Synchronous Communications*

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Summary—It can be shown that present usage of amplitude modulation does not permit the inherent capabilities of the modulation process to be realized. In order to achieve the ultimate performance of which AM is capable synchronous or coherent detection techniques must be used at the receiver and carrier suppression must be employed at the transmitter.

When a performance comparison is made between a synchronous AM system and a single-sideband system it is shown that many of the advantages normally attributed to single sideband no longer exist. SSB has no power advantage over the synchronous AM (DSB) system and SSB is shown to be more susceptible to jamming. The performance of the two systems with regard to multipath or selective fading conditions is also discussed. The DSB system shows a decided advantage over SSB with regard to system complexity, especially at the transmitter. The bandwidth saving of SSB over DSB is considered and it is shown that factors other than signal bandwidth must be considered. The number of *usable* channels is not necessarily doubled by the use of SSB and in many practical situations *no increase* in the number of usable channels results from the use of SSB.

The transmitting and receiving equipment which has been developed under Air Force sponsorship is discussed. The receiving system design involves a local oscillator phase-control system which derives carrier phase information from the sidebands alone and does not require the use of a pilot carrier or synchronizing tone. The avoidance of superheterodyne techniques in this receiver is explained and the versatility of such a receiving system with regard to the reception of many different types of signals is pointed out.

System test results to date are presented and discussed.

INTRODUCTION

FOR A good many years, a very large percentage of all military and commercial communications systems have employed amplitude modulation for the transmission of information. In spite of certain well-known shortcomings of conventional AM, its use has been continued mainly due to the simplicity of this system as compared to other modulation methods which have been proposed. During the last few years, however, it has been felt by many responsible engineers that the increased demands being made on communications facilities could not be met by the use of conventional AM and that new modulation techniques would have to be employed in spite of the additional system complexity. Of these new techniques, single sideband has been singled out as the logical replacement for conventional AM and a great deal of publicity and financial support has been given SSB as a consequence.

Many technical reasons have been given to support the claim that SSB is better than AM and these points will be discussed in some detail later in this paper. In addition, many experiments have been performed which also indicate a superiority for SSB over AM. Some care must be taken, however, in drawing conclusions from the above statements. *We cannot conclude that SSB is superior to AM because we have no assurance whatever that conventional AM systems make efficient use of the modulation process employed.* In other words, AM as a modulation process may be capable of far better performance than that which is obtained in conventional AM systems. If an analysis is made of AM and SSB systems, it will be found that existing SSB systems are very nearly optimum with respect to the modulation process employed whereas conventional AM systems fall far short of realizing the full potential of the modulation process employed. In fact, it could honestly be said that we have been misusing rather than using AM in the past. Realization of the above situation raises some immediate questions: What are the equipment requirements of the optimum AM system? How does the performance of the optimum AM system compare with that of SSB? Which shows the greater promise of fulfilling future military and commercial communications requirements, optimum AM or SSB? The remainder of this paper will be devoted mainly to answering these questions.

SYNCHRONOUS COMMUNICATIONS—THE OPTIMUM AM SYSTEM

Receiver

Conventional AM systems fail to obtain the full benefits of the modulation process for two main reasons: Inefficient use of generated power at the transmitter and inefficient detection methods at the receiver. Starting with the receiver it can be shown that if maximum receiver performance is to be obtained the detection process must involve the use of a phase-locked oscillator and a synchronous or coherent detector. The basic synchronous receiver is shown in Fig. 1. The incoming signal is mixed or multiplied with the coherent local oscillator signal in the detector and the demodulated audio output is thereby directly produced. The audio signal is then filtered and amplified. The local oscillator must be main-

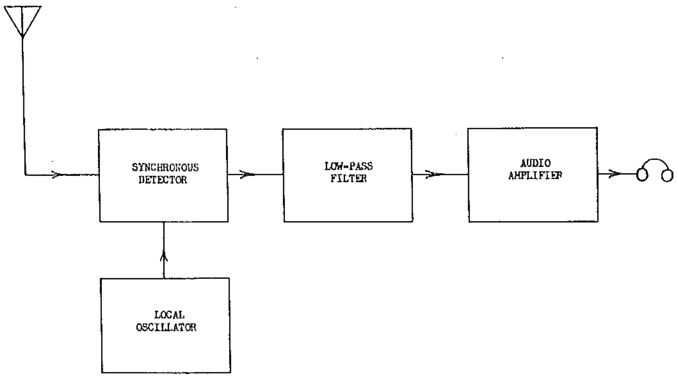

Fig. 1—Basic synchronous receiver.

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tained at proper phase so that the audio output contributions of the upper and lower sidebands reinforce one another. If the oscillator phase is 90° away from the optimum value a null in audio output will result which is typical of detectors of this type. The actual method of phase control will be explained shortly, but for the purpose of this discussion maintenance of correct oscillator phase shall be assumed.

In spite of the simplicity of this type of receiver, there are several important advantages worthy of note. To begin with, no IF system is employed which eliminates completely the problem of image responses. The opportunity to effectively use post-detector filtering allows extreme selectivity to be obtained without difficulty. The selectivity curve of such a receiver will be found to be the low-pass filter characteristic mirror-imaged about the operating frequency. Not only is a high order of selectivity obtained in this manner, but the selectivity of the receiver may be easily changed by low-pass filter switching. The carrier component of the AM signal is not in any way involved in the demodulation process and need not be transmitted when using such a receiver. Furthermore, detection may be accomplished at very low level and consequently the bulk of total receiver gain may be at audio frequencies. This permits an obvious application of transistors but more important it allows the selectivity determining low-pass filter to be inserted at a low-level point in the receiver which aids immeasurably in protecting against spurious responses from very strong undesired signals.

Phase Control: To obtain a practical synchronous receiving system some additions to the basic receiver of Fig. 1 are required. A more complete synchronous receiver is shown in Fig. 2. The first thing to be noted about this diagram is that we have essentially two basic receivers with the same input signal but with local oscillator signals in phase quadrature to each other. To understand the operation of the phase-control circuit consider that the local oscillator signal is of the same phase as the carrier component of the incoming AM signal. Under these conditions, the in-phase or I audio amplifier output will contain the demodulated audio signal while the quadrature or Q audio amplifier will have no output due to the quadrature null effect of the Q synchronous detector. If now the local oscillator phase drifts from its proper value by a few degrees the I audio will remain essentially unaffected but there will now appear some audio output from the Q channel. This Q channel audio will have the same polarity as the I channel audio for one direction of local oscillator phase drift and opposite polarity for the opposite direction of local oscillator phase drift. The Q audio level is proportional to the magnitude of the local oscillator phase angle error for small errors. Thus by simply combining the I and Q audio signals in the audio phase discriminator a dc control signal is obtained which automatically corrects for local oscillator phase errors. It should be noted that phase control information is derived entirely from the sideband components of the AM signal and that the carrier if present is not used in any way. Thus since both synchronization and demodulation are accomplished in complete independence of carrier, suppressed-carrier transmissions may be employed.

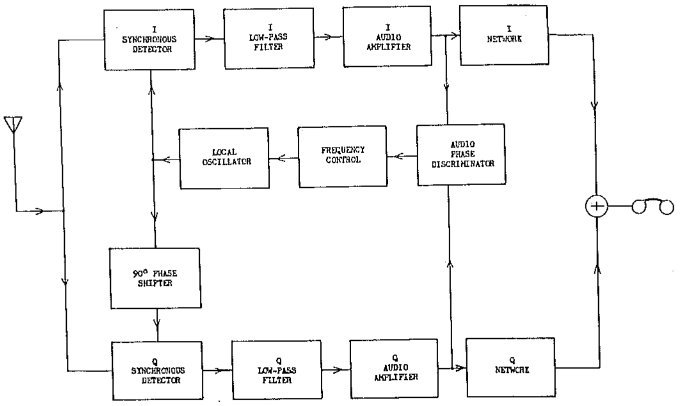

Fig. 2—Two-phase synchronous receiver.

It is unfortunate that many engineers tend to avoid phase-locked systems. It is true that a certain amount of stability is a prerequisite but it has been determined by experiment that for this application the stability requirements of single-sideband voice are more than adequate. Once a certain degree of stability is obtained, the step to phase lock is a simple one. It is interesting to note that this phase-control system can be modified quite readily to correct for large frequency errors when receiving AM due to Doppler shift in air-to-air or ground-to-air links.

It is apparent that phase control ceases with modulation and that phase lock will have to be reestablished with the reappearance of modulation. This has not proved to be a serious problem since lock-up normally occurs so rapidly that no perceptible distortion results when receiving voice transmission. It should be further noted that such a phase control system is inherently immune to carrier capture or jamming. In addition it has been found that due to the narrow noise bandwidth of the phase-control loop, synchronization is maintained at noise levels which render the channel useless for voice communications.

Interference Suppression: The post-detector filters provide the sharp selectivity which, of course, contributes significantly to interference suppression. However, these filters cannot protect against interfering signal components which fall within the pass band of the receiver. Such interference can be reduced and sometimes eliminated by proper combination of the I and Q channel audio signals. To understand this process consider that the receiver is properly locked to a desired AM signal and that an undesired signal appears, some of whose components fall within the receiver pass band. Under these conditions the I channel will contain the desired audio signal plus an undesired component due to the interference. The Q channel will contain only an interference component also arising from the presence of the interfering signal. In general the interference component in the I channel and the interference component in the Q channel are related to one another or they may be said to be correlated. Advantage may be taken of this correlation by treating the I and Q voltages with the I and Q networks and adding these network outputs. If properly done this process will reduce and sometimes eliminate the interfering signal from the receiver output as a result of destructive addition of the I and Q interference voltages.

The design of these networks is determined by the spectrum of the interfering signal and the details of network design may be found a report by the author.[1] Although such details cannot be given here it is interesting to consider one special interference case. If the interfering signal spectrum is confined entirely to one side of the desired signal carrier frequency the optimum I and Q networks become the familiar 90° phasing networks common in single-sideband work. Such operation does not however result in single-sideband reception of the desired signal since both desired signal sidebands contribute to receiver output at all times. This can be seen by noting that the Q channel contains no desired signal component so that network treatment and addition effects only the undesired audio signal components. The phasing networks are optimum only for the interference condition assumed above. If there is an overlap of the carrier frequency by the undesired signal spectrum the phasing networks are no longer optimum and a different network design is required for the greatest interference suppression.

This two-phase method of AM signal reception can aid materially in reducing interference. As a matter of fact it can be shown that the true anti-jam characteristics of AM cannot be realized unless a receiving system of the type discussed above is used. If we now compare the anti-jam characteristics of single sideband and suppressed-carrier AM properly received it will be found that intelligent jamming of each type of signal will result in a two-to-one power advantage for AM. The bandwidth reduction obtained with single sideband does not come without penalty. One of the penalties as we see here is that single sideband is more easily jammed than double sideband.

Transmitter

The synchronous receiver described above is capable of receiving suppressed-carrier AM transmissions. If a carrier is present as in standard AM this will cause no trouble but the receiver obviously makes no use whatever of the carrier component. The opportunity to employ carrier-suppressed AM transmissions can be used to good advantage in transmitter design. There are many ways in which to generate carrier-suppressed AM signals and one of the more successful methods is shown in Fig. 3. A pair of class-C beam power amplifiers are screen modulated by a push-pull audio signal and are driven in push-pull from an rf exciter. The screens are returned to ground or to some negative bias value by means of the driver transformer center tap. Thus in the absence of modulation no rf output results and during modulation the tubes conduct alternately with audio polarity change. The circuit is extremely simple and a given pair of tubes used in such a transmitter can easily match the average rf power output of the same pair of tubes used in SSB linear amplifier service. The circuit is self-neutralizing and the tune-up procedure is very much the same as in any other class-C rf power amplifier. The excitation requirements are modest and as an example the order of 8 w of audio are required to produce a sideband power output equivalent to a standard AM carrier output of 1 kw. Modulation linearity is good and the circuit is amenable to various feedback techniques for obtaining very low distortion which may be required for multiplex transmissions.

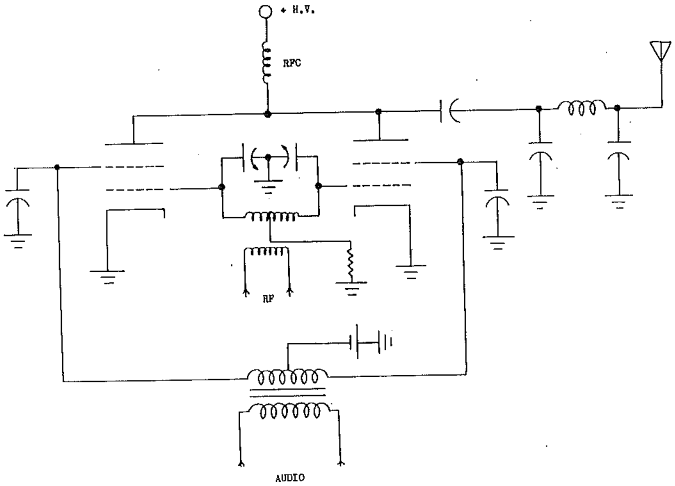

Fig. 3—Suppressed-carrier AM transmitter.

This transmitter circuit is by no means new. The information is presented here to indicate the equipment simplicity which can be realized by use of synchronous AM communications.

PROTOTYPE EQUIPMENT

A synchronous receiver covering the frequency range of 2–32 mc is shown in Fig. 4. The theory of operation of this receiver is essentially that of the two-phase synchronous receiver discussed earlier. This is a direct conversion receiver and the superheterodyne principle is not used. A rather unusual frequency synthesis system is employed to give high stability with very low spurious response. Only one crystal is used and this is a 100 kc oven-controlled unit.

This receiver will demodulate standard AM, suppressed-carrier AM, single sideband, narrow-band fm, phase modulation, and cw signals in an optimum man-

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[1] J. P. Costas, "Interference Filtering," Mass. Inst. Tech. Res. Lab. of Elec., Tech. Rep. no. 185.

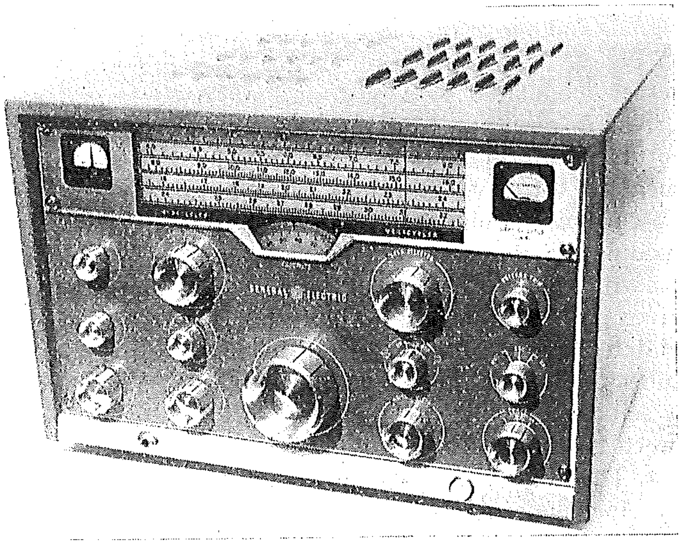

Fig. 4—The AN/FRR—48 (XW-1) synchronous receiver.

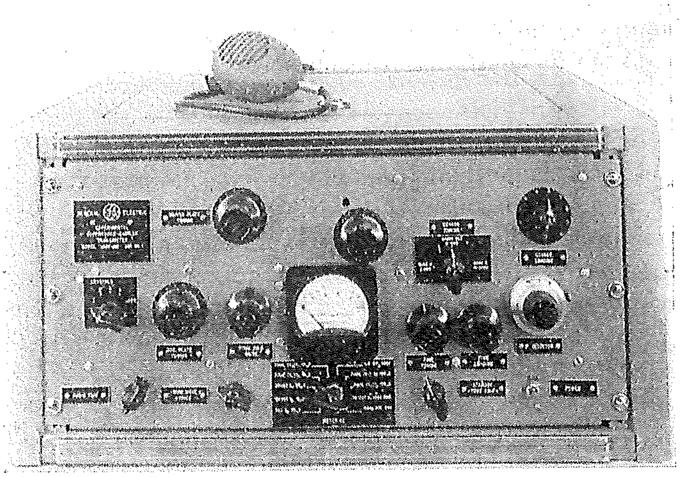

Fig. 5—The AN/FRT—29 (XW-1) suppressed-carrier AM transmitter.

ner. This versatility is a natural by-product of the synchronous detection system and no great effort is required to obtain this performance.

Fig. 5 shows a suppressed-carrier AM transmitter using a pair of 6146 tubes in the final. This unit is capable of 150-w peak sideband power output for continuous sine-wave modulation. The modulator is a single 12BH7 miniature double triode. Fig. 6 shows a transmitter capable of 1000-w peak sideband power output under continuous sine wave audio conditions. The final tubes are 4-250-A's and the modulator uses a pair of 6L6's. Both of these transmitters are continuously tunable over 2–30 mc.

A Comparison of Synchronous AM and Single Sideband

It is interesting at this point to compare the relative advantages and disadvantages of synchronous AM and single-sideband systems. Although single sideband has a clear advantage over conventional AM this picture is radically changed when synchronous AM is considered.

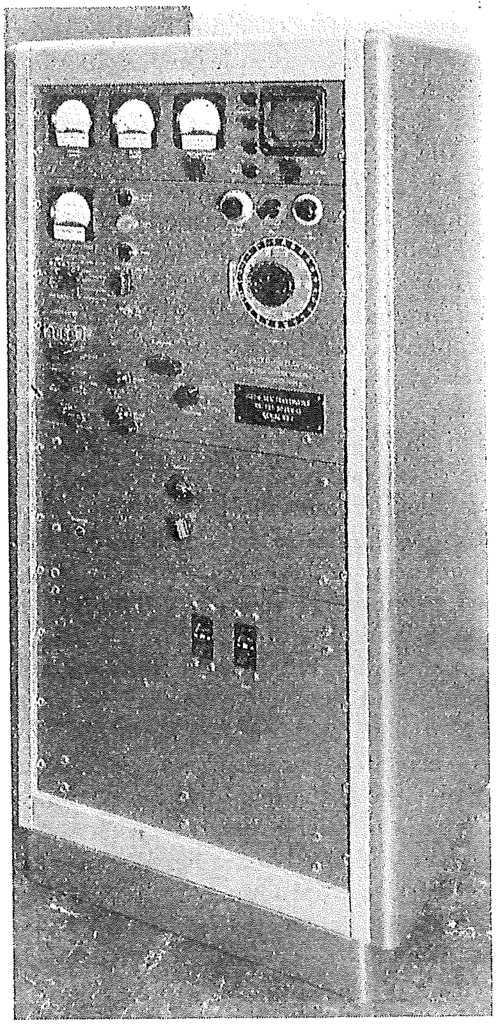

Fig. 6—The AN/FRT—30 (XW-1) suppressed-carrier AM transmitter.

Signal-to-Noise Ratio

If equal average powers are assumed for SSB and synchronous AM it can easily be shown that identical s/n ratios will result at the receiver. The additional noise involved from the reception of two sidebands is exactly compensated for by the coherent addition of these sidebands. The 9-db advantage often quoted for SSB is based on a full AM carrier and a peak power comparison. Since we have eliminated the carrier and since a given pair of tubes will give the same average power in suppressed-carrier AM or SSB service there is actually no advantage either way. If intelligent jamming rather than noise is considered there exists a clear advantage of two-to-one in average power in favor of synchronous AM.

System Complexity

Since the receiver described is also capable of SSB reception it would appear that synchronous AM and SSB systems involve roughly the same receiver complexity. This is not altogether true since much tighter design specifications must be imposed if high quality SSB reception is to be obtained. If AM reception only is considered these specifications may be relaxed considerably without materially affecting performance. The synchronous receiver described earlier may possess important advantages over conventional superheterodyne receivers but this point is not an issue here.

The suppressed-carrier AM transmitter is actually simpler than a conventional AM transmitter. It is of course far simpler than any SSB transmitter. There are no linear amplifiers, filters, phasing networks, or frequency translators involved. Personnel capable of operating or maintaining standard AM equipment will have no difficulty in adapting to suppressed-carrier AM. The military and commercial significance of this situation is rather obvious and further discussion of this point is not warranted.

Long-Range Communications

The selective fading and multipath conditions encountered in long-range circuits tend to vary the amplitude and phase of one sideband component relative to the other. This would perhaps tend to indicate an advantage for SSB but tests to date do not confirm this. Synchronous AM reception of standard AM signals over long paths has been consistently as good as SSB reception of the same signal. In some cases it was noted that the SSB receiver output contained a serious flutter which was only slightly discernible in the synchronous receiver output. Some attempt has been made to explain these results but as yet no complete explanation is available. One interesting fact about the synchronous receiver is that the local oscillator phase changes as the sidebands are modified by the medium since phase control is derived directly from the sidebands. In a study of special cases of signal distortion, it was found that the oscillator orients itself in phase in such a way as to attempt to compensate for the distortion caused by the medium. This may partially explain the good results which have been obtained. Perhaps another point of view would be that the synchronous receiver is taking advantage of the inherent diversity feature provided by the two AM sidebands.

Test results to date indicate that synchronous AM and single-sideband provide much the same performance for long-range communications. The AM system has been found on occasion to be better but since extensive tests have not been performed and a complete explanation of these results is not yet available it would be unfair to claim any advantage at this time for AM.

Spectrum Utilization

In theory, single-sideband transmissions require only half the bandwidth of equivalent AM transmissions and this fact has led to the popular belief that conversion to single sideband will result in an increase in usable channels by a factor of two. If a complete conversion to single sideband were made those who believe that twice the number of usable channels would be available might be in for a rather rude awakening. There are many factors which determine frequency allocation besides modulation bandwidth. Under many conditions it actually turns out that modulation bandwidth is not a consideration. This is a complicated problem and only a few of the more pertinent points can be discussed briefly here.

To begin with the elimination of one sideband is a complicated and delicate business. Any one of several misadjustments of the SSB transmitter will result in an empty sideband which is not actually empty. We are not thinking here of a telephone company point-to-point system staffed by career personnel, but rather we have in mind the majority of military and commercial field installations. This is in no way meant to be a criticism, but the technical personnel problem faced by the military especially in time of war is a serious one and this simple fact of life cannot be ignored in future system planning. Thus we must concede that single-sideband transmissions will in practice not always be confined to one sideband and that those who allocate frequencies must take this into consideration.

There may be those who would argue that SSB transmitting equipment can be designed for simple operation. This is probably true but in general operational simplicity can only be obtained at the expense of additional complexity in manufacture and maintenance. This of course trades one set of problems for another but if we assume ideal SSB transmission we are still faced with an even more serious allocation problem. We refer here to the problem of receiver nonlinearity which becomes a dominant factor when trying to receive a weak signal in the presence of one or more near-frequency strong signals. Under such conditions the single-signal selectivity curves often shown by manufacturers are next to meaningless. This strong undesired-weak desired signal situation often arises in practice especially in the military where close physical spacing of equipment is mandatory as in the case of ships or aircraft and where the signal environment changes due to the changing locations of these vehicles. Because of this situation allocations to some extent must be made practically independent of modulation bandwidth and the theoretical spectrum conservation of single sideband cannot always be advantageously used.

The problem of receiver nonlinearity is especially serious in multiple conversion superheterodyne receivers for obvious reasons. This was the dominant factor in choosing a direct conversion scheme in the synchronous receiver described earlier. Although this approach has given good results and continued refinement has indicated that significant advances over prior art can be obtained, it cannot be said however that the receiver problem is solved. This problem will probably remain a serious one until new materials and components are made available. This is a relatively slow process and it is not at all absurd to consider that by the time this problem is eliminated new modulation processes will have appeared which will eclipse both of those now being considered.

In short, the spectrum economies of SSB which exist in theory cannot always be realized in practice as there exist many important military and commercial communications situations in which no increase in usable channels will result from the adoption of single sideband.

Jamming

The reduction of transmission bandwidth afforded by single sideband must be paid for in one form or another. A system has yet to be proposed which offers nothing but advantages. One of the prices paid for this reduction in bandwidth is greater susceptibility to jamming as was previously mentioned. There is an understandable tendency at times to ignore jamming since the systems with which we are usually concerned provide us with ample worries without any outside aid. Jamming of course cannot be ignored and from a military point of view this raises a very serious question. If we concede for the moment that by proper frequency allocation single sideband offers a normal channel capacity advantage over AM, what will happen to this advantage when we have the greatest need for communications? It is almost a certainty that at the time of greatest need jamming will have to be reckoned with. Under these conditions any channel capacity advantage of SSB could easily vanish. A definite statement to this effect cannot be made of course without additional study but this is a factor well worth considering.

Conclusion

There is an undeniable need for improved communications and to date it appears that single sideband has been almost exclusively considered to supplant conventional AM. It has been the main purpose of this paper to point out that the improved performance needed can be obtained in another way. The synchronous AM system can compete more than favorably with single-sideband when all factors are taken into account.

Acknowledgment

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The Phase-Shift Method of Single-Sideband Signal Generation*

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Summary—A general expression is developed for sideband suppression obtained with the phase-shift method of single-sideband signal generation. The sideband suppression ratio is expressed in terms of four systems parameters, three of which are governed by the characteristics of wide-band phase-shift networks employed in such signal generators. Several typical phase-shift network configurations are analyzed and shown to be equivalent to a cascade of networks of "simplest" type. In addition, certain special network combinations are presented.

A simple dual-channel multiplex single-sideband generator of the phase-shift type is shown. Use of the phase-shift method in combination with band-pass filters to enhance system performance is discussed. The role of a modified phase-shift type of signal generator as a system-test signal source is outlined. The effects of intermodulation distortion on signal purity and the performance stability of the phase-shift method are discussed from the system viewpoint.

Introduction

THE PROBLEM of generating single-sideband signals having the required amounts of unwanted sideband suppression, channel bandwidth, and a suitably low-modulation frequency cutoff presents a challenge to the designer of single-sideband apparatus. The phase-shift method of generating single-sideband signals provides a means for extending the useful bandwidth of single-sideband systems or for increasing unwanted sideband attenuation in systems where sharp cutoff filters are used. In conjunction with appropriately designed filters, either or both of these signal characteristics can be enhanced by use of the phase-shift method.

In addition, the phase-shift method permits economical simultaneous generation of a two-channel single-sideband signal in which upper and lower sidebands convey different intelligence. Since, fundamentally, no band-pass filters are required in the application of the method, frequency conversion to a specified operating band is not necessary, and certain advantages of cost, weight, simplicity, and reliability may be obtained in many cases.

It is the purpose of this paper to analyze the phase-shift method of single-sideband signal generation and to relate system performance to the parameters of the

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