periodic, with a period equal to the period of the recovered frequency. This is shown in Figure 2. Here the cross-correlation between two periodic signals with the same frequency is plotted at different relative phase angles. From this it is clear that the correlation value is a maximum when the two signals are exactly in phase. The relative phase difference between the signals can also be determined from the calculated value.

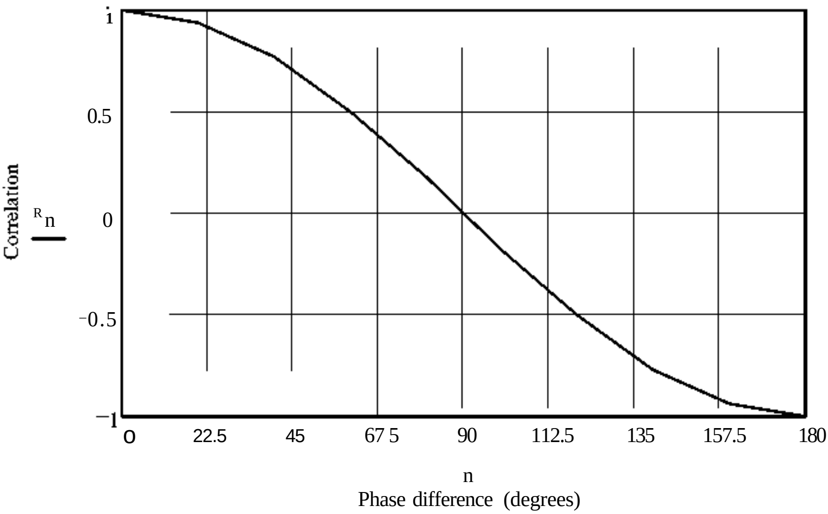

Figure 2: Cross-correlation between two periodic signals at different relative phase angles.

Due to the accuracy and stability of the crystal-controlled oscillators on both the transmitter and receiver DSP boards, the process as described proved to be sufficient and very small adjustments were required to keep the oscillators in phase.

4. ACQUISITION CHARACTERISTICS

Typically, in the case of loops using self-acquisition, the time required for the acquisition of the correct phase varies widely as a function of the initial phase error [7]. In the system under consideration, the local oscillator of the receiver is free-running for the first 12 samples. At this stage the first correlation calculation is performed and the phase of the local oscillator is synchronized with the regenerated signal - that is read from the built-in sinetable. This typically entails a substantial phase adjustment. All subsequent correlation calculations result in very modest, or even no phase corrections. During acquisition of the next eleven samples, a series of values are read from the sinetable - which are used for the detection of the received signal. These values correspond with the in-phase and quadrature carrier waves. This process is repeated every eleven samples.

From the above it is clear that for the first

\2xj- = 625\xs

(or 2.0625 cycles of the carrier wave) after the beginning of reception, the transmitting and receiving oscillators are running unsynchronized. At this instant, the correlation between the oscillators is calculated for the first time. This normally results in a large initial phase adjustment. As from this moment on, the two oscillators can be regarded as synchronized and no major phase adjustment should be required subsequently.

An acquisition time of:

$$N = 0.7j_r \text{ cycles} \qquad (5)$$

where p is the -3 dB bandwidth of the carrier bandpass filter, is considered to be totally acceptable [8]. For the system under consideration this can be written as:

$$t = Nj-$$

$$= \frac{0.7 \times 3600}{200} \times 3600$$

= 3.5 ms.

This is substantially less-demanding than the 625 s specified for the proposed system.

Since the free-running frequencies of the transmitter and receiver carrier oscillators corresponds very closely, and since the relative phases are adjusted every eleventh sample, this is followed by a series of small subsequent adjustments.

5. IMPLEMENTATION

The proposed system was implemented using two SIG-56 DSP development boards, one as transmitter and the other as receiver. The performance thereof was evaluated with the amplitude of the pilot tone at different levels, as well as at different signal-to-noise levels.

The receiver steps through the sinetable in order to generate the carrier frequency. The step size determines the frequency and the relative position on the table corresponds to an instantaneous voltage. Every eleventh sample the phase difference between this signal and the received carrier wave is determined and, if necessary, an adjustment in phase is made by a single adjustment of the step size. The top trace in Figure 3 shows the relative position (angle) on the sinetable from which a value is read, whilst the bottom trace shows the instantaneous values of one of the set of two regenerated carrier waves. By connecting the points with steps, it became easierto interpret the graph.

Initially the receiver oscillator is operating in a random phase, but after twelve samples the phase is adjusted dramatically. At this point in time the oscillators became locked and no big phase adjustments were required subsequently. The bottom graph shows the waveform of the synchronized cosine wave. The initial adjustment twelve samples after initiation of the receiver - is obviously very large, but no other such big phase changes were required subsequently.

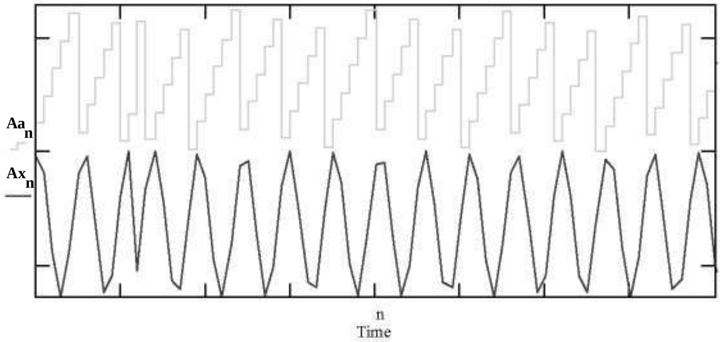

Figure 3: Position on sinetable before, during and after acquisition of synchronization.

Figure 4 shows a typical acquisition and tracking response for the carrier recovery system during the transmission of a pseudo random data sequence. An initial phase change in the order of 125 degrees is shown, followed by a series of very small adjustments - none of which was in excess of 5,7 degrees - at regular intervals of 11 samples.

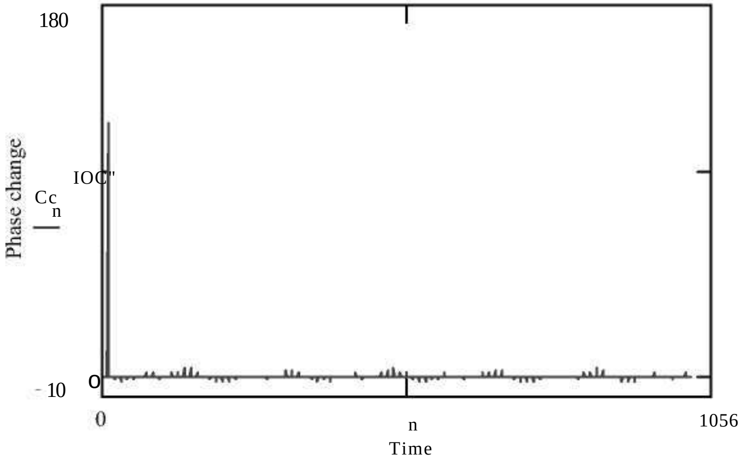

Figure 4: Typical phase adjustments of carrier recovery circuit.

The actual waveforms of the received signal, as well as the synchronized carrier wave, are shown in Figure 5. The top trace shows the carrier wave of the transmitter, whilst the middle trace shows the generated signal at the receiver. This signal is correlated with a series of values derived from the built-in sinetable (as described above). The bottom trace shows the regenerated, synchronised signal - after an initial, large phase correction as shown. Subsequent phase corrections were relatively small and are not easily discernable in the relevant trace.

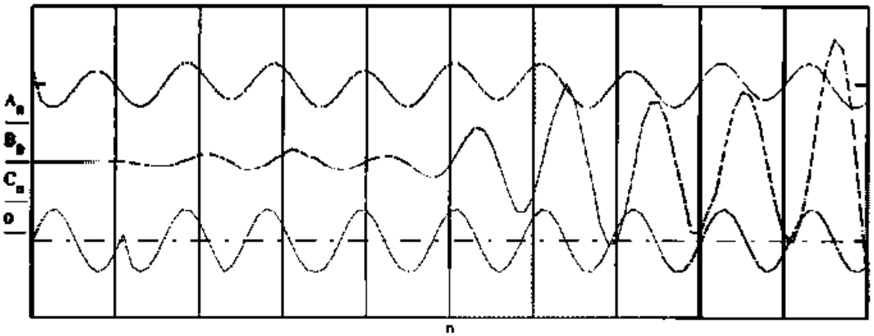

Figure 5: Received and synchronized carrier signals.

The extent to which the performance of the synchronization scheme is dependent on the level of the pilot tone was also investigated. The average size of the steady state phase adjustments was found to be related to the level of the pilot tone transmitted in that a lower level pilot tone results in less-satisfactory tracking. With the level of the pilot tone below approximately -35 dB with respect to the level of the data, there was a sharp increase in the extend to which the phase angle have to be adjusted to maintain synchronization. Obviously use of such low levels of pilot tone is to be avoided. The width of the distribution of the relative size of phase adjustments also increases at lower levels for the pilot tone. At -40dB the distribution is deteriorating seriously and the distribution is hardly normal anymore. Figure 6(a) shows the distribution for a pilot tone of -23 dB and Figure 6(b) that of a tone of-40 dB.

The frequency of the recovered signal is centered at 3.6 kHz - with very little noise in the frequency domain. Figure 7 shows this characteristic for a pilot tone of -23 dB. The relative purity of the frequency characteristic deteriorated with a reduction of the pilot tone level. However, transmission of a pilot tone at higher levels resulted in ever better frequency characteristics.

The scheme as described was used successfully to demodulate a 49QPRS data signal. Very good synchronization was achieved with a pilot tone level of as low as -30 dB relative to the data signal. At lower levels the phase adjustments became excessive.

Measurements were also done at different signal-to-noise ratios (SNR) of the received signal, with the pilot tone constant at approximately -12 dB. No substantial deterioration of the tracking performance was noted, until the signal became so degraded by noise that the data could not be extracted successfully, irrespective of the availability of the carrier wave. Hence, the operation of the developed carrier recovery system was found to be such that, with a pilot tone of not less than -12 dB, the system would stay synchronised for input signals which are suffering from noise to such an extent that the demodulation and detection processes malfunction.

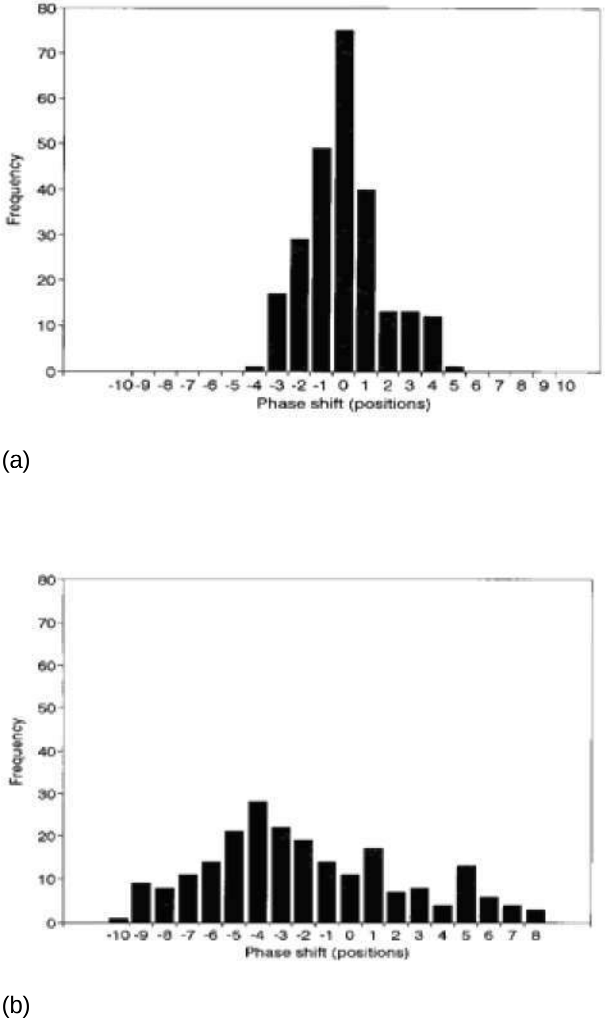

Figure 6: Phase shift in number of positions on the sinetable with pilot tones at (a) -23 dB and at (b) -40 dB.

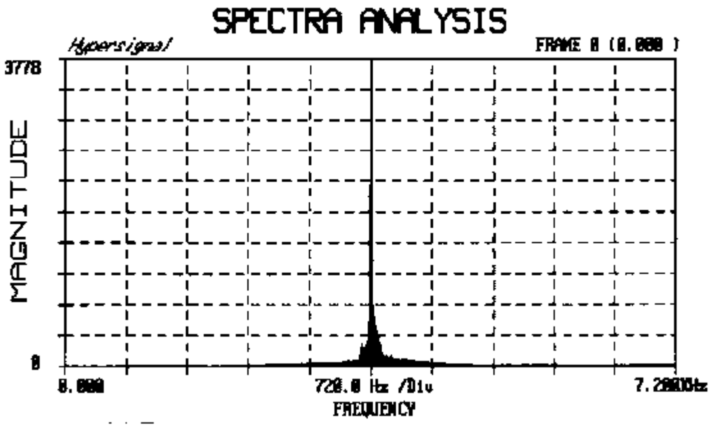

Figure 7: Recovered carrier wave in frequency domain.

The carrier recovery scheme as proposed was also implemented in a 49QPRS system with a carrier frequency of 1800 Hz and a pilot tone at 900 Hz. The performance was also very good, but due to the fact that this configuration implied a doubling of the recovered frequency rather than a tripling - there was a phase ambiguity of 180 degrees.

6. SUMMARY

A carrier recovery scheme, employing a pilot tone at one third the frequency of the carrier, was developed and was used successfully to demodulate a 49QPRS signal using DSP techniques. By optimizing the execution speed of the software, and limiting the data length used to calculate the cross-correlation between a frequency-multiplied version of the received pilot tone and a locally generated carrier wave, the proposed scheme had the following characteristics:

- Extremely fast initial phase acquisition and subsequent correction.
- Very good performance was attained at relatively low levels of pilot tone with very small phase adjustments.
- Maximum phase adjustments of less than 10 degrees with pilot tone levels of not smaller than -35 dB below the level of the data signal.
- A high degree of noise immunity.
- More frequent calculations of the correlation values should lead to even smaller phase adjustments than those measured.
- Using a sinetable with more values than the 256 values of the built-in table should improve the overall performance of the system.
- The frequency characteristic of a 49QPRS signal is especially suitable for this type of carrier recovery.
- Limiting the length of correlation calculations still resulted in good performance with fast execution times.

7. REFERENCES

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