The Lenkurt Demodulator

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CROSSTALK

Crosstalk, ancient enemy of electrical communications, may occur whenever more than one communications channel is sent over the same path. The causes of crosstalk are many, and its control is often difficult. This article reviews some of the more important aspects of crosstalk.

Privacy is one of the vital requirements of any communications system, whether the system be privately owned or commercial. Crosstalk tends to violate this privacy by "leaking" the signal from its alloted channel to other channels. Even where privacy is not particularly important, crosstalk has a very disturbing effect if it is intelligible. This disturbance is so great that special care is taken to make crosstalk unintelligible if it cannot be eliminated entirely. Because of this, crosstalk is generally classed as either *intelligible crosstalk* or *unintelligible crosstalk*.

One form of unintelligible crosstalk that may be almost as disturbing as intelligible crosstalk, is *babble*, which consists of "scraps" of sounds from several other communications channels. Although babble may approach noise in its randomness and its lack of intelligibility, it is usually syllabic in pattern, thus increasing its resemblance to speech and its disturbing effect.

There are many ways that signals may slip from one channel to another. One way is by simple leakage through an imperfect insulator. Good design and improved materials and manufacturing techniques have virtually eliminated this as an important source of crosstalk, however.

In radio and carrier, excessive or improper modulation may cause signal energy from one channel to appear in another. In frequency-division multiplex, channels are separated by filters which accept certain frequencies and attenuate others. If signal levels become excessive, or if the filters don't have enough selectivity, some signals from outside the desired band may appear. Such crosstalk is relatively easy to control by good equipment design and by proper operating procedures. Much more of a problem is crosstalk that occurs between circuits consisting of open wire line and cable.

When an electrical signal passes through a conductor, it sets up electromagnetic and electrostatic fields in the space around the conductor. These fields vary in strength according to the strength of the signal itself. Where the fields encounter other conductors, they cause a current to flow in these conductors, due to inductive and capacitive coupling. Inductive coupling is caused by the electromagnetic field which surrounds the disturbing circuit, while capacitive coupling results from the electrostatic field.

The greater the coupling between circuits, the greater the strength of the crosstalk that will appear in the disturbed circuit. Coupling usually increases in proportion to how close together the two circuits are, how long they are, and the disturbing signal frequency. The crosstalk coupling transfers signal energy from one circuit to another in a fixed ratio which is independent of signal strength. If the signal level in the disturbing circuit is relatively high, the crosstalk will tend to be high. If the level of the disturbing signal is reduced, the crosstalk will be lower in the same proportion.

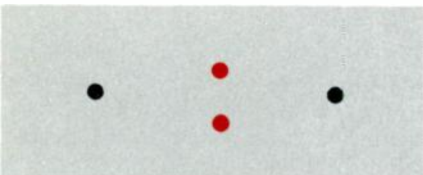

Figure 1. Two pairs arranged so that both conductors of each pair are equidistant from disturbing conductors. Such arrangements are impractical for many pairs.

Circuit Balance

The first telephone and telegraph circuits consisted of single wires between users, with the circuits completed through ground. This reduced the cost of wire, but made the circuits extremely vulnerable to interference, crosstalk, electrical storms, and even earth currents. Modern communications use balanced pairs or coaxial conductors to reduce these external influences. In theory, any disturbance which appears on one conductor of the pair will also appear on the other conductor, and the two will cancel each other out. While this is generally true for large-scale external influences such as electrical storms or ignition noise, it is not true for nearby disturbing influences such as adjacent pairs. The difficulty lies in the fact that it is impossible to achieve a *perfect* balance between the two conductors of a pair. Furthermore, it is impractical to arrange conductors so that both wires of each pair are equidistant from the others. As a result, there is more crosstalk coupling to a near conductor than to the more distant one. The two opposed crosstalk currents are not equal and cannot cancel completely. The excess crosstalk remains as a disturbing signal.

In cables, the problem is greater than in open wire lines. Many conductors are necessarily packed close together, some pairs spaced close together, others more separated. Without special techniques to neutralize crosstalk, it would be impossible to arrange conductors so that both wires of a pair are equidistant from all the nearby disturbing conductors.

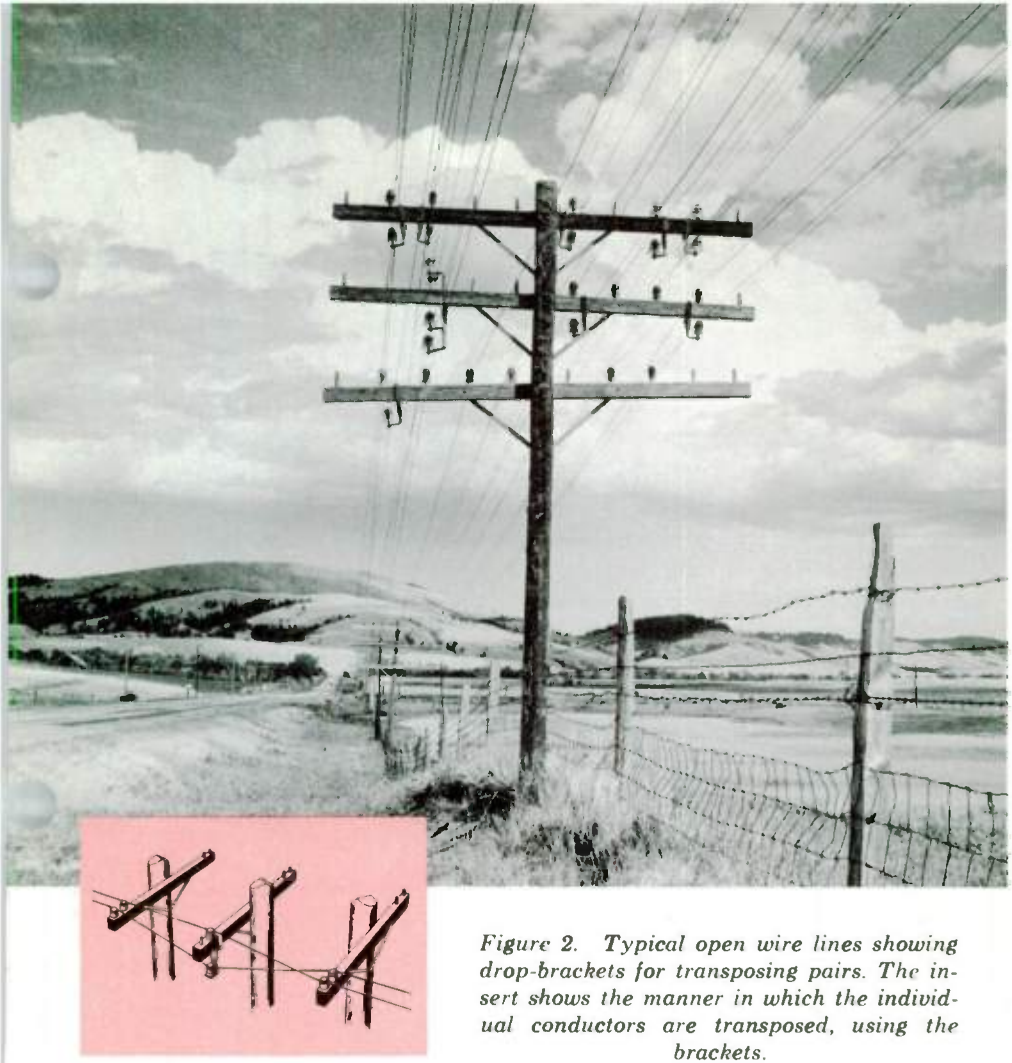

Figure 2. Typical open wire lines showing drop-brackets for transposing pairs. The insert shows the manner in which the individual conductors are transposed, using the brackets.

Even if both wires of a pair are equally spaced from a disturbing circuit, crosstalk will appear in the circuit if the pair is electrically unbalanced. One conductor might have greater resistance than the other, perhaps because of a poorly-made connection. One conductor or the other may have greater mutual inductance or capacitance with the disturbing circuit. Then, the crosstalk may be more strongly coupled to one wire than the other. Instead of being balanced out, the crosstalk in one conductor will predominate, and will appear at one end or the other of the circuit.

Transpositions

Since it is practically impossible to space each wire of a pair equally distant from all other disturbing conductors, the next best thing is to arrange the wires so that they "take turns" in sharing positions nearer and farther from disturbing conductors. This is done by transposing the wires systematically. Transpositions must be designed to can-

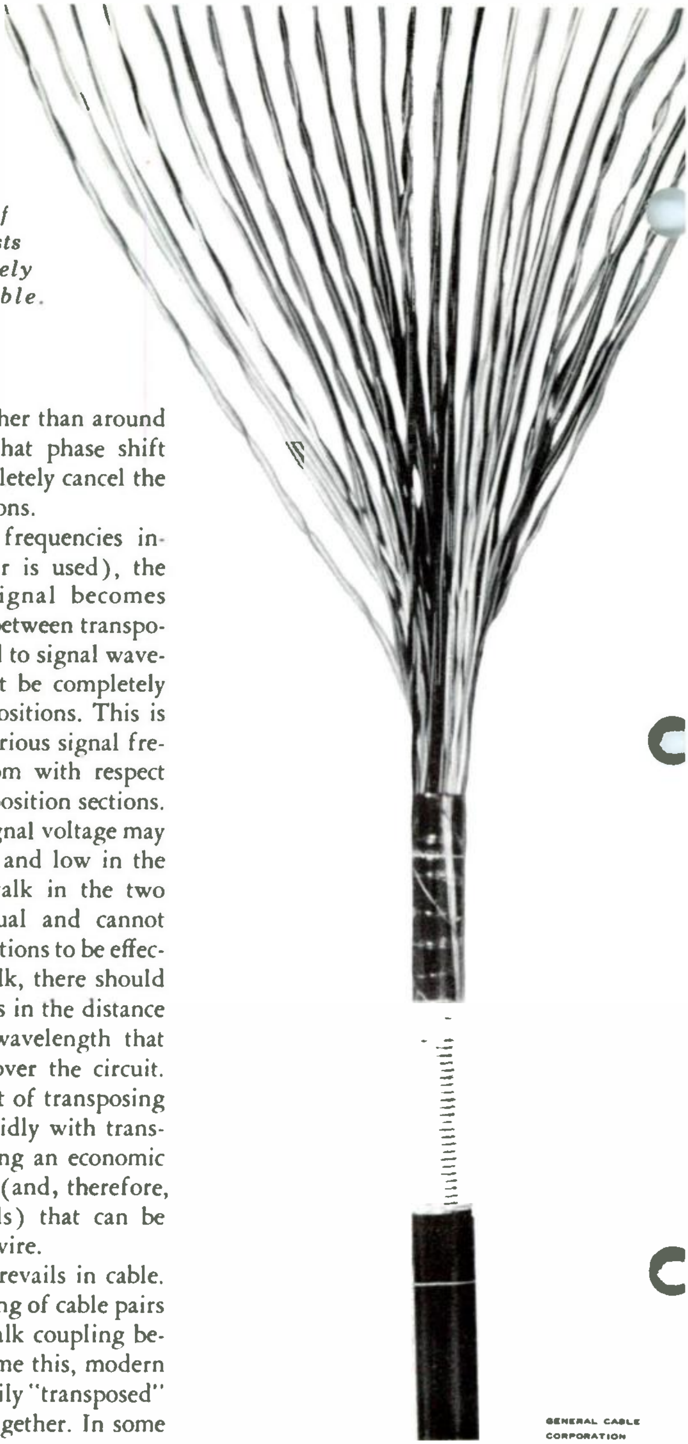

Figure 3. Typical modern plastic-insulated telephone cable. Note that each pair has a different rate of twist. Pairs having twists nearly alike are widely separated in the cable.

GENERAL CABLE CORPORATION

cel crosstalk locally, rather than around the whole circuit, so that phase shift won't partially or completely cancel the effect of the transpositions.

As communications frequencies increase (as when carrier is used), the wavelength of the signal becomes shorter. If the spacing between transpositions is long compared to signal wavelength, crosstalk cannot be completely cancelled by the transpositions. This is because the phase of various signal frequencies will be random with respect to the location of transposition sections. At any given instant, signal voltage may be high in one section and low in the next. Obviously, crosstalk in the two sections will be unequal and cannot cancel out. For transpositions to be effective in reducing crosstalk, there should be several transpositions in the distance equal to the shortest wavelength that might be transmitted over the circuit. For this reason, the cost of transposing pairs goes up quite rapidly with transmitted frequency, placing an economic limit on the frequencies (and, therefore, the number of channels) that can be transmitted over open wire.

A similar situation prevails in cable. The close physical spacing of cable pairs tends to increase crosstalk coupling between pairs. To overcome this, modern cable pairs are very heavily "transposed" by twisting each pair together. In some cable, two pairs are twisted to form a "quad" and the quads in each layer are spiraled around the center in opposite directions. In all modern cables, the pitch or rate of twist of each pair will be different from other pairs in its group. This is necessary because where two adjacent pairs have the same twist rate, the wires in each pair maintain the same relationship over the entire length of cable. Any unbalance in either pair will permit crosstalk to build up. By varying the twist, the relationship continuously changes so that any coupling between the two pairs at one point will be reversed farther down the cable.

In conventional paper-insulated cables, crosstalk may be further reduced by "random splicing" so that pairs will not be adjacent to each other in successive splicing sections, thus reducing the coupling. Newer plastic-insulated cable, such as shown in Figure 3, employs increased numbers of pair twist lengths and careful location of the pairs and groups of pairs within the cable, so that there is minimum coupling between pairs of similar or near-similar twist lengths. As a result, there may be less crosstalk advantage in random-splicing these newer cables.

Near-end Crosstalk

Since crosstalk may result from both capacitive and inductive coupling, each provides an independent disturbing signal voltage. As shown in Figure 4, capacitively-coupled crosstalk may be represented by a signal source or generator connected *across* the disturbed pair. Inductive coupling, however, can be represented by a signal source connected *in series* with one of the conductors in the disturbed pair. The direction of current flow from the two sources is such that they add or reinforce each other at the "near" end of the disturbed circuit (the same end as that from which the disturbing signal starts), but oppose each other at the far end. The two types of coupling (inductive and capacitive) vary with frequency and spacing between pairs. The closer the spacing, the greater the capacitive coupling. In modern cable, capacitively-coupled crosstalk currents in *adjacent pairs* will be about ten times as great as the inductively-coupled currents at voice frequencies. At 10 kc, the two types of current will be equal, and at 1 mc, inductively-coupled currents will be twice as great as the capacitively-coupled crosstalk currents. If the pairs are not adjacent, or if the distance between pairs is increased, inductively-coupled currents are predominant at all frequencies above the voice band.

Frequency Staggering

Near-end crosstalk occurs primarily in voice-frequency circuits and between pairs transmitting carrier channels of the same frequency. Near-end crosstalk may be greatly reduced if different trans-

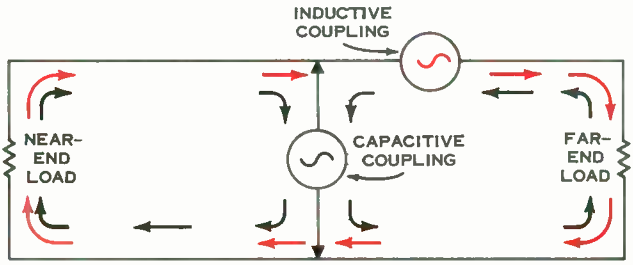

Figure 4. Where inductive and capacitive coupling are equal, they cancel at the far-end, add at the near-end. Inductive coupling predominates at high frequencies.

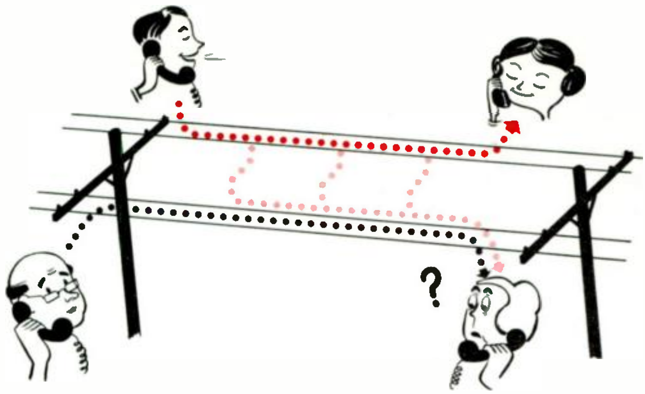

Figure 5. Transverse far-end crosstalk reaches far end without reversing direction in process, is due mostly to inductive coupling.

mission frequencies are used for each direction of transmission. Even though signal energy is coupled from one pair to another, the crosstalk is in the wrong portion of the frequency spectrum to pass the carrier channel filters. This "frequency staggering" not only reduces the effective crosstalk coupling between circuits, but it changes the nature of whatever crosstalk does get through, to a form that is much less annoying than the crosstalk between non-staggered channels.

Another way of coping with near-end crosstalk is to use separate cables for each direction of transmission. All the signals in the cable go in the same direction, so that high-level signals at the output of a west-east repeater are not physically adjacent to the low-level signals just entering the east-west repeater. Even if there is near-end crosstalk, it cannot be heard at the near-end because it terminates at the output of the transmitting amplifier, which is a one-way device. The use of separate cables for each direction, of course, is undesirable as a general practice because of the duplicate facilities required.

Far-end Crosstalk

As stated above, inductive and capacitive coupling tend to cancel each other at the far end of a circuit at low frequencies. In carrier systems, however, transmission frequencies are much higher than in voice-frequency circuits, and inductive coupling becomes much greater than the capacitive coupling. In addition, at these higher frequencies, overall coupling becomes greater, thus providing much higher chance for far-end crosstalk. Since near-end crosstalk is rather easily controlled by frequency staggering, far-end crosstalk is more of a problem in carrier communications. An exception to this may be found in high-speed pulse systems, such as in PCM (pulse code modulation) carrier systems. In such systems no carriers are used; the required bandwidth is a function of the pulse rate, which is determined by the number of channels, the sampling rate for each channel, and the number of code pulses or "digits" for each sample. A practical pulse code carrier system "uses up" the bandwidth provided by ordinary exchange cable and leaves no room for such techniques as frequency staggering. As a result, near-end crosstalk may be quite troublesome.

Several types of far-end crosstalk commonly occur. Where the disturbing signal is coupled inductively and appears at the far end without reversing direction, it is known as *transverse far-end crosstalk*. One way of reducing this type of crosstalk is to use balancing coils between pairs. These balancing coils are actually dual transformers connected between the interfering pairs. The coils are connected so that they oppose each other in their action. They may be adjusted so that one dominates the other to any degree required. By adjusting them so that the coupling provided by the coils just equals and opposes the crosstalk coupling between the pairs, the crosstalk is cancelled out. In a similar fashion, the residual capacitive coupling between pairs may be cancelled out by using small variable capacitors. This balancing method was devised for the first carrier system for use over cables. With the advent of compandors, it has received little use.

Far-end crosstalk may be increased if transmission levels in adjacent circuits are not equal, or if repeater sections are too long. For instance, if one circuit is operated at a level 5 db below a paralleling circuit, crosstalk will be 5 db greater than if both circuits were operated at the same level. Crosstalk is coupled from the disturbing circuit to the disturbed circuit *in proportion to the level of the disturbing signal*. The lower the level of the disturbed signal, the less the difference between the signal and the crosstalk. When additional amplification brings the signal up to the level required at the terminal, the crosstalk is also amplified this additional amount.

If repeater sections are unusually long, more amplification will be required at each repeater. Crosstalk is usually increased where fewer repeaters but higher repeater gain is employed. This results from the greater difference in signal level at the input and output of each repeater. Since signal level is very low at the input of the repeater, the circuit is more vulnerable to crosstalk. The great relative difference between input levels and output levels supports the chance of crosstalk between the output of repeaters and the inputs of other repeaters. Where "frequency frogging" is used, i.e., high signal frequencies are translated to low frequencies, and low to high, at each repeater, this problem is avoided because the high-level and low-level signals are always in different frequency bands, thus providing a form of frequency staggering.

Still another type of far-end crosstalk is known as *reflected near-end crosstalk*.

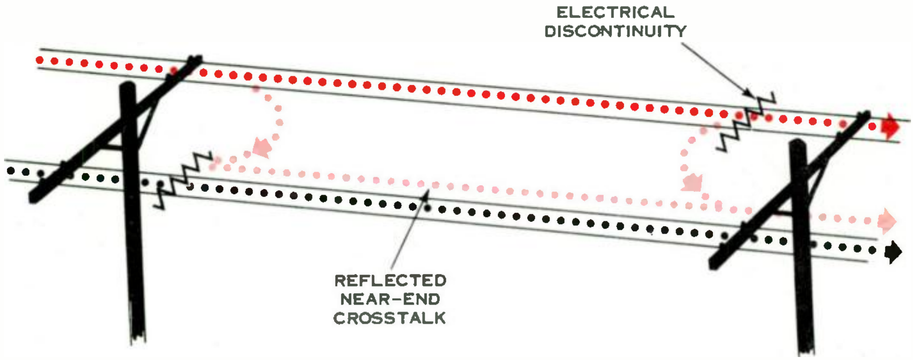

Figure 6. Two types of far-end crosstalk resulting from near-end coupling and reflection from an electrical discontinuity, such as an impedance mismatch.

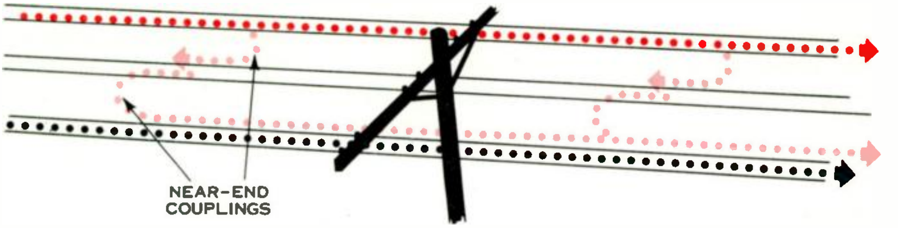

Figure 7. Simple interaction crosstalk, where no repeaters are involved. Far-end crosstalk results from near-end coupling to intermediate ("tertiary") circuit, then to disturbed circuit by similar near-end coupling. Two direction reversals are involved.

If the disturbed circuit has some sort of electrical discontinuity, such as an impedance mismatch, ordinary near-end crosstalk may be reflected toward the far end. This type of crosstalk may also occur if the far-end receiver does not match the impedance of the line. In this case, part of the received signal energy is reflected, then coupled back into the far end of the disturbed circuit by near-end coupling, as illustrated in Figure 6.

Interaction Crosstalk

Several important forms of far-end crosstalk are labeled *interaction crosstalk* because more than one coupling is involved. As shown in Figure 7, the disturbing signal appears in a third or "tertiary" circuit by *near-end* coupling, and is then transferred to the disturbed circuit by another near-end coupling. The crosstalk signal appears at the far end of the disturbed signal, but has reversed direction twice in so doing.

Runaround Crosstalk is a special case of interaction crosstalk, and refers to the signal from the output of a repeater "running around" to the input circuits of the same or other repeaters. As in the case above, the high-level output from the repeater appears in a tertiary circuit by near-end coupling. The tertiary circuit, which may not have a repeater, then couples the signal to the low-level *input* side of circuits with repeaters. This type of crosstalk usually requires more than one type of circuit (such as voice circuits and carrier circuits) in the same cable or open wire path. If all circuits have repeaters at the same location, there is no tertiary path by which the signals can "run around" from the output to the input. Where the required dissimi-

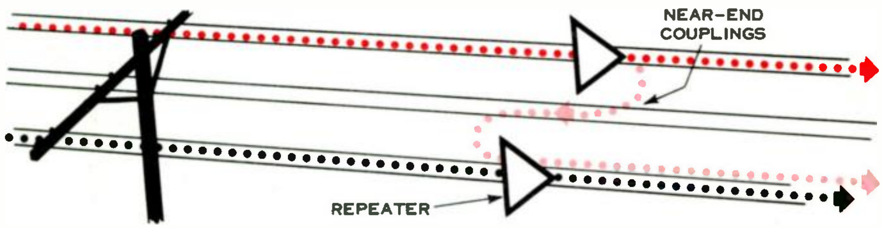

Figure 8. "Runaround" crosstalk is similar to interaction, but may be more troublesome because of couplings from high-level repeaters output to low-level input of same or other repeaters. Less gain per repeater, more repeaters reduce this type of crosstalk.

lar circuit exists, runaround crosstalk may be avoided by inserting a suitable "crosstalk suppression" filter so that the crosstalk frequency is blocked but the desired signal is passed with little loss.

Measuring Crosstalk

In designing a communications system, it is important that all known disturbing factors be taken into account so that they can be corrected or avoided. Crosstalk is one such factor, one that requires considerable effort to control. Like noise, special units of measurement are required for specifying crosstalk effects. Crosstalk, however, is more complicated than noise, since various types of crosstalk are more disturbing than others, and may result from more diverse causes. As a result, several units of measurement have been used to express crosstalk, its net effect, or the electrical coupling from which it results. All the units are related, since they refer to some aspect of how much the signal in one circuit will interfere with that in an adjacent circuit.

The *Crosstalk Unit* is the oldest unit used for expressing crosstalk coupling, and is abbreviated *cu*. It is one million times the ratio of the induced crosstalk voltage or current to the disturbing crosstalk voltage or current, where the impedances of the two circuits are equal. Where the impedance of the disturbing circuit differs from the impedance of the circuit in which the crosstalk appears, cu is one million times the square root of the ratio of crosstalk power to disturbing signal power, or

$$cu = 10^6 \cdot \sqrt{\frac{\textit{disturbing signal power}}{\textit{crosstalk signal power}}}.$$

Crosstalk units provide a direct measure of the coupling between two circuits. Larger *cu* values mean more crosstalk.

Another way of expressing coupling is as a "loss" between the disturbing and disturbed circuits. The term *coupling loss* refers to the fact that there is a *fixed attenuation* between any two circuits. Where the coupling (and crosstalk) is great, crosstalk coupling loss is low. Thus, if the coupling loss between two pairs is 50 db, a signal having a level of -5 dbm will appear in the other pair at a level of -55 dbm. If the disturbing signal is raised to +3 dbm, the crosstalk level will then be -47 dbm.

Db above Reference Coupling, or *dbx*, takes into account the different interfering effects of different frequencies. This term was invented to permit crosstalk measurements using a standard noise measuring set (such as described in the DEMODULATOR, *April*, 1960). The "reference coupling" is taken as a coupling loss of 90 db between the disturbing and disturbed circuits. Thus, if a 90 dba test-tone were inserted on the disturbing circuit, and the same noise weighting network were used in measuring the level in both circuits, the reference coupling would give an indication of 0 dba. Crosstalk coupling in dbx is equal to 90 minus the coupling loss in db. Figure 9 shows the relationship between coupling loss in db, coupling in dbx, and crosstalk units (cu).

Crosstalk Index

An attempt has been made to evaluate the crosstalk performance of a given transmission facility in terms of the actual disturbing effect of crosstalk. Since the disturbing effect of crosstalk is a function of intelligibility or syllabic pattern, many factors can reduce the actual disturbance that a listener experiences.

Ordinary noise in the system reduces the annoying effect of crosstalk. Even background noise at the listener's location can mask out crosstalk. Several car-

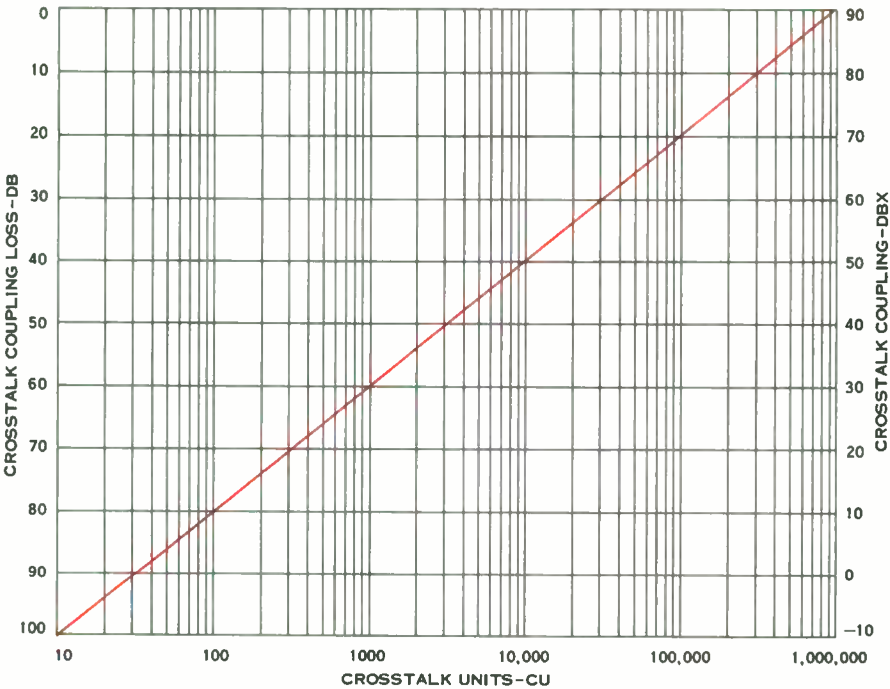

Figure 9. ***Relationship between crosstalk coupling loss in db, crosstalk units, and crosstalk coupling in dbx. Crosstalk units are little-used now, having given way to coupling loss and dbx coupling for measurements of circuit characteristics, and to crosstalk index for subjective performance rating.***

rier systems have been designed which take advantage of this masking effect by including noise generators for use if crosstalk is otherwise excessive. The larger the number of disturbing circuits which contribute to the crosstalk in a circuit, the less annoying the crosstalk tends to be. In this case, the disturbing signals become more and more random as the number of disturbers increases, so that the crosstalk becomes more and more like noise. Offsetting this, however, is the fact that the total power of the crosstalk increases with the number of disturbers. A final comparison of actual annoying effect would depend on the nature of the crosstalk, staggering advantage, and background noise. Because so many variables are involved, the principal value of a crosstalk index is to provide a single numerical value which indicates the overall crosstalk performance. One such index that is widely quoted uses the following scale of merit:

Index	*Quality of Performance*
.01	Excellent
.1	Very Good
1.0	Good
5.0	Fair
10.0	Poor
20.0	Very Poor

These values result from experimental studies which take into account the amount of time that crosstalk exceeds a reference level, and the opinions of observers as to how much annoyance the crosstalk provides under various traffic conditions.

Compandors

One of the most effective ways of coping with crosstalk is the *compandor,* a device which doesn't actually reduce crosstalk, but does reduce its apparent effect. The compandor takes advantage of the fact that crosstalk is not very noticeable during speech, but becomes objectionable during pauses or other silent periods.

The compandor consists of a speech compressor at the transmitting end of the circuit, and an expandor at the receiving end. The amplitude range of the transmitted signal is "compressed" so that soft speech sounds are amplified greatly, while louder sounds are amplified less. Very loud sounds may actually be reduced in level. By reducing the amplitude range of the signal, even the softest sounds are substantially stronger than the crosstalk and noise acquired during transmission, yet the louder sounds are restricted from overloading amplifiers, modulators, and repeaters.

At the receiving end, the amplitude-compressed signal is "expanded" to its original amplitude range. The softer sounds are reduced in level, and the louder sounds may be amplified. Noise and crosstalk are by far the weakest sounds present and receive the greatest attenuation. Compandors usually provide a 20-28 db advantage over noise and crosstalk.

Other devices may be used in a similar fashion to reduce receiver gain during periods when there is no speech. A level-sensitive "gate" raises receiver gain to the level necessary for clear reception whenever speech is present. Between speech sounds, gain is reduced enough that noise and crosstalk are less noticeable. Response time and detector characteristics have an important bearing on the effect produced.

Conclusion

Crosstalk has become more of a problem as the various transmission media have become more congested. The battle against crosstalk is becoming more difficult as more and more new communications services are required by an increasingly complex society. This problem is bound to become even greater in the future because of growing populations and the need for even more elaborate communications services. Improved designs, new techniques, and unrelenting research will be required to prevent crosstalk and other detriments from setting a limit on this growth. •

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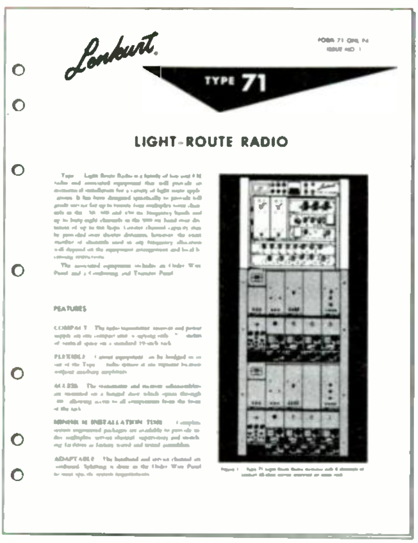

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