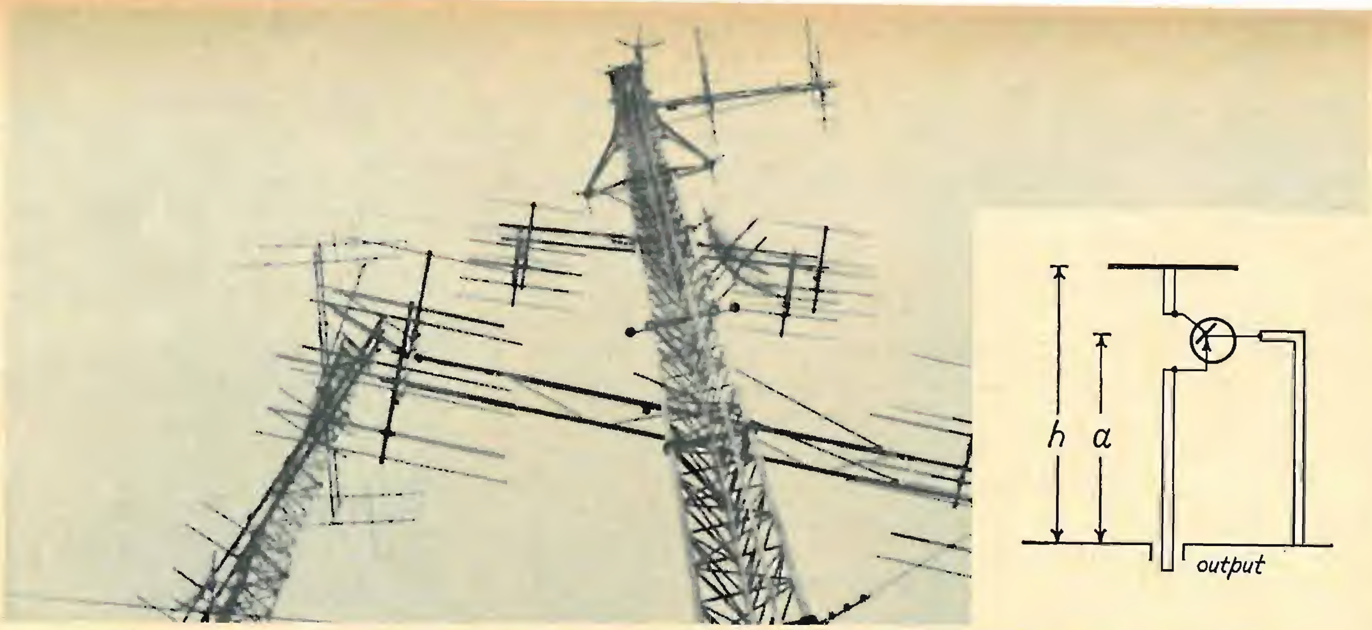


Subminiature integrated antennas (inset) less than 20-in tall may eventually replace huge arrays on steel structures across the country. A top-loaded 20-in SIA whose capacitance is 10 pF, will resonate at frequencies from 10 to 80 MHz. The exact frequency is controlled by the ratio of the dimensions "a" and "h" but the SIA works best at communications frequencies below 30 MHz.

Tiny antennas push state-of-art

By PAUL E. MAYES / Technical Consultant, JFD Electronics Co.

Subminiature integrated antennas are being used at frequencies below 30 MHz, but it may be some time before the roof-top TV antenna disappears.

THERE has been a lot of talk in the industry about eliminating outdoor television antennas, but until recently, the basis for this conjecture was the analogy to AM radio receivers in which ferrite loops have replaced long-wire antennas. Of course, television is not the only communications medium in which engineers would like to get rid of the large and bulky receiving antennas. Furthermore, interest has been stimulated by recent publicity disclosing the development (under Air Force sponsorship) of a subminiature integrated antenna (SIA). Because of this antenna development's widespread implications to the communications industry, the problems bearing on replacing large antennas with small ones and the current status of research in this area are reviewed.

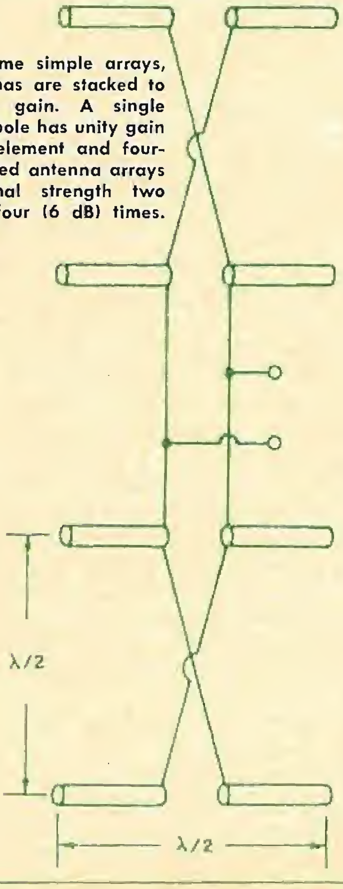
Several years ago, E.M. Turner of the Air Force Avionics Laboratory in Dayton, Ohio, suggested that the performance of small antennas might be improved if active elements were placed in the antenna rather than at the junction of the antenna and input line. The suggestion was taken up by Professor H. Meinke and his colleagues at the Technische Hochschule in Munich, West Germany. They utilized transistors in single and dual monopole configurations to match tiny antennas to the input lines of radio sets.

In general, the miniature antenna performed well because the transistor saw a very low source resistance and thus provided a good match. However, the technique worked best at frequencies below 30 MHz. Antenna line reactance, antenna directivity, balancing, and suitable transistor characteristics are all problems which haven't been licked and which limit applications of SIA antennas at v.h.f.

The Match's the Thing

The principal task of any receiving antenna is to extract energy from a passing electromagnetic wave and produce

Fig. 1. In some simple arrays, dipole antennas are stacked to increase the gain. A single half-wave dipole has unity gain (0 dB); two-element and four-element stacked antenna arrays increase signal strength two (3 dB) and four (6 dB) times.



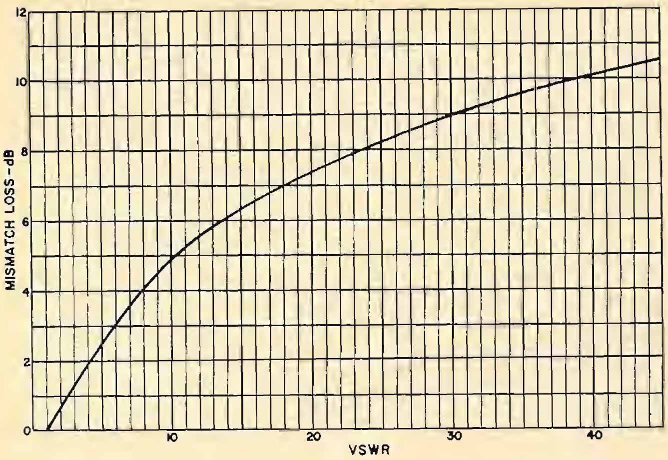


Fig. 2. This graph is used to relate v.s.w.r. and mismatch loss.

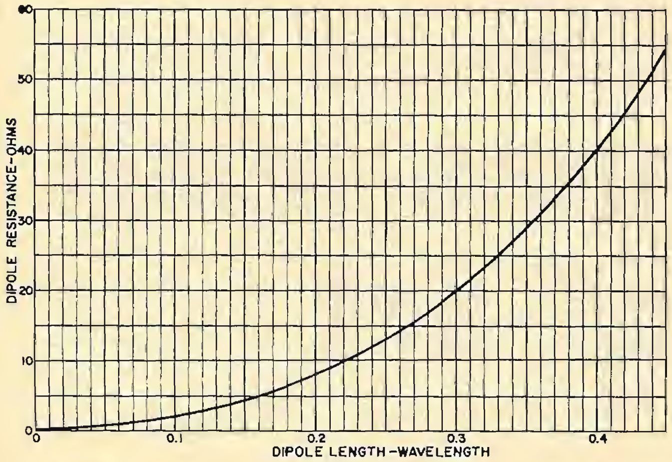


Fig. 3. Dipole resistance is not a linear function of length.

at its terminals a usable r.f. voltage that represents a signal. If the electromagnetic wave carrying the signal were the only field present at the antenna, then the evaluation of performance would be a relatively easy task. But man-made and terrestrial noise make the evaluation difficult.

Antenna gain, a figure of merit, is the result of comparing a normal antenna with an ideal antenna, usually a half-wave dipole. Engineers are interested in the power available at the antenna's terminals. The ratio of the antenna power is the relative gain and is usually expressed in decibels.

One method of increasing the gain of an antenna system is to use several elements as dipoles, in an array like the system shown in Fig. 1. Here the elements are stacked vertically (placed one above the other with approximately one-half wavelength spacing) and connected so that the antenna currents are all of the same phase. This array is called a broad-side configuration since the direction of maximum response is perpendicular to the plane of the dipoles. Each time the number of elements is doubled, or the antenna size increased by a factor of two, the gain increases by two, or approximately 3 dB. It should be emphasized, however, that this relationship between gain and size holds only for antennas which are one-half wavelength or larger in dimensions. The difference in gain between a half-wave dipole and one which is very small (in terms of wavelength) is only 0.4 dB. Hence, a small antenna is almost as good as a half-wave dipole when judged on the basis of gain alone.

Another commonly used term and one which is closely related to gain is the effective area or as it is sometimes called, the capture area. When used to describe receiving antennas, the effective area is defined as the ratio of power available at the antenna terminals to the power per unit area of an incident wave. The link between effective area, A, and the gain, g, is given by the following formula:

$$A = (\lambda^2/4\pi)\,g \ldots\ldots\ldots\ldots (1)$$

where λ is the wavelength and g is the gain relative to a hypothetical omnidirectional antenna. The effective area of a half-wave dipole is approximately 0.13 square wavelength and that of a very small dipole is about 0.12 square wavelength. Since the gains are almost equal, there is little difference between the effective areas of a small dipole and a half-wave dipole.

However, in order to utilize fully the effective area of an antenna, it is necessary that the impedance of the antenna be matched to that of the load. An imperfect impedance match causes power loss. Actual antenna gain is the ideal gain minus the mismatch loss (in decibels).

A widely used method of evaluating the impedance match is to observe the voltage standing wave ratio (v.s.w.r.) on a transmission line. The line is terminated by an antenna at one end and excited by a generator at the other end. Fig. 2 shows the relationship between the v.s.w.r. and mismatch loss in decibels.

Fig. 3 shows the resistive part of Z_{in} and dipole length. Suppose a dipole which is 1/10 wavelength were made to resonate by adding a lossless coil at its base. The resistance of the dipole is approximately two ohms. On a 75-ohm line, this load would produce a v.s.w.r. of 37.5 and cause a mismatch loss of about 10 dB. In this case, the actual antenna's gain is about -8.64 dB and there is a loss factor of 0.0915 when compared to an ideal half-wave dipole. Less than one-tenth of the available power is being delivered to the line. In addition, this figure is reduced by resistive losses in the tuning coil.

Noise

Why is it important that a receiving antenna deliver a high signal level to the receiver or that the antenna have a high gain and be properly matched? If the receiver were perfect, it could be designed with enough amplification stages to raise the signal to any desired level. However, no receiver is perfect and several factors prevent amplified signals from being exact duplicates of the input. One of these is internally generated receiver noise. The perturbation of a signal due to noise voltages can be kept negligible only if the signal voltage is much larger than the noise levels. Consequently, the most crucial point in a receiver is the input stage because it is here that the signal is at its lowest strength. To reproduce a signal faithfully, the ratio of signal power S to noise power N must be large.

Since noise is random, noise voltages must be averaged over a long time period to yield a time-independent measurement. Thus, mean-square voltages are used in computing signal-to-noise ratios. The ratio of the mean-square voltages is also the ratio of powers since both voltages appear across the same impedances.

In most electronic circuitry noise is caused by resistances. When molecules are thermally agitated, they generate a noise voltage across the resistor terminals. The equation for noise power is:

$$N = kTB \ldots\ldots\ldots\ldots (2)$$

where k is Boltzmann's constant (1.372×10^{-23} joule per degree Kelvin), T is the temperature of the resistance in degrees Kelvin, and B is the bandwidth of succeeding circuitry, in hertz. Since resistance in transmission lines and input and output circuits of amplifiers is unavoidable, the signal-to-noise ratio at the output of a two-port network is always less than at the input. Active elements, such as transistors and tubes, add more noise to the circuits.

If the only noise sources were internal to the receiver, the signal-to-noise ratio at the input would be infinite. However, there are many external noise sources which induce noise voltages in the antenna. One way to increase the antenna's signal-to-noise ratio is to make it absolutely unidirectional. But, since it is not practical to build an antenna which receives in one direction only, the desired result must be approximated. This can be done by designing the antenna to receive electromagnetic waves arriving in a small cone of angles near the antenna's center. Thus, in this circumstance, an antenna's response decreases as the radio wave's angle of arrival moves away from the cone. The angle at which the received signal power drops to one-half of its maximum value is called the half-power beamwidth and is generally governed by the size of the antenna as measured in wavelengths. The beamwidth of a small dipole is about the same as that for a half-wave dipole—approximately 80 degrees.

In addition, the ratio of the maximum response in one hemisphere (where the response is greatest) to the response in the opposite hemisphere is called the front-to-back ratio and is, in fact, a measure of the effectiveness of an antenna in discriminating against extraneous radio waves. Like gain, the front-to-back ratio is usually expressed in dB. High front-to-back ratios can be obtained by combining the output signals of two closely spaced small antennas. A small antenna system is capable of a front-to-back ratio and directivity almost equal to that of a two-element half-wave dipole array. In practice, high directivity is achieved by increasing the antenna size.

Although most noise sources are external to the antenna terminals, it is still convenient to use equation (2) to represent the noise power. External noise is often expressed as a noise temperature, T_a, which is greater than the ambient temperature. Increasing the antenna directivity by decreasing the beamwidth and/or increasing the front-to-back ratio, is the only effective means of reducing antenna noise temperature.

The level of most external noise changes with frequency as noise temperature changes. This is shown in Fig. 4. Time variations are indicated by the shaded area. Thus, high signal-to-noise ratios often depend upon the operating frequency. For example, below 30 MHz, external noise strength is quite high and increasing the actual antenna gain does very little, if anything, to raise signal-to-noise ratio. The point of diminishing return is reached when the external noise delivered to the receiver by the antenna is larger than the receiver's internal noise. Sometimes this happens just above 30 MHz, and often above 100 MHz. Then the only way to improve the signal-to-noise ratio is to increase the effective area and reduce the mismatch losses.

A figure of merit for the noise performance of two-port networks is the noise factor:

$$F = (S_i/N_i)\ /\ (S_o/N_o) \ldots . (3)$$

where S_i/N_i is the signal-to-noise ratio at the input and S_o/N_o is the signal-to-noise ratio at the output. More frequently used is the noise figure f which is 10 $\log_{10}F$. For a television receiver, the noise figure in the v.h.f. band is typically between 3 and 6 dB and in the u.h.f. band between 5 and 10 dB. Radar receivers in the 1-GHz range have noise figures ranging from 10 to 15 dB and communications receivers in the h.f. band have noise figures of from 8 to 12 dB. Parametric amplifiers, on the other hand, may have noise figures as low as 1 to 2 dB.

From the foregoing discussion, it is clear that the antenna must be able to develop a signal voltage which is greater than the noise voltage level of the receiver's input stage. However, an antenna with a high enough actual gain may be of little advantage below 30 MHz because the signal-to-noise ratio is determined by external noise. At these frequencies, a small antenna may be quite adequate. At higher frequencies, the situation is quite different. Here an antenna with high actual gain can be utilized to increase the signal-to-noise ratio since the principal noise source is the receiver.

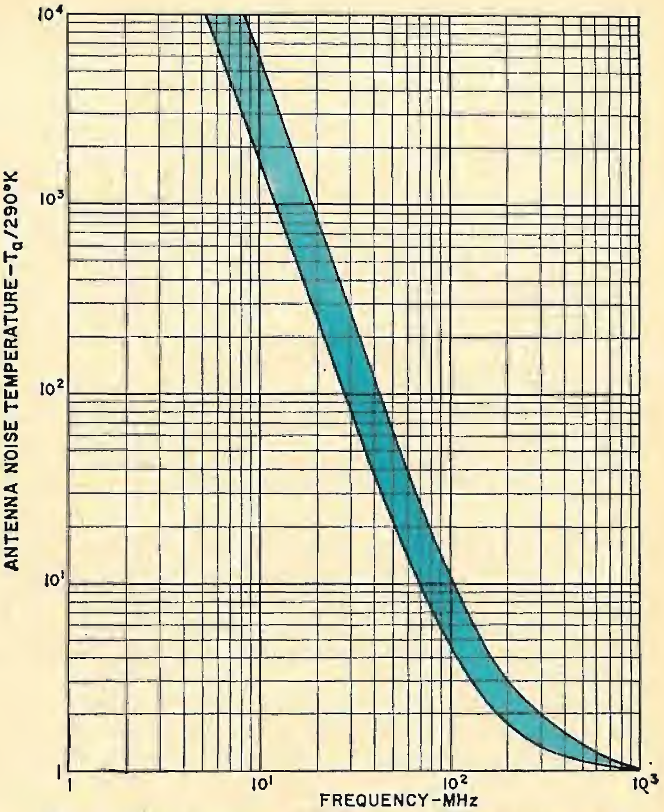
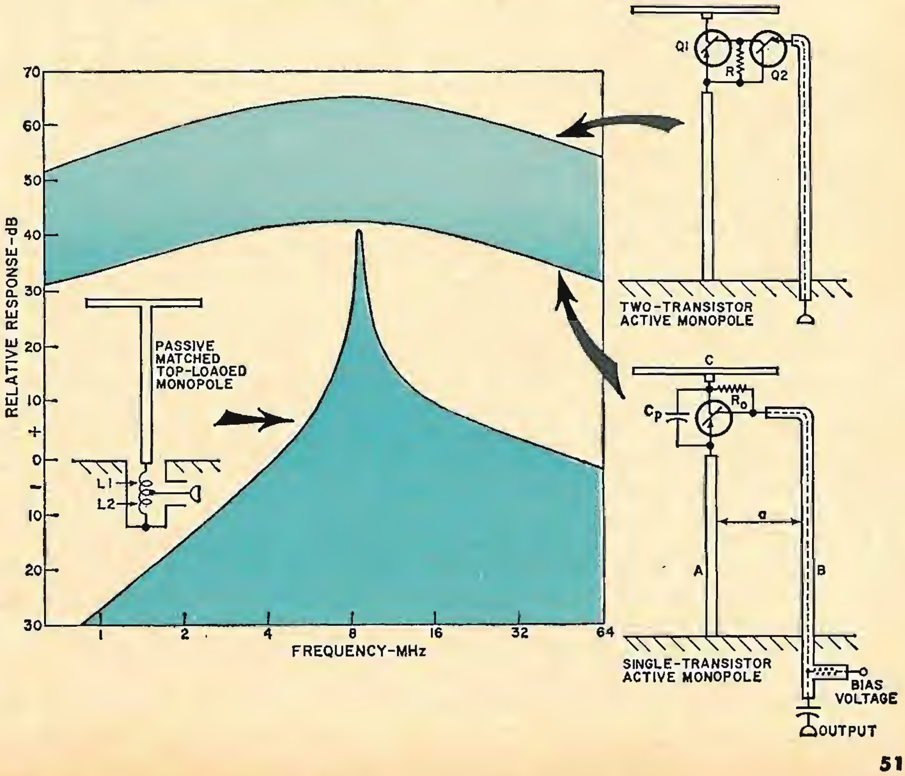


Fig. 4. External noise amplitude depends on frequency and temperature. Time variations are shown by the shaded area.

Improving Noise Figure with Preamplification

In conventional small antenna systems, mismatch occurs

Fig. 5. Active transistor monopoles broaden the antenna bandwidth.



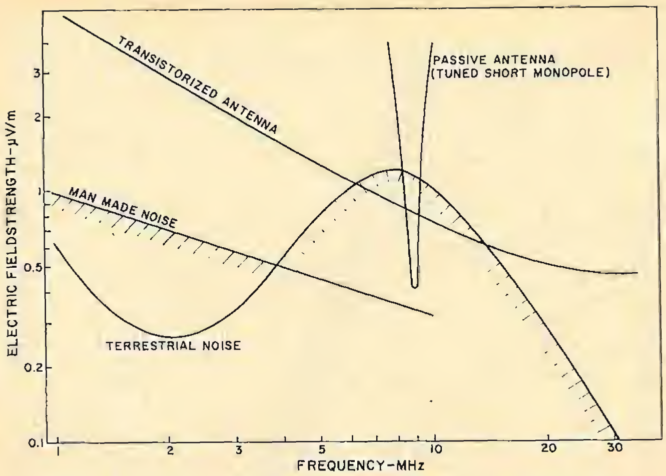


Fig. 6. Small antennas have good S/N ratios, but high fields are needed to overcome terrestrial and man-made noise sources.

between the antenna and the transmission line which leads to the receiver. In some systems, a matching circuit is placed between the antenna and the transmission line. However, the matching circuit and the line degrade the signal-to-noise ratio at the antenna since the circuit element's resistive components add noise.

Since the signal-to-noise ratio at the receiver input may be considerably less than that at the antenna, some engineers place an amplifier at the antenna to compensate for the mismatch loss. This does not raise the amplifier's signal-to-noise ratio, but it does improve the signal-to noise ratio *at the receiver input.*

The noise factor of a transmission line with loss factor K (power gain less than unity) is:

$$F = (1/K) \qquad (4)$$

Since the line is lossy, the noise factor of the line is greater than one.

The noise factor of two cascaded stages is given by:

$$F = F_1 + (F_2 - 1)/G_1 \qquad (5)$$

where F_1 and G_1 are the noise factor and power gain of the first stage and F_2 is the noise factor of the second stage. In the case where the matching circuit and line are the first stage, the gain is less than one and the over-all noise factor is degraded. The amplifier's noise factor then becomes:

$$F_{1a} = (1/K) + (F_2 - 1)/K \qquad (6)$$

If the amplifier is placed between the antenna and the transmission line, the over-all noise factor is nearly that of the amplifier, or

$$F_{a1} = F_2 + [(1-K)/K/G_2] \qquad (7)$$

and the amplifier gain G_2 reduces the effect of noise added by the transmission line.

As an example, suppose the loss factor of the line is 0.5 (−3 dB), the amplifier noise factor is 4 (6 dB), and the amplifier gain 10 (10 dB). The noise factor of the combination when the line is first is: $F_{1a} = 2.0 + (4-1)/0.5 = 8$. When the amplifier is first, the noise factor is $F_{a1} = 4 + (2-1)/10 = 4.1$, which is almost the same as that for the amplifier alone. Obviously, an amplifier stage at the antenna is a good idea when the losses in matching circuits and lines are high. However, this still does not solve the basic problem of the small antenna, namely, the small resistive and large reactive components in the antenna impedance.

Prof. H. Meinke and his colleagues attempted to solve this problem by placing solid-state active elements in the antenna. They pointed out that although a transistor at the base of a short monopole will indeed see a very small source resistance, the resistance at a gap some distance above the base is much greater and, as a consequence, an improved match is obtained. However, this technique does not do anything to solve the problem of high reactance.

An indication that the mismatch problem has not been eliminated is given in the relative response curve published in a paper "Active Antennas with Transistors," (International Electronics Conference, Toronto, 1967) by Meinke and reproduced in Fig. 5. Although the signal is amplified many times by a transistor at the gap of the monopole, the output power of a single transistor circuit is about the same as that of a matched lossless antenna of the same height. To increase the signal level significantly above that of a matched passive monopole, a two-transistor circuit was employed. In both instances the bandwidth of the active antennas were much broader than those of the passive antennas. A small active antenna operates far from the resonant point of the input circuit and the mismatch loss remains nearly constant over a wide frequency band.

The noise performance of some of Meinke's antennas is reproduced in Fig. 6. The vertical scale is the field strength necessary to achieve a unity signal-to-noise ratio at the antenna output. Also indicated is a predicted curve of noise from terrestrial and man-made sources. Although better signal-to-noise ratio is obtained by a small matched passive antenna over a narrow band, the active antenna noise performance is better over a much wider bandwidth. Between 6 and 15 MHz, high electromagnetic fields are needed to overcome external noise and achieve a unity S/N ratio. Above 30 MHz, however, the external noise has dropped to such low values that an antenna with a noise output less than that of the subminiature integrated antenna could be used to advantage.

Cross-Modulation and Intermodulation

The nonlinear characteristic of an overloaded transistor also causes noise. For example, when a strong modulated carrier at a frequency different from the frequency of a second carrier is impressed across a slightly nonlinear transistor element, each carrier will have the modulation of the other on it. No amount of selectivity in succeeding circuits will remove the interference. Also, a signal at the correct frequency can be produced when two off-frequency carriers or harmonics combine in the nonlinear element. The evaluation of these effects in transistorized antennas is just beginning. To date, circuits have been deliberately mismatched to keep off-carrier signal levels low and reduce cross-modulation and intermodulation effects. However, as progress is made on lowering mismatch loss and improving signal-to-noise ratios, the interference caused by cross-modulation and intermodulation will become more severe. Elimination of these undesirable sources of noise must depend upon suitable preselectivity and/or the use of transistors with improved linearity over a much wider dynamic range.

For the Future

The outlook for the very small antenna for communications services below 30 MHz has been enhanced by the work of Meinke and his group. Indeed, a number of small antennas with low-noise preamplifiers in or near the antenna are being used. But television, FM radio, and other services which operate above 30 MHz, have not been able to utilize small antennas. Techniques for improving the noise performance of the SIA's must be developed and balanced antennas with directivity, rather than omnidirectional monopoles, are needed for best results. It is also difficult to obtain perfectly matched transistor circuits for balanced dipoles.

Thus considerable work remains to be done before the conventional roof-top antenna (which has high gain and high directivity, and very low mismatch loss) can be eliminated for either television or FM reception. It seems likely, however, that the use of antennas which are small in wavelengths will grow in popularity. ▲