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THE IMPLEMENTATION OF A 16-QAM MOBILE DATA SYSTEM USING  
TTIB-BASED FADING CORRECTION TECHNIQUES

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**ABSTRACT**

The transmission of high speed data to and from a mobile terminal is far from simple. This paper presents practical results for one solution to the problem, namely reference-based channel sounding. A 9600bps 16-QAM data system is employed together with the Transparent Tone-In-Band (TTIB) reference processing technique. Excellent performance under both static and fading conditions is observed.

**1. Introduction**

Data modulation techniques such as M-ary QAM, which utilize both amplitude and phase for information transfer, are known to provide greater spectral efficiency than those exploiting phase or amplitude alone. There is already widespread use of QAM formats for landline modems (V.29 and V.32) and for fixed link satellite communications. When considering data modulation formats for mobile communications, however, the effects of severe multipath induced gain and phase distortion must be taken into account, and QAM techniques appear in a less favorable light. It is in fact commonplace to find simple binary FSK used for mobile communications by virtue of its relative insensitivity to gain and phase errors. Needless to say, the spectral efficiency achieved is very poor.

If techniques such as QAM are to be entertained for mobile applications, some means of multipath compensation must be implemented either before, or as an integral part of the data modem. A number of techniques have been proposed for this purpose, with by far the majority involving transmission of a low level reference tone(s) to act as both gain and phase reference for the receiver modem circuitry [1-5].

Probably the most flexible of these techniques is the Transparent Tone-In-Band (TTIB) system which, as the name suggests, permits the insertion of a reference tone

within the data signal in a manner entirely transparent to the user and independent the modulation type employed. For this reason, TTIB is becoming widely adopted for analogue voice transmission in conventional single sideband mobile radio transceivers, and proving popular for forthcoming all-data systems. Performance curves for a TTIB-based coherent CPSK data system have already been published [6], however no one has yet reported on the use of TTIB, or for that matter, any other reference-based data system, for the much higher level modulation types to which it is ideally suited.

This paper contains details of experimental measurements made using a GEC 9629 modem (V.29 standard) under static and simulated fading conditions when coupled to a TTIB compensated data link. The modulation formats investigated are QPSK (4800 bps), 8-QAM (7200 bps) and 16-QAM (9600 bps), each contained within a bandwidth of 2700Hz. For the 16-QAM format, this corresponds to a bandwidth efficiency of 3.5 bps/Hz. The data signal can be accommodated well within the 5kHz channel spacing currently allocated for linear mobile radio systems, (SSB), and thus allows digital voice transmission to be offered as an alternative to the conventional analogue voice systems. It is shown that the prohibitive irreducible error rate associated with such high level modulation methods when subject to multipath fading is virtually eliminated.

As a necessary precursor to the presentation and discussion of the data results obtained, a brief overview of reference based channel sounding systems is given.

**2. Data Modulation in Multipath Fading.**

Multipath fading causes considerable performance degradation for both analogue and digital communication systems, with increasing prominence in the more bandwidth efficient multilevel data modulation techniques which one would like to adopt for mobile communications. It is unfortunate that the coherent modulation/demodulation techniques boasting the best performance in additive white Gaussian noise (AWGN) are the worst affected by multipath distortion. For this very reason, non-coherent data formats such as FSK and DPSK are to be found in the majority of existing mobile data communication systems. Even these basic techniques however are highly sensitive to random FM, with error rates as high as 1% occurring for operation in the 900MHz band, irrespective of channel noise level [6].

Improvement in modem performance can be envisaged in two main areas;- firstly in the development of multipath measurement and correction techniques allied to conventional coherent multilevel data modems, (such as

those in use on fixed satellite links), and secondly in the application of low redundancy coding schemes, eg. interleaving and trellis coding with redundant signal sets [7], which possess greater "intelligence" to cope with the time varying nature of the mobile channel and the shape of error patterns observed. Both of these areas are being addressed in research activities worldwide, aided significantly by the advent of extremely powerful digital signal processing hardware ideally suited to the adaptive processing techniques required. The results presented in this paper are for a data system using multipath correction techniques (channel sounding) alone. Further improvements are anticipated with the application of coding.

### 3. Channel Sounding.

With suitable processing it is both feasible and practical to completely characterise and compensate for the random AM and FM in a narrowband mobile radio channel - all that is required is a means of measuring the channel induced distortion. Two approaches are possible:

**Data-derived Channel Sounding:** An example of a non-reference or data derived channel sounding process is to be found in the carrier recovery and subsequent coherent detection of binary phase shift keying (BPSK). By squaring and filtering an incoming fading BPSK data signal, a twice frequency carrier reference can be regenerated. This signal is corrupted by, and therefore characterises, both the random amplitude and phase variations introduced by the vehicle motion, the phase/frequency error being exactly twice that imposed on the data modulation itself. To obtain a carrier component that is truly coherent with the incoming data modulated signal, precise frequency and phase division by a factor of two is therefore required. Herein lies a fundamental problem with all such data derived channel sounding techniques, since accurate continuous phase division cannot be achieved in practice. The end result is that the application of conventional carrier recovery (data derived channel sounding) techniques in a multipath fading environment are met with an even greater irreducible error rate than those observed with binary FSK or DPSK using non-coherent detection [8]. The problem is accentuated in the higher order, Nth power, carrier recovery systems required for multilevel modem operation. This failing of conventional demodulation techniques in the mobile environment has spurred the use of a separate dedicated sounding signal alongside the data modulation.

**Pilot-based Channel Sounding:** The simplest mechanism for dedicated channel sounding is to send a sinusoidal reference tone (pilot) which is separated in frequency from the data modulation components by an amount dictated by the degree of Doppler spreading and residual system frequency error experienced by both signals. The addition of this reference tone inevitably destroys any constant envelope properties that may have been present in the original data modulated signal, and thus linear or linearised RF amplification techniques must be used for transmission. This apparently major disadvantage of reference-based systems can however be turned to good advantage as,

through its solution, it frees the system designer to exploit the superior non-constant envelope data modulation formats such as Mary-QAM. If further gives him full flexibility for system modification in the future.

Whilst simple in concept, the application of reference based channel sounding raises a number of questions regarding the optimal implementation of the sounding technique. The TTIB system outlined below, is arguably the front runner.

#### 3.1 Transparent Tone-In-Band:

The over-riding advantage of the TTIB system over its competitors is that it enables a reference component to be positioned anywhere within the RF modulation passband without loss of channel transparency. (ie no pulse shaping, line coding or notch filtering is required). This means the the reference can always be sited at the optimum point in the RF band for channel sounding purposes. Typically this corresponds to the band centre.

Flexibility in the positioning of the reference tone and the variable degree of separation between reference and modulation components that is offered by the TTIB system is achieved by a novel process of band-splitting and recombination about the reference insertion point. For the example shown in Fig 1, the input, subcarrier modulated data signal, is split into two frequency sub-bands by appropriate filtering, with the higher portion translated upwards in frequency and the lower portion translated downwards in frequency to create the required spectral null. (A complementary process in the receiver serves to restore the baseband spectrum to its original form). As no

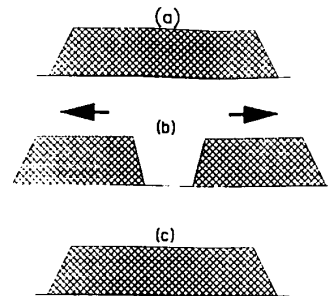


Fig 1. a) Input message signal, b) TTIB processed signal  
c) TTIB reconstructed message signal

information is lost or removed by this process, the channel, as far as the end user is concerned, is completely transparent to the input message signal. The TTIB system provides, in effect, three information channels, Fig 2 - the standard message channel, signalling within the band gap, and signalling by varying the band gap width. It is important to realise that the TTIB mechanism will operate for any data modulation format and does not rely on the reference tone or tones for sub-band recombination.

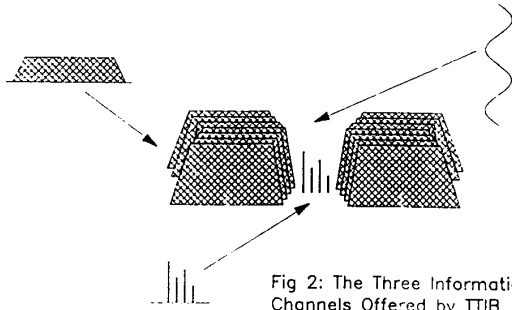


Fig 2: The Three Information Channels Offered by TTIB

The major system benefits of TTIB for mobile data communications are brought about by the flexibility of reference position and band separation, as summarised in the following:-

- The channel sounding reference signal can be accommodated anywhere within the RF band where it is least affected by adjacent channel interference.
- The spacing between reference and modulation components at the band edges is minimised, effectively doubling the fading correlation bandwidth compared with systems having a tone at the band edge.
- Distortion introduced by channel filtering and amplification is at a minimum at the channel centre, particularly in the case of SSB-based LM generation systems employing IF crystal filtering techniques.
- Minimum overall channel bandwidth is achieved compared with techniques incorporating the reference at the band edges.
- The technique is applicable to all current terrestrial and satellite mobile bands, with complete flexibility in the frequency separation between reference and modulation components for accommodation of varying degrees of frequency uncertainty and oscillator phase noise.
- The reference tone can be positioned at the unmodulated data carrier frequency and thus used in the receiver for coherent data detection, simultaneously with channel sounding. This property is particularly attractive for multilevel modulation formats where the  $E_b/N_0$  penalty associated with imperfect carrier regeneration in conventional data aided tracking systems becomes significant.
- The degree of sub-band separation can be used to convey bit or symbol timing information from transmitter to receiver, eliminating the need for separate clock recovery circuitry.
- For direct conversion receiver systems, the central band gap generated by the TTIB process permits the simple ac-coupling of the I/Q receiver paths without loss of information.

The ability to insert the reference tone at the data subcarrier frequency after band splitting, allows the same reference, once extracted in the receiver, to directly demodulate the data, given that the two sub-bands have been restored to their original place in the spectrum. By virtue of the reference being independent of the data format used, the above principle can be applied to the simple detection of multilevel data systems such as M-ary PSK without recourse to complex carrier or clock recovery processing. By incorporating fast acting feedforward gain control [9] to compensate for the residual random amplitude fading, it is also feasible to transmit and coherently detect combined amplitude and phase modulation formats in the mobile environment, with the obvious improvement in power and bandwidth utilization afforded by these techniques.

### 3.2 Alternative Reference-based Channel Sounding Techniques.

A number of alternative reference-based channel sounding techniques have surfaced in recent years, which possess some, but not all of the benefits of the TTIB approach. The salient points of each system are outlined below.

**Orthogonal reference BPSK:** This technique, proposed by Yokoyama [2], transmits the reference as an orthogonal component to the BPSK data stream. Such a scheme immediately precludes the use of multi-level data modulation formats which themselves exploit orthogonality of the channel and hence would inhibit the reference signal recovery.

**Tone Calibration Technique:** The tone calibration technique [4] employs data shaping and/or encoding to create a spectral null about the reference carrier frequency. The width of the spectral null and hence the tolerance to system frequency error is controlled by the degree of spectral shaping imposed. For the size of frequency error experienced in UHF and SHF operating systems, the degree of shaping required cannot be achieved without significant loss in system performance, particularly with multi-level data formats.

**Dual Tone Calibration Technique:** A development of the single tone-calibration technique uses two reference tones positioned at either edge of the data modulation spectrum [3]. This method removes the need for a central band notch and thus overcomes spectral shaping limitations, but does so at the expense of placing the reference tones at the extremes of the data channel and hence vulnerable to adjacent channel interference. Fading correlation is degraded compared with that of a central band reference system. The technique also suffers from the need to employ differential encoding of the data stream due to the phase ambiguity inherent in the carrier recovery process. Using the two tones does however allow bit timing information to be conveyed by the tone separation factor in a similar manner to the sub-band separation of the TTIB system.

### 4. Performance of 16-QAM using a TTIB compensated channel

In order to establish the viability of reference-based channel sounding for high speed data transmission, an

existing TTIB analogue speech modem was converted for data transmission. This primarily entailed the replacement of non-linear filtering with linear phase filters throughout. The resulting audio response of the link was 300Hz - 3400Hz, of which only the range 300Hz - 3000Hz was exploited by the GEC data modem used for the trials. A central band gap of 800Hz was chosen, with the reference inserted at a frequency of 1850Hz and at a level of -10dB w.r.t the average data symbol energy.

A Weaver upconverter was employed to achieve an operating frequency of 70MHz, compatible with multipath fading simulator. Subsequent Weaver downconversion provided the baseband signals for the TTIB recombination circuitry [10]. Prior to the TTIB system, a gain and phase correction technique, (Feedforward Signal Regeneration FFSR), was implemented, operating on the received fading pilot tone. This stage was capable of correcting for fades in excess of 40dB, and with fading rates in excess of 300Hz. All of the baseband processing was implemented using digital signal processing technology.

The data sub-carrier modulation, subsequent carrier/bit timing recovery, and the data detection were all performed within the GEC V29 modem, interfacing to the TTIB link via the line interface, Fig 3. In this case therefore, the facilities offered by TTIB of bit and carrier recovery were not exploited.

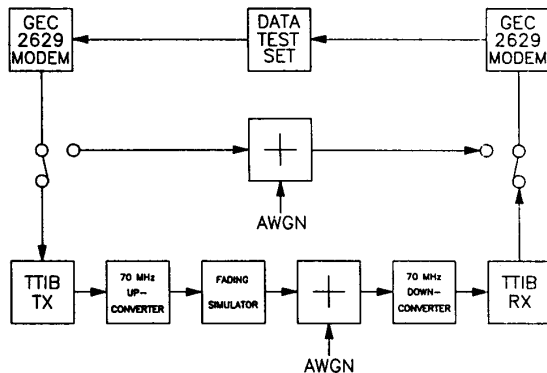


Fig. 3 Experimental Data Test Configuration

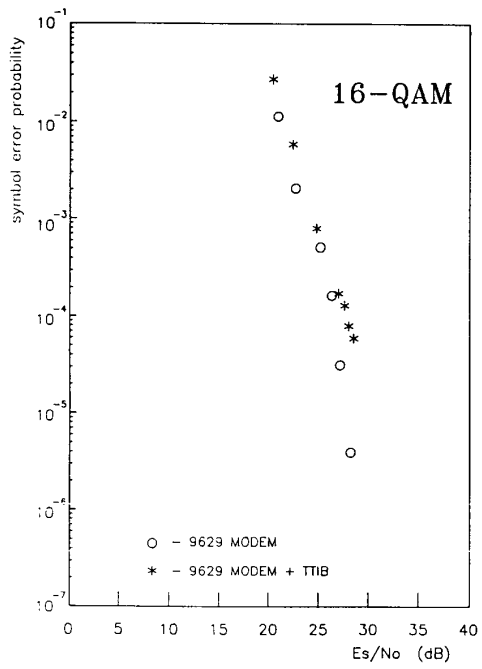
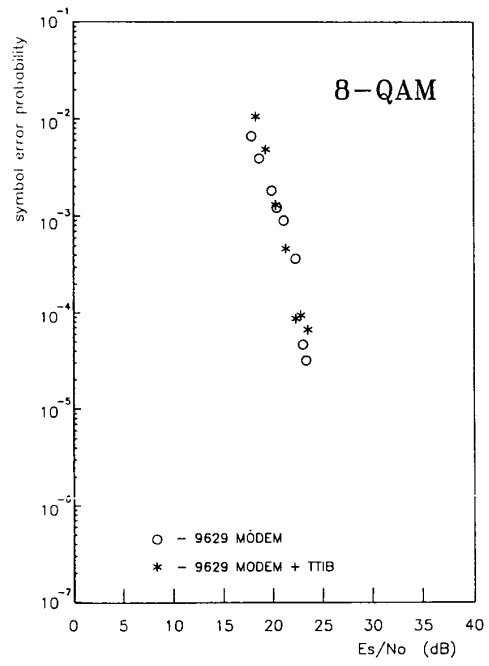
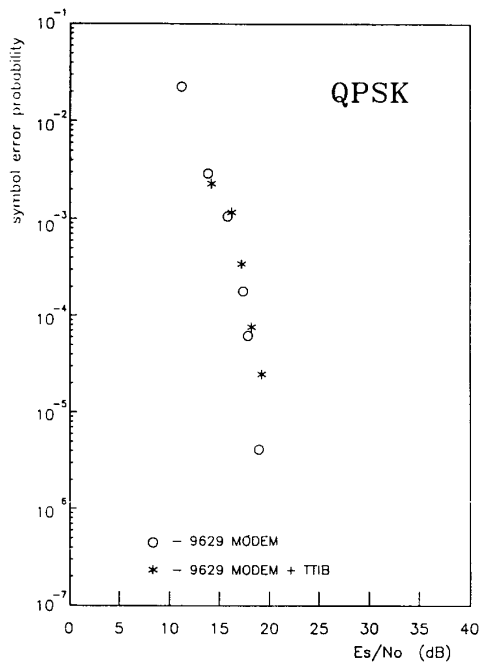
Using the experimental set up described, tests of the modem were performed with and without fading present, the fading having a Rayleigh envelope distribution. For the static (no-fading) case, symbol error rate measurements were taken for various values of  $E_s/N_0$  as plotted in Fig 4. The back to back operation of the GEC-modem provides a performance reference. From these results, it is evident that the degradation introduced by the TTIB link is negligible for all three modulation types, despite the underlying band-splitting, reference insertion, fading correction and band-recombination processing that is being performed. For a true comparison to be made, the system performance should be compared on an equal transmit power basis. Even taking into account the additional power used by the pilot reference tone, the TTIB results are only degraded by a further 0.5dB.

Comprehensive evaluation of the modem performance with fading present has yet to be completed, and full details will be presented at the conference. From the preliminary tests at high signal strength it has been found that the GEC modem operating without fading correction cannot synchronise for any of the three modulation types, adding weight to the claim that conventional coherent detection schemes are incompatible with mobile operation. With fading correction incorporated, not only did the modem obtain synchronisation, but a bit error rate of less than 0.01% was recorded for QPSK, 8-QAM and 16-QAM. This impressive performance was maintained with fade rates up to the 300Hz limit imposed by the FFSR processing. It is anticipated that the system performance in noise will follow closely the theoretical curves obtained for Rayleigh fading assuming ideal coherent detection in the receiver. Further tests are to be performed with simulated Rician fading, and with actual field trial data.

With 8kbps speech codecs now capable of providing quality voice transmission with bit error rates in excess of 0.1%, it is evident, based on the results quoted above, that digital voice is viable over the TTIB link, providing a sufficient received signal level can be maintained. With the application of coding techniques such as interleaving, trellis coding, etc, (there is no coding in the present system) a very respectable data communications link can be envisaged. High speed graphics transfer to mobiles has already been demonstrated using the experimental system, a facility generating considerable interest amongst the service industries.

The use of even higher modulation formats, 32-QAM and 64-QAM, for mobile communications is under investigation, but it is anticipated that the poor interference immunity of such systems will make them too vulnerable for all but the tamest of mobile links. The obvious attraction of higher formats is the improved bandwidth efficiency, however it must be borne in mind that this does not necessarily imply increased spectral efficiency, (channel/unit area), and in fact uncoded 32-QAM is less spectrally efficient than 16-QAM [11].

It is important to note, that whilst the discussion has been centred on voiceband data systems, (5kHz RF channeling), the only restriction on channel width is in fact the bandwidth over which fading correlation between the channel sounding signal and the wanted data modulation is maintained. This bandwidth is dictated primarily by the operating frequency and delay spread associated with a given mobile environment. In practice, it is quite feasible to operate a linearly modulation system with single, central band reference sounding over channel bandwidths in excess of 100kHz at a 900MHz carrier frequency before the fading correlation is too poor. Consequently, very high data transmission rates can be accommodated by suitable choice of channel width and data format. By the same principle, multiple narrowband channel working can be implemented, with each channel sharing a common pilot. The power expended in channel sounding now becomes a negligible part of the multi-channel power budget.



**Fig 4. Symbol Error Rate Curves  
for Static (no fading) Case**

### 5. Conclusions:

The prime motivation in writing this paper has been to present some practical results of high speed data transmission in a mobile environment, using the TTIB-based reference channel sounding system. A standard telephone line modem (GEC 2629) capable of operating with QPSK (4800bps), 8-QAM (7200bps) and 16-QAM (9600bps) formats was selected for the trials.

Under static (non-fading) conditions, it is shown that the implementation loss of the reference system is less than 1dB when compared with the back to back performance of the data modem. This is inclusive of the power allocation to the reference tone (0.5dB). The performance in Rayleigh fading at high signal strengths is found to be more than adequate, with a residual error floor of less than 0.01% with fading rates of upto 300 fades/second. No coding is used. It is significant that the data modem itself was unable to synchronise when the fading correction circuitry was disabled.

Further tests are in progress using the GEC 2932 modem which offers a 32-QAM operating mode, with half-rate trellis coding. The motivation behind these trials is to demonstrate the very accurate gain and phase correction that can be achieved with a TTIB-based channel correction system, and to further prove the transparency (and phase coherency) of the TTIB bandsplitting/recombination process itself.

A parallel research program at Bristol is concerned with the design and testing of a modem which forms an integral part of the TTIB system - using the reference tone as the data carrier, and the sub-band separation as the symbol timing reference [12]. Channel coding is to be included in the design. It is anticipated that the very strict bounds on carrier recovery phase error which are required for such coded systems, (eg. coded octal PSK [13]) will be, and can only be satisfied in a fading environment, by adopting the reference tone approach.

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