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SPEECH COMMUNICATION OVER A 942 MHz TONE-ABOVE-BAND  
SINGLE SIDEBAND MOBILE RADIO CHANNEL (6.25 kHz) INCORPORATING  
FEEDFORWARD SIGNAL REGENERATION

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The contribution is primarily concerned with the transmission of speech over a 942 MHz tone-above-band SSB mobile radio link. It has been found that the use of feedforward signal regeneration enables a speech quality to be obtained in the Rayleigh fading environment which is superior to that achieved by a conventional 25 kHz FM system. Finally, a new optimised form of SSB, phaselocked transparent tone-in-band, is shown to be also capable of transmitting and receiving coherent data such as CPSK in the mobile radio environment.

### Introduction

Since the World Administrative Radio Conference (WARC) in September 1979, there has been considerable effort into the ways in which the radio spectrum is used. In the field of civil land mobile radio, the finite spectrum available has manifested itself in the form of severe spectrum congestion in the large conurbations of the developed world. This situation was apparent for some years prior to WARC and had already initiated research into ways of improving spectrum utilisation. At this point in time, the UK land mobile radio service used 12.5 kHz AM and FM systems and VHF and 25 kHz FM at UHF whereas in the USA, 25 kHz and 30 kHz channelled FM was used at both VHF and UHF. In the UK, the previously adopted solution of splitting the channel bandwidth was not thought acceptable for either the AM or FM systems and other more radical solutions sought. Although it was already recognised that the efficiency of channel usage could be improved by the use of schemes such as dynamic channel allocation and cellular radio, the application of these techniques is, in general, equally applicable to other forms of modulation such as narrowband single sideband (SSB). Pilot tone SSB in 5 kHz channels has been the subject of considerable investigation throughout the world (Wells<sup>1</sup>, Lusignan<sup>2</sup> and Gosling et al<sup>3</sup>) and recently the UK Home Office<sup>4</sup> Directorate of Radio Technology has issued a report on an extensive series of field trials comparing a prototype pilot carrier SSB system with 25 kHz FM and 12.5 kHz AM and FM systems at high-band VHF. Although it is acknowledged that the performance of the test receivers could be improved, the outcome of the trials was extremely encouraging for the proponents of SSB for the civil land mobile radio service.

At the University of Bath, we have long recognised the fact that for pilot tone SSB to be universally adopted, any proposed system must be capable of vertical integration across the frequency bands, i.e. the system and spectrum configuration used at VHF must be those used, with minor modifications, at UHF. With this in mind, we have been developing techniques which enable SSB to function correctly for speech and data (coherent and non-coherent) at frequencies up to 1 GHz in the multipath fading environment. In this contribution, it is intended to briefly review the work in pilot tone SSB systems for mobile radio and to show that of the four contending systems only tone-above-band (TAB) and phaselocked transparent tone-in-band (TTIB) SSB have the flexibility to operate

at frequencies up to 1 GHz with techniques such as feedforward signal regeneration (FFSR). SSB being an AM-type modulation is subject to both the random envelope and phase induced fluctuations of multipath propagation and FFSR (an audio signal processing technique) is required to suppress these unwanted variations from the receiver output. After describing the basic operation principles of FFSR, preliminary results are given for a TAB SSB/FM comparison of speech communications at 942 MHz and for data communications over a TTIB SSB link at 900 MHz.

### Single sideband systems

To date, the greater part of the research into SSB mobile radio has concentrated upon three systems which differ essentially in the positioning of the low level pilot tone (-7.5 to -15 dB with respect to peak envelope power) within the audio band. The diminished level pilot reference being required for automatic frequency control (AFC) and automatic gain control (AGC) purposes within the receiver. The systems are:

- a) pilot carrier SSB<sup>1</sup> developed by Philips Research Laboratories,
- b) pilot tone-above-band SSB<sup>2</sup> investigated at Stanford University for the FCC, and
- c) pilot tone-in-band SSB<sup>3</sup> researched at the University of Bath.

At VHF, no one system has clearly emerged as the system to use even though, to the authors' knowledge, TAB SSB is produced commercially by two companies. However, it is generally accepted that TIB is the most radical approach, or so it would appear, since a part of the audio spectrum is removed from the central region of the audio band by a notch filter for the tone to be inserted. In doing so, the original aim at Bath of achieving the most spectrum efficient speech system is satisfied together with a system which offers the greatest degree of adjacent channel protection, a good correlation between fades on the pilot tone and fades on the audio signal and finally, a large symmetrical pull-in range for the frequency control circuitry to operate. These three points were felt to be particularly important if SSB were to be eventually extended in its VHF form to the higher frequency bands. Although tone-in-band SSB has proven entirely satisfactory for speech, and data provided the tone position is carefully selected, the system, it must be admitted, has not received universal acceptance through its non-transparency with all data systems.

In this respect, TAB and pilot carrier SSB have a definite advantage. However, for each of these two systems, transparency is achieved at the expense of placing the reference pilot to one side of the audio spectrum, thus rendering the tone more vulnerable to adjacent channel interference and requiring an asymmetric pull-in behaviour from the automatic frequency control circuitry. Furthermore, unless frequency off-setting techniques are employed, the

pilot tone for each of these two systems will be positioned in a region of high differential group delay with respect to the majority of the audio band attributable to the IF crystal filter, and this can degrade the performance of the AGC and AFC systems. However, as events in the mobile communications field have shown us in recent years, no one modulation system can be considered as having a monopoly over spectrum usage, either today or tomorrow. It is therefore pertinent to ask what would happen if we now wished to extend SSB operation to the 450 MHz and 900 MHz bands. There is already considerable interest in North America in the use of SSB in mobile-satellite communications and clearly, now would be the ideal time to establish the preferred pilot-based configuration for future SSB systems which are capable of vertical integration from VHF to 1 GHz.

A good starting point for such a system design would be to require the advantages of TIB but without the problem of non-transparency. In addition, as the frequency of operation increases, not only do the transmitter and receiver oscillator drift increase, but the rapid random amplitude and phase fluctuations superimposed on the received signal by multipath propagation become severe. At VHF, these 'fast fades', up to 35 dB deep, can occur at rates of up to 36 Hz for a vehicle travelling at 70 mph and a carrier frequency of 164 MHz. At UHF with a carrier frequency of 457 MHz, such fades occur at rates up to 100 Hz at 70 mph and at 900 MHz, they can occur at rates up to 200 times per second. Such variations can severely degrade the intelligibility of speech communications and cause data systems to have an unacceptable high error rate. In these circumstances for SSB we need to employ some form of feedforward automatic gain and frequency control to mitigate the effects of the multipath induced fading. It is known that such systems require good correlation between fades on the pilot reference and fades on the audio information. Time delay spread of the received signal through propagation effects is known not to be a problem provided the pilot tone spacing is less than about 3 kHz. Moreover, decorrelation between the pilot and audio information can occur in the receiver primarily through the intermediate frequency selection filter. Reference to the amplitude and group delay characteristics of a 10.7 MHz IF crystal filter in figure 1 shows that if the pilot tone is placed at either the pilot carrier or above-band-tone positions, it can suffer a differential time delay,  $\Delta t$ , with respect to the majority of the audio band (the ratio being as large as 2:1) and as a result of multipath induced spreading of the pilot tone (100 Hz at 457 MHz and 70 mph), the spread pilot tone will suffer a variation in filter gain across its bandwidth. Both of these effects will cause a severe degradation in the performance of any feedforward system employed. Furthermore, as the frequency of operation increases, the problem of separating unambiguously the spread pilot tone from the audio information arises. Bearing in mind the penalties of incorporating time delay in any feedback loop and the limitations of real filters in terms of roll-off, there is a definite requirement to be able to vary the separation between the pilot tone and its neighbouring information components. This flexibility is not available with pilot carrier systems but is for TAB systems. However, TAB does not completely satisfy our specified requirements for an ideal system in relation to adjacent channel protection, symmetrical pull-in range and good pilot-tone/signal correlation with fading.

For this reason, we at the University of Bath have developed a new SSB spectrum configuration called phase-locked TTIB<sup>10</sup> which possesses all the desired

system properties and which, furthermore, is transparent to data. For the sake of brevity, it is not our intention to describe the system in detail other than to say it relies on fairly straightforward audio signal processing techniques in the transmitter and receiver and can be implemented in one of two forms. In its first form, a simple modification to the TTIB processing allows data, coherent and non-coherent, to be transmitted in the fading environment. In its second form, a combined TTIB/FFSR system can be used to transmit and receive both speech and data at frequencies up to and including the 900 MHz mobile radio band. However, with either form of TTIB it is particularly easy to use coherent data formats such as CPSK in the Rayleigh fading environment. In our investigations, we have been primarily concerned with this second form of TTIB processing together with the commercially adopted TAB system at an operating frequency of 941.725 MHz. When used to transmit speech, both systems rely heavily on FFSR for high quality reception and it is necessary to now consider in some detail the basic operation principles of the technique.

### Principles of FFSR Operation

To illustrate the salient features of FFSR operation, a mathematical description of the received fading signal,  $y_1(t)$  is utilised where:

$$y_1(t) = Ex(t)\cos(\omega_1 t + \omega_p t + y(t)) + Sx(t)\cos(\omega_1 t + \omega_s t + y(t)) \quad (1)$$

The random amplitude modulation is represented by  $x(t)$  and the random phase modulation by  $y(t)$ .  $\omega_p$  and  $\omega_s$  are the angular frequencies of the pilot tone<sup>p</sup> and audio signal components respectively with E and S the corresponding amplitudes.  $\omega_1$  represents an IF frequency of the receiver. The action of FFSR is to generate a control signal  $\eta(t)$  at a second intermediate frequency  $\omega_2$  given by:

$$\eta(t) = \frac{C}{x(t)} \cos(\omega_2 t + y(t)) \quad (2)$$

where C is a constant. By using  $\eta(t)$  to linearly mix down the received signal  $y_1(t)$ , an output signal  $y_0(t)$  is generated with both the unwanted random amplitude and phase variations,  $x(t)$  and  $y(t)$ , removed:

$$y_0(t) = \frac{EC}{2} \cos(\omega_p t + (\omega_1 - \omega_2)t) + \frac{SC}{2} \cos(\omega_s t + (\omega_1 - \omega_2)t) \quad (3)$$

If the receiver is configured such that  $\omega_1$  equals  $\omega_2$  in the above expression, the required signal is demodulated to baseband.

### Implementation of FFSR

There are several ways of implementing FFSR processing<sup>5</sup> the most general of which is shown in figure 2. The technique operates at an "intermediate frequency" in the receiver and can be used with all the pilot tone SSB configurations currently being investigated. Let us assume that the signal at the input to the circuit, point A, is of the form:

$$g(t)_A = Ex(t)\cos(\omega_1 t + \omega_p t + \omega_e t + y(t)) + Sx(t)\cos(\omega_s t + \omega_1 t + \omega_e t + y(t)) \quad (4)$$

where  $\omega_e$  represents the angular frequency error in the receiver IF frequency,  $\omega_1$ . After mixing and filtering to extract the fading pilot tone, the signal at point B is given by:

$$g(t)_B = E x(t) \cos((\omega_1 - \omega_2)t + \omega_p t + \omega_e t + y(t)) \Big|_{t \rightarrow t - \tau_a} \quad (5)$$

Providing that the amplitude of the pilot envelope is above a predetermined threshold level, then the action of the processing within the block 'Z' is to generate a control signal at point C of the form:

$$g(t)_C = \frac{M}{x(t)} \cos((\omega_1 - \omega_2)t + \omega_p t + \omega_e t + y(t)) \Big|_{t \rightarrow t - \tau_a - \tau_c} \quad (6)$$

where M is a constant. If this control signal is now used to linearly mix-down a delayed version of the input signal to circuit then the regenerated signal at point D is given by:

$$g(t)_D = \frac{ME}{2} \cos \omega_2 t + \frac{MS}{2} \cos(\omega_s t + (\omega_2 - \omega_p)t) \Big|_{t \rightarrow t - \tau_b - \tau_d} \quad (7)$$

provided that the time delays in the upper and lower signal paths are matched, i.e.  $\tau_b = \tau_a + \tau_c$ . If  $\omega_2 = \omega_p$  then the resulting output signal is correctly demodulated to baseband. For pilot carrier SSB systems,  $\omega_2 = \omega_p = 0$  and the first mixer and oscillator in the control path can be removed.

It is noteworthy that this method in common with the other forms of implementation removes any frequency error,  $\omega_e$ , from the input signal thus compensating for any receiver mistuning arising from local oscillator drift in either the transmitter or receiver. Whilst this property may not be a significant factor at HF and VHF, the problem of oscillator stability at UHF is paramount. Without the use of FFSR processing, the necessity of maintaining frequency errors to within a few Hertz, desirable for high quality speech communication systems, requires complicated and expensive synthesiser and frequency locking techniques.

One means of implementing the module, Z, as shown in figure 3, uses a squaring detector for envelope extraction. If the configuration is subject at point 'a' to the fading pilot input signal described by:

$$P(t)_a = x(t) \cos(\omega_p t + y(t)) \quad (8)$$

then the output of the mixer at point 'b' is given by:

$$P(t)_b = k(x^2(t) + x^2(t) \cos 2(\omega_p t + y(t))) \quad (9)$$

After passing through the low pass filter, to remove the  $2\omega$  term, gives:

$$P(t)_c = kx^2(t) \Big|_{t \rightarrow t - \tau} \quad (10)$$

which means that the signal at the output of the threshold is:

$$P(t)_d = k \max \{x^2(t), v\} \Big|_{t \rightarrow t - \tau} \quad (11)$$

resulting in a control signal:

$$P(t)_e = \frac{k' x(t) \cos(\omega_p t + y(t))}{\max \{x^2(t), v\}} \Big|_{t \rightarrow t - \tau} \quad (12)$$

For  $x(t)$  greater than the threshold level,  $v$ , the control signal becomes:

$$P(t)_e = \frac{k'}{x(t)} \cos(\omega_p t + y(t)) \Big|_{t \rightarrow t - \tau} \quad (13)$$

Unlike other implementations of the Z module for generating the control signal  $P(t)_e$ , the squaring action of the envelope processing in figure 3 causes the resulting dynamic range requirements (measured in dB's) of the subsequent circuitry to be doubled. The justification for using 'squarer-type' envelope detection lies in the restriction of the generated harmonics to within twice the pilot tone frequency and the restriction of the harmonics of the envelope term,  $x^2(t)$ , to within twice Doppler frequency. By way of contrast, the full wave rectification process generates an infinite number of even order harmonics of the pilot tone with the phase error,  $y(t)$ , superimposed and results in a significant harmonic content of the envelope,  $x(t)$ , extending to several times the Doppler frequency. This makes it difficult or impossible to separate the pilot envelope from the related harmonics.

#### Field tests

An experimental 942 MHz TAB SSB system, operating in a 6.25 kHz channel bandwidth, has been set-up together with a 25 kHz FM scheme for comparison purposes. Both systems use the same RF linear power amplifier. For the TAB SSB system, the diminished level reference tone (-10 dB with respect to pep) is positioned at 3.9 kHz in relation to the audio band, 300 Hz - 3.4 kHz. This pilot tone-to-information separation allows for the multipath induced spreading of the pilot and information components and the finite roll-off of presently available filters. As a result, the pilot tone and its associated fading induced sidebands may be extracted uniquely for subsequent AGC and AFC processing in the receiver. To facilitate the use of existing FFSR circuitry, the intermediate frequency of the pilot tone at the processing input was set at 6.2 kHz. Figure 4 depicts the processing and frequencies actually used in the experimental system (threshold set at -20 dB) and shows that it is implemented almost entirely in software form using Intel 2920 "analogue" microprocessors. This situation has arisen through the present lack of suitable signal processing ic's and it is well recognised by the authors that a custom designed LSI chip set will produce a more optimum and superior FFSR system performance. The TAB SSB audio signal processing also employs 2;1<sub>8</sub> amplitude syllabic companding described elsewhere<sup>8</sup> to enhance the low and medium signal strength performance of the channel. For the FM system, a "hybrid system" was developed using standard 25 kHz FM techniques but with signal processing based on the AMPS scheme. Following the measurement procedure used in the UK Home Office (Directorate of Radio Technology) SSB comparative trials, the pep's for the SSB and FM transmissions were equalised. For the preliminary results reported here, the transmitter was mounted in a large European estate car and the receivers located in the Wolfson Communications Laboratory of the School of Electrical Engineering. This arrangement proved extremely successful in that it allowed the performance of each of the systems to be easily optimised and recorded.

Based upon our detailed knowledge of the fading characteristics of Bath, a test route was selected which embraced low, medium and high signal strengths. A source tape, containing recorded phrases by male and female speakers, was played over the two radio systems and used to prepare a master tape for panel assessment. The vehicle speed during the recordings was 50 mph. Prior to the listening test, each member of the assessment panel was issued with written instructions (similar to those used in the UK Home Office trials) explaining the organisation and voting method of the test. The listener was not informed that the tests referred to an FM/SSB comparison. Voting was conducted on the basis of a 5-point CCIR scale of unusable/poor/fair/good/excellent in respect of quality. Before the actual test tape was played to subjects, a control tape, recorded under laboratory conditions with the aid of a fading simulator for the respective signal strengths, was used to stabilise their aural sense and voting patterns. The members of the panel were not informed that the control section of the tape was being used for this purpose. A total of 64 votes was received for each signal strength and for each system. These preliminary results indicated that the prototype 6.25 kHz SSB equipment incorporating FFSR processing was superior to 25 kHz FM at a carrier frequency of 941.725 MHz at all signal strengths.

Finally, detailed analysis and experiments of data transmission (DPSK, FSK and CPSK) have been conducted at 900 MHz using a phaselocked TTIB SSB system incorporating FFSR. The results are shown in figure 5 and clearly demonstrate the effectiveness of FFSR in overcoming the irreducible error rate due to Rayleigh fading. More importantly, the inclusion of CPSK as a data format for mobile radio communications should be noted since it has the lowest bit error rate with respect to other forms of data transmission and can be easily implemented with TTIB SSB.

#### Conclusions

The paper has described the preliminary results for speech and data communications over a 942 MHz SSB mobile radio link incorporating feedforward signal regeneration. The quality of the speech communications obtained in the field (in relation to FM) under narrow band conditions, and the ability to transmit conventional data formats as well as CPSK without the associated 'high-level' irreducible error rates clearly demonstrate that diminished level pilot tone SSB should be considered as a carrier over the entire mobile radio bands up to 1 GHz.

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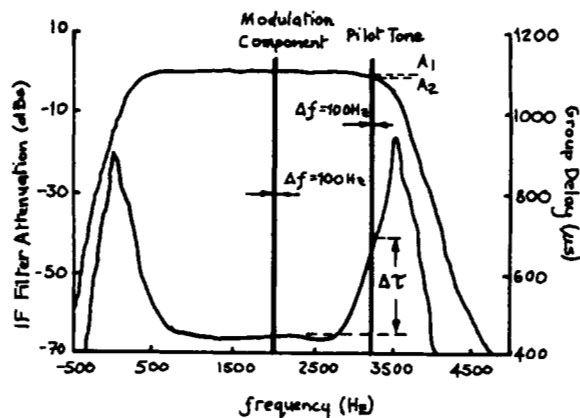


Figure 1 Typical 10.7 MHz IF crystal filter characteristic for 5 kHz channel spacing

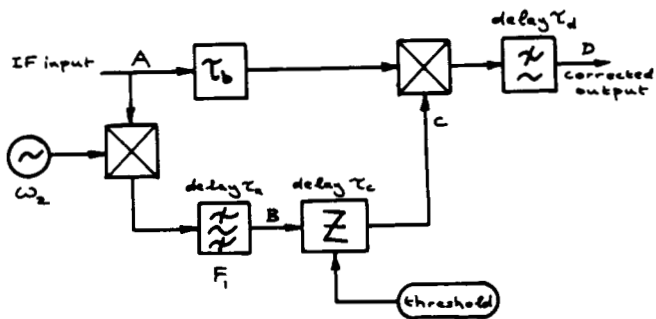


Figure 2 An implementation of feedforward signal regeneration (FFSR)

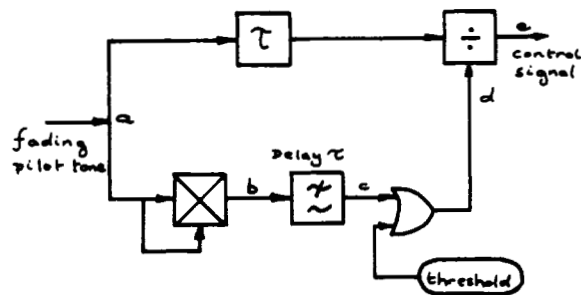


Figure 3 Possible 'Z' module implementation

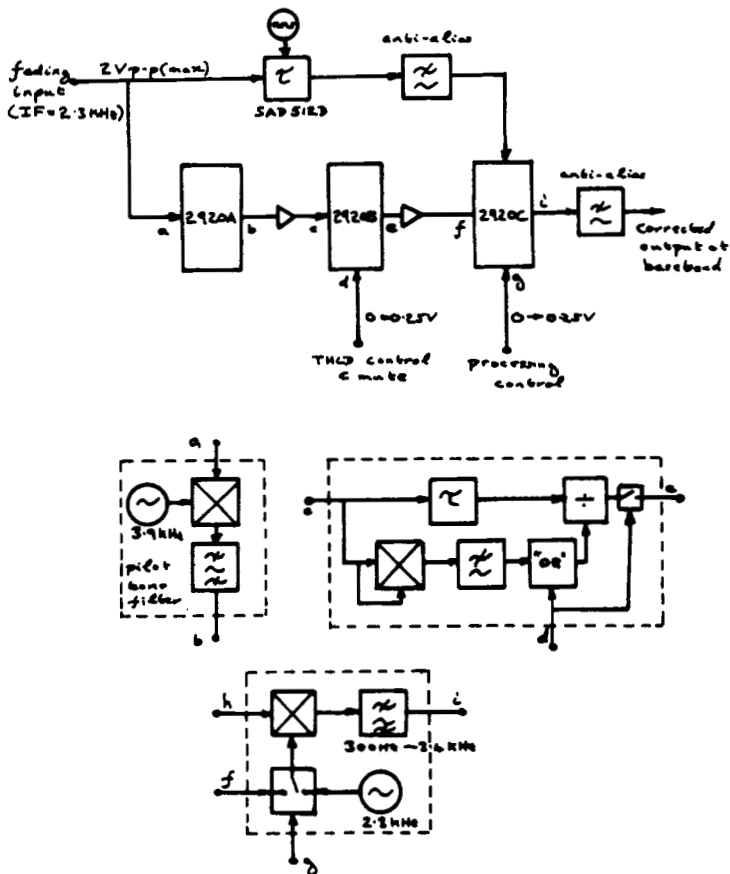


Figure 4 'Analogue microprocessor (2920)' implementation of FFSR processing

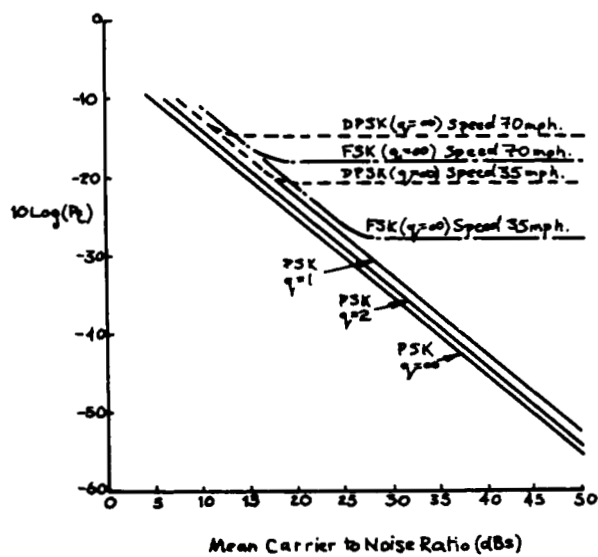


Figure 5 Bit error rates for PSK, DPSK and FSK with Rayleigh fading