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RECENT IMPROVEMENTS IN MASTER ANTENNA SYSTEMS

J. G. Aceves*

Presented before the Club on January 11, 1940

In previous papers the theory and practice of modern antenna systems have been outlined. On these occasions the operation of individual receivers rather than multiple-unit operation was analyzed in greater detail. In the present paper, however, the latter aspect of the subject is considered, but without losing sight of the fundamental principles.

As the function of an antenna system is to deliver signal energy with a minimum of interference, it should not be rated solely by the microwatts which it can supply to a radio receiver. The important matter is the ratio of the signal strength delivered to the strength of the interference picked up. Only in the most quiet locations is the actual strength of the signals per se of prime importance. Radio receivers are so sensitive that the pickup of a small loop within the cabinet is sufficient, at least for local reception. Therefore, unless an antenna system can give a better signal-to-noise ratio than that from a loop, or indoor antenna, it is not particularly useful.

Multiple-Unit Operation of Radio Receivers

Multiple-unit, or "master" antenna systems may be considered as consisting of four parts, namely:

A. A collector of electromagnetic radiation;
B. Means of coupling the collector to a line;
C. Transmission or distribution lines; and
D. A plurality of couplers from the lines to the individual receivers.

The most general problem to be solved may be stated as requiring:

1. Maximum signal transfer to a given number of radio receivers;
2. Minimum extraneous interference in the system; and
3. Minimum interaction between the radio receivers.

It is obvious that the three requirements are conflicting, and, therefore, the solution is a matter of compromise according to local specified conditions. The solution of any particular case demands good engineering judgment rather than conclusions from deductive reasoning a priori.

In designing a master antenna system, we have to contend with these additional considerations:

a. Various types of radio receivers of different input impedances;
b. The limits of signal strength delivered;
c. Safety from electrical hazards;
d. Restrictions from an esthetic or architectural viewpoint; and
e. Simplicity of installation and low maintenance and installation costs.

The Wave Collector

Of the several forms of antennas which can be chosen for all-wave multiple unit operation, the doublet with a suitable coupler is the most desirable because its dipole action furnishes the highest signal-to-noise ratio over the higher-frequency bands, while when acting as a Marconi antenna in conjunction with a local ground and a suitable coupler, it is hard to surpass for quiet reception in the 0.5-1.6 Mc. standard broadcast band.

When the upper-frequency bands are of less importance, the doublet may be replaced by a half doublet, Zepplin or Marconi antenna. When short-wave reception is less important, it is better to have the single-arm antenna oriented vertically rather than horizontally because standard broadcast signals are mostly vertically polarized. The characteristics of some commercial forms of such masts as compared to horizontal inverted L or T antennas at frequencies between 550 and 1700 kc. are illustrated by some examples given below.

In Fig. 1, note that the average signal-level difference

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*Engineer, Amy, Aceves & King, Inc.

in the standard broadcast band is about 3 db lower using a vertical 24-foot pole over a 30x30-foot doublet acting as a Marconi antenna. The antenna transformers were the best for the particular constants of each structure over the frequency bands considered. In the short-wave broadcast band, 6 to 20 Mc., there is about 2.5 db in favor of the doublet.

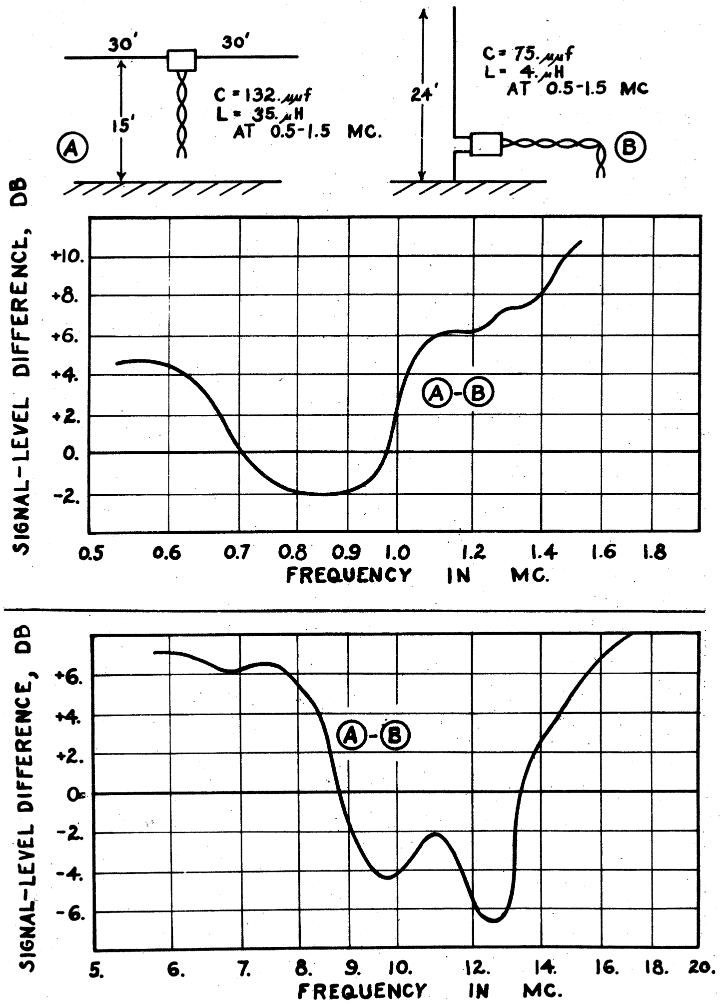

Fig. 1 - Comparisons between horizontal and vertical antennas.

Fig. 2 shows the relative levels of signals in the broadcast band using poles 12, 18 and 24 feet high. The same transformer was used in all cases. From Fig. 2, the average gain from a 12 to 24-foot pole is about 8 db, while from 18 to 24, it is 4 db. Hence, the height increase does not bring in a proportionately higher signal level. There appears, however, a gain of 4 db for every 6 feet. The signal levels were measured at the end of a 100-ohm line.

The vertical masts give somewhat less signal strength than horizontal inverted-L antennas, (Fig. 1). But due to the fact that the mast inherently is farther away from noise sources and can be installed at the highest point over the roof, the interference picked up will be found smaller than the amount collected by an average T or L type. The signal-to-noise ratio is greater with the mast than with an average Marconi antenna, if the distribution system connected thereto is free from noise pickup.

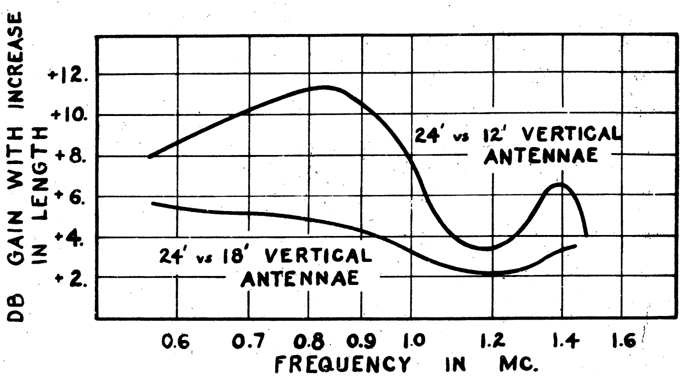

Fig. 2 - Effect of length of vertical antenna on signal strength.

For u-h-f reception, and particularly for visual signals, these types of antennas are not suitable. A very directive antenna structure, fairly resonant to the narrow band to be received, is necessary; for example, simple dipoles or double dipoles with or without one or more reflectors. Reflectors are a great help in avoiding reception from more than one path to eliminate ghosts, and are almost indispensable in metropolitan areas where high buildings prevail.[1]

Diamond and V antennas are better when there is sufficient space available to make the arms several wavelengths long, on account of their directivity and strong pickup. They may be the best form of television antenna for store-demonstration purposes in suburban towns assuming that they are properly directed and terminated to become uni-directional.

Revival of loop-operated radio sets has caused questions concerning the possible obsolence of antenna systems. There should be no fear on this account, particularly in large metropolitan centers. Apartment houses contain not only a steel frame but a multitude of other conductors such as piping, wiring, copings, etc., which would render the operation of loop sets inadequate except in the complete absence of interference. Measurements on typical loop and antenna structures are shown in Fig. 3. Inspection of the graphs, shows the much greater signal delivered by the tuned and aperiodic antennas. The loop was located about 3 feet from the nearest window on the 13th floor of a 15 story building.

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[1] S.W. Seeley, *R. C. A. Review*, April, 1938

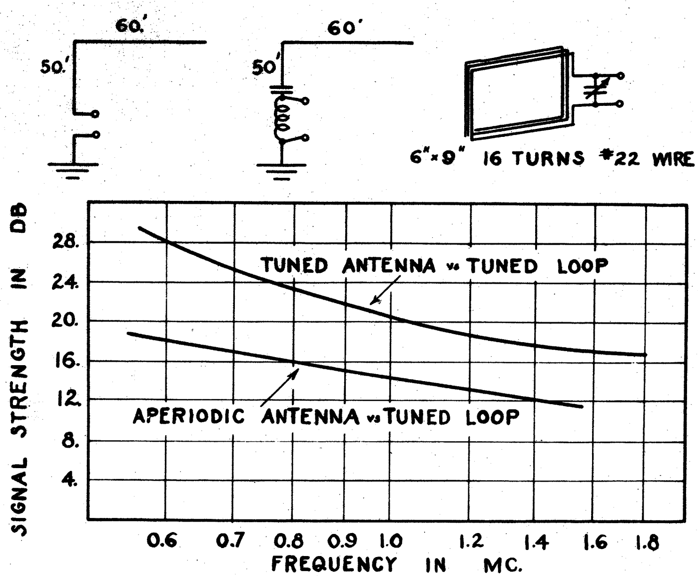

Fig. 3 - Comparative signal strength induced in an aperiodic antenna, a tuned antenna, and a loop.

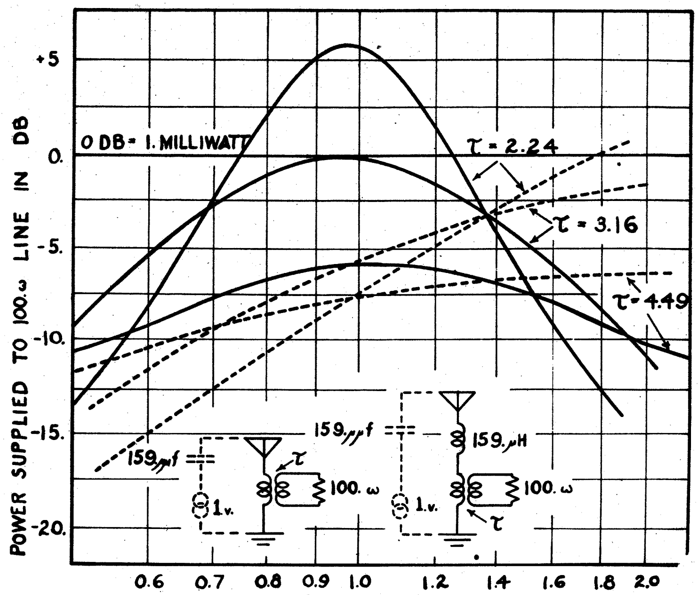

Fig. 4 - Examples of antenna-transformer design permitting choice of best transformation ratio. Solid curves with series inductor, dotted curves without

Antenna Couplers

Antenna couplers may be classified into two types:

1. The passive type; and
2. The active type provided with amplifiers.

Passive antenna couplers transfer the energy from the collector to the line without added energy. To do so efficiently, they must act as an impedance-matching device at all frequencies, and must also change the operation of the antenna from one type to another, such as from a doublet to a Marconi or inverted L, according to the frequency of the signal. There is an additional function which is very important, that is, to isolate the signal-pickup circuit from the paths of man-made interference.

The theory and design of antenna couplers for single-receiver operation has been previously outlined.[1] For multiple-unit operation, and so long as the transformers contained in the antenna coupler are to match the same type of transmission line as used for a single set, it does not matter whether there is only one radio receiver connected to the line or any number. It is the receiver coupler that has to be modified to accommodate various numbers of receivers.

Fig. 4 shows how the ratio of transformation of an ideal transformer to couple a Marconi antenna, having a capacity of 159 mmf to a 100 ohm transmission line, has to be determined for optimum energy transfer and good distribution within the band selected. The ordinates represent power supplied to the line when 1 volt is induced in the antenna. In the graph, zero db corresponds to 1 milliwatt. The solid lines refer to the case where an inductance of 159 microhenrys is placed in series with the antenna to balance out its reactance at mid-frequency. The dotted curves show the same but without the inductance, that is, an untuned antenna. In designing the transformer, the leakage reactance may be used for tuning purposes. By inspection, it appears that, using the neutralizing—inductance design, the best ratio of transformation in about 3:1 for good energy transfer and uniform distribution.

For all-wave and television reception, the antenna coupler must change from dipole operation to elevated-capacity operation at given frequency limits. Fig. 5 illustrates a triple-transformer coupler that transfers energy at about 50 Mc. from a television-type dipole to the line. At 0.5 to 20 Mc., however, the structure acts as an elevated capacity over a local ground, but again induces circulating currents in the transmission line.

In this example, the u-h-f transformer T_1 has condensers of 25 to 50 mmf in series with the secondary winding which tune it very broadly to about 45 Mc., thereby making it possible to get optimum energy transfer on frequency-modulated as well as television signals. A second transformer T_2 serves to transfer the energy of signals in the 6-20 Mc. band, using the antenna structure as an elevated capacity. A thrid transformer T_3 converts the structure to a Marconi antenna, using it as an elevated capacity over a local ground *G* on the roof and inducing a signal voltage across the transmission line with the excellent signal-to-noise ratio. This coupler is suitable for operation in conjunction with short dipoles (about 7 feet for each arm) designed specially for 40 to 60 Mc.

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[1] *Proceedings of The Radio Club of America,* May, 1938, Vol. 15 No. 4

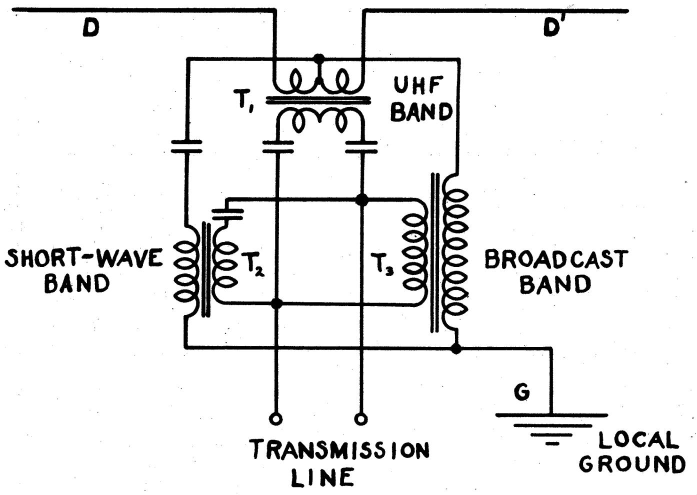

Fig. 5 - Antenna coupler covering u-h-f, short-wave and standard broadcast bands.

In planning a system for multiple operation, the position of the receivers will decide the method of connection to be used. The ideal way is to have the antenna coupler at the junction of the antenna and line, and the receiver couplers at various intervals along one single line, without branch lines. This is shown in Fig. 6a. The most practical form has the outlets in a single vertical or horizontal line. If, however, there are two or more vertical lines, for example when a four-story building requires sixteen outlets, then there are several ways of connecting the outlets: **First,** the "up-and-down" way which is equivalent to a straight line. This method is probably the best for systems to carry television signals with a minimum of reflections, (Fig. 6b).

Second, by a number of parallel lines fed from one antenna transformer by suitable redesign of the secondary windings (Fig. 6c). Here it is important to note that each individual line must come directly to the transformer and not from a remote junction through another piece of line as, for example, in Fig. 6e, because this method would introduce both reflections and mismatching of impedances at the junctions. It is unsuitable for good television service without specially designed distribution transformers. In Fig. 7, this effect is illustrated by measuring the received signal strength with two risers in parallel joined directly at the antenna transformer or at a point separated therefrom by a 50-foot line of the same kind as used in the risers.

Third, by means of auxiliary distribution transformers having the closest coupling between windings and a very broad frequency response. (Fig. 6d). The antenna-transformer ratios are the same as for a single line. The distribution transformers are more easily designed and built for a 2-to-1 step-down ratio which would be best

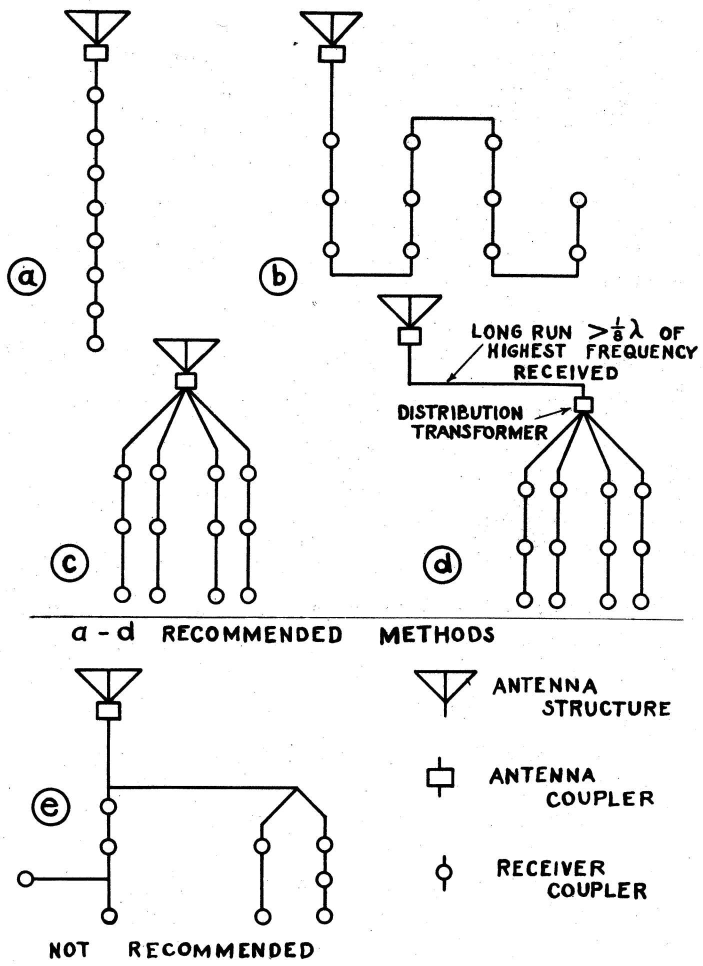

Fig. 6 - Block diagrams of methods of distributing signal energy to a plurality of outlets.

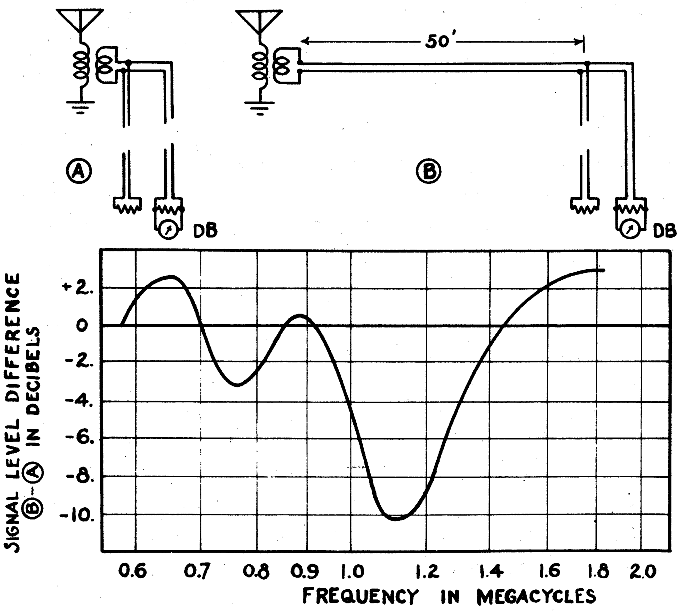

Fig. 7 - Effect of a length of transmission line interposed between the antenna coupler and a junction of parallel lines.

used to feed four lines effectively in parallel. This last system requires more complicated distribution transformer units with suitable filters to prevent reflections in u-h-f operation, and to separate properly the flow of signals of the various frequency bands.

When the number of radio receivers is so large that the attenuation of the line or lines is excessive, amplifiers are associated with transformers between the antenna and the lines. Of these, there are two general types:

(a) Broadly tuned; and
(b) Aperiodic, but with band-pass frequency-limiting filters.

Both types may have frequency equalizers and inverse feedback to overcome cross-modulation from one or more strong stations.

Amplifying systems of the first kind contain a number of band-pass amplifying tubes overlapping each other. They are sometimes made to cover only a portion of a given band. For example in one form[1] there are three channels within the standard broadcast band, and a number of channels in the higher-frequency bands up to about 20 Mc. Other forms cover the spectrum from 150 kc. to 15 Mc. in only two channels, using high-transconductance tubes[2]. This system may also be considered as belonging to the second class because the amplifers are almost aperiodic.

The second type usually contains a band-pass input-filter covering about 500 to 2500 kc. with sharp cutoff against 455 kc. (which is the i.f. used in most superhet receivers). There is inverse feedback from a push-pull hair of power tubes to another pair of amplifying tubes that reduces cross-modulation. A number of rejectors for the purpose of equalizing to a certain degree the various local-station signals precede the amplifier tubes. High-pass filters are placed so that frequencies above 2500 kc. are bypassed around the amplifier and fed directly from the antenna structure to the line so that short waves may be received, but without added gain. At the same time, feedback for broadcast frequencies around the amplifier is prevented by the high-pass filter.

Transmission Lines

The transmission line by itself presents relatively simple problems and its attenuation and terminal impedance can be measured or calculated without serious difficulties[3]. In general, for frequencies below 20 Mc. the line attenuation per se is negligible when it is less than about 500 feet long.

However, it is the effective attenuation of lines with a number of outlet boxes, containing set couplers of various descriptions, that is of practical importance. This applies to signal attenuation and reflection.

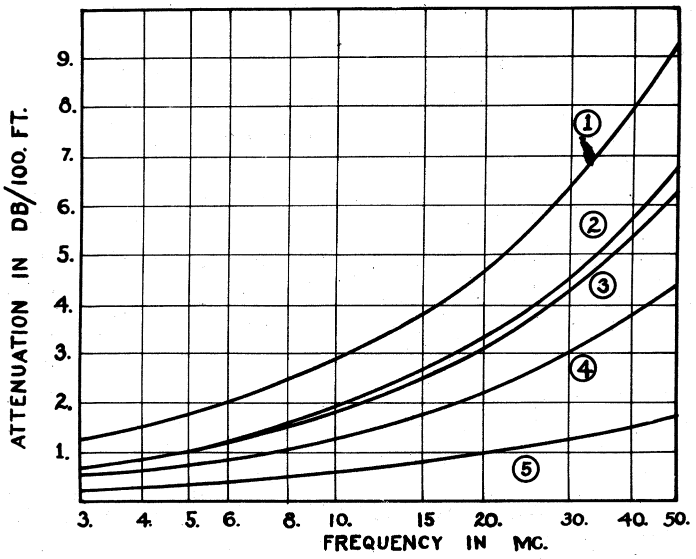

Fig. 8 - Attenuation of typical transmission lines -

(1) 16/30 twisted pair, 1/32 inch, 30% rubber wall. Z_0 - 110 ohms. Sample exposed to outdoor weather conditions.
(2) Same as (1) but not previously exposed.
(3) Coaxial low-loss rubber dielectric. Z_0 - 64 ohms.
(4) Type 9882 two No. 12 solid conductors, paraffin braid. Z_0 - 100 ohms.
(5) Coaxial, spun-glass dielectric. Z_0 - 71 ohms.

When the outlets are spaced at less than one-eighth wavelength or so, they may be considered as lumped conductances from which an additional equivalent distributed conductance per unit length may be computed. By adding this to the conductance per unit length of the line alone, the attenuation of a line with couplers may be calculated with a fair degree of approximation, as follows:

The attenuation of a transmission line is approximately

$$\alpha = 4.34 \left(\frac{R}{Z} + GZ \right)$$

where the result is in db per unit length, R and G being the resistance and conductance per unit length respectively and Z the surge impedance in ohms.

When couplers are shunted across the line, an additional loss is introduced, which can be expressed in terms of an effective conductance g. If there are n couplers having an effective resistance ρ, shunted across the line of length l, the conductance due to the couplers will be:

$$g = n/\rho l$$

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[1] V.D. Landon, *I.R.E. Proceedings*, March, 1932
R.C.A. Review, January, 1937
[2] Dr. D.J. Fruin, *Electronics*, November, 1939
[3] Stuart Ballantine, Measurements of H-F. Lines
Electronics, April, 1938.

Substituting in (1), we get a new attenuation

$$\alpha' = 4.34\left(\frac{R'}{Z} + GZ + gZ\right) = \alpha + 4.34\frac{n}{\rho l}Z$$

The total attenuation of the line will be:

$$A = \alpha' l = \alpha l + 4.34\frac{n}{\rho}Z$$

If the couplers consist of transformers having a transformation ratio τ (secondary-to-primary), the reflected resistance into the line will be: $\rho = \frac{r}{\tau^2}$ where r is the input resistance of the radio receiver. Hence:

$$A = \alpha l + 4.34\frac{n\tau^2}{\tau}Z$$

If we consider the total attenuation from the head of the line to the terminals of the radio receiver, then this attenuation A' will be:

$$A' = A - 20 \log \tau$$

Therefore:

$$A' = \alpha l + 4.34\frac{n\tau^2}{r}Z - 20 \log \tau$$

Example:

Let a line 200 feet long, having an attenuation of 0.5 db per 100 feet, supply n radio receivers of 5000-ohm input resistance by means of ideal transformers having a secondary-to-primary turns ratio τ . For n = 5, 10 and 20, the values of A' have been calculated for various values of τ . By plotting them with as abscissas and A' as ordinates, the curves of Fig. 9 were obtained. From these graphs the two-to-one ratio seems to be satisfactory for most conditions.

In practice, the effective conductance of an outlet varies with frequency, with the impedance of the radio receiver, with the length of line from the receiver to the coupler, and with other less important factors. The outlet should contain such a circuit that the variation of output impedance (input looking into the line), may be held within reasonable limits. Decoupling means such as resistance or reactance or mutual inductance will be shown in connection with the design of receiver couplers. Various compromises have to be reached between conflicting requirements such as the following:

1. Minimum effective shunt conductance, so that the line attenuation will not be excessive;
2. Maximum energy transfer from the line to all the radio receivers;
3. Minimum variations in admittance due to changes in adjustments of radio receivers; and
4. Energy transfer to be a maximum for signals and a minimum for any other radio-frequency currents of steady or transient nature.

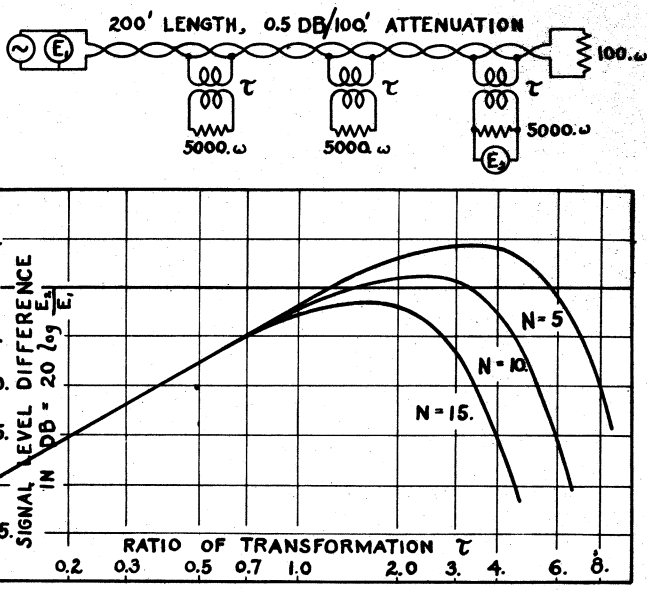

Fig. 9 - Signal attenuation in a line feeding a given number of outlets containing transformers of different ratios. Optimum ratio for a given number of outlets is shown by the curves.

All these requirements cannot be fulfilled, but which takes precedence over the other is determined by the conditions specified in any given application of the antenna system. Here a good deal of experience and sound engineering judgment are necessary. The design of a good coupler is the result of economic as well as technical considerations.

Receiver Couplers

There are three important types of receiver couplers:

1. Conductive; 2. Inductive; and 3. Composite of the first two.

The conductive coupler comprises a simple series impedance which may or may not vary with frequency, the object being to minimize the load-impedance variations as the receiver is adjusted. In the second type no direct metallic connection exists between the line and the receiver. The coupler acts as an isolation unit. In the third class there is a common circuit for the load and the line, at least at some frequencies, while at others the main energy transfer takes place by induction. From the standpoint of noise elimination, the second type furnishes the best solution, but it is the most expensive, particularly when several frequency-selecting transformers are required for efficient operation. Fig. 10 represents an inductive coupler suitable for reception between 0.5 and 20 Mc.

In designing inductive couplers there is an additional difficulty encountered in the sudden impedance variations of a radio set when the band-changing switch is operated.

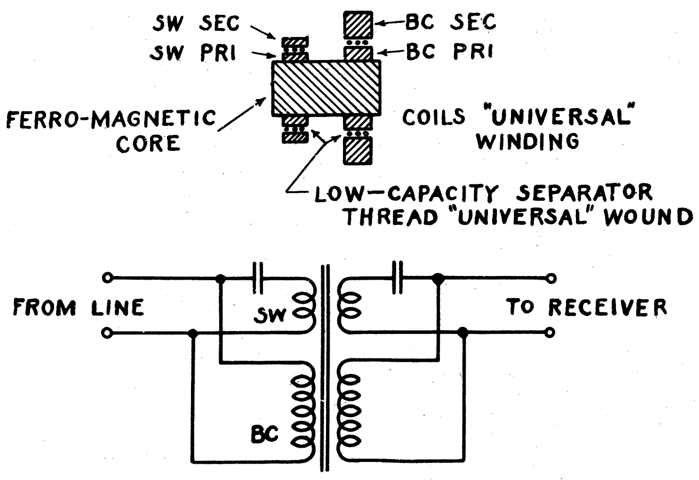

Fig. 10 - Inductive-type receiver coupler for all-wave Reception.

As the receiver is seldom placed very close to the outlet, it follows that if there is a twisted pair between them this short line is practically equivalent to a condenser of about 25 mmf per foot for frequencies in the standard broadcast band. For example, 12 feet will be 300 mmf, and at 1.550 Mc. its impedance is 342 ohms, but at 0.55 Mc. it is 964 ohms. As these impedances are lower than that of the receiver, they should be considered as part of the load in designing the transformer and they should fix the leakage reactance between windings as well as the primary inductance.

The inductive type of receiver coupler has an additional advantage over the conductive coupler: it prevents transients and low-frequency power currents from entering the transmission line via the receiver coupler itself. Currents from the power-supply line pass through the radio receiver and may be propagated via the transmission line into the entire distribution system unless blocked by inductive couplers. In an actual case, the noise reduction effected by the replacement of conductive couplers with inductive couplers has surpassed 15 db in a system with only 5 couplers.

Composite couplers are sometimes designed to be less expensive than inductive couplers. They may contain only one transformer, having very efficient transfer between 0.5 and 1.7 Mc. through close coupling secured by a ferromagnetic core and careful winding design. It may be designed with a high distributed capacity between the two high-side ends of the windings, so that frequencies above 6 Mc. are transmitted mostly through this distributed capacity. This type does not possess the efficiency of the two-transformer type for shortwave operation, but it is less expensive.

The conductive type of coupler is in reality a "decoupler". It minimizes reactions between sets and between sets and the line as a whole. A simple series condenser alone is not good enough for all-wave operation because its reactance decreases to a detrimentally low value at high frequencies.

Resistance alone is not satisfactory because it consumes signal energy and also because with defective or bad connections in the radio sets it allows power currents to pass and very often is burned out as a result. A satisfactory compromise consists of a blocking condenser of 200 mmf which stops power currents and decouples the receiver from the line to a limited extent at 0.5 to 1.7 Mc. In series with this condenser is an inductance of 20 microhenrys with a resistance of 200 to 500 ohms in parallel. The resistance serves to decouple the receivers at frequencies above the broadcast band, while the low inductance by-passes broadcast frequencies around the resistance.

Couplers for all-wave and television use are of the composite type. Fig. 11 shows a form of coupler containing all the elements of the all-wave coupler of Fig. 10. and in addition two condensers, C, C' of 50 mmf to transmit the u-h-f signals while substantially blocking signals of the lower bands. Two chokes L, L' (or preferably anti-resonant traps) in series with the inductive-coupler elements for these lower-frequency bands substantially block u-h-f from the two lower-frequency transformers, which act like capacities for u-h-f currents and, therefore, would not only bypass some of the signal energy, but what is worse, would introduce reflections into the line. In using Fig. 11, connect the television set directly to C, C' or through twisted pair having a surge impedance equal to that of the set itself, to prevent reflection. The all-wave part or an entirely separate receiver, may be connected to the terminals marked "A" and "G" by a twisted pair, preferably not longer than 12 feet.

In an experiment using the type of receiver coupler described, six television input circuits, one of them part

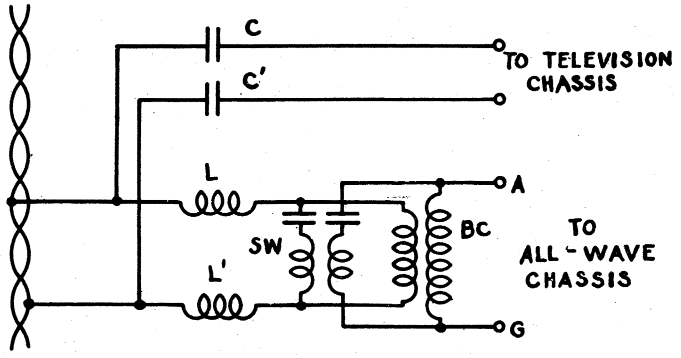

Fig. 11 - Composite-type receiver coupler for all-wave and ultra-high frequency (television) reception

of an actual television receiver, were operated with as good a picture as when the television receiver alone was connected to the line. At the same time, six all-wave input circuits, including two actual all-wave receivers, were also operated. The antenna supplying all the signal energy was a doublet with a noise-reducing antenna coupler of the type of Fig. 5.

All-Wave and U-H-F Distribution Methods

There are three main methods of distributing ultra-high frequencies, together with the regular broadcasting channels from about 0.5 to 20 Mc. Figs. 12, 13 and 14 illustrate the manner in which signal energy from a doublet antenna, preferably with reflector and with a coupling unit such as shown in Fig. 5, is distributed to a number of outlets containing low- (below 22 Mc.) and high-frequency terminals.

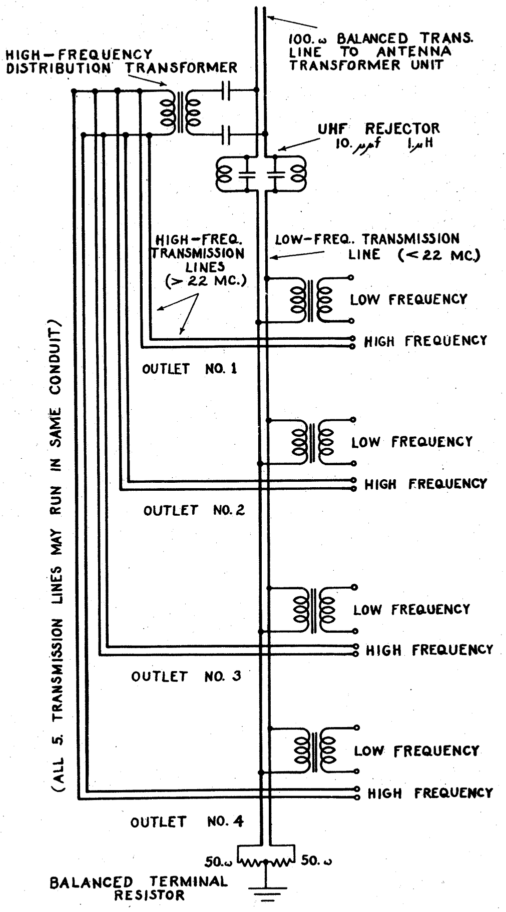

Fig. 12 - Separate-channel distribution system for high-frequency and low-frequency signals. Individual channel for each u-h-f-receiver.

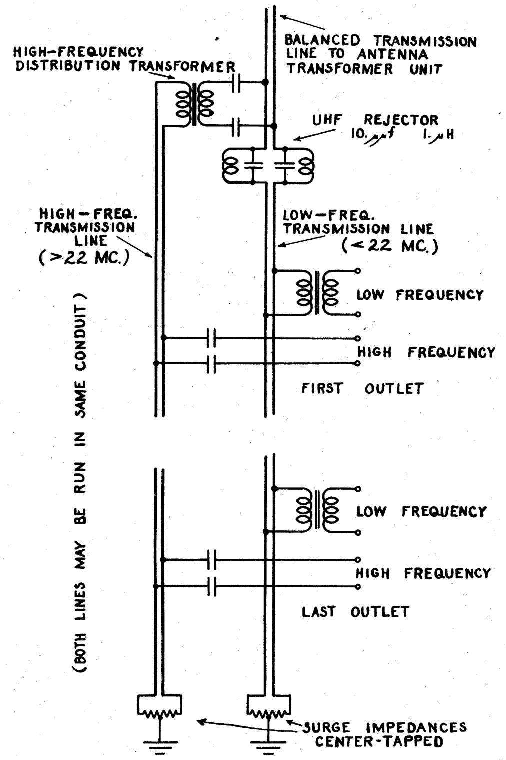

Fig. 13 - Two-channel distribution system for frequencies above and below 22 Mc.

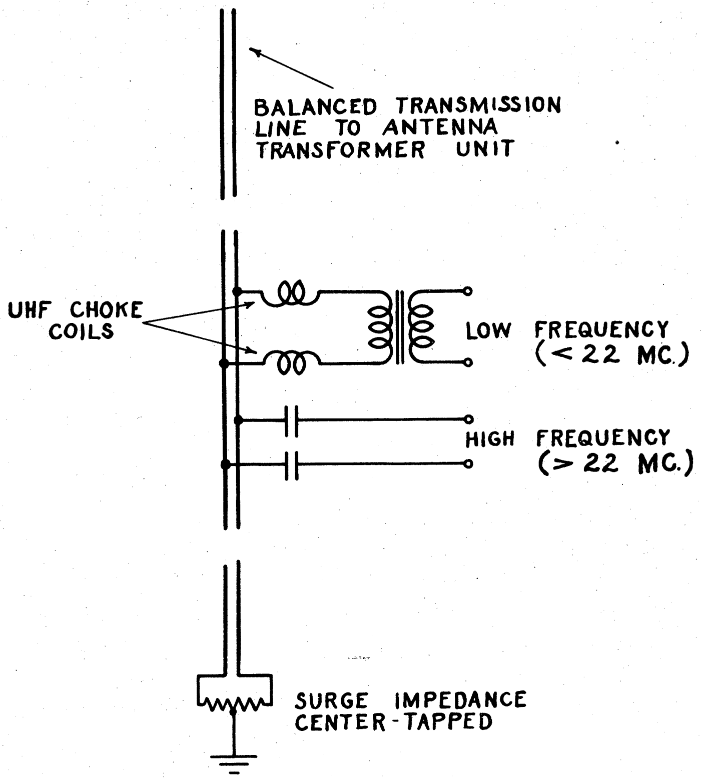

Fig. 14 - Single-channel distribution system for frequencies above and below 22 Mc.

Radio receivers having two chassis are considered as separate sets, one for high and one for low frequencies, because many television models on the market are really made of two separate chassis.

In Fig. 12, a distribution transformer is used for the high-frequency outlets with separate feeders to each set. The low-frequency channel has the standard all-wave couplers bridged across the line in the conventional manner.

In Fig. 13, the low-frequency channel is the same as in Fig. 12. The high-frequency distribution is not carried out with separate feeders to each set, however, but with decoupling capacities to each set bridged across the line. These capacities can be followed by individual high-frequency transformers if the extra expense is warranted.

In Fig. 14, the same line handles both high and low frequencies but each coupler is provided with added filter elements to prevent shunting effects.

In connection with this general problem, it is needless to point out the fact that the local superheterodyne oscillations of one set may raise havoc with the reception of some other set. This difficulty is not limited to master antenna systems, because some receivers can radiate enough energy (even without any antenna or wires attached to their input terminals) to ruin the reception of a channel upon which the frequency of the oscillator is located.

Noise Reduction

The same principles in the *Proceedings of The Radio Club*, May 1938 apply to multiple-unit operation as to the individual-receiver case. There, however, we are confronted with other sources of interference not present in the single-unit operation. In the first place, one radio receiver can act as a source of interference for other receivers, not only because it may introduce power-line noises into the system but on account of r-f oscillations. The installation of a multiple-unit system does not include connections from the radio receiver to the outlet, and this is a likely place to pick up all kinds of strays unless instructions are followed never to use long exposed leads in the vicinity of sources of transient voltages. Another problem is that of the proper grounding of the receiver, particularly in the case of ac-dc receivers having no ground terminal. The chassis must be returned to the ground terminal of the outlet by a series condenser. Otherwise there would be a loss of signal in case of the inductive coupler and a consequent increase of line noise.

Another difficulty introduced in the design of a multiple-unit system, not encountered in individual reception is as follows. In the latter case the coupler is usually attached by very short leads to the chassis and the transmission line directly to the coupler, while in the multiple-unit system the coupler is in an outlet box sometimes quite far from the radio set, and of necessity an additional line must go from the coupler to the set. Such line can be considered as a condenser for the broadcast-band frequencies because the impedance of most radio receivers in this band is high in comparison with the capacity reactance of a short piece of twisted pair. Therefore, the coupler may be considered as furnishing leading current to a condenser of about 25 mmf per foot of line. It is upon this basis that the coupler for the broadcast band should be designed. However, if the band switch of any radio receiver is turned to a higher-frequency band, the line may act as a small inductance or resistance even for broadcast frequencies and the leakage reactance of the coupler transformer for this band should be such that a dead short may be avoided under these conditions. Otherwise a decoupling series element should be incorporated in the unit.

For the higher-frequency bands, the short twisted pair may be considered more like a transmission line, often terminated at impedances several times greater or smaller than its surge impedance. It is quite impossible to predetermine or even guess at the transmission properties of this line.

Conclusion

From the foregoing considerations we see that by judiciously compromising some conflicting requirements, a system of radio-wave collection and distribution for multiple-unit operation can be devised for a very wide frequency range, namely, from 0.5 to 80 Mc.

The necessity of a substantial noise reduction in the system cannot be emphasized too much. The real *raison d'etre* of such a system is an improved signal-to-noise ratio over the values obtainable by individual pickups of the indoor type, or of any kind, whenever the number of receivers in the building is of the order found in an average metropolitan apartment house. This holds true now more than ever with the advent of television.

If we have made these points clear, and have indicated the way to solve the problems, the purpose of this paper will be fulfilled. If so, it will be due to the invaluable assistance from Messrs. E. V. Amy, Frank King, and Edward Sieminski.

Paul F. Godley

CONSULTING RADIO ENGINEER

Montclair, N. J. **Montclair 2-7859**