



Bateman, A., McGeehan, J. P., Kanso, A., & Marvill, J. D. (1987).  
Cochannel measurements for amplitude companded SSB voice  
communications. In 37th IEEE Vehicular Technology Conference (1987),  
Tampa, Florida. (pp. 505 - 511). Institute of Electrical and Electronics  
Engineers (IEEE).

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## INTRODUCTION

The overwhelming interest and demand that mobile radio communications has aroused is clearly evident from the growing number of publications, government committees, research proposals and commercial products that are addressing this particular topic. The boom in both public and private mobile radio systems is providing substantial financial rewards for both manufacturers and operators alike, with every prospect of a healthy future provided that spectrum is available to accommodate these services. Herein lies a fundamental hurdle for the radio communications industry.

As existing frequency allocations for mobile radio become saturated, three possible options present themselves for consideration. The first option is to exploit higher and higher frequency bands as the technology and economic climate permit, bearing in mind the worsening propagation conditions which prevail as the wavelength is reduced. The second option is to displace fixed link communications services from the prime mobile radio bands, (eg. VHF and UHF), into the microwave and millimeter wave bands with the justification that fixed systems can better tolerate the adverse propagation characteristics. This option is however hampered by complex political and economic factors. The third option, and one which is currying most favour with the regulatory authorities, although not all radio manufacturers, is to make more efficient use of the current mobile spectrum allocation. How can one hope to justify a demand for new spectrum allocations, when those currently available are known to be poorly utilised?

One of the most significant steps towards increased spectrum utilisation is the cellular radio system, or more fundamentally the structured reuse of frequencies on a geographical basis to optimise system capacity. The spectral efficiency of a cellular system depends on a number of factors. These can be divided into two main areas. Those factors associated with the networking of the system, eg. signalling protocols, network topologies, message handling, and those factors relating to the radio communications task, eg. channel sounding, interference immunity, signal quality, information transfer rate and channel transparency. The latter considerations are all very closely tied in with the modulation method employed and form the subject of this paper. More precisely, the paper compares the spectral efficiency of current

cellular systems based on non-linear frequency modulation with a system using linear single sideband modulation, (LM), for a given grade and type of service.

Aside from the spectral efficiency arguments are the commercial considerations of prospective cellular networks such as base station and mobile cost, cell size and hence numbers of base station sites, power requirements and hand portable compatibility, commercial risk, service flexibility and growth potential, etc. It is evident that the spectral efficiency gains of new cellular systems must be able to offset any commercial disadvantage that may be involved.

## SPECTRAL EFFICIENCY CRITERION

The efficiency of spectrum utilization can be expressed in terms of the number of available channels per MHz of bandwidth in a given cell area,

$$\text{Efficiency (E)} = \frac{1}{N \cdot B \cdot A}$$

where N is the number of cells in a cluster, A is the cell area and B is the required channel bandwidth in MHz.

If we stipulate that the cell area is fixed, (either by geographical or commercial constraints), then the efficiency can be expressed as,

$$E \propto \frac{1}{N \cdot B}$$

and the relative spectral efficiency between two competing modulation systems becomes,

$$\frac{E_1}{E_2} = \frac{N_2 \cdot B_2}{N_1 \cdot B_1}$$

The number of cells in a cluster, N, is primarily governed by the tolerance of a given modulation format to interference from a nearby cell reusing a given channel frequency, (assuming the ambient noise level to be insignificant). This quantity is commonly expressed as a co-channel to interference protection ratio, C/I. If a fourth power propagation law is assumed to prevail in the urban environment, the number of cells in a cluster can be related to the ratio C/I by the following equation [1],

$$N = \sqrt{\frac{2}{3}} (C/I)$$

If a rigid hexagonal cell structure is assumed for the cellular model, then the values of N are restricted to 1,3,4,7,9..., however, in practice, such a regular structure cannot be enforced and for the purposes of system comparison, no restriction is placed on the values of N which are valid.

The relative spectral efficiency between two competing systems can thus be written as,

$$\frac{E_1}{E_2} = \frac{1/(C/I)_2 \cdot B_2}{1/(C/I)_1 \cdot B_1}$$

This equation demonstrates the interesting property that the relative system efficiency decreases as the square root of the increase in C/I, but directly in proportion to the channel bandwidth. In other words, a modulation technique which offers a bandwidth saving of two can afford an increase of four in the ratio C/I to maintain the same spectral efficiency.

The bandwidth occupied by any given modulation type is easily defined and can be readily applied to the above equation. The figure for co-channel to interference protection ratio is not so apparent. For the case of voice communications, the tolerable levels of interference are clearly a matter for subjective assessment. If the voice is digitized prior to transmission, then comparative assessment between 'digital' systems is simplified and can be based on error probability measurements. Note: the distribution of errors plays an important part in system performance. Comparison between a digitized voice system and an analogue system, or between two analogue systems is unfortunately far more difficult to predict. Interference affects the performance of demodulation techniques in different ways and consequently yields varying subjective results. It is naive to postulate the subjective performance of one modulation system from the measured performance of another.

To generate a meaningful figure of merit for co-channel protection ratio in a cellular system it is essential to perform subjective comparisons of each modulation system or codec under realistic operating conditions. This was the purpose of a UK Department of Trade and Industry funded research contract at the University of Bristol which made the comparison between an FM cellular radio operating on the British TACS system and two types of Amplitude Companded SSB radio.

#### FM/SSB-LM CO-CHANNEL INTERFERENCE COMPARISON

The main objective of the comparative study was to

provide a definitive figure for the relative co-channel interference immunity of an FM and LM mobile radio system under realistic operating conditions.

#### System Specification

The FM system chosen for the trial was the NEC TRS E600-3A cellular radio operating on the UK TACS network and requiring 25KHz channel spacing. The SSB Linear Modulation tests were performed on two sets of equipment, one a modified VHF SSB radio manufactured by Stephens Engineering Associates (SEA), and the second, a development system engineered at the University of Bristol. Both systems employed an in-band pilot reference configuration based on the Transparent Tone-in-band (TTIB) technique [2], and Feedforward Signal Regeneration (FFSR) [3] for multipath fading correction. In addition, 4:1 companding was implemented based on a feedforward design described in [4]. The entire signal processing was implemented using the Texas Instruments TMS320-20 DSP device which also performed the channel filtering and system control functions.

The FM and development SSB radios provided a nominal audio bandwidth of 300-3100Hz, however, transceiver filtering in the SEA SSB radio limited the upper frequency range to 2800Hz.

The system architectures of the three radio types, FM, LM1 and LM2 are illustrated in Figs 1a, 1b and 1c. The two SSB LM radios differ primarily in the RF radio architecture, the SEA radio using conventional superheterodyne modulation and demodulation techniques, with channel filtering performed at IF, whilst the Bristol development radio employed a direct conversion transceiver architecture. The main advantage of a direct conversion architecture in this context is that channel filtering is performed at baseband and can thus be significantly enhanced compared with conventional IF crystal filter techniques. The SEA radios incorporated slow acting automatic feedback gain and frequency control as shown. Both radios were designed to operate with a 5KHz channel spacing \*\*.

For each system under test, three radio sets were provided, one acting as the wanted RF source, one as the co-channel interfering source and one as the receiver. The radios were connected as shown in Fig 2, with provision for variable attenuation of the interfering source relative to the wanted source. A Rayleigh fading simulator connected to each RF source provided the necessary channel distortion, with facility for variable fading rate up to a maximum of 100Hz Doppler. The wanted audio source consisted of a series of unrelated groups of sentences, five sentences per group, provided by the British Telecom Research Laboratories. The interfering audio source

was continuous speech.

#### Co-channel Measurement Procedure

For each radio system, measurements were made under conditions of no fading, (ie. static vehicle), and Rayleigh fading, (vehicle moving).

a) Static Case: The first test setup was designed to assess the system performance under "static" conditions with no signal fading or Doppler

\*\* With direct conversion receiver architectures, 4KHz channel spacing is quite feasible with no degradation of audio quality or co-channel interference immunity. shift. A fixed frequency offset in the range 200Hz was introduced between wanted and interfering sources to simulate the effect of RF local oscillator error. For each of the systems under test, the frequency offset was adjusted to provide worst case subjective performance. The FM system performance was found to be virtually independent of frequency error within 200Hz, however the performance of the SSB radios was noticeably degraded with frequency offsets in the range 5Hz to 20Hz. This was due to the two received pilot tones beating together and causing artificial signal fading at approximately the syllabic rate. The static tests were thus performed with a 10Hz fixed frequency error.

Recordings of the received speech were made for ratios of wanted to unwanted signal in the range 0dB to 25dB in favour of the wanted source.

b) Mobile Case: The mobile tests incorporated the fading simulator in addition to the fixed frequency offset of the two signal sources. As for the static case, a worst case performance was sought for each radio system, relating to the fading rate imposed. For the FM radio, the worst performance occurred at fading rates in the range 5Hz to 20Hz where the FM receiver was capturing the interfering source at approximately the syllabic rate. The same result was noted for the LM systems although the subjective effect of fading on the two modulation types, FM and LM, was noticeably different. Consequently, the mobile tests were performed with fading of 10Hz and static frequency error of 10Hz for worst case assessment.

Recordings of the received speech signal were made for values of co-channel interference protection ratio in the range 0dB to 25dB as for the static case.

#### SUBJECTIVE ASSESSMENT AND RESULTS

A panel of 24 listeners was assembled to assess the recorded speech passages which were reproduced in a random order according to established assessment practice. The panel were asked to grade each group

of sentences heard according to the standard CCIR five point scale of 5 = excellent, 4 = good, 3 = average, 2 = poor, 1 = unusable. Voting was to be based on the listeners assessment of speech quality and intelligibility for a potential cellular car phone system.

The results obtained for the initial trials are presented graphically in Figs 3 and 4 for the static and fading cases. The most surprising outcome of the trials is that there is little difference in the subjective rating for the three radio systems. The modified SEA SSB system performs worst overall primarily due to the adverse narrowband crystal filtering which produces a relatively low subjective rating, even with no interference. For the static tests, the LM performance is also hampered slightly by the artificial fading phenomena mentioned earlier. This degradation can be significantly reduced however by ensuring a smaller or greater fixed frequency error in the co-channel source so that fading does not occur at the syllabic rate. Alternatively, a coded pilot system can be adopted [5]. For the fading case, subjective assessment shows that the co-channel performance of 25KHz FM is comparable to that of 5KHz SSB LM to within approximately 1dB, irrespective of the level of interference. Thus, from Eqn 1, the spectral efficiency of SSB LM is at least 4-5 times that of current cellular FM systems, ie. directly proportional to the bandwidth saving of the LM systems. Thus, if a 4KHz channel LM system were used, the efficiency can be further increased to 6 times that of FM.

This substantial increase in spectral efficiency afforded by adopting LM techniques, begs two key questions. Firstly; How does this improvement compare with that offered by alternative "new" technologies? Secondly; Is LM a viable commercial concern?

In answer to the first question, the prime contenders for second and third generation cellular systems are the so-called digital cellular techniques, ie. those which involve voice coding and subsequent data transmission techniques. The proposed pan-european cellular systems are to employ 16kbps RELP voice coding and a TDMA access strategy. The most recent evaluations of these systems suggest a potential improvement in spectral efficiency of between 1 to 1.5 times that of existing FM systems for similar performance criterion. Clearly, therefore it is questionable as to the wisdom of choosing such a system in the light of considerably more spectrally efficient alternatives. Low bit rate vocoding techniques such as 2.4kbps or 4.8kbps Linear Predictive Coding, LPC, provide a highly bandwidth efficient means of speech transmission, but as yet have failed to produce acceptable quality speech. A recent comparison of 2.4kbps LPC, SSB-LM and

narrowband FM [6] for mobile satellite communications has shown that LPC does not score higher than a rating of 2 on the aforementioned CCIR scale.

In answer to the second question, regarding the commercial viability of SSB-LM, it is the authors opinion that by taking full advantage of the latest developments in signal processing technology, transceiver architecture design, and fading correction techniques, a very competitive LM system can be engineered. Already, cost competitive VHF SSB systems have been manufactured in the USA for a number of years, including a handportable set. The technical risk involved in the design and manufacture of a LM cellular system is significantly less than that for a "digital cellular" scheme of the type proposed in Europe, and the development phase considerably shorter.

To have a realistic chance of success in the cellular radio market place, SSB-LM must however be capable of supporting not only speech traffic, but the growing volume of mobile data traffic. Ideally, it should allow a smooth transition from the current predominance of analogue voice traffic to a possible future predominance of data traffic. In this respect, there are several, well documented methods for data transfer using LM, particularly those involving the TTIB technique[7], which provide excellent coherent data transmission in the mobile environment. In many cases, the bit error performance achieved is considerably better than that accomplished with current FM technology. Note: for data communications which require channel bandwidths in excess of the 4 to 5KHz occupied by analogue voice, the bandwidth of the pilot based LM system can be extended to the coherence limit of the channel without sacrificing performance. Further information on the data communications potential of LM is provided in a companion paper entitled "Narrowband Coherent Data Communications - Mobile" to be presented at this conference.

## CONCLUSIONS

The major conclusion to be drawn from the FM/LM comparison is that SSB Linear Modulation can provide at least a four to five fold improvement in spectral efficiency over the current FM cellular systems, with no degradation in performance. In fact, the LM systems have a considerably better tolerance to ambient noise[8] and as such can maintain communications well below the usable SNR of FM equipment, thus improving the effective coverage area of cells. With the enormous potential of these LM techniques for relieving spectral congestion, the question arises as to the commercial viability of such techniques. The majority of the system processing required to achieve the quoted performance for LM is readily performed using a single off the shelf DSP,

and is certainly amenable to LSI fabrication as is currently being investigated by a number of semiconductor manufactures. Application of new developments in transceiver design and frequency synthesisers means that compact, low power LM systems are certainly feasible.

The flexibility of a Linear Modulation system, the ability to provide a transparent channel, the low power and bandwidth requirements, the high subjective speech quality, the data communications potential, all suggest that LM is likely to be one of the most prominent analogue and digital mobile radio technologies of the future.

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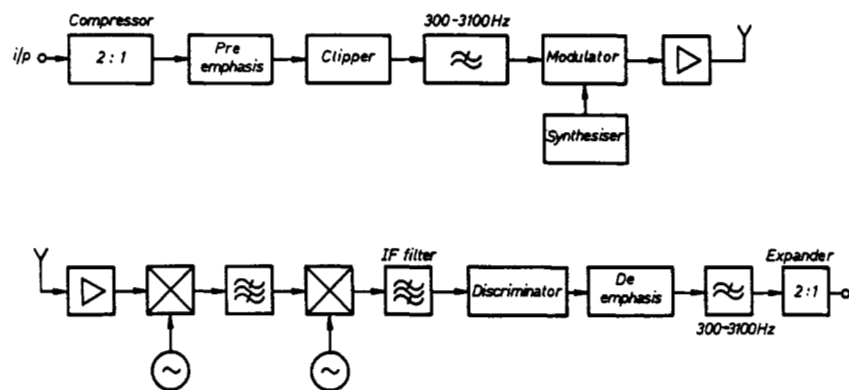


FIG. 1a FM TRANCEIVER PROCESSING

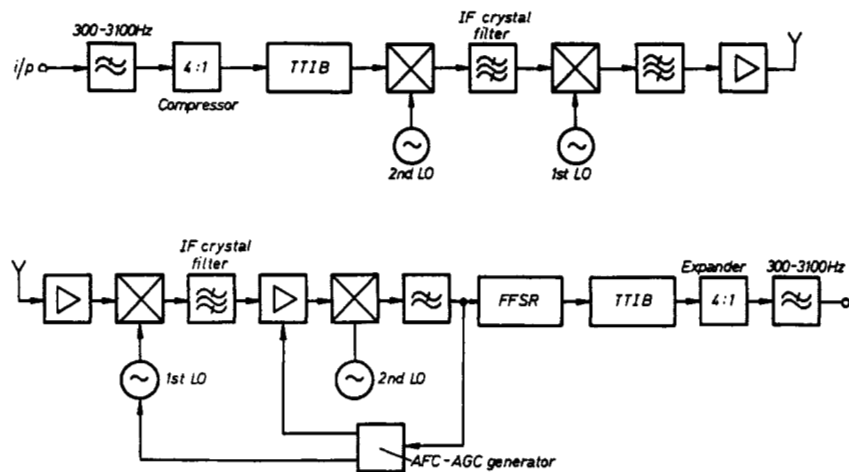


FIG. 1b LM1 TRANCEIVER PROCESSING

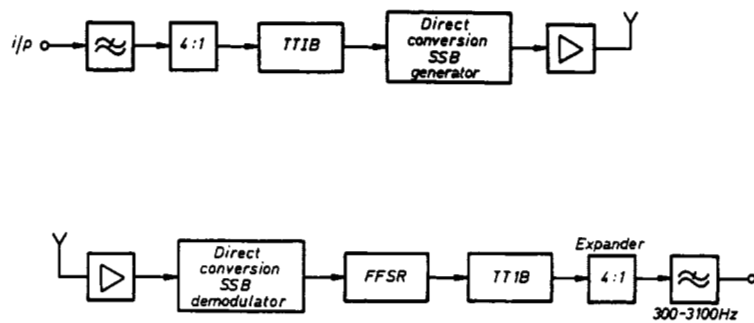


FIG. 1c LM2 TRANCEIVER PROCESSING

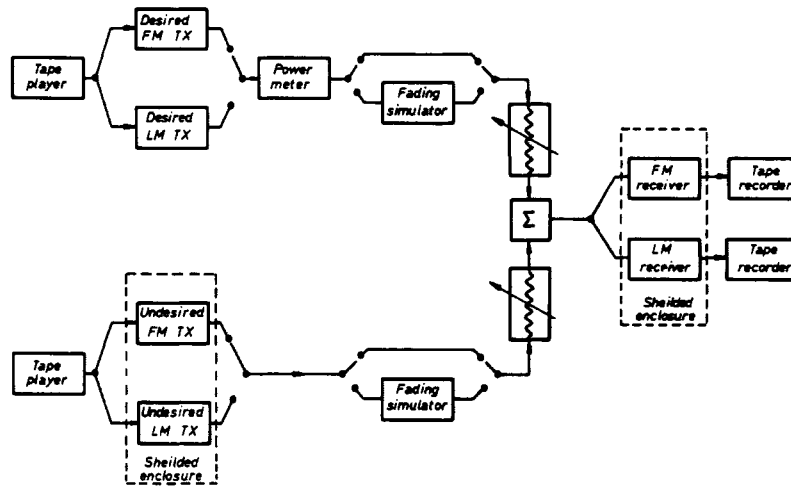


FIG.2 CO-CHANNEL INTERFERENCE MEASUREMENT CONFIGURATION

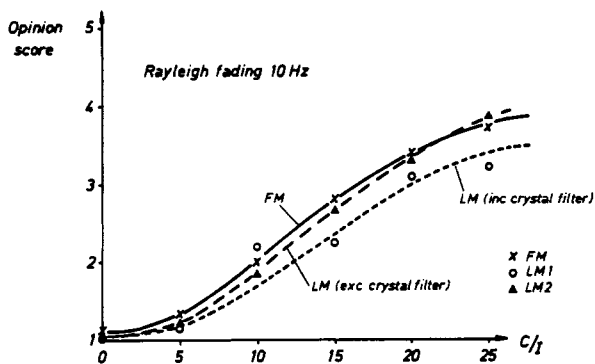


FIG.3 PERFORMANCE OF FM AND LM RADIOS WITH CO-CHANNEL INTERFERENCE AND RAYLEIGH FADING

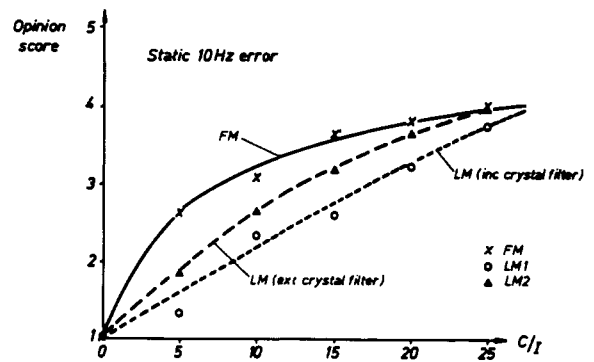


FIG.4 PERFORMANCE OF FM AND LM RADIOS WITH CO-CHANNEL INTERFERENCE, NO FADING