THE USE OF TRANSPARENT TONE-IN-BAND (TTIB) FOR COHERENT DATA SCHEMES WITH PARTICULAR REFERENCE TO SINGLE SIDEBAND MODULATION

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ABSTRACT

The paper briefly reviews a new pilot tone SSB configuration, transparent tone-in-band (TTIB), which may be used in mobile radio systems from low-band VHF to microwave frequencies.
Results are presented for the system performance when it is used to transmit coherent PSK, non-coherent FSK and DPSK data formats under white noise and Rayleigh fading conditions.

INTRODUCTION

During the past five years a considerable amount of research and development has been conducted in both the UK and the USA into the use of narrowband single sideband (SSB) modulation for the civil land mobile radio service at VHF and UHF. This work has been stimulated by the severe spectrum congestion being experienced in the major conurbations with current AM and FM systems. Each of the proposed SSB systems to date requires the transmission of a low level pilot, some 10-to-15 dB down on peak envelope power, together with the wanted modulation to provide the receiver with a reference for the automataic gain control (AGC) and automatic frequency control (AFC) circuitry. The "transparent" tone-in-band (TTIB) system implemented in our studies allows the pilot tone to be positioned in the central region of the transmitted spectrum, thereby retaining the many system advantages of the original Wolfson tone-in-band system, without the necessity to notch out part of the wanted modulation spectrum. Although a form of TTIB suitable for speech communication has been described elsewhere, a modified TTIB technique, phaselocked TTIB, has recently been developed (Ref.1) which allows both speech and data (coherent and non-coherent) to be transmitted. In this contribution, a necessarily brief description of TTIB will first be given before describing its application to the transmission of coherent data schemes over a UHF SSB mobile radio link. The first form of TTIB processing described is suitable for data signalling alone whereas a second form of TTIB processing incorporating feedforward signal regeneration (FFSR) (Ref.2) in the receiver is suitable for the transmission of both speech and data.

THEORY OF TTIB

The basic operation of TTIB is relatively simple to understand and is illustrated in figure 1. The baseband signal's spectrum, which is usually accepted to extend from 300 Hz to 3 kHz in mobile communication systems is split into two approximately equal frequency segments, e.g. 300 Hz - 1.7 kHz and 1.7 kHz - 3 kHz, by suitable filtering. The upper frequency band is translated up in frequency by an amount equal to the required "notch" width and then added to the lower frequency band. If, for example, the required "notch" width or band separation is 1.2 kHz (an extreme figure but useful in demonstrating the flexibility of TTIB) the circuit output will comprise a signal extending from 300 Hz - 1.7 kHz and 2.9 kHz - 4.2 kHz. The low level reference pilot tone is then added to the centre of the resulting notch, which for our particular example, would be 2.3 kHz. This composite signal is then transmitted using conventional techniques. In the receiver, the final stages of the audio processing remove the pilot in the usual way for AGC and AFC purposes and perform a complementary downwards frequency translation of the upper half of the audio spectrum, thereby regenerating the original baseband signal. Thus TTIB gives the user a complete 300 Hz - 3 kHz channel while retaining all the system advantages of tone-in-band SSB. TTIB trades-off transmitted spectrum width for "notch" width directly. Consequently, at UHF, where a wider separation is required between the pilot and its neighbouring information components than at VHF, the "notch" width can be simply increased. In this way, the fading pilot tone can be extracted unambigously for use in an FFSR circuit.

There are clearly many ways of implementing TTIB with the method shown in figure 1 being perhaps the most general and flexible approach. Simpler forms of implementation do exist, but tend to suffer from various limitations such as restricted "notch" width range. Our discussion so far has assumed ideal systems components, i.e. 'brickwall' filters, etc. In practice, the TTIB circuits described use filters with non-ideal roll-off characteristics and this leads to a small interference band in the centre of the

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received signal's spectrum. Although it can be shown that this imperfection has no detectable effect on speech quality, and can be made arbitrarily narrow by the use of high order CCD or SC filters, the requirement of channel transparency for data communications calls for some modification to be made to the original design concept.

Phase-locked TTIB with non-ideal filters

For data communications with a bit error rate performance equal to or better than that obtained with pilot carrier and above band tone systems, the TTIB processing at the transmitter and receiver must be locked in frequency and phase to eliminate the interference region of the unlocked system. This requires a frequency and phase reference to be generated from the received signal for use in the proposed phase-locked tracking circuit. Unfortunately, the pilot tone transmitted with TTIB cannot be used for this purpose since the tone suffers from the effects of multipath propagation and possible frequency error due to misalignment of the transmitter and receiver local oscillators. The only means of obtaining the correct reference is by transmitting the required information as the difference frequency and phase between two signals from which the translation frequency in both the transmitter and receiver processing can be regenerated. By utilising a difference frequency procedure, the random frequency effects induced by multipath propagation and any system frequency error are eliminated as they are common to both signals. The only problem remaining is to decide the most approriate way of transmitting suitable reference signals without affecting the transparency or complexity of the system. A technique for performing this task is shown in figure 1 (dashed area) and uses the frequency and phase relationships which exist between the upper and lower bands of the transmitted spectrum within the transition (or interference) region. The receiver phase-lock processing has been shown (Ref.1) to operate such that the signal controlling the VCO, point i, contains only the required information concerning the frequency and phase error between the transmitter and receiver translating oscillators. This signal in turn modifies the VCO frequency and phase such that the frequency error is eliminated and the phase error minimised. When this occurs the loop is said to be in lock. Experimentation has shown that a simple passive lag (RC) filter in the PLL gave optimum performance in the presence of speech and data and that the loop parameters used were non-critical within reasonable limits. The system implemented experimentally has been shown to eliminate the interference region and to be completely satisfactory for both speech and data.

COHERENT DATA SYSTEMS FOR SSB

It is well known that coherent detection of data, whether it be PSK, MSK, etc., gives superior bit error rate performance than the corresponding non-coherent detection when the received signal is corrupted by white Gaussian noise. Unfortunately, the extraction of the coherent phase reference in the receiver is not always a simple task. Several techniques for obtaining a coherent reference have been developed and these can be divided into two main categories, namely; (1) those which derive the reference from the data modulated signal itself, e.g. N^{th} order tracking loops, Costas loops, etc., and (2) those which make use of a transmitted reference, e.g. adjacent tone reference systems. The data derived reference systems require only sufficient transmission bandwidth to pass the modulated data carrier, without undue distortion, whereas the adjacent tone systems necessitate the additional bandwidth occupied by the reference tone. In such systems, the increased bandwidth is traded for simplicity in the reference extraction circuitry of the receiver, bandpass filtering or simple phase-locked loops being used in place of the complex tracking systems required for data derived references. This becomes increasingly important for M-ary systems, $M > 2$, where the complexity of the processing is often prohibitive.

In the application of coherent data systems to SSB mobile communications, the task of extracting a coherent reference in the receiver is complicated by the frequency uncertainty associated with SSB modulation and by the multipath induced fading of the received signal. The combination of these effects results in the need for much wider tracking systems to obtain a coherent data derived reference. As a result, the noise modulation of the coherent reference is greatly enhanced. Random amplitude and phase modulation and frequency error are also present with the adjacent tone systems. However, since the detection process is essentially linear, unlike the data derived reference systems the effects are less disruptive. The following discussion is only concerned with tone reference systems for coherent data schemes and, in particular, the ease with which these schemes may be implemented with TTIB. Further work concerning the use of data derived tracking systems compared with tone reference systems is the subject of a subsequent paper.

Adjacent tone reference systems for coherent detection

With SSB modulation, unless a carrier reference is transmitted for the purpose of coherent demodulation, the received signal will contain a frequency error, $\Delta\omega_e$, between transmitter and receiver local oscillators. With pilot carrier SSB, the pilot tone can be extracted at a suitable intermediate frequency and then used for final demodulation in the receiver. In this case, the demodulated carrier is at dc and cannot be used to generate a reference for subsequent data demodulation. This requires the transmission of an additional reference tone which in turn increases the signal bandwidth, and power requirement. For this reason, and for reasons discussed in a paper by the authors (Ref.2) concerning the correlation between fades on the pilot and modulation components, and frequency correction systems, this form of reference tone SSB is dismissed. The transmission of a reference at any frequency other than at the SSB carrier frequency, except with TTIB systems, means it cannot be used for coherent demodulation of the received signal and the frequency uncertainty, $\Delta\omega_e$, will always be present in the baseband output. Accepting this inherent frequency error, let us now consider the feasibility of adjacent tone reference systems for coherent SSB data schemes. Assume the reference tone frequency to be some fraction 'n' of the data carrier frequency. The received carrier, D(t), and reference, R(t), may then be written as:

$$D(t) = D\cos(\omega_s t + \phi(t) + \Delta\omega_e) \qquad (1)$$

$$R(t) = R\cos\left(\frac{\omega_s t}{n} + \Delta\omega_e\right) \qquad (2)$$

where D and R represent the carrier and reference amplitudes respectively, and $\phi(t)$ represents the phase or frequency modulation due to the data stream. If the received data tone, R(t), is now multiplied by a factor 'n' to obtain the 'coherent' reference R'(t):

$$R'(t) = R\cos(\omega_s t + n\Delta\omega_e) \qquad (3)$$

there is a residual frequency error of $(n - 1)\Delta\omega_e$ between the data carrier and reference tone. The only means of reducing this frequency error to zero is by making 'n' equal to unity, i.e. the reference tone is transmitted at the carrier frequency as is possible with TTIB.

The application of TTIB to coherent data systems

For the sake of simplicity and brevity, the following discussion is confined to the application of TTIB to coherent M-ary PSK systems and binary PSK (M = 2) in particular. Two possible configurations for such a system are shown in figures 2(a) and 2(b). The first system, figure 2(a), is applicable to data systems alone with the reference tone inserted at the data carrier frequency serving no other purpose than to provide coherent demodulation of the received data signal. The second system, figure 2(b), provides a common link for both speech and data transmission. Here the transmitted reference, again at the data carrier frequency, is used for the correction of the multipath induced random amplitude and phase distortion of the received signal by FFSR. The regenerated output is essentially free of these random amplitude and phase fluctuations. After reconstruction in the phase-locked TTIB receiver processing, the data signal can be coherently demodulated by the locally generated FFSR reference, which has the exact frequency and phase of the unmodulated data carrier. In both systems, the transmitted pilot tone is available for use in frequency control circuitry of the receiver. It should be noted that the phase of the reference tone relative to the data carrier at the transmitter is maintained by means of the phaselocked TTIB technique at the receiver. Hence, there is no phase ambiguity in the data demodulation process. This is not the case with data derived reference systems which require some means of resolving the phase ambiguity such as differential encoding of the data prior to modulation. Both TTIB systems are easily extended to M-ary PSK by simply generating the required phase shifted references in the receiver.

With all coherent systems, the derived reference, whether it be obtained from the received data signal or from an additional reference tone, is corrupted by noise along with the received modulation. As previously mentioned, the frequency uncertainty associated with SSB modulation and the multipath induced distortion necessitate the use of wide tracking systems for data derived references to ensure phase locking and accurate tracking of the imposed random phase modulation. Consequently, the immunity to noise is poor. Similarly with tone reference system, the bandpass filter used to extract the reference requires sufficient bandwidth to accommodate the expected Doppler frequency shift and any frequency off-set which may be present.

For the case of TTIB, the bit error probability has been calculated for coherent binary PSK, with a noisy reference tone, and is presented in figure 3 as a graph of bit error probability versus carrier-to-noise ratio at the demodulator input. Also shown is the expected error rate for DPSK when used in conjunction with FFSR. A more rigorous theoretical treatment of the bit error rate probability will be the subject of a subsequent publication. The parameter 'q' in Figure 3 is a measure of the noise power associated with the received data signal to that of the reference tone and is defined as the ratio of the reference tone-to-noise power ratio at the pilot filter output to the carrier-to-noise power ratio at the demodulator input.

The value of 'q' is governed by the ratio of the reference filter bandwidth to that of the receiver modem filter and by the data carrier-to-reference power ratio, which for the case of Gaussian white noise, as the sole interference becomes:

$$q = \frac{P_R\, B_{DATA}}{P_D\, B_{REF}}$$

where P_R is the reference tone power
P_D is the data signal power
B_{DATA} is the bandwidth of the receiver modem filter prior to the demodulator
B_{REF} is the bandwidth of the pilot extraction filter

For the majority of applications the bandwidths of both filters will be fixed by the data rate and Doppler frequency shift. The performance of the modem is then governed by the ratio of carrier-to-reference power. Increasing the reference level with respect to the data carrier gives an improvement in bit error probability for a given CNR but requires an increase in transmitter power to maintain the same CNR at the receiver input. Clearly, there is a carrier-to-reference power ratio which will give an optimum performance for a given application. Typical values of 'q' for an SSB mobile radio system operating at 457 MHz, with an available data bandwidth of 3 kHz and a data carrier-to-reference tone ratio of 10 dB's, lie in the range 1 → 3.

Modem performance with Rayleigh fading

So far, the analysis has assumed a stationary vehicle such that the amplitude and phase of the received signal can be considered to be constant over several bit periods. Once the vehicle is in motion, the amplitude and phase of the received signal fluctuate rapidly due to multipath propagation effects and obey Rayleigh statistics. This type of fading is found to be characteristic of many types of environemnt and will be used to illustrate the performance of a coherent TTIB data system for a non-stationary vehicle. The bit error probability versus CNR for binary PSK in the Rayleigh fading environment is shown graphically in figure 4 for various values of 'q'. Also included are the error rates for DPSK and FSK with discriminator detection for comparison purposes. The irreducible error rates for DPSK and FSK systems arise due to the random phase modulation and are based on the work of Voelker (Ref.3) and Jakes (Ref.4) - a bit rate of 1200 bps and an SSB carrier frequency of 900 MHz are assumed in calculating the quoted results. By using the FFSR processing prior to detection to remove the random phase modulation, the irreducible error rate can be overcome but at the expense of a slight increase in bit error probability over the optimum due to the noisy reference used for the FFSR processing. The resulting error rate/CNR curves are given in figure 5 for the case of Rayleigh envelope fading and uniform phase distribution together with curves showing the improvement achievable by the use of two-branch diversity assuming maximal ratio combining. The circuit configuration of figure 2(b) has been implemented to provide experimental verification of the theoretical graphs given in this paper. The results obtained so far show excellent agreement with the theory and will be the subject of a further publication.

CONCLUSIONS

A system utilising the novel features of TTIB has been suggested which allows the use of coherent data systems with SSB mobile radio. The system offers combined speech and data operation and a transparent channel for all types of data systems, whether coherent or noncoherent. The receiver processing required to obtain a coherent reference for data demodulation is greatly simplified compared to that used with conventional data derived reference systems and M-ary data schemes in particular. The application of FFSR in combatting the random phase modulation is shown to overcome the irreducible bit error probability arising with uncorrected systems at the expense of a slight worsening in the overall performance of the modem. By suitable choice of data carrier-to-tone reference levels this degradation can be made negligible resulting in a high performance coherent data scheme. It is important to note that the TTIB system is not confined to SSB modulation formats alone but can be applied to conventional AM and FM systems where it is considered that the simplicity with which coherent data systems can be achieved is advantageous or when the use of in-band tone signalling is required without the removal of part of the audio spectrum.

Finally, it is well recognised that some form of diversity is required to obtain acceptable error rates for data communications in a Rayleigh fading environment at 900 MHz. The transmission of a reference tone with the modulated signal facilitates the use of comparatively simple co-phasing circuitry for equal gain or maximal ratio diversity systems and this alone may justify the additional bandwidth occupied by the pilot tone compared with data derived reference schemes.

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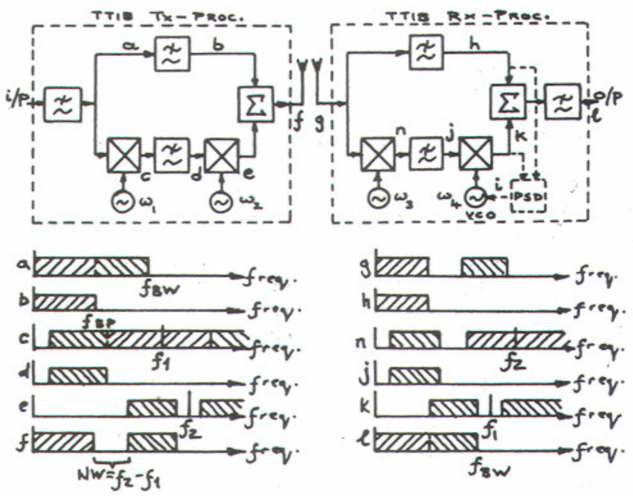

Figure 1 General implementation of transparent tone-in band (TTIB)

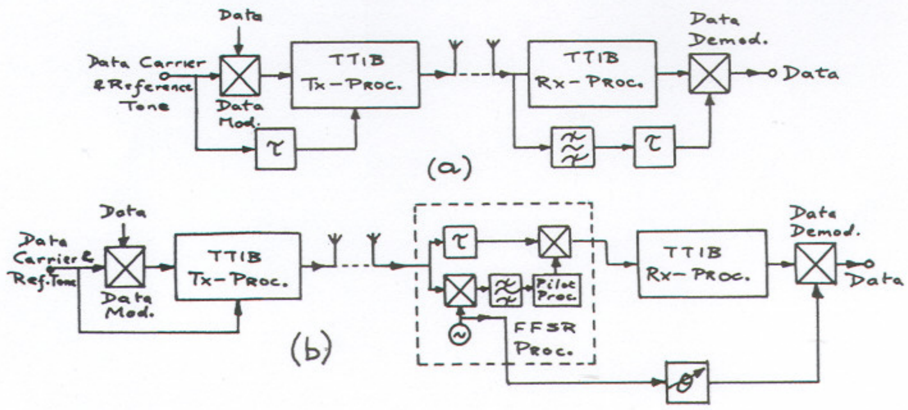

Figure 2 TTIB/FFSR audio processing for coherent data systems

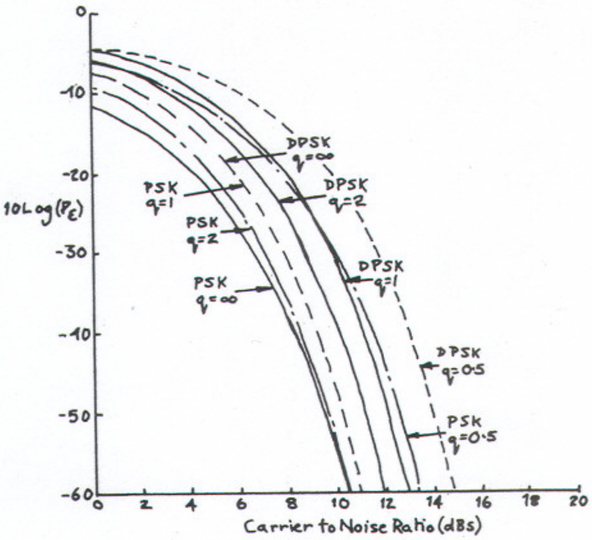

Figure 3 Bit error rates for PSK and DPSK

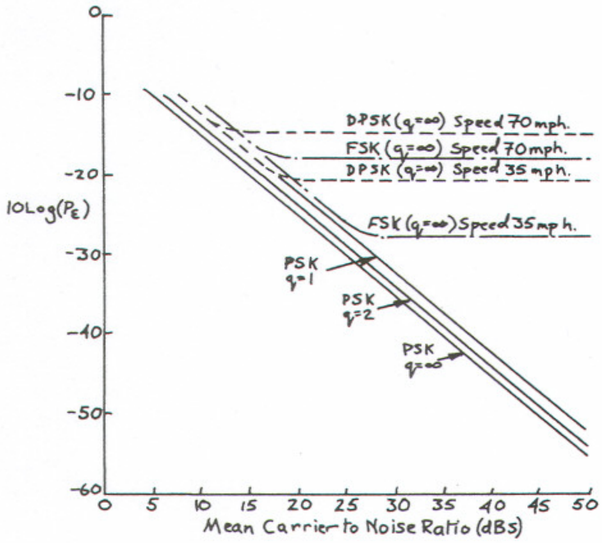

Figure 4 Bit error rates for PSK, DPSK and FSK with Rayleigh fading

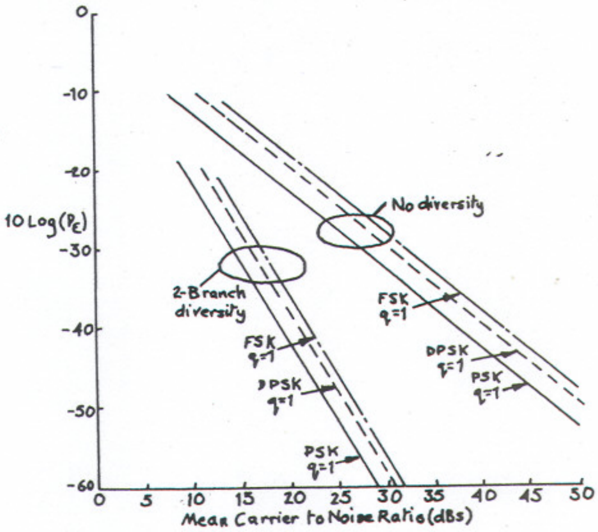

Figure 5 Bit error rates with diversity and FFSR processing

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