diversity reception:

an answer to high frequency signal fading

Diversity reception techniques are discussed with ideas on how they can be implemented with today's equipment

Signal fading is one of the principal problems confronting Amateurs in the high-frequency or short-wave bands. This seems strange, because fading was one of the earliest high frequency problems to be investigated. A 1927 *QST* article[1] shows that a worthwhile reduction in the adverse effects of fading can be obtained by using diversity reception.

What is diversity reception? With diversity reception, two or more different, or diverse, antenna/receiver combinations are used to receive the same signal. A two-channel system is known as dual diversity; a three-channel system, triple diversity. Diversity reception is widely and effectively used in commercial high frequency installations but has never been popular with Amateurs. One wonders why. Considering what the development of stereo did for the hi-fi industry, I'm surprised that the receiver manufacturers didn't push diversity reception years ago.

In this article I discuss fading and explain how diversity reception can minimize signal loss due to fading. I then discuss equipment considerations for a diversity reception system.

diversity reception

Although it's not apparent to a listener with one receiver and one antenna, fading is not uniform over the surface of the earth. If the listener had several antennas separated by between two and ten wavelengths, with each antenna connected to its own receiver, he'd find that the signal received by the various antennas faded more or less independently of one another. The probability of all receivers being in a fade at the same time is very small. So, if several receivers are connected so that the receiver with the strongest signal can be chosen, the effect of fading can be greatly reduced.

Fig. 1 is a strip-chart recording of a CW signal received on 19 MHz using a triple space-diversity system. The first three rows show each channel individually, while the bottom row shows the combined signal. Note the reduction in fading of the combined output.

The fading characteristics of the two signals of a dual-diversity system may be described mathematically by what is known as the correlation coefficient of fading, R. This coefficient may have any value between -1 and $+1$. When $R = +1$, the two signals will vary in the same direction; *i.e., both signal will be either above or below a reference "minimum usable signal level" (MUSL) at the same time. In this case, diversity operation will obviously not provide any improvement.*

When $P = -1$, the two signals will always fade in opposite directions; when one signal is above the MUSL, the other will always be below it. In this situation, diversity operation will provide fade-free reception, since one of the signals will always be above the MUSL. Unfortunately, negative correlation factors are seldom found in practice.

When $R = 0$, the two signals will fade completely independently of each other. In this case, the proportion of time that both signals spend below the MUSL simultaneously is equal to the product of the proportion of time that each signal will be below that MUSL individually.

The advantage of diversity reception is measured by what is called "diversity gain" and is given in dB. Diversity gain is the increase in average signal level obtained from a diversity receiving system compared with the level obtained from a single-channel receiver averaged over a period of time, usually 5 to 10 minutes. Diversity gains of between 3 and 20 dB are typical in commercial practice, and gains approaching these values are probably obtainable in Amateur practice, a worthwhile improvement in average received signal level.

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Commercial stations using high frequency propagation commonly use three antenna/receiver combinations; the law of diminishing returns applies for more than three. A substantial improvement can be obtained, however, using only two receiving systems, and it's doubtful if more than two channels are justified for Amateur applications.

fading

To understand how diversity reception improves reliability, it's necessary to understand the fading phenomenon. Fading in the high frequency, or shortwave, bands is basically of two types: path failure and multipath.

Path failure occurs when the ionosphere can no longer reflect the transmitted frequency back to earth. A good example of this is the way signals on 10, 15, and 20 meters fade out at night: The signals just gradually disappear into the noise. This type of fading is also known as "flat fading," since all frequencies over the usual information bandwidths fade together. Nothing can be done to overcome this type of fading except to change frequency; if the signal is not there, two receivers are not going to hear it any better than one. Path failure isn't a serious problem anyway, because propagation forecasts can generally predict which frequencies will fade and when, so that you can arrange your operating plans accordingly.

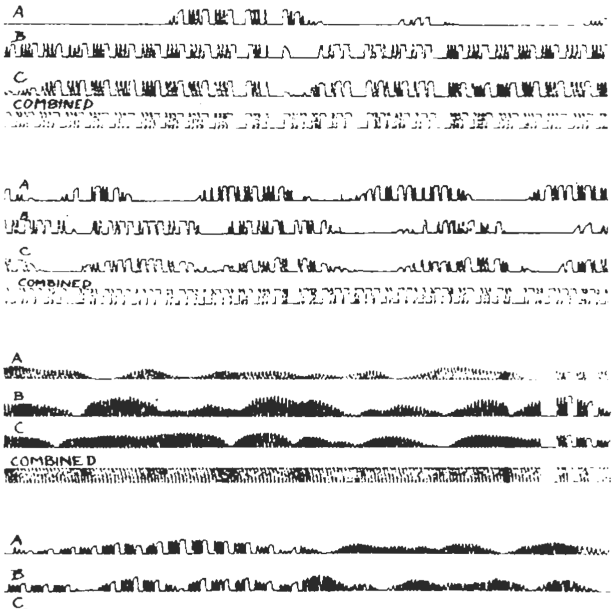

fig. 1. Strip chart recording of keyed CW signals from the output of the three separate channels of a triple-diversity receiver is shown in rows A, B, and C. The combined output is shown in the bottom row, illustrating the reduction in fading possible with this type of system (from reference 2, page 543).

Multipath fading is much more annoying and is the result of two or more waves from the same transmitter traveling over different paths and arriving at the receiver with different phase relationships. If the length of these paths differs by an odd multiple of a half wavelength, which is only about 10 meters (35 feet) at 14 MHz, the two waves will arrive out of phase, and a fade will occur at that frequency. If their path lengths differ by one wavelength, the two waves will arrive in phase, and a "fade-up" will occur.

The distance from the East Coast to the West Coast of the United States is about 5000 km (3000 miles), and the radio path is slightly longer because of its round trip to the ionosphere. A path difference of only 10 meters (35 feet) represents a very small percentage difference between the two, so it isn't any wonder that multipath fading occurs and creates the problem it does.

types of diversity reception

The ionosphere is not stationary but dynamic — more so at some times than others. Paths are constantly changing in both number and length. Therefore signals fade in and out randomly at different locations, at different times, and on different frequencies, all depending on the signal polarity and its angle of arrival. This phenomenon gives rise to five different types of diversity reception: space, polarization, angle of arrival, time, and frequency.

Space diversity. The most common form of diversity reception used by commercial high-frequency stations is space diversity. In commercial practice triple diversity is usually used, with the three antennas spaced at the corners of an isosceles triangle measuring two to ten wavelengths on a side.[2] Increasing the spacing beyond this amount doesn't materially improve reception, nor does using more than three antennas. Many experimenters, including Amateurs, have found that a worthwhile diversity gain can be obtained on the 20-meter band by using only two antennas spaced about 15 meters (50 feet) apart. Therefore, space diversity can be practical for Amateur stations restricted to a modest suburban lot. With correlation coefficients of fading as high as 0.6, space diversity can still provide a significant diversity gain.

Polarization diversity. Where space is a limiting factor, as it is at many Amateur locations, a considerable reduction in the effects of fading can be obtained from polarization diversity; that is, using one horizontal antenna and one vertical antenna, each connected to its own receiver. The same tower that supports the horizontal antenna, or one end of it, can also act as the vertical antenna. Polarization diversity is possible because the vertical and horizontal components of the received signal do not usually fade simultaneously, even at the same location.

Some Amateurs report an unusual effect when using polarization diversity: The ionosphere gets hung up on one polarization for extended periods of time, often several days. When this happens, a single-receiver channel using the wrong polarization would report that conditions were bad, whereas a polarization diversity system would report good conditions.

The advantages of space over polarization diversity, if any, are not clear. Grisdale *et al.*[3] report more diversity gain with space than with polarization diversity under some conditions, and *vice versa under* other conditions; th*e differences are too detailed to* list here. In any event, significant diversity gains are obtainable with either type of diversity, with the difference between the two usually limited to 2.5-3 dB.

Angle-of-arrival diversity. This method uses one or more antennas with lobes at various vertical angles of arrival. Experiments have shown that waves arriving at vertical angles differing by as little as two degrees will give significant diversity gains. Close control of the vertical radiation pattern requires a vertical antenna many wavelengths tall; therefore this type of diversity system doesn't appear to be practical for most Amateurs.

Frequency diversity. Two separate frequencies are used to transmit the same message, because different frequencies don't necessarily fade at the same time. By transmitting the same message simultaneously on different frequencies and listening to the stronger of the two, circuit reliability can be improved. Frequency separations as small as 400 Hz will give considerable improvement on long-haul, high-frequency paths. It therefore appears possible to receive the two sidebands of an a-m or DSB signal, demodulating each sideband separately with two different SSB receivers, thus receiving frequency diversity. (I will discuss this later.)

Time diversity. Time diversity uses two channels, usually with the same transmitter, antennas, and receiver. Imagine a transmitter capable of transmitting two teletype signals simultaneously. Start a message on channel A and a minute or so later restart the same message on channel B. At the receiving end, match the messages received on the two channels. The probability of the circuit fading out during the same portion of each message is much lower than the probability of a fade on only one channel, so that an improvement in circuit reliability can be obtained. Delay times of between 0.05 and 95 seconds, depending on conditions, have been found to give improvement.

Note that both frequency and time diversity improve reliability by sacrificing channel capacity, *i.e.*, by halving the number of messages that can be transmitted over the circuits in a given period of time. If there were no fading, two different messages could be transmitted over the same two circuits. Space, angle of arrival, or polarization diversity, however, don't reduce the channel capacity.

diversity transmission?

Diversity reception has been shown to increase the average signal level, so one might reasonably ask if additional improvement could be obtained by transmitting over two or more antennas. The answer is no. Because fading is caused by multipath, using two transmitting antennas with either space or polarization diversity would double the number of possible different signals reaching the receiver, thereby increasing the possibility of multipath fading.

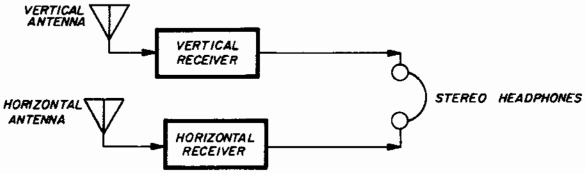

fig. 2. A simple polarization diversity receiving system.

The best thing that the transmitter can do is to concentrate its available energy in as small a beam as possible, *i.e.*, use an antenna with as much gain as is practicable. This is standard practice anyway, so no changes are necessary at the transmitter.

diversity receiving techniques

If we assume polarization diversity, which appears to be the most practical for Amateur use, the simplest form of a diversity receiving system consists of two separate receivers, one connected to a vertical antenna and the other to a horizontal antenna. The output of each receiver is connected to separate headphones, such as are commonly sold for stereo use; see **fig. 2**. This is a simple and effective method, but it has the disadvantage that the receiver whose input signal is "down" generates noise, making it difficult for the operator, since the noise changes from ear-to-ear.

This problem can be easily corrected by tying together the agc circuits of the two receivers. In this way the agc of the "up" receiver will tend to mute the "down" receiver, minimizing the noise in the down channel; see the sketch in **fig. 3**.

The next obvious step is to combine the audio output of the two receivers in a common amplifier, as shown in **fig. 4**. However, this technique can only be used for phone reception, a-m or SSB; not for CW. The reason is that for CW the audio-tone output of each receiver has a phase that depends upon the phase of the rf signal received by the respective antenna. As the relative phases of each rf signal vary in a random manner because of multipath effects, the phase of each audio tone will vary randomly, too, and there will be times when the audio tones will be 180 degrees out of phase. A fade will then occur in the receiver combined output, even though the signal in each receiver is strong. This is just what we are trying to avoid!

There are two solutions to this problem. The first, used by the commercials, is to take the second-detector output as a dc pulse and add the pulses in a simple summing network. The resulting pulses will be relatively fade-free and are used to key an audio oscillator, which the operator hears in his headset.

The second technique uses what is called a "heter*otone*"[4] oscillator, which is simply a multivibrator operating at about 400 Hz generating two square waves 180 degrees out of phase. These are used to alternately gate each diversity i-f channel. This signal modulates the CW signal at the intermediate frequency.

Tuning a CW signal using a hetero*tone* oscillator is definitely different from tuning one with a heterodyne oscillator, or BFO; with the heterotone no change occurs in pitch as you tune through the signal.

early diversity receivers

Considering all the advantages of diversity reception, there have been surprisingly few attempts to develop diversity techniques for Amateur use. The earliest attempt of which I am aware was in 1936 by Carll Roland,[5] who used two antennas 183 meters (600 feet) apart connected to two short wave broadcast receivers. Even with such primitive equipment and many trials and errors, Roland's results were good. The final sentence in his article reads: "If the broadcast listeners had not wanted their receivers back, we would have kept on using diversity reception."

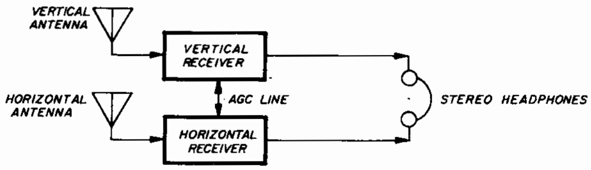

fig. 3. A polarization diversity receiving system with agc muting of the "down" receiver.

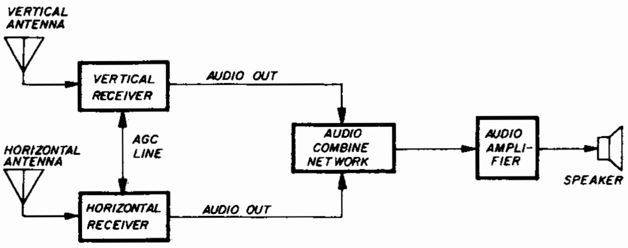

fig. 4. A full dual-polarization diversity receiver for phone work.

The second step was taken by James J. Lamb and J. L. A. McLaughlin,[6] who designed what is probably the first single-tuning-control diversity receiver. They developed this receiver specifically for Dr. James M. B. Hard, an American who will be remembered by old timers as XE1G in Mexico City.

QST for December of 1937 describes the third step in an article by J. L. A. McLaughlin and Karl W. Miles.[7] They refer to the May, 1936, receiver (my reference 6) and say, in part:

> It has conclusively demonstrated the practicability and desirability of diversity reception for amateur and experimental communications work. Even with two antennas spaced but 50 feet apart, good diversity action has been obtained, especially on the 14-Mc band. Dr. Hard reports that many times when fading conditions and heterodyne interference became so bad as to make his other single receivers useless, the dual diversity still brings in an intelligible signal.

This receiver was considerably improved over the earlier version, mostly in a simplified mechanical design and an improved i-f amplifier. Apparently it was also built specifically for Dr. Hard and became the prototype of the Hallicrafters dual diversity receiver model DD-1. It contains many unique and advanced engineering features, even by today's standards. I'll not go into detail now; see the photograph of my model in **fig. 5**. It's a very impressive piece of equipment!

With diversity reception it's not necessary to use specially made receivers or even identical receivers. Taylor[8] describes a 10-meter diversity system using a Hallicrafters SX-17 and a Skyrider 5-10 receiver. His antennas were a horizontal 10-meter dipole and one-half of a vertical 5-meter beam. One end of the 10-meter dipole was attached to the pole that held the 5-meter beam.

As an example of his results, Taylor describes the 10-meter reception of a GM6 late one afternoon:

> . . . most of the Britishers had already passed out of the picture. With a single receiver and antenna his signal was

so hashed up by a fast fade from S9-plus down into the mud that only about one word out of five was understandable. On switching in the other half of the diversity combination his signal was brought up and smoothed off at a level which rarely fell below S-8; a solid and completely intelligible signal . . .. We will guarantee a thrill the first time you see one of the "S" meters . . . drop down to the bottom of the scale with the signal still pouring out of the 'phones in fine style.

A slightly different approach to diversity reception has been suggested by Bartlett.[9] Bartlett connects each antenna to a separate rf preamplifier; the output of each of the two preamplifiers is connected in parallel to a single receiver of conventional design; this would be the normal station receiver. The preamplifier stages are switched on and off, 180 degrees out of phase, at an audio rate usually between 300 and 1000 Hz. A block diagram is shown in **fig. 6**. In this manner only one antenna at a time is connected to the receiver so that phase relationships between the two antennas are not important. The receiver output is proportional to the strongest signal present in either antenna at any instant of time.

Because the incoming signal is modulated at the switching frequency this method is useful only for CW. This method also has an unusual effect on the receiver output. If the signal in one antenna is up and the other completely down, the signal reaching the receiver is modulated at the switching frequency. If both antennas receive equal signal levels, the signal reaching the receiver is modulated at twice the switching frequency.

If one antenna has a strong signal with the signal from the other antenna fading in and out, the effect on the output is a changing tone that depends on the strength of the fading signal. Bartlett claims this effect is "very pleasing" to most CW operators; I haven't tried it myself. It sticks in my memory that a device similar to this was advertised in *QST* right after World War II, but I've not been able to find the advertisement in my old magazines.

fig. 5. A Hallicrafters dual-diversity receiver, Model DD-1. This is the only commercially made receiver intended for diversity reception, circa 1939.

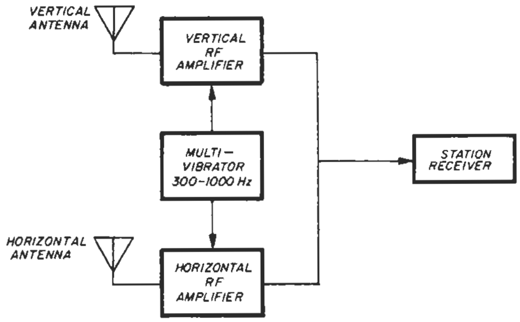

fig. 6. Block diagram of Bartlett's dual-diversity preselector/adapter for CW work.

Bartlett[9] also states that when using polarization diversity, there may be "days at a time" when the vertical signal is 10 to 15 dB lower than that of the horizontal signal. I don't know if this is true in general, or if it results from the use of a smaller vertical antenna than horizontal antenna.

equipment considerations — receivers

By now you may be wondering what changes are needed to equipment designs to make diversity reception practical. The design of a diversity receiving system is not that difficult. At one time a diversity receiver was a truly substantial piece of equipment in both size and cost; fortunately, the development of modern semiconductor devices has reduced both the size and the cost of receiver components. And, since the second receiver will be a duplicate of the first, there will be no additional engineering costs.

As the details of different receivers vary considerably, and as each receiver designer/builder has his own ideas as to what a good receiver should be, I'm not going to discuss a detailed receiver design. The characteristics required of a good diversity receiver are the same as those needed for a good single-channel receiver: sensitivity, stability, low noise figure, low intermodulation response, good shielding, and so on. The only difference is that you build it twice! Numerous articles on this subject have been published by *ham radio*; I need not repeat that information.

Good shielding is very important. First, it's necessary to keep the horizontal and vertical channels electrically separate. Leak-through from one to the other before final detection will cause a loss in diversity effectiveness. With two separate receivers, using separate local oscillators, leak-through of one oscillator to the other mixer will cause birdies, because the two oscillators will, in general, not be on exactly the same frequency.

There are several ways of minimizing the oscillator leak-through problem other than the use of shielding.

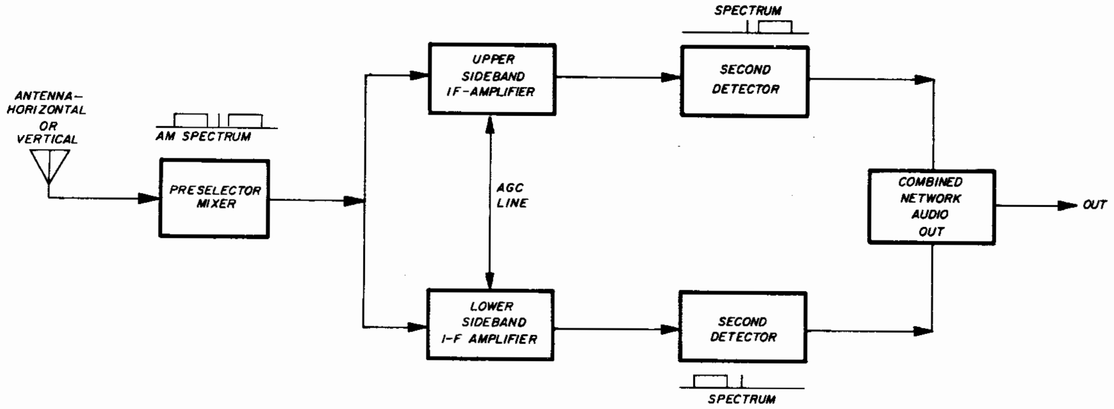

fig. 7. Simple frequency diversity receiver for independent demodulation of the upper and lower sidebands of an a-m signal.

One is to use receivers with different i-fs. Taylor[8] used a Hallicrafters SX-17 with a 465-kHz i-f and a Skyrider 5-10 with a 1600-kHz i-f with good results.

If receivers with the same i-f are used, one oscillator can be realigned to put it on the high side, with the other oscillator on the low side, of the signal. (This may have an adverse effect on tracking in the modified receiver.)

Probably the best arrangement is to use the same oscillator for both channels. Even here, though, considerable care must be used in mixer design to ensure that the received signal from one channel doesn't leak through the common oscillator bus into the other channel. What has been said concerning the local oscillator applies equally well, of course, to all local oscillators in a multiple conversion or SSB receiver.

adapting current transceiver designs

Because the current trend in Amateur equipment design is toward the transceiver, I'll present some general ideas on adapting current transceiver designs to diversity reception. As pointed out earlier, there's nothing the transmitter can do to improve diversity reception, thus the transmitter portion of a transceiver will remain unchanged. Most of the bulk, weight, and cost of a modern high frequency transceiver is in the transmitter section, the transmitter power supply, and the frequency control unit (synthesizer); the receiver itself is very small. And this is the only portion of the transceiver that must be duplicated.

Probably the single most important thing that transceiver manufacturers can do to aid in diversity reception is to make the various oscillator injection voltages and agc bus available, suitably buffered, on the *back apron of the transceiver*. This will permit an external adapter, either commercially manufactured or homemade, to be easily attached. It will then be practical to add an external diversity adapter containing the rf, i-f, audio, and combining circuits necessary to complete the diversity receiving system.

In the preceding material I've assumed a simple summing network for combining the output of the two receivers, as this appears to be the simplest and most appropriate for Amateur use. Actually, the subject of an optimum combining law for two (or more) signals has occupied many, many pages in various journals.

Combining laws can vary from a hard-switching law (*i.e.*, switching to the receiver with the strongest signal) to more sophisticated and beneficial laws. Leonard R. Kahn[10] has asked this question: "For a given ratio of diversity signal levels, how much of the weaker signal and its noise should be added to the stronger signal and its noise to obtain the optimum signal-to-noise ratio?" He then answers his own question by showing that a square-law is best. That is, the ratio of the two signal levels should be squared, then summed.

The method I've sketched, summing the detected signals and tying the agc buses of the two receivers together, will have a combining law that depends on the agc characteristics of the receivers. The most desirable law for Amateur purposes probably can be determined only after considerable experimentation.

The types of combining described so far are known as "post-detection combining." The combining is accomplished after detection, when the rf/i-f phase information has been removed. Additional diversity gain is possible by using "predetection combining," combining the signal before detection. This method requires that the signals be added in phase and is much more difficult to achieve.

equipment considerations — the antenna

Assuming polarization diversity, it's essential that

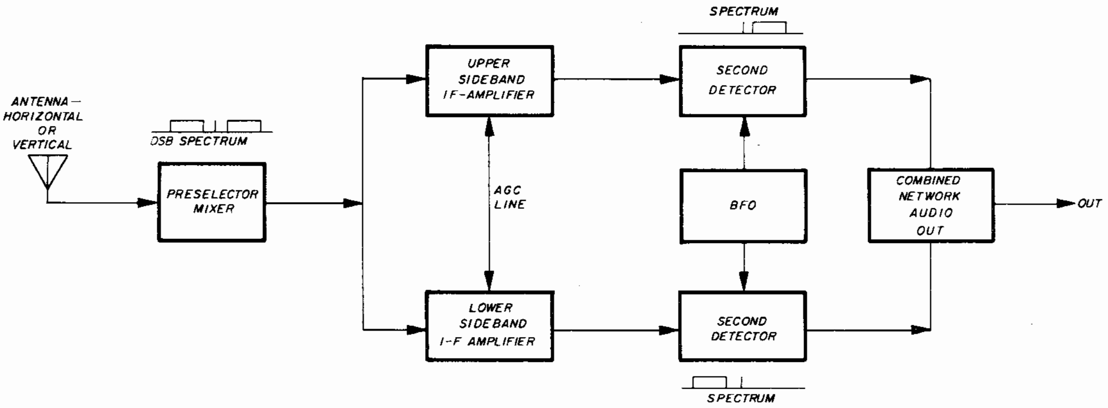

fig. 8. Simple frequency diversity receiver for independent demodulation of the upper and lower sidebands of a DSB signal.

the horizontal antenna *and its transmission line* respond only to the horizontal component of the received signal. Similarly, the vertical antenna and its transmission line should respond only to the vertical component of the received signal.

In both cases, the transmission lines are probably the biggest problems. For the horizontal antenna, the vertical down-lead is the problem area. With the vertical antenna, horizontal runs away from the antenna are potential trouble spots.

If coaxial cable is used, it should have a tight shield braid, or, better yet, be double-shielded.* A high-grade balun should certainly be used in both antennas.

frequency diversity

In describing frequency diversity, I mentioned that frequency separations as small as 400 Hz could be used to provide diversity gain. Since audio frequencies below about 300 Hz are usually filtered out in a voice transmitter, the two sidebands in an a-m or DSB signal will be at least 600 Hz apart, giving rise to the possibility of using frequency diversity.

The simplest embodiment of a frequency diversity receiving system for a-m or DSB signals is shown in **fig. 7**. Here a single antenna, receiver front-end (rf amplifier, mixer, and local oscillator) drives two i-f amplifiers. One i-f amplifier has a filter that covers the carrier and upper sideband; the other i-f amplifier covers the carrier and lower sideband. Each amplifier output is separately detected, then combined in a common audio amplifier. The agc bus of the two amplifiers may be tied together. In this way, the two sidebands are independently received and detected, then combined. Summation does not take place until after the rf phase information has been removed from both sidebands, so that multipath effects between the upper and lower sidebands will not cause fading.

This system gives a surprising amount of diversity gain, except when the carrier itself is in a fade; then the two sidebands don't have anything to beat against, so that demodulation is not possible. The receiver output sounds like a DSB signal with the BFO off.

The next obvious improvement is to provide a locally generated, fade-free, noise-free carrier to demodulate the two sidebands. This scheme is shown in **fig. 8**. Since the carrier is no longer needed to demodulate the sidebands, why transmit it? Put the carrier energy into the sidebands to increase talk power and transmit a DSB.

As I write this, I can imagine *ham radio* readers coming to a full stop! Didn't we fight the SSB vs DSB battle 25 years ago and decide on SSB?

The answer, of course, is, yes, we did. DSB lost for three basic reasons:

1. When the two sidebands of a DSB signal are demodulated in the same detector, the stability required of the locally generated carrier is extremely critical.

2. Multipath effects between the upper and lower sidebands cause fading.

3. Extra bandwidth is required in an already overcrowded spectrum.

In a frequency diversity receiver, items **1** and **2** don't apply because the two sidebands are demodulated in separate detectors — not in the same detector. The frequency stability required of the inserted carrier may be somewhat higher than for SSB; if it gets too far off, one sideband sounds like Smokey the Bear, the other like Squeaky the Squir-

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*A point well taken. Many Amateurs tend to take coaxial transmission lines for granted. Many types of coax cable are offered for sale. Most are marginal as far as shielding is concerned. If you're interested in diversity receiving systems, it's well worth obtaining good-quality coax cable. The *ARRL Handbook* describes problems that can occur when using marginal-quality coaxial transmission lines. **Editor**.

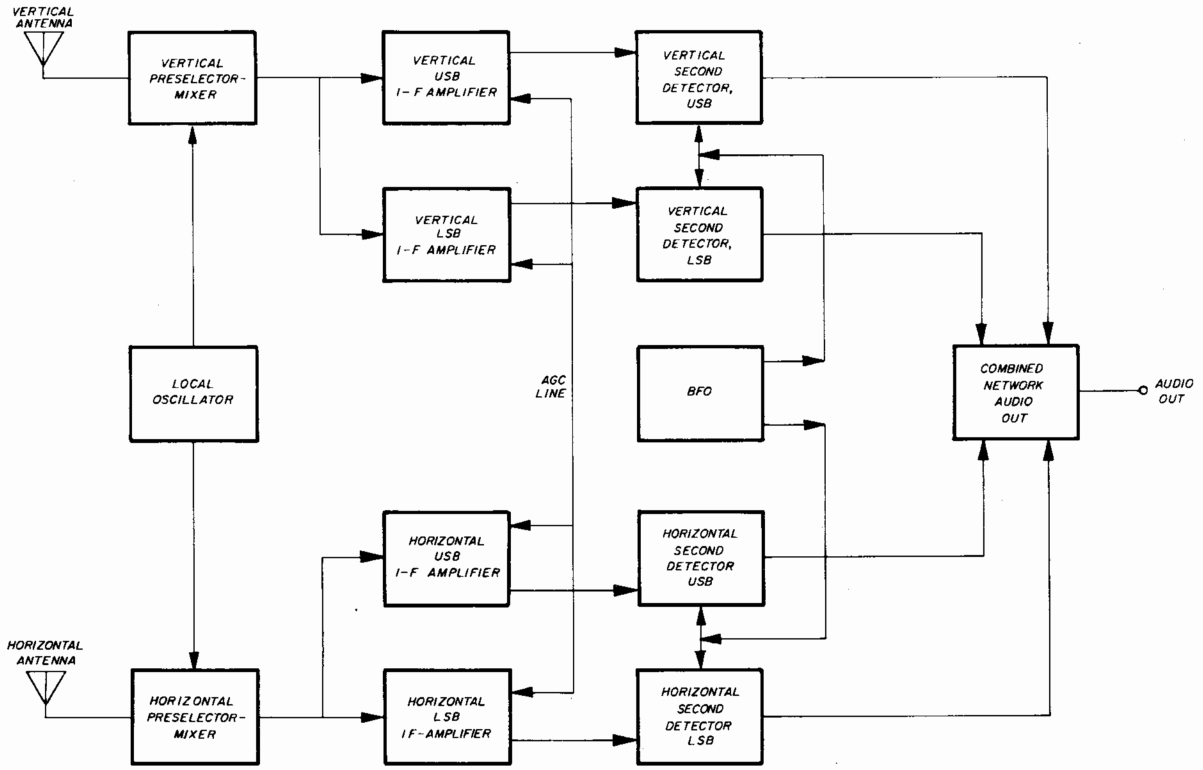

fig. 9. Simplified block diagram of a compound diversity receiver using both frequency and polarization diversity to receive an a-m or DSB signal.

rel. The stability, however, is only on the order of a few hertz instead of a few degrees.

Detecting the two sidebands separately also eliminates fading caused by the two sidebands being 180 degrees out of phase because of multipath. Furthermore, since the probability of *both* sidebands being below the MUSL simultaneously is considerably lower than that of *either* sideband being below the MUSL separately, fading should be considerably less of a problem with the sidebands independently demodulated.

The additional bandwidth will still be with us and may be considered the price paid for diversity gain.

With present-day technology, it's not impractical or expensive to build a compound diversity receiver, using both frequency and polarization diversity. A block diagram of such a receiver is shown in **fig. 9**.

conclusion

I've described the advantages of the variious types of diversity reception and shown how they can be implemented with Amateur equipment. Because of space limitations I have hit only the highlights. Anyone who's going to pursue this type of work should become familiar with the references cited. Much of the original work on this technique was done 40 years ago, so I am, admittedly, reinventing the wheel. I firmly believe, however, that diversity reception will be the next step in advanced Amateur receiving techniques. I hope this article helps to start Amateurs experimenting with diversity reception and encourages manufacturers to supply equipment for this purpose.

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