Single-sideband transmission for land mobile radio

From seven to ten times as many channels could be made available in existing VHF and UHF bands

Existing mobile radio bands could be used more effectively to accommodate more traffic in the same bandwidth. With available technologies, from seven to ten times as many channels could be obtained in existing VHF and UHF bands, states a recent study for the UHF Task Force of the U.S. Federal Communications Commission.

These and other conclusions are the result of tests on an experimental system that combines single-sideband (SSB) amplitude modulation with amplitude and frequency compandors—integrated circuits that modify the basic voice signals to make more efficient use of the transmission channels. In addition, digital frequency synthesizers and temperature-corrected crystals increase the flexibility of channel selection and provide the necessary precision for tight spacing of channels. With the experimental system, voice signals are transmitted within a radio-frequency bandwidth of 1.7 kHz, permitting a channel separation of 2.0 to 2.5 kHz. (Current FM mobile radios occupy a radio-frequency bandwidth of 16 kHz and require a channel separation of 20 or 25 kHz.) Although commercial equipment is not yet available, it is expected that such systems could be produced at costs comparable to current equipment.

This article compares FM, AM, and SSB modulation techniques combined with syllabic amplitude and frequency compandors. In the quality range important to mobile radio—15- to 30-dB signal-to-noise ratios—the amplitude-compandored SSB system and the amplitude- and frequency-compandored SSB system provide the same or better quality reception than FM systems that have comparable transmitter power. Three to five channels of the narrow-band system can be used between the channels of the present 25-kHz spaced FM channels without unacceptable interference on either system. Ten narrow-band channels can operate in the 25-kHz bandwidth if there are no FM channels present.

Analytical basis

The AM and SSB signals have fixed-frequency bandwidths; FM has a range of bandwidths that depend on the modulation index selected. As long as the FM signal strength remains above the so-called "threshold" (knee of the characteristic performance curve), FM provides good signal quality for much less transmitter power than standard AM. Although the amplitude-modulation and single-sideband systems use only one third to one fifth as much bandwidth, their increased power requirements have outweighed this advantage—at least when an abundant radio spectrum was available.

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The two new technologies that change this picture are amplitude and frequency compandors. The amplitude compandor reduces the amplitude of loud syllables and increases the amplitude of quiet passages of transmitted signals. The net result is that the signal-to-noise ratio occurring during quiet passages is substantially improved, and during loud passages is somewhat degraded. However, the degradation is masked by the loudness of the passage itself. Upon reception, signal expansion restores the signal to its original form. Typical amplitude compandors give a 1-dB output variation for every 2 dB of input variation and can yield a 15-dB signal-to-noise improvement. Compandors using greater compression are under development and should provide even greater improvement.

In frequency companding, the voice frequencies are compressed prior to transmission and expanded upon reception. The experimental system tested takes advantage of the tendency in human speech for either low (vowel) sounds or high (consonant) sounds to be used, but not both at the same time. The system folds the higher frequencies down over the lower frequencies and transmits both simultaneously. Expansion at the receiver gives a high-quality signal that has been transmitted in about 60 percent of the bandwidth normally required for intelligible voice.

The two techniques can be applied to the basic voice signals at baseband and used with most modulation schemes. The amplitude compandor, however, does not work well with FM below threshold.

The frequency compandor results in a 60-percent reduction (−2.2 dB) in both power required and bandwidth used to achieve the same signal quality.

The amplitude compandor provides a 15-dB improvement in signal-to-noise ratio at baseband with no change in bandwidth. In the AM and SSB systems this results in a 15-dB reduction in transmitter power required to achieve a given signal-to-noise ratio. With the FM system, the modulation index, and thus the bandwidth, should be adjusted to stay just above the FM threshold at the desired signal-to-noise ratio. Amplitude compandors thus offer both a power and bandwidth reduction for FM systems; however, for mobile radio, this reduction is not nearly as great as the reduction for AM or SSB systems. At the signal qualities desired for mobile radio, FM is already used with a relatively small modulation index—about 1.7. Further narrowing of the FM bandwidth rapidly reduces the FM advantage and also the benefit of the amplitude compandor.

The use of amplitude compandors in AM and SSB eliminates the power-range advantage of FM modulation for mobile radio. Because the AM and SSB signals are inherently more frequency-conserving, these systems are

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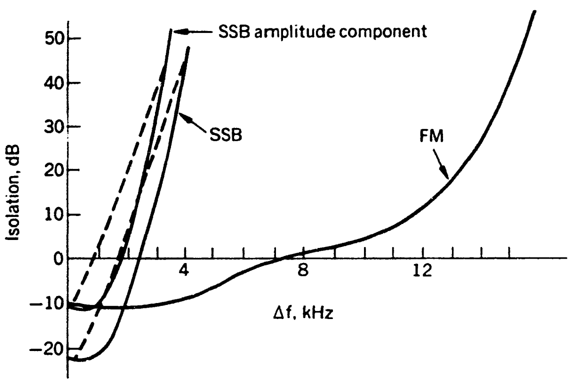
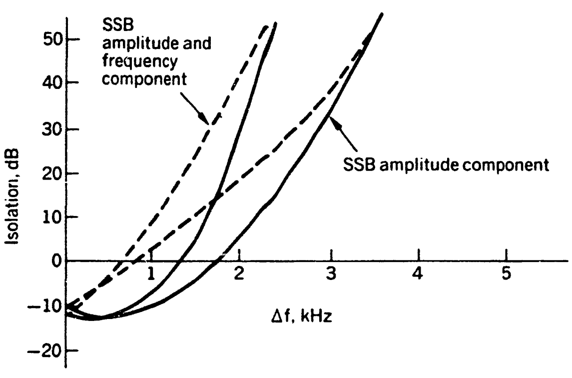
[1] A comparison of FM, SSB, and SSB-with-amplitude compandor (A) indicates that with cochannel interference (ΔF = 0), normal SSB requires 11 to 13 dB more separation than FM, but the addition of the amplitude compandors reduces isolation to FM levels. Separation depends on whether the interferer has a higher or lower frequency. The dashed lines represent best separation; the solid lines, worst separation. The frequency- and amplitude-compandored SSB system (B) exhibits isolation characteristics similar to FM for cochannel discrimination. Tests to determine how the FM and new SSB systems could share a common band (C) show the isolation between an FM system and an SSB system with amplitude and frequency compandors. The narrow and wide curves repeat the self-isolation seen in Fig. 1A. The intermediate curves present the interference of the FM on the SSB system, and vice versa.



A

B



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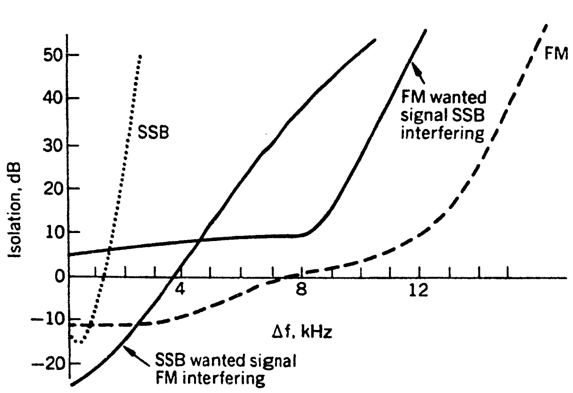

particularly effective when the frequency spectrum is crowded. SSB with amplitude compandors provides five to seven channels in the same spectrum now occupied by one FM signal. With additional frequency compandors, ten channels can fit into the frequency spectrum required for one FM channel.

The efficiency of spectrum management depends on the number of people who can use a given spectrum. In this measure—users per unit area per MHz—the separation distance required to reuse the same channel is as important as the actual spectrum occupied by a channel. This distance is a direct function of the desired-to-undesired ratio for cochannel interference: the smaller the ratio, the closer the cochannel separation distance. The ratio for FM is of the order of 11 dB; normal SSB is 22 to 24 dB. The amplitude compandor, however, improves cochannel interference in SSB by about 10 to 11 dB, and results in a cochannel separation that is comparable to FM. Because amplitude- and frequency-compandored SSB has the same cochannel interference rejection as FM and seven to ten times better frequency utilization, a full seven- to tenfold advantage could be achieved in spectrum-use efficiency;

Implications of the narrow-band research

A key finding of the narrow-band research is that the performance of single sideband with amplitude compandor is very close to the performance of FM with 5-kHz deviation and 30-dB signal-to-noise ratio, and is very different from the performance of single sideband without amplitude compandor. The frequency compandor is an addition that may be desirable if the modification of voice quality is acceptable.

Based on preliminary field tests, the narrow-band technology appears to have a good potential for improving the spectrum utilization of mobile voice communications. However, the feasibility has not yet been fully proven; pilot tests are planned but not yet underway. At the point where the project is shown to be feasible, industry cooperation will be required for its smooth introduction into the marketplace. Until then, it would be inappropriate for the Commission to take action. Other techniques for achieving higher-spectrum utilization should also be studied.

Introducing any technique different from the one currently in use will require close coordination between industry and the FCC. Because the spectrum does not have a price tag, an engineer strives to meet desired performance at minimum cost, usually without regard to bandwidth. In other words, market forces place a higher emphasis on cost per unit than on spectrum efficiency. Incentives must be developed to encourage industry participation in achieving efficient use of the spectrum resource.

If the tests indicate the practicality of the system, the UHF Task Force will investigate the best frequency-assignment policy for narrow-band techniques. Studies are also aimed at developing the special circuits commonly required for mobile telecommunications, and at economically achieving the high-frequency stability required by narrow-band operations at the higher UHF frequencies. The Electronic Industries Association, at the request of the Land Mobile Communications Council, has set up a committee to review the narrow-band proposal. This committee consists of representatives of U.S. manufacturers of land mobile equipment.

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the advantage translates into seven to ten times as many users per square mile.

Experimental results

Extensive tests were conducted to confirm analytic predictions. The transceiver used was the ICOM Model IC-245 with a single sideband adapter. The unit could be switched between SSB modulation and FM with 5-kHz deviation. The FM transmitter power was 10 watts; SSB peak transmitter power was also 10 watts, but typical average power during loud passages was about 6 dB below that—2.5 watts.

External units were constructed to hold an amplitude compandor, the Signetics NE-570 integrated circuit, and a frequency compandor circuit, which used a 1.7-kHz bandwidth. By simple switching, any one of eight modes could be selected to provide a direct comparison of different techniques under identical radio-frequency conditions. The transceivers operated in the 144-MHz band. At this frequency, both rapid fading and high ignition noise can occur during road tests. (The frequency compandor used in these tests was developed at the laboratories of VBC, Inc., Stockton, Calif., by R. W. Harris, J. F. Cleveland, and T. M. Lott.)

For the signal-to-noise measurements, one transmitter was used, and its received power was varied in relation to an external radio-frequency noise source. In the cochannel interference tests, two transmitters were used. One transmitter was kept tuned to the wanted signal, while another transmitter, the interferer, was adjusted to the desired power and offset frequencies. One of two tape recorders played a standard audio message—a "rainbow" passage containing all the sounds in the English language. The other played the interfering signals. The results were recorded at the receiver and observed on an audio spectrum analyzer.

Signal to noise. At a high signal-to-noise ratio, the normal FM and SSB systems both restricted the voice signal bandwidth about the same degree. When an amplitude compandor was added to a noiseless signal, there was no noticeable difference. When a frequency compandor was used, the transmitted audio bandwidth was much narrower, about 1.7 kHz, and the recovered bandwidth was a little wider than normal, about 3.5 kHz.

A 1-kHz tone was transmitted alternately on two modulations to permit a comparison of FM and normal SSB performance at various noise levels, and the ratio of 1-kHz signal power to total-audio-noise power was measured in the received audio spectrum. Without compandors, the results display the classic FM improvement

I. Impact of narrow-band channels* (2.5-kHz spacing)

Band: Frequency: Spacing:	Low 30–50 MHz 20 kHz	High 150–170 MHz 15 kHz	VHF 450–470 MHz 25 kHz	Total
Public Safety				
Current FM channels	316	255	74	645
Additional interlaced narrow-band (NB) channels				
Clear NB channels	316	—	222	538
Moderate-isolation NB channels	632	255	148	1 035
Full use of NB channels	2 528	1 530	740	4 798
Industrial				
Current FM channels	254	145†	205	604
Additional interlaced NB channels				
Clear NB channels	254	—	615	869
Moderate-isolation NB channels	508	145	410	1 063
Full use of NB channels	2 032	870	2 050	4 952
Transportation				
Current FM channels	64	158	34	256
Additional interlaced NB channels				
Clear NB channels	64	—	102	168
Moderate-isolation NB channels	128	158	68	354
Full use of NB channels	512	948	340	1 800
Domestic public				
Current FM channels	14	29‡	38	81
Additional interlaced NB channels				
Clear NB channels	14	145	114	273
Moderate-isolation NB channels	28	58	76	162
Full use of NB channels	112	348	380	840
Summary				
Total current FM channels				1 586
Additional interlaced NB channels				
Total clear NB channels				1 848
Total moderate-isolation NB channels				2 614
Total possible NB channels				12 390

* There were several assumptions made when the number of channels was computed. Where frequencies were identified as being paired, they were counted as one channel. No frequencies were included when they were identified as being assigned only for fixed use. No frequencies in the 72-76-MHz band were included. Frequencies that are shared between services were counted in the lowest-numbered Rule Part. Frequencies available only for hydrological purposes were omitted.

† Some of the industrial channels in the 150-170-MHz band are spaced at 30 kHz, and will yield more NB channels than shown.

‡ Domestic public land-mobile services use 30-kHz, rather than 15-kHz, channel spacing in the 150-170-MHz band.

and threshold. Above threshold, FM is over 15 dB better than SSB, but falls below SSB performance as signal strength is reduced below the FM noise threshold. For mobile radio applications, FM operates on or near the knee of this threshold curve.

The effect of the amplitude compandor becomes very noticeable once the noise level becomes bothersome. In the SSB system a subjective improvement of about 15 dB was evident. Loud noise was dramatically reduced when the amplitude compandor was switched in. However, for FM noise below the threshold, the improvement was not nearly as great. The amplitude-compandored SSB sounded as good as normal FM at higher transmitter powers and far better at low signal powers.

When the frequency and amplitude compandors were used together, the subjective noise improvement was about the same as with the amplitude compandor alone. The 2-dB added improvement expected from the frequency compandor was not enough to notice in a moderate noise environment.

Cochannel and adjacent-channel interference. Figure 1A compares the results of interference tests for SSB and FM systems. The curves show the interference-to-carrier ratio necessary to produce a reference interference level, as a function of frequency separation of the interfering and desired signals. With cochannel interference, $\Delta F = 0$, FM requires 10 to 11 dB above the interference signal; normal SSB requires 22 to 24 dB. However, the addition of amplitude compandors to SSB results in a system that is comparable to FM in cochannel discrimination. The frequency- and amplitude-compandored SSB system is also similar to FM on cochannel discrimination (Fig. 1B).

Figure 1 also presents the results of adjacent-channel interference measurements for the different systems. The curves show the minimum frequency separation between channels needed to achieve a given isolation. In the data recorded here, a 15-kHz separation in FM produces an interference that is audible, but not objectionable (20 dB below signal level), with the interferer 40 dB greater in received power. This separation is currently used in some mobile radio bands. The frequency separation for SSB channels would be 3.5 kHz if the same criteria were used. For amplitude-compandored SSB, it would be 3.0 kHz; and for frequency- and amplitude-compandored SSB, it would be 2 kHz. For 50- to 60-dB isolation, the separation would be about 30 to 40 percent greater.

A perspective

This article is essentially the report to the FCC UHF Task Force given by Messrs. Harris, Lusignan, and Wilmotte. The report has stimulated an ongoing technical controversy in the communications industry and caused concerns about its implications within land mobile user groups. The Electronic Industries Association, at the request of the Land Mobile Communications Council, has organized an industry committee to examine the technical conclusions of the report, many of which are not consistent with industry experiences in the real, practical, mobile radio world.

Readers should be aware that only cursory system tests have been performed in an attempt to demonstrate the system's technical feasibility and its applicability to land mobile radio. The UHF Task Force has said it plans additional field tests during the next 18 months to look at specific system performance characteristics of narrow-band SSB with amplitude compandors.

Many professional technical people, in and out of the land mobile industry, and in the U.S. and Europe, seriously doubt that the narrow-band system (2.5-kHz channel spacing) as proposed by the UHF Task Force study can be implemented with reasonable cost and system performance. The practical design of hand-held personal radios, which are needed increasingly by land-mobile radio users, whether construction workers or law-enforcement agencies, is especially doubtful because the radio must be small and light in weight, which puts stringent constraints on circuit power consumption and component selection.

What are the technical challenges that seem so formidable? I shall briefly mention three that are imposed by the 2.5-kHz channel spacing:

1. How to realize acceptable system area coverage and reliable performance with only 40-dB adjacent-channel isolation; present industry experience indicates that 70 dB or more is needed.

2. How to improve low-cost oscillators and filters so that their stabilities (short and long term) constrain the sum of all frequency drifts to be insignificant compared with the 1.7-kHz modulation bandwidth; present tolerances on these components would require that the bandwidth be more than double the 1.7-kHz modulation bandwidth to accommodate the frequency uncertainties in the receiver.

3. How to devise a practical amplitude compandor system requiring no bandwidth for pilot tones that provides the same cochannel interference protection under multipath conditions as the present FM systems do; hence, allowing reuse of the frequency without additional geographic protection over present FM systems.

Increasing the channel spacing from 2.5 kHz to 8 kHz, for example, would provide bandwidth for adjacent-channel protection, receiver-frequency drift, and compandor pilots. Even then, I see difficult circuit-development programs to realize automatic gain and frequency controls that perform satisfactorily in the rapid-fading, multipath environment. Amplitude compandors, noise blankers, selective calling, and data-transmission options are also needed. The magnitude of the development program and of the technical risk that solutions will be found for all the system needs is causing the proposed system to be thoroughly studied to appraise its technical feasibility in total. EIA's Land Mobile Committee for Spectrum-Efficient Technology will undoubtedly address these issues (and others) in more detail.

Perhaps the technical challenges of the proposed system will stimulate readers to suggest potential solutions; I hope that will be the case. As an example of the challenges, consider the oscillator in a personal radio. What emerging technology will allow building a 2-milliwatt personal-radio oscillator that has a frequency stability of 0.1 ppm for six months over a temperature range of -30 to 60°C and that can be packaged in 0.15 cubic inch and will consume less than 15 milliwatts?

The author has proposed a specific system that he believes will utilize the spectrum more efficiently. However, single sideband is only one of several proposals for improving the spectral efficiency of land mobile systems; spread-spectrum and 12.5-kHz channel FM are among others. Which is really the most efficient when the three dimensions (time, frequency, and space) are considered? How much more efficient is the best system than the present 25-kHz FM channels? What is the cost to the users to convert to the new system, and how do these costs compare with potential spectrum savings by other user groups? These are the deeper questions being raised implicitly by the specific proposal in the study report to the FCC's UHF Task Force.

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These results are pertinent to channel planning for bands using only one class of modulation. A series of adjacent-channel interference measurements were made to determine how the old and new systems could share a common band (Fig. 1C). If the 40-dB isolation criterion is again followed, the narrow-band systems could be assigned to within 10 or 11 kHz of the current FM channel assignments without unacceptable interference on either system.

Additional tests checked performance under actual road conditions, with slow and rapid fading, ignition noise, and steady background noise at long range. These tests confirmed the performances predicted by analysis and bench tests. They identified the need to use a noise-blanking circuit with SSB to achieve good performance under marginal conditions, including discrete ignition noise, and they indicated adequate performance of both FM and SSB with rapid amplitude fading.

Application to land mobile radio

These measurements indicate that a channel separation of 2 or 2.5 kHz would be acceptable for frequency- and amplitude-compressed SSB radios: 2 kHz would correspond to the practice of using 15-kHz spacing (channel splitting) with conventional FM, and 2.5 kHz would allow additional margin for reference frequency drift and would provide 50 to 60 dB isolation. For only amplitude-compression, spacings would have to be 3.0 or 3.5 kHz for comparable performance.

FM mobile radio currently uses either 15-, 20-, 25-, or 30-kHz channel spacings. To introduce narrow-band equipment into already used bands would require spacings that are submultiples of the current assignments. With current 25-kHz channels, three 2.5-kHz narrow-band channels may be placed in between the existing FM systems without interference to either the FM or narrow-band channels. Two more narrow-band channels could be accommodated with moderate isolation from the FM systems (10 to 20 dB). An additional five channels could be used on a cochannel interference basis. Ultimately, ten channels 2.5 kHz wide could be placed in the 25 kHz that formerly held one FM channel.

If narrow-band systems were introduced into the present frequency bands with 2.5-kHz spacing, the impact on channel availability would be great (Table I).

Exclusive use of the narrow-band technology could increase the number of land mobile channels below 470 MHz from 1586 to 12 390. If narrow-band is interlaced with existing channels, channels below 470 MHz would increase from 1586 to 3434. Similar spectrum savings could be obtained at frequencies above 470 MHz.

A review of the narrow-band technology for land mobile services requires consideration of several additional factors—among them intermodulation, frequency stability, and cost. Intermodulation is a problem that occurs when many transmitters are located close together. The narrow-band systems—although probably no more sensitive to intermodulation than FM—may aggravate the problem because it is possible to operate many more stations inside a given band. Increasing the number of channels increases the problem of intermodulation and may place a limit on the practical number of stations that can be located close together. This problem may be mitigated by the fact that the proposed narrow-band systems require only 0.25 to 0.1 of the average radio power of FM for comparable performance.

Narrow-band equipment will require better frequency stability than present FM mobile radio. With SSB, the receiver must track to within 20 to 40 Hz of the transmit frequency for best performance. With greater than 100-Hz difference, speech intelligibility is impaired. In the citizens and amateur radio services, manual tuning controls are used to maintain an intelligible signal; however, this is not considered suitable for the land mobile services. Thus, the requirements for frequency stability (or, more precisely, frequency synchronization between transmitter and receiver) are much stricter with the narrow-band system than they are with FM.

There are a variety of approaches to obtain the required frequency synchronization. The one likely to be most efficient is the use of state-of-the-art crystals to bring the frequency within ±200 Hz of the desired value, and use of an automatic-frequency control (AFC) circuit on the receiver to lock in from there. In this approach, a low-power carrier either below or above the voice information would provide the frequency reference. This signal would also serve as a reference for an automatic-gain-control (AGC) circuit. It could also be frequency-modulated at low deviation for a tone-squelch feature.

The crystal-frequency stability required for this approach is ±3 ppm for low band and ±1 ppm at high band—well within the capability of today's mobile radio technology. At 400 MHz, however, the crystal accuracy needed is ±0.5 ppm, which is available today only at considerable cost. The improvement in stability required for UHF may come either through use of temperature control (ovens) and temperature compensation, or from using dual-mode crystals for better temperature correction—a technique described by Hewlett-Packard in a recent patent. Alternatively, the lock-in range of the AFC circuit could be widened to ±400 Hz, thereby allowing the use of a ±1-ppm crystal at the cost of an additional 400 Hz in channel separation at the 400-MHz band.

The cost of narrow-band radios can only be estimated at this time. Amplitude compandors currently are priced at less than $3. The frequency compandor tested would sell from $20 to $30 in large-scale IC production. The AFC, AGC, and tone-squelch circuits would cost from about $10 to $20. Narrow-band equipment thus may add about $30 to $90 to the manufacturer's cost of a typical radio, depending on whether the system uses simplex or duplex operation. Once circuits are standardized, the long-term potential exists for reduced costs. ◆

This article is based on the Federal Communications Commissions's report "Spectrum Efficient Technology for Voice Communications." The report is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161.

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