Speech and Data Communications Over 942 MHz TAB and TTIB Single Sideband Mobile Radio Systems Incorporating Feed-Forward Signal Regeneration

ANDREW J. BATEMAN, GARY LIGHTFOOT, ANTHONY LYMER, AND JOSEPH P. McGEEHAN, MEMBER, IEEE

Abstract—**The transmission of speech and data over 942 MHz pilot tone single sideband (SSB) mobile radio links is the main concern of this paper. 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 25 kHz Advanced Mobile Phone Service (AMPS) type FM system and markedly superior to that obtained with a 12.5 kHz FM system. A new optimized form of SSB, phase-locked transparent tone-in-band (TTIB), is shown to be capable of achieving coherent data transmission such as *M*-ary phase shift keying (PSK) in the presence of Rayleigh fading without the usual "high-level" irreducible error rates. The signal processing described has wide application from line to satellite communications.**

INTRODUCTION

SINCE THE World Administrative Radio Conference (WARC) in September 1979, there has been considerable research 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 spawned research into means of improving spectrum utilization. At this point in time, the U.K. land mobile radio service used 12.5 kHz AM and FM systems at VHF and 25 kHz FM at UHF whereas, in the U.S., 25 kHz and 30 kHz channelled FM were used at both VHF and UHF. In the U.K. 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 were sought. Although it was already recognized 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 narrow-band single sideband (SSB). Pilot tone SSB in 5 kHz channels has been the subject of considerable investigation throughout the world (Wells [1], Lusignan [2], and Gosling *et al.* [3]) and recently, the U.K. Home Office[1] Directorate of Radio Technology has issued a report [4] 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 was acknowledged that the performance of the SSB 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 recognized the fact that for pilot tone SSB to be universally adopted in private mobile radio and radio telephone services any proposed system must be capable of vertical integration across the frequency bands, i.e., the system and spectrum configurations used at VHF must be those used, with minor modifications, at UHF. With this in mind, we have been developing techniques which will enable SSB to function correctly for speech and data transmission (coherent and noncoherent) at frequencies up to 1 GHz in the multipath fading environment. In this contribution, it is intended to review briefly the work in pilot tone amplitude companded SSB systems for mobile radio and to show that of the four contending systems only tone-above-band (TAB) and phase-locked transparent tone-in-band (TTIB) SSB have the flexibility to operate at frequencies up to 1 GHz with techniques such as feed-forward signal regeneration [5] (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 briefly reviewing the basic principles of TTIB and FFSR operation, preliminary results are given for a TAB SSB/FM comparison of speech communications and for data communications over a TTIB SSB link at 942 MHz in the fading environment. The results are important since the signal processing techniques developed for mobile radio have ready application in line, radio, and satellite communications.

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 (pep)) within the

Manuscript received April 20, 1984; revised November 1, 1984. This work was supported by a British Telecom research contract and by the U.K. Science and Engineering Research Council.

A. J. Bateman is with the School of Electrical Engineering, University of Bath, Claverton Down, Bath BA2 7AY, Avon, United Kingdom.

G. Lightfoot was with the School of Electrical Engineering, University of Bath, Claverton Down, Avon, United Kingdom. He is now with the Communications Division, Thorn-EMI Ltd., Wells, England.

A. Lymer was with the School of Electrical Engineering, University of Bath, Claverton Down, Avon, United Kingdom. He is now with Hewlett-Packard Ltd., South Queensferry, West Lothian, Scotland EH30 9TG.

J. P. McGeehan was with the School of Electrical Engineering, University of Bath, Claverton Down, Avon, United Kingdom. He is now with the Department of Electrical and Electronic Engineering, Engineering Laboratories, University of Bristol, University Walk, Bristol, England BS8 1TR. Telephone 0272 24161.

[1] The Directorate of Radio Technology is no longer part of the Home Office but is a division within the Department of Trade and Industry

0018-9545/85/0200-0013$01.00

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

1) pilot carrier SSB [1] developed by Philips Research Laboratories;
2) pilot tone-above-band SSB [2] investigated at Stanford University for the Federal Communications Commission (FCC); and
3) pilot tone-in-band SSB [3] researched at the University of Bath.

Of these, 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. These three points were felt to be particulary 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 are carefully selected, the system, it must be admitted, has not received universal acceptance through its nontransparency with all data formats.

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 valuable to adjacent channel interference and requiring an asymmetric pull-in behavior from the automatic frequency control circuitry. Furthermore, unless frequency off-setting techniques are employed [6], the pilot tone for each of these two systems will be positioned, see Fig. 1, 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 [7] and AFC [8], [9] 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, neither today nor 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 the U.S. and Canada 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 nontransparency. 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 traveling 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 mi/h and at 900 MHz, they can occur at rates up to 200 times per second. Such variations 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 feed-forward automatic gain and frequency control [5] 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 with a pilot tone spacing of less than 3 kHz. However, 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 Fig. 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 $\Delta\tau$ 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 mi/h), 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 neighboring information components. This flexibility is not available with pilot carrier systems but is for TAB systems. It is almost certainly for this reason that the four SSB systems commercially produced at this time, employ the TAB spectrum configuration. 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.

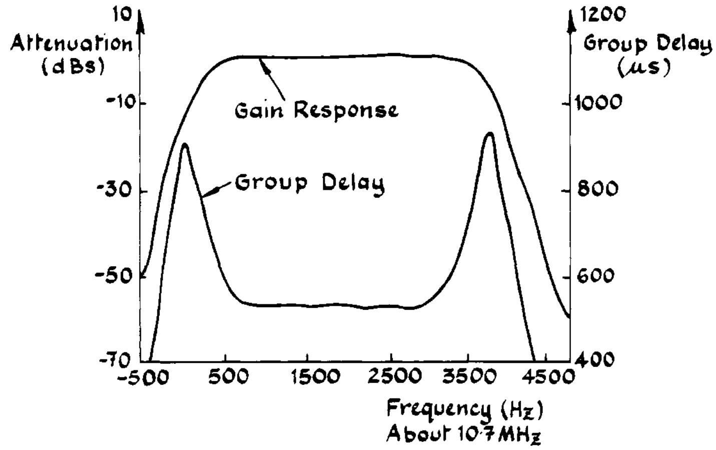


Fig. 1. Amplitude and group delay characteristics of a typical 10.7 MHz IF crystal filter for 5 KHz channelled SSB.

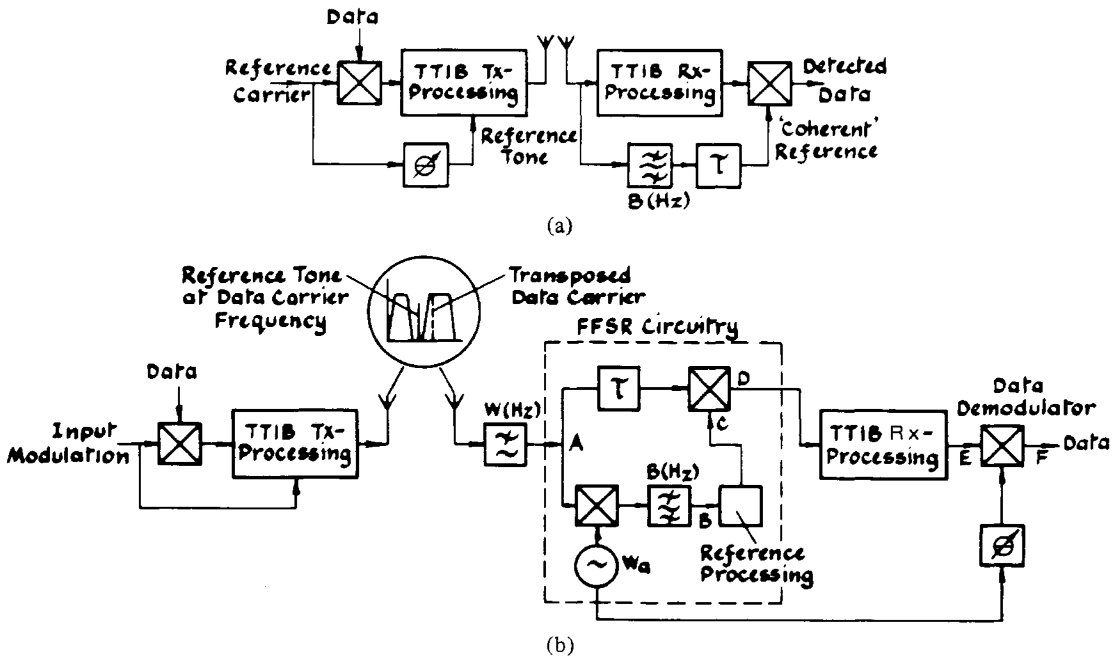


Fig. 2. (a) TTIB processing for coherent data detection of PSK. (b) TTIB/FFSR reference processing for correction of speech and coherent data detection in multipath fading.

For this reason, we at the University of Bath have developed a new SSB spectrum configuration called phase-locked TTIB [10] 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 straightforward audio signal processing techniques in the transmitter and receiver and can be implemented in one of two forms. In its first form, Fig. 2(a), a simple modification to the TTIB processing allows data, coherent and noncoherent, to be transmitted in the fading environment. In its second form, Fig. 2(b), 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 [11]. 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 SSB configurations rely heavily on FFSR for high quality reception and it is necessary to now reconsider briefly the basic operation principles of this very important technique.

PRINCIPLES OF FFSR OPERATION

To illustrate the salient features of FFSR operation, a simple mathematical description of the received fading signal $y_i(t)$ is utilized where

$$y_i(t) = Er(t) \cos (w_1 t + w_p t + \phi(t)) + Sr(t) \cos (w_1 t + w_s t + \phi(t)). \quad (1)$$

The random amplitude modulation is represented by $r(t)$ and the random phase modulation by $\phi(t)$, w_p, and w_s are the angular frequencies of the pilot tone and audio signal components, respectively, with E and S the corresponding amplitudes. w_1 represents an audio IF frequency of the receiver. The action of FFSR is to generate a control signal $n(t)$ at a second intermediate frequency w_0 given by

$$n(t) = \frac{C}{r(t)} \cos (w_0 t + \phi(t)) \quad (2)$$

where C is a constant. By using $n(t)$ to linearly mix down the received signal $y_i(t)$, an output signal $y_0(t)$ is generated with both the unwanted random amplitude and phase variations $r(t)$ and $\phi(t)$ removed

$$y_0(t) = \frac{EC}{2} \cos (w_p t + (w_1 - w_0)t) + \frac{SC}{2} \cos (w_s t + (w_1 - w_0)t). \quad (3)$$

If the receiver is configured such that w_1 equals w_0 in the above expression, the required signal is coherently demodulated to baseband.

A. Implementation of FFSR

There are several ways of implementing FFSR processing [5], the most general of which is shown in Fig. 3. The technique operates at an "audio 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

$$g(t)_A = Er(t) \cos (w_1 t + w_p t + w_e t + \phi(t)) + Sr(t) \cos (w_s t + w_1 t + w_e t + \phi(t)) \quad (4)$$

where w_e represents the angular frequency error in the

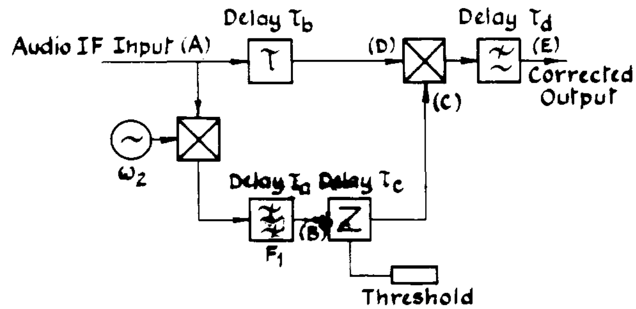


Fig. 3. FFSR processing.

receiver IF frequency, w_1. After mixing and filtering to extract the fading pilot tone, the signal at point B is given by

$$g(t)_B = Er(t) \cos((w_1 - w_2)t + w_p t + w_e t + \phi(t))\,|_{t \to t - \tau_a}. \tag{5}$$

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

$$g(t)_C = \frac{M}{r(t)} \cos((w_1 - w_2)t + w_p t + w_e t + \phi(t))\,|_{t \to t - \tau_a - \tau_c} \tag{6}$$

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

$$g(t)_D = \frac{ME}{2} \cos w_2 t + \frac{MS}{2} \cos(w_s t + (w_2 - w_p)t)\,|_{t \to t - \tau_b - \tau_d}$$

provided that the time delays in the upper and lower signal paths are matched, i.e., $\tau_b = \tau_a + \tau_c$. If $w_2 = w_p$ then the resulting regenerated output signal is correctly demodulated to baseband. For pilot carrier SSB systems, $w_2 = w_p = 0$ 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 w_e from the input signal thus compensating for receiver mistuning arising from local oscillator drift in either the transmitter or receiver. While 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 Fig. 4, uses a squaring detector for envelope extraction. If the configuration is subject at point a to the fading pilot input signal described by

$$P(t)_a = r(t) \cos(w_p t + \phi(t)) \tag{8}$$

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

$$P(t)_b = k(r^2(t) + r^2(t) \cos(2w_p t + \phi(t)). \tag{9}$$

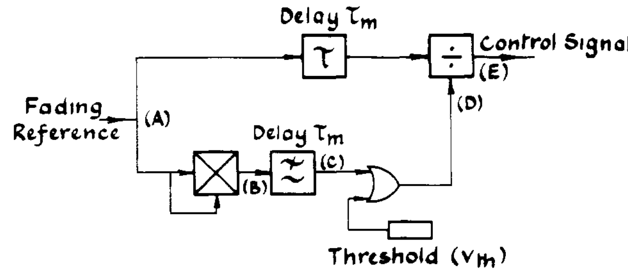


Fig. 4. Implementation of processing module Z.

where k is a constant multiplier. After passing through the low-pass filter, to remove the $2w$ term, the resulting waveform is given by

$$P(t)_c = kr^2(t)\,|_{t \to t - \tau} \tag{10}$$

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

$$P(t)_d = k \max\{r^2(t), v\}\,|_{t \to t - \tau} \tag{11}$$

resulting in a control signal

$$P(t)_e = \frac{k' r(t) \cos(w_p t + \phi(t))}{\max \cdot \{r^2(t), v\}}\bigg|_{t \to t - \tau}. \tag{12}$$

For $r(t)$ greater than the threshold level v the control signal becomes

$$P(t)_e = \frac{k'}{r(t)} \cos(w_p t + \phi(t))\,|_{t \to t - \tau}. \tag{13}$$

Unlike other implementations of the Z module for generating the control signal $P(t)_e$, the squaring action of the envelope processing in Fig. 4 causes the resulting dynamic range requirements (measured in dB) 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, $r^2(t)$, to within twice the Doppler frequency shift. 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, $\phi(t)$, superimposed and results in a significant harmonic content of the envelope, $r(t)$, extending to several times the Doppler frequency. This makes it difficult or impossible to separate the pilot envelope from the related harmonics.

FIELD TESTS

A. Experiment

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 (5 kHz deviation) for comparison purposes. The lack of suitable and, consequently, nonoptimized components and filters for the SSB system meant that a bandwidth larger than 5 kHz had to be used in these initial trials. Both the SSB and FM systems use the same RF linear power amplifier and the same low noise RF front-end in the receiver. 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

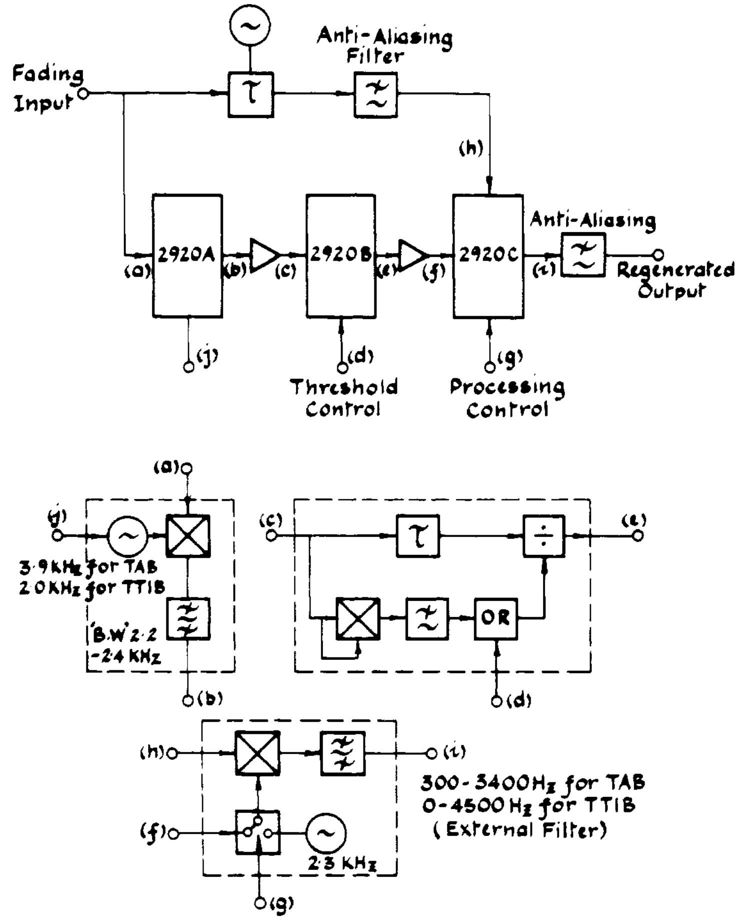
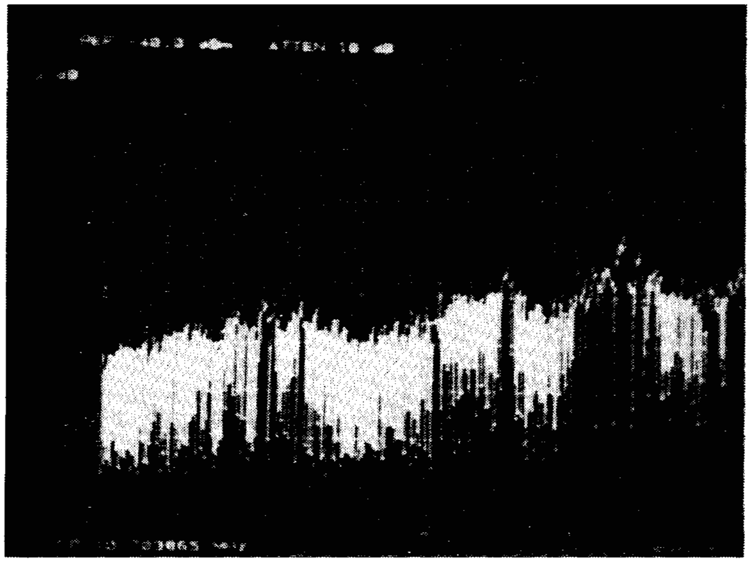


Fig. 5. Processing for experimental FFSR system.

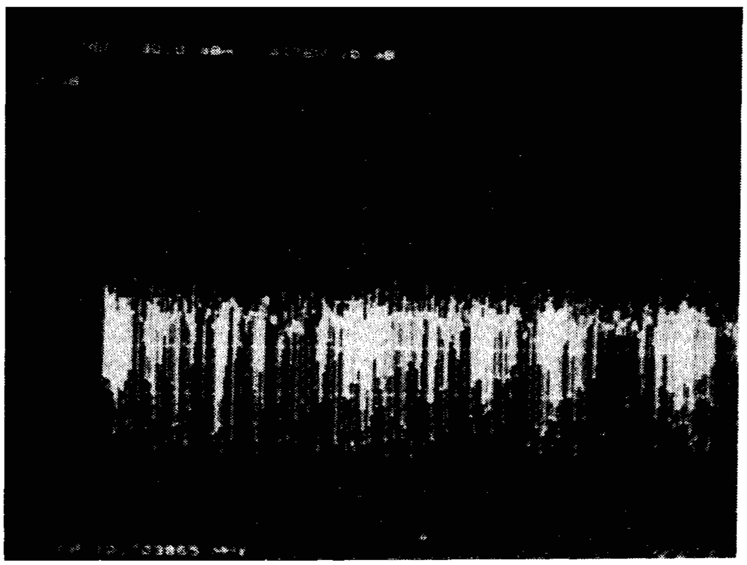
pilot tone-to-information separation allows for the multipath induced spreading of the pilot and information components and the finite roll-off of presently available filters. As a result, the pilot tone and its associated fading induced sidebands may be extracted unambiguously for subsequent AGC and 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. Fig. 5 depicts the processing and frequencies actually used in the experimental system (the threshold was initially set at -20 dB, which incidentally agrees with the value arrived at theoretically by Leland and Sollenberger [12]) and shows that it is implemented almost entirely in software form using Intel D2920 "analog" microprocessors. This situation has arisen through the present lack of suitable signal processing ic's and it is well recognized by the authors that a custom designed large scale integration (LSI) chip set will produce a more optimum and superior FFSR system performance. The TAB SSB audio signal processing also employs 2:1 amplitude syllabic companding described elsewhere [13], [14], to enhance the low and medium signal strength performance of the channel. Although 4:1 companding will improve the overall performance of the SSB system still further, it was decided in these preliminary trials to use the same degree of companding in both the FM and SSB radio links. For the FM system, a "hybrid system" was developed using standard 25 kHz FM techniques but with signal processing based on the AMPS scheme [15]. Following the measurement procedure used in the U.K. Home Office (Directorate of Radio Technology) SSB comparative trials, the pep's for the SSB and FM transmissions were equalized. 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 optimized and recorded. Furtermore, a separate control link facility existed which enabled independent observers to monitor the comparative performance of the SSB and FM systems under all field trial conditions at will from the laboratory. That is to say, the VHF AM link allowed rapid switching between each of the modulations at the transmitter.

B. Speech Trials

Based upon our detailed knowledge of the fading characteristics within the city of Bath, a test route was selected which embraced low, medium, and high signal strengths. A source tape provided by British Telecom Research Laboratories, 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 mi/h and a photographic description of the envelope fading experienced along the route is shown in Fig. 6. Prior to the listening test, each member of the assessment



(a)



(b)

Fig. 6. Received SSB pilot amplitude versus time at 25 mi/h. Vertical: 10 dB/div. Horizontal: 3 s/div. Resolution bandwidth: 300 Hz. (a) Fixed receiver gain. (b) Receiver with AGC.

panel was issued with written instructions (similar to those used in the U.K. Home Office trials [4]) explaining the organization and voting method of the test. The listener was not informed that the tests referred to an FM/SSB comparison. Voting was conducted electronically on the basis of a five-point International Radio Consultative Committee (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, was used to stabilize their aural senses 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, shown in simple block diagrammatic form of Fig. 7, indicated that the prototype 6.25 kHz SSB equipment incorporating FFSR processing was superior at all signal strengths by about one unit to the AMPS type 25 kHz FM system at a carrier frequency of 941·725 MHz at all signal strengths by about one unit. The results so obtained were directly reflected in the comments and appraisals of a number of independent assessors experienced in mobile communications. The quality of the FM channel under varying signal strength conditions was also felt by these experienced independent observers to be extremely similar and, therefore, representative of the cellular AMPS system. Several key factors appear to emerge from the experimental tests undertaken. Firstly, users and listeners found the noise bursts and clicks of the FM system, caused by the received signal fading into the noise at low and medium signal strength conditions, to be particularly annoying. By comparison, the noise induced in the SSB system by multipath fading had characteristics which were much softer and far less harsh to the ear. Secondly, and most significantly, it was found that by controlling the threshold level of the FFSR, such

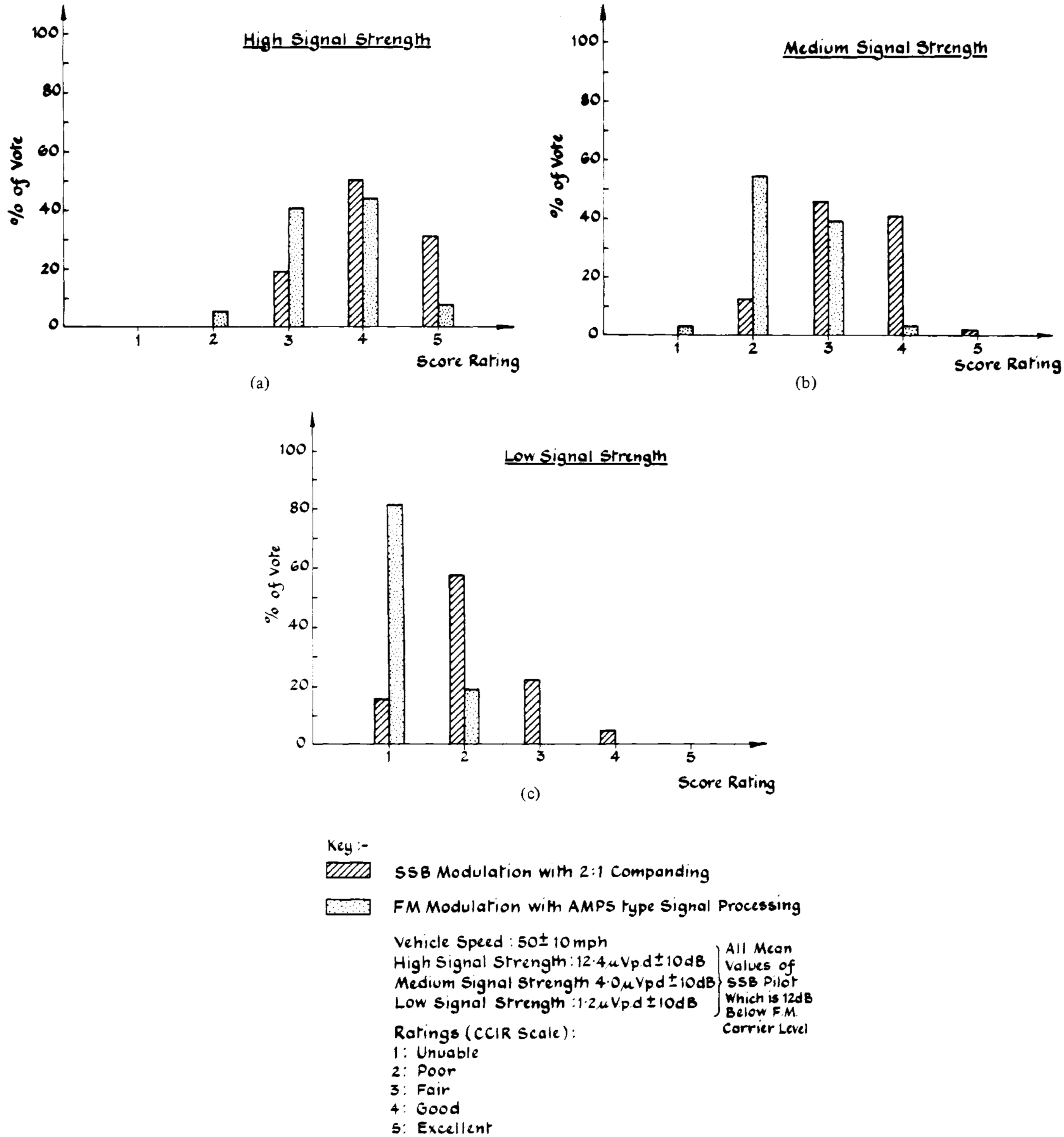


Fig. 7. Subjective comparison of amplitude companded SSB with 25 KHz AMPS type system (5 KHz deviation) under fading conditions in the City of Bath at 941·725 MHz.

that at low signal strengths the amount of available gain correction is progressively reduced to zero prior to squelching the audio output at a predetermined signal level, brought about a considerable improvement in audio quality. Although in our field trials, the control function was set by ear, it is expected that a further improvement in subjective quality will be brought about by a more detailed investigation of the effect. It is noteworthy, in view of the present deliberations by the FCC in respect of the reserve spectrum at 800 MHz, that a similar series of trials at Bath between 12.5 kHz FM, 2.5 kHz deviation, and 6.25 kHz SSB with 2:1 amplitude companding showed SSB to be *markedly superior* to the FM system at 942 MHz. Interestingly, an independent research investigation by Visser *et al.* [16], of the Alberta Department of Communications, supports our general findings in relation to FM in that 12.5 kHz FM performance is extremely poor at UHF and is less spectrally efficient than 25 kHz FM. These findings would appear to be contrary to the views and proposals expressed in Docket 82-10 [17] before the FCC.

C. Data Trials

Finally, detailed analyses and field tests on narrow-band data transmission have been conducted at 942 MHz using a phase-locked TTIB system incorporating FFSR. Although the commonly used data formats such as FSK (1.2 kbit/s) and DPSK (2.4 kbit/s) were considered in some detail initially, the major part of our effort has been directed toward the transmission of coherent data schemes, and CPSK in particular, in the Rayleigh fading environment. The possible deployment of CPSK in mobile radio communications is extremely significant since it has the lowest bit error rate of all data types in white noise. Furthermore, the use of CPSK and other forms of coherent data can easily be accommodated with TTIB-based SSB. Indeed, TTIB processing is such that simultaneous carrier and bit synchronization is simple to achieve both for binary and M-ary systems [18] as is coherent signal demodulation. The CPSK modem used in our investigations, was designed and constructed at Bath and was capable of signalling at 1 kbit/s. The 1 kbit/s signalling rate was determined solely on the grounds of convenience by the clocks used in our signal processing and was not limited by the channel bandwidth.

Fig. 8 shows the results of a comprehensive series of experiments under nonfading and Rayleigh fading conditions in which a TTIB/FFSR system has been compared with a digital squaring-filter (SQF) system, similar in operation to a Costas loop [19]. It can be seen that under stationary conditions (nonfading) there is little difference between the SQF and TTIB/FFSR systems when transmitting and receiving CPSK data. However, when subjected to Rayleigh fading (with a hardware simulator [20] provided by British Telecom Research Laboratories) high irreducible error rates were measured for the SQF system (dashed lines) but not for the TTIB/FFSR system. The theoretically computed performance of the TTIB/FFSR system with both envelope and phase distortion can be seen to be in good agreement with experiment and theoretically identical to that computed for the SQF system *with envelope fading alone* (i.e., random FM induced by multipath propagation is assumed negligible). In this respect, a paper by McGeehan and Sladen [21] addresses the problems of narrow-band phase-locked loop tracking in the multipath environment. Further evidence of TTIB/FFSR's excellent performance in fading is shown in Fig. 9. Here a 942 MHz SSB mobile radio link with the simultaneous carrier and bit synchronization circuit installed has been used to transmit DPSK and CPSK data. It will be noted that when the FFSR circuit is disabled, high irreducible error rates are recorded for the noncoherent DPSK system. With the FFSR incorporated, the error limit caused through random FM is removed. It is also evident from these curves that the use of CPSK in the fading environment offers the system engineer the expected advantage over DPSK. Recently, Kanso *et al.* [19] at Bath have shown that a new diversity technique based upon FFSR processing can be employed to bring about a further dramatic reduction in error rate.

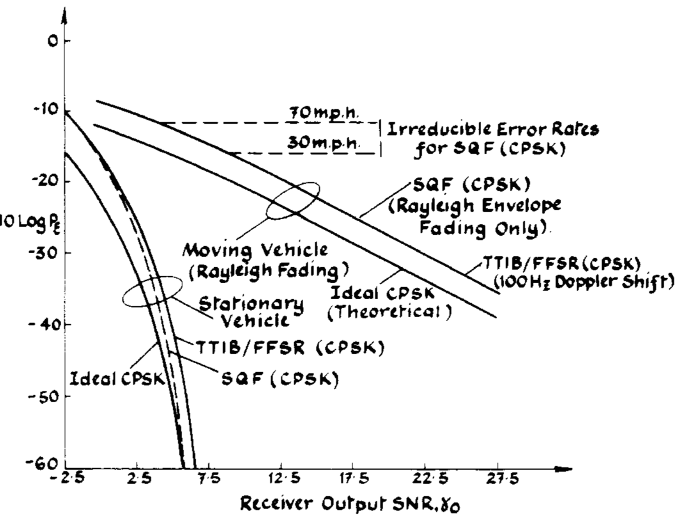


Fig. 8. CPSK data transmission with TTIB/FFSR and SQF systems in fading.

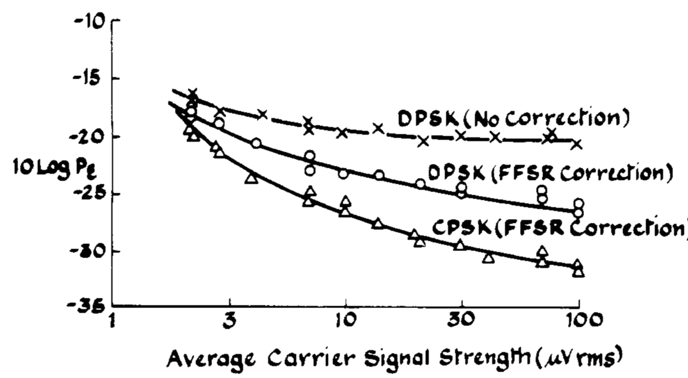


Fig. 9. Measured bit error probabilities for various data formats transmitted across an SSB link in the city of Bath (data rate: 1000 bit/s, vehicle speed: 40 mi/h).

CONCLUSION

The paper presents preliminary results for both 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 comparison with FM[2] and the ability to transmit conventional data formats as well as CPSK without the associated "high-level" irreducible error rates clearly demonstrate that pilot tone amplitude companded SSB should be considered as a suitable modulation form for mobile radio over all operational frequency bands up to 1 GHz. The improvement in speech quality over 25 kHz FM may amount to as much as 1 point on the CCIR scale for all signal strengths, whereas the base-error rate achieved with coherent data systems such as CPSK, is far superior to that obtainable with conventional noncoherent FSK or DPSK systems operating in the multipath environment. In this respect, it is worth emphasising that SSB offers a *linear channel*, and thus holds the possibility of conveying combined

[2] Preliminary trials with 12.5 kHz channelled (2.5 kHz deviation) FM proved to be markedly inferior to the SSB system, and hence comparative trials were only conducted with a 25 kHz FM system (5 kHz deviation).

amplitude/phase encoded digital information with the associated improvment in bandwidth efficiency and error performance.

These factors, combined with the improved utilization of the radio spectrum, up to a fivefold advantage over 25 kHz channel FM, must make SSB a possible if not imperative replacement for conventional mobile radio systems in this age of severe spectrum congestion. Furthermore, the audio signal processing described has application in line and satellite communications.

ACKNOWLEDGMENT

The authors are grateful to British Telecom for permission to publish the results. One of the authors (Dr. A. J. Bateman) is grateful to the U.K. Science and Engineering Research Council for its support during this research through the award of a research studentship. The SERC also supported the research effort into FFSR processing techniques.

REFERENCES

[1] R. Wells, "SSB for VHF mobile radio at 5 kHz channel spacing," *IERE Conf. Proc. Radio Receivers and Associated Syst.*, Southampton, July 1978, pp. 29-36.

[2] B. B. Lusignan, "Single-sideband transmissions for land mobile radio," *IEEE Spectrum*, pp. 33-37, July 1978.

[3] W. Gosling, J. P. McGeehan, and P. G. Holland, "Receivers for the Wolfson single sideband VHF land mobile radio system," *Radio Electron. Eng.*, vol. 49, pp. 321-325, 1979.

[4] Home Office Directorate of Radio Technology, "Report on comparative tests for modulation methods for private mobile radio," Apr. 1982.

[5] J. P. McGeehan and A. J. Bateman, "Theoretical and experimental investigation of feedforward signal regeneration (FFSR) as a means of combatting multipath propagation effects in pilot-based SSB mobile radio systems," *IEEE Trans. Veh. Technol.*, vol. VT-32, pp. 106-120, 1983.

[6] J. R. Ball and D. W. J. Holmes, "An SSB with pilot receiver for mobile radio," *Clerk Maxwell Conf. Radio Receivers and Associated Syst., IERE* Pub. No. 50, Leeds, 1981, pp. 429-435.

[7] D. F. Burrows and J. P. McGeehan, "Time delay in receiver AGC systems," *Clerk Maxwell Conf. Radio Receivers and Associated Syst., IERE*, Pub. No. 50, Leeds, 1981, pp. 73-88.

[8] J. P. McGeehan and A. Lymer, "Acquisition performance of 2nd-order phase-locked loops in the presence of time delay for switched and swept signal conditions," Proc. *Inst. Elec. Eng.*, vol. 130, pt. G, no. 4, pp. 131-137, 1983.

[9] J. P. McGeehan and J. P. H. Sladen, "Elimination of false locking in long loop phaselocked receivers," *IEEE Trans. Communic.*, vol. COM-30, no. 8, pp. 2391-2397, 1982.

[10] J. P. McGeehan and A. J. Bateman, "Phaselocked transparent tone-in-band (TTIB): a new spectrum configuration particularly suited to the transmission of data over SSB mobile radio networks," *IEEE Trans. Commun.*, vol. COM-32, no. 1, pp. 81-87, Jan. 1984.

[11] A. J. Bateman and J. P. McGeehan, "Data communications over UHF fading mobile radio channels," *Proc. Inst. Elec. Eng.*, Pt. F, vol. 131, no. 4, pp. 364-374, 1984.

[12] K. W. Leland and N. R. Sollenberger, "Impairment mechanisms for SSB mobile communications at UHF with pilot-based Doppler/fading correction," *Bell Syst. Tech. J.*, vol. 59, pp. 1923-1942, 1980.

[13] B. B. Lusignan, "AGC, AFC, tone select circuits for narrow-band mobile radio," presented at Int. Telecommun. Exposition, Dallas, TX, Feb. 1979.

[14] J. P. McGeehan and A. J. Bateman, "Subjective performance of amplitude companding in SSB mobile radio systems," *Electron. Lett.*, vol. 17, no. 22, pp. 859-860, 1981.

[15] G. A. Arredondo, J. C. Feggeler, and J. I. Smith, "Voice and data transmission," *Bell Syst. Tech. J.*, vol. 58, no. 1, pp. 97-122, 1979.

[16] B. Visser, K. Lalonde, and G. Pompori, "Channel spacing in cellular FM mobile communications systems," in *Proc. 33rd IEEE Conf. Veh. Technol.*, Toronto, May 1983, pp. 293-296.

[17] Docket No. 82-10 before the Federal Communications Commission; "Future private land mobile telecommunications requirements."

[18] J. P. McGeehan and A. J. Bateman, "A simple simultaneous carrier and bit synchronisation system for narrowband data transmission," *Proc. Inst. Elec. Eng.*, Pt. F, 1985, to be published.

[19] F. M. Gardner, *Phase-lock Techniques*, 2nd ed. New York: Wiley, 1979.

[20] J. R. Ball, "A real-time fading simulator for mobile radio," *Radio Electron. Eng.*, vol. 52, pp. 475-478, 1982.

[21] J. P. McGeehan and J. P. H. Sladen, "The tracking performance of a narrowband phaselocked loop in the mobile multipath environment," *Proc. Inst. Elec. Eng.*, Pt. F, 1985, to be published.

[22] A. Kanso, J. Griffiths, and J. P. McGeehan, "An FFSR diversity combining system for pilot-based SSB mobile radio schemes of UHF," IEE Colloquium on Characterisation and Investigation of Multipath Interference Effects, Digest No. 1983/52, London, May 1983, pp. 7/1-7/3.

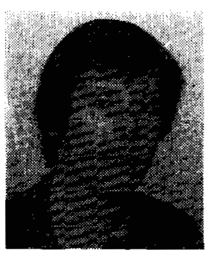
Andrew J. Bateman was born in Poole, England, on September 3, 1959. He received a first class honours degree in electrical and electronic engineering from Bath University, England, in 1980, and received the Ph.D. degree in 1983.

Since 1983 he has held the position of Research Officer at the University of Bath, where he is primarily concerned with research into the fundamental theory of open waveguide systems, while maintaining his interests in mobile communications technology.

Gary Lightfoot was born in St. Helens, Merseyside, in 1952. He received the B.Sc. degree in Electronics from the University of Sussex in 1974 and the M.Sc. degree in electrical engineering for research into microwave circulators from the University of Lancaster in 1979.

Until 1983 he was employed as a Research Officer at the University of Bath working on SSB mobile communications at UHF and VHF. Since then he has been with Thorn EMI Communications Division, Wells, Somerset, doing research and development in microwave communications.

He has been an Associate Member of the Institution of Electrical Engineers (U.K.) since 1981.



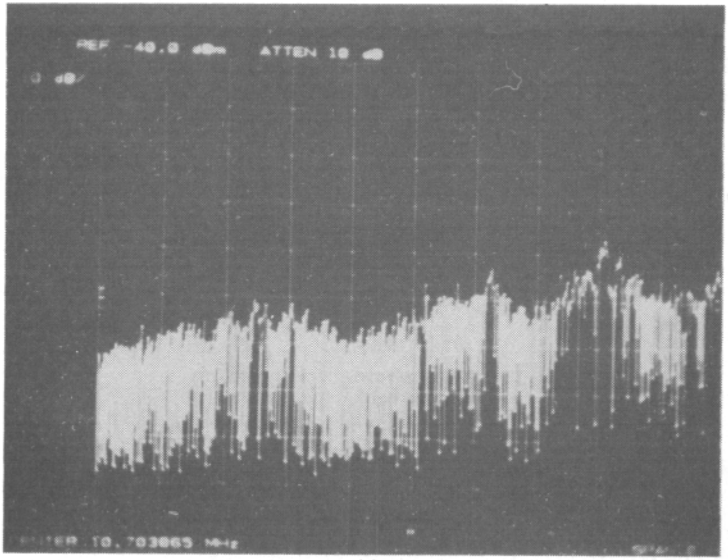
Anthony Lymer received a degree in electrical and electronic engineering from the University of Wales, Bangor, in 1975.

He joined the Marconi Research Laboratories in Great Baddow to work on mobile radio data systems. In 1977 he moved to Bath University, where he developed single sideband radio receivers. He is currently employed by Hewlett-Packard Ltd. at South Queensferry, Scotland.

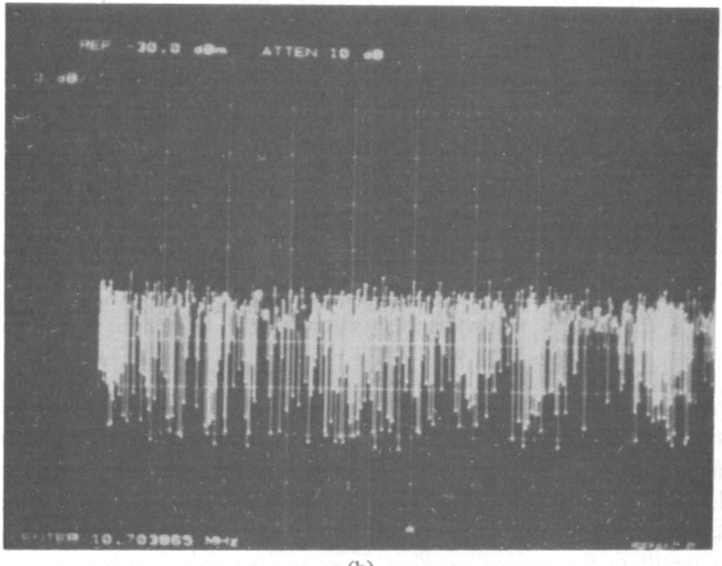
Joseph P. McGeehan (M'83) was born in Bootle, Merseyside, on February 15, 1946. He received the B.Eng. and Ph.D. degrees in electrical engineering from the University of Liverpool in 1967 and 1972, respectively.

From 1970 to 1972 he held the position of Senior Scientist at the Allen Clark Research Centre, The Plessey Company Ltd., where he was primarily concerned with research into solid-state microwave devices and their applications. In September 1972 he was appointed Lecturer in the School of Electrical Engineering at the University of Bath and promoted to Senior Lecturer in 1983, and has led project teams conducting research into the application of signal processing techniques to single-sideband mobile radio communication systems and millimetric open waveguide techniques and systems. He has recently been appointed to the Chair of Communications Engineering in the Department of Electrical and Electronic Engineering at the University of Bristol.

Dr. McGeehan is a member of U.K. Study Group 8A of the International Radio Consultive Committee. He is the author of some 70 scientific papers. In recent years, he has served as a member of the U.K. Home Office (Directorate of Radio Technology) Working Group on single-sideband land mobile radio.



(a)



(b)

Fig. 6. Received SSB pilot amplitude versus time at 25 mi/h. Vertical: 10 dB/div. Horizontal: 3 s/div. Resolution bandwidth: 300 Hz. (a) Fixed receiver gain. (b) Receiver with AGC.