The Lenkurt® Demodulator

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FILTER FLANKING

What and Why?

Frequency-selective filters, the very heart of modern carrier systems, have certain characteristics which may seem surprising. Why should some filters, which are designed to provide as much isolation as possible between their respective channels, require the presence of each other for proper functioning? The answer lies in certain unavoidable side-effects of the way in which filters operate.

These characteristics have considerable practical importance. In some cases, the removal of, say, the channel 5 filter will degrade the performance of channels 4 and 6, and a channel group which is only partially equipped may function quite poorly. This article discusses this "filter flanking" effect, how it occurs, and some means for minimizing adverse effects.

Where bandwidth requirements are not stringent, carrier channels are often separated by relatively large guard bands and filters can be simple. In such cases there is little interaction between adjacent channel filters. But modern carrier systems are usually required to transmit the maximum number of channels in the narrowest possible bandwidth, with the result that guard bands are narrow and filters must have very sharp cut-off characteristics. In this situation adjacent filters affect each other even though their passbands do not overlap. The smaller the guard band between adjacent filters, the more important this interaction or "flanking" effect is in achieving the required attenuation. In effect, adjacent filters serve as additional elements of each other. As a consequence, high-performance channel banks may not achieve their proper performance if one or more channels are removed. These characteristics are a natural result of the way in which a filter must operate to provide the necessary attenuation.

A conventional electrical filter consists of a network of reactive elements such as capacitors, inductors and possibly transformers which, ideally, are loss-free. They are able to store energy (by virtue of their inductance and capacitance), but cannot dissipate it. Thus, all power delivered to the input of the network must eventually appear at the output. The reactance of capacitors and inductors varies with frequency as shown in Figure 1. This permits networks to be built which have high input reactance at some frequencies, but low input reactance at others. At frequencies where input impedance is essentially resistive, power is accepted and transferred to the output by the network, but is blocked at frequencies where input impedance is mainly reactive.

Figure 2 shows a reactance network operating between a generator, E, with internal resistance R_G and a resistive load, R_L. The reactance network is assumed to operate as an ideal filter — without internal losses. Within its passband, the filter presents to the generator an impedance which is essentially resistive and approximately equal in value to R_G. Thus, maximum power transfer can occur, and the filter absorbs virtually all the available power of the generator, transferring it to the load, R_L.

The out-of-band impedance of the filter, as seen by the generator, is almost a pure reactance. At frequencies outside the passband, the filter absorbs negligible power from the generator, and hence delivers virtually no power to the load. Therefore the presence of the load resistance, R_L, has essentially no influence on the input impedance. However, to say that no out-of-band power is transferred from the generator to the filter is not the same as saying that the filter has no input current at these frequencies; the input current flows, but since it is 90° out of phase with the input voltage, no power is absorbed (because the power factor is zero.)*

*See page 6 for a brief summary of power factor and "complex" notation.

Thus, the method of attenuation of a filter is not at all like that of a resistive pad. The pad accepts the signal and dissipates some (or possibly most) of the energy internally, whereas the filter refuses to accept the signal at all.

Filters in Parallel

Parallel filter operation can be illustrated by considering the simple case of two filters — one lowpass and one highpass, so designed that the passband of each coincides with the stopband of the

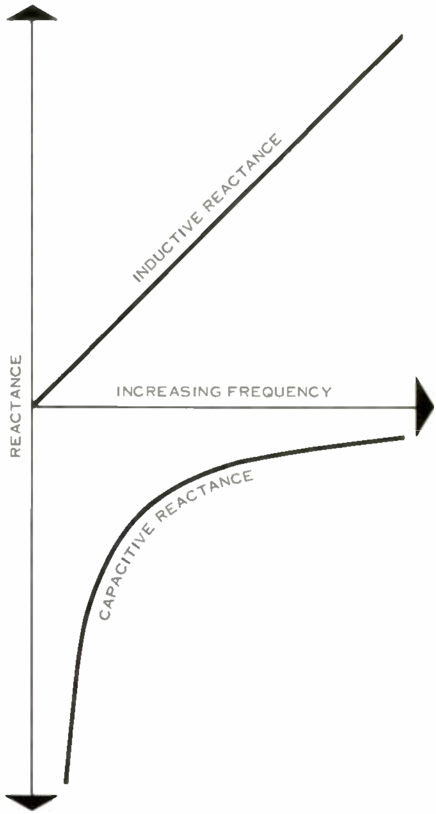


Figure 1. Higher frequencies cause inductive reactance to increase while capacitive reactance decreases. The two reactances are 180° out of phase.

other. When the inputs of two such filters are connected in parallel and driven by a common impedance-matched generator, it is possible, in principle, for each filter to absorb the maximum power available from the generator at frequencies lying within its own passband. It can do this because, at these frequencies, the other filter cannot accept any power. It is this ability to select power at certain frequencies that makes it possible for filters to be operated efficiently in parallel without "loading" the generator.

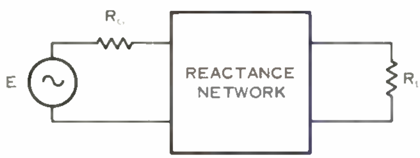


Figure 2. A filter is a network of reactive elements. For maximum power transfer, filter impedance within the passband should match the generator impedance (R_G).

The two filters, operating together, act as a frequency-selective power divider. Therefore, when the two filters are designed to operate in parallel, the input impedance at the common terminals should equal the generator impedance (R_G) over both passbands because maximum power transfer can occur only when the filter impedance matches the generator impedance. Accordingly, within its own passband each of the paralleled filters will also match the generator.

Since the net impedance of all filters as well as the individual impedance of each filter equals the generator impedance, it might seem possible to remove one or more filters without disturbing the impedance match between the signal source and the frequency-selective filters. Unfortunately, this is not so. Filter characteristics are affected by the overlapping electrical effects of adjacent filters, thus requiring careful design to balance one against the other.

Filter Admittance

In discussing the characteristics of filters to be connected in parallel, it is simpler to think in terms of *admittance* (Y), the reciprocal of impedance. Admittances connected in parallel add directly, while impedances do not. Like impedance, which is the sum of the two quantities, resistance and reactance, admittance is the sum of *conductance* (G), and *susceptance* (B). These two components of admittance are at right angles to each other, as indicated in mathematical expressions by the term j.

If the input admittance of the low-pass filter is assumed to be

$$Y_L = G_L + jB_L,$$

and that of the high-pass filter is assumed to be

$$Y_H = G_H + jB_H,$$

then the input admittance of the parallel combination is

$$Y = (G_L + G_H) + j(B_L + B_H).$$

Since, in effect, only the conductance portion of the admittance absorbs power, an *ideal* filter pair would have no net susceptance across the passbands, and the combined conductance of the pair would be equal to the reciprocal of the generator resistance, $1/R_G$. In other words, an ideal pair of filters would meet the mathematical conditions

$$G_L + G_H = 1/R_G$$

and

$$B_L + B_H = 0.$$

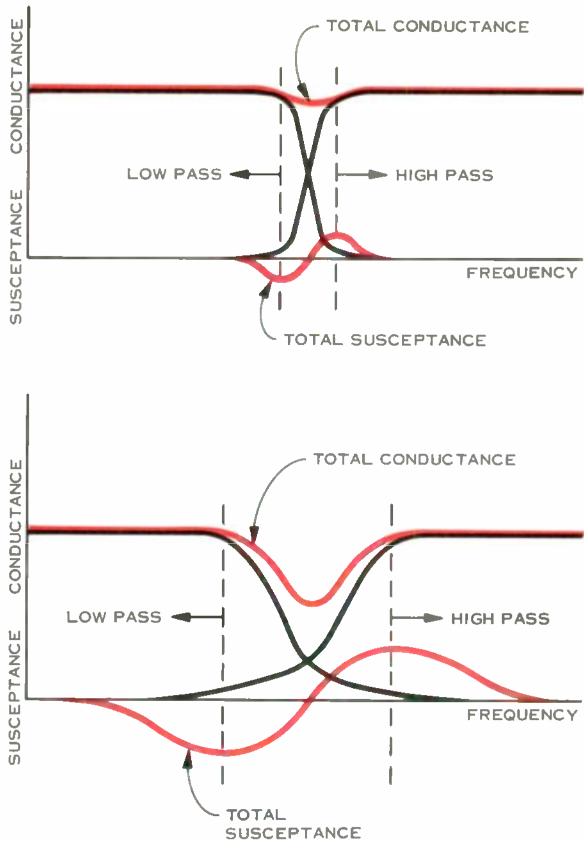


Figure 3. As the separation between filter passbands increases, the total susceptance deviates farther from zero and interferes more with passband performance.

For these conditions to be readily met, it is necessary for both filters to be designed for minimum susceptance. This does not mean that no susceptance can be present—but rather the susceptances of the two filters must have equal magnitudes and opposite signs at all frequencies within their passbands. Thus, the susceptances must always "cancel" each other. If they do not cancel, the input admittance will appear either capacitive or inductive and will cause the filters to reject part of the desired signal.

If the filters have minimum susceptance, it is only necessary to design them so that

$$G_L + G_H = 1/R_G$$

over the passbands. Then the condition

$$B_L + B_H = 0$$

will be closely approached when the gap between the passbands is small. As this gap becomes progressively larger, the total susceptance deviates farther from zero. (Figure 3 compares the effects of varying the gap between the passbands.) Eventually the error becomes intolerable and it is necessary to connect a network of reactive elements, producing essentially pure susceptance, across the input terminals to cancel the net susceptance of the filter combination. This *susceptance-annulling network* usually consists of one (or pos-

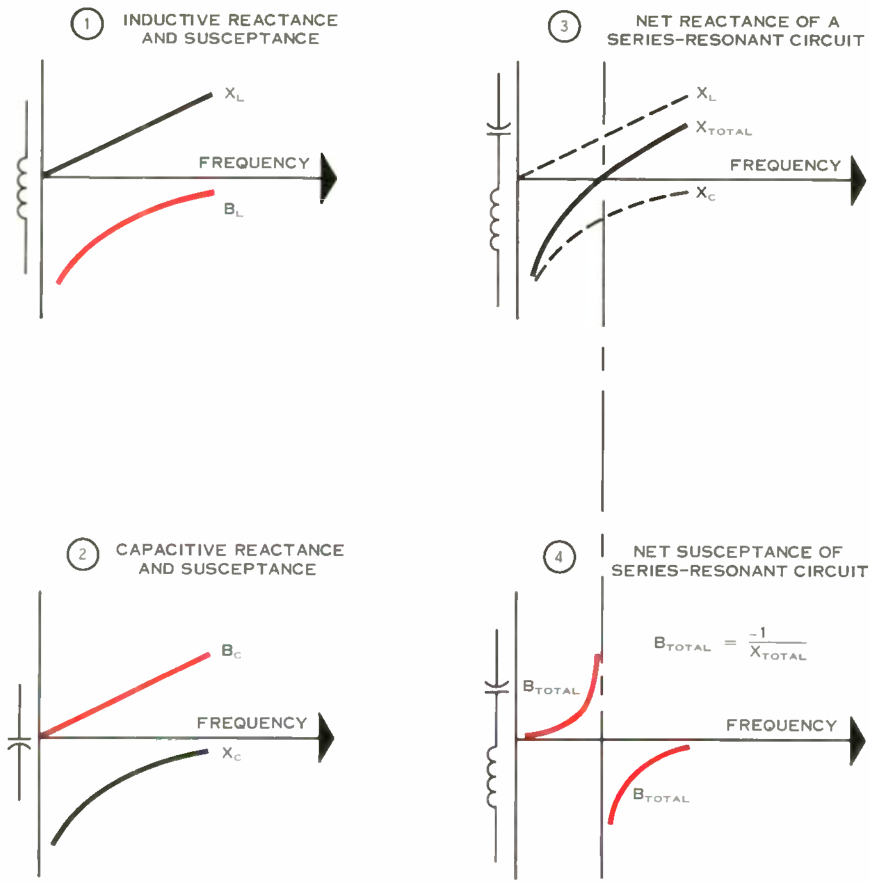


Figure 4. Relationship between reactance and susceptance of circuit elements as frequency varies.

sibly two) tuned circuits. Figure 5 shows the effect of the annulling network in cancelling the susceptance of the two filters.

Another network, essentially a third filter, can be used as a *conductance-correcting network* to maintain a constant value of conductance. Its use is not so widespread, however, because most of the conductance deviation occurs in the area of transition between lowpass and highpass, and the conductance here is not normally of interest — it is usually sufficient to maintain a constant value within the passbands, without concern for the transition region.

Thus, even in the simple case of two filters flanking each other, one depends on the other and often both depend on the annulling network for satisfactory operation. Filters designed for flanking do not usually provide satisfactory performance if they are not flanked; and a

(Continued on page 8)

For those not familiar with the "complex" numbers used to describe impedance and admittance, here is a brief explanation of the "real" and "imaginary" components of

Impedance and Admittance

Impedance is made up of two components, resistance and reactance. Although both are measured in terms of ohms, they are not the same quantity. Resistance is contributed by elements which *dissipate* electrical energy, passing it off as heat. Reactance, on the other hand, is contributed by elements which *store* energy (inductors and capacitors) without dissipation. It is the phase relationship between resistance and reactance of a circuit element which controls the phase angle between current and voltage — and hence controls the power transferred by a given current and voltage. The phase angle between the current through a resistor and the voltage across a resistor is zero. Thus, current and voltage are in phase, the *power factor* (the cosine of the angle between them) is unity, and the resistor dissipates power according to the relation

$$P = I^2R\ .$$

By contrast, current through an ideal inductor or capacitor is 90° out of phase with the applied voltage — current lags by 90° in the inductor and leads by 90° in the capacitor (assuming a sinusoidal steady-state condition). Thus, the power factor is zero ($\cos 90° = 0$) and no power is absorbed by the inductor or capacitor.

Since the phase or "directional" relationship between resistance and reactance controls power transfer, it becomes apparent that magnitude alone cannot completely specify these two quantities. They have both magnitude and direction. The direction is normally specified in terms of the phase angle between them. And since both resistance and reactance are required to define impedance, it too is a directional quantity. Impedance is the *vector sum* of resistance and reactance (shown graphically below). By convention, the resistance R is considered to have an angle of 0°. Hence, it is the reference and is called the *real* part of impedance. Reactance, with the symbol X, has an angle of $\pm 90°$ ($+90°$ for inductive reactance and $-90°$ for capacitive reactance) and is the imaginary part of impedance — although the concept of reactance is not fictitious. These are called *complex* quantities because of their composite nature.

Impedance, Z, is expressed mathematically as

$$Z = R + jX\ ,$$

where the "j" indicates the 90° phase difference between R and X. Impedance can also be expressed as

$$Z = \sqrt{R^2 + X^2}\,\angle\theta\ ,$$

where $\sqrt{R^2+X^2}$ is the magnitude and $\angle\theta$ indicates the direction.

The component parts of impedances *in series* add directly. For example, if

$$Z_1 = R_1 + jX_1$$

and

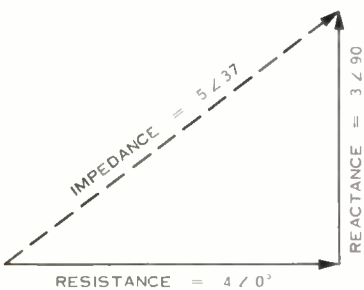
$$Z_2 = R_2 + jX_2 ,$$

then

$$Z \text{ total} = R_1 + R_2 + j\,(X_1 + X_2).$$

However, the same is not true of impedances *in parallel:* the *reciprocals* of the paralleled impedances must be added:

$$\frac{1}{Z \text{ total}} = \frac{1}{Z_1} + \frac{1}{Z_2}.$$



Resistance and reactance add at right angles to form impedance. Their relative magnitude determines the angle of the impedance.

The expression for total impedance then becomes less convenient:

$$Z \text{ total} = \frac{Z_1 Z_2}{Z_1 + Z_2}$$

$$= \frac{(R_1 + jX_1)\ (R_2 + jX_2)}{R_1 + R_2 + j(X_1 + X_2)}.$$

Because of the awkwardness of such expressions, it is often easier to speak in terms of *admittance*, (Y), the reciprocal of impedance. Admittances in parallel add directly just as do impedances in series. Like impedance, admittance is a complex quantity; that is, it has a "real" component and an "imaginary" component with a 90° angle between them. The real part is called *conductance*, (G), and the imaginary part is called *susceptance*, (B). Thus,

$$\text{Admittance (Y)} = \frac{1}{\text{impedance}} = \frac{1}{Z}$$

$$= \frac{1}{R + jX}$$

$$= \text{conductance} + j(\text{susceptance})$$

$$= G + jB .$$

In general, a large resistance implies a small conductance, and a positive reactance implies a negative susceptance. However, conductance is not the reciprocal of resistance, and susceptance is not the reciprocal of reactance because the definition of each is based on the complex quantities impedance and admittance.

For admittances in parallel, if

$$Y_1 = G_1 + jB_1$$

and

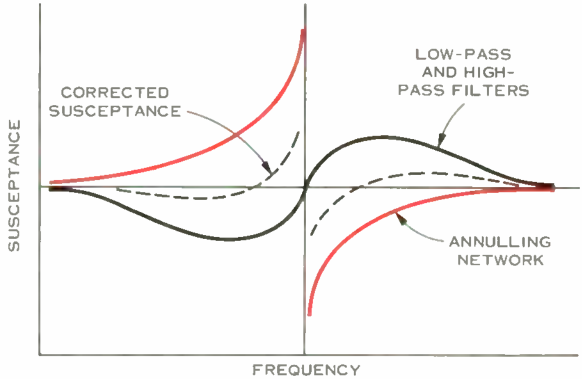
$$Y_2 = G_2 + jB_2 ,$$

then

$$Y \text{ total} = G_1 + G_2 + j(B_1 + B_2).$$

The admittance across the passband of an *ideal* filter would necessarily consist entirely of conductance. Any susceptance present would introduce a phase shift between current and voltage, thus lowering the power factor and reducing the power transferred. Since the filter is composed of less-than-ideal reactive elements, susceptance is inevitable. This can be countered, however, by cancelling each positive susceptance with a negative susceptance to produce a net result approximating zero. ●

Figure 5. Annulling network provides susceptance opposite to that of the filters, partially cancelling excess susceptance.



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filter designed for individual operation cannot be arbitrarily flanked without altering its characteristics.

Practical Filter Groups

This discussion has so far considered only the simplest case: a single low-pass and a single high-pass filter operating in parallel. Modern carrier systems, however, may use many bandpass filters in parallel, as indicated in Figure 6. Each base group shown consists of 12 filters, each with a nominal 4-kc passband, covering the frequency range of 60-108 kc. The actual voice-frequency input to each channel is 0.3-3.5 kc; thus, 4-kc channel spacing allows an 800-cps guard band between channels.

In the next modulation step, five 12-channel groups are combined to form a 60-channel supergroup occupying the 312-552-kc band. The bandpass filters used with these five groups are spaced 48 kc apart. This "stacking" of frequencies can be carried on almost indefinitely, but the principle remains the same. Within each level (group, supergroup, etc.) filter flanking occurs.

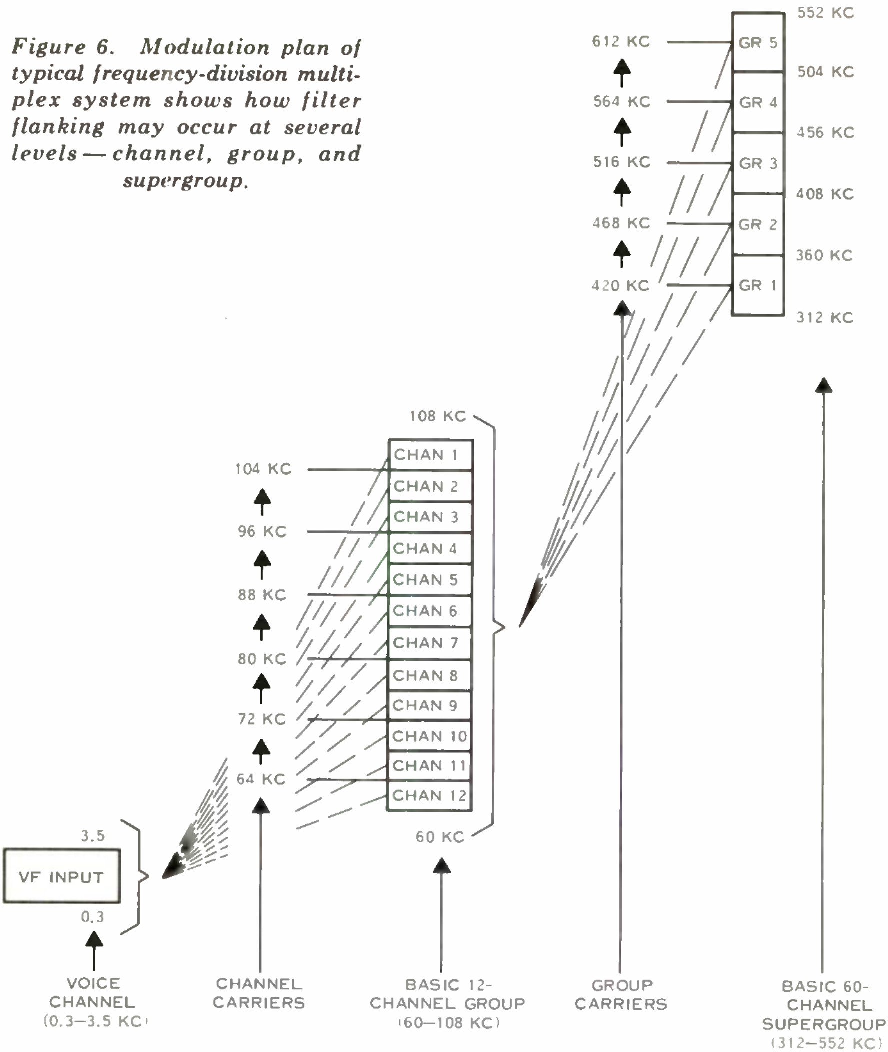
Each filter affects *all* the others to some extent, but the effect is most pronounced on the adjacent filters. For example, the arbitrary removal of the channel 3 filter would not have a serious effect on channels 1 and 5, and would affect channel 6 even less—but the characteristics of channels 2 and 4 would be severely altered. As shown in Figure 7, this would normally reduce the sharpness of the cutoff on the side toward the missing filter.

Since the effect of one filter on the adjacent one depends on the frequency separation between them, widely spaced filters can usually be flanked without fear of interaction. In practical carrier systems, this characteristic may make it desirable to split a group into two subgroups, composed of even-numbered and odd-numbered channels. In this arrangement, channels 1, 3, 5, 7, 9, and 11 operate directly in parallel and are connected through a hybrid to the parallel combination of channels 2, 4, 6, 8, 10, and 12. This technique is in common use because it minimizes the problems inherent in designing filters for flanked operation with close spacing. The filters can often be designed to operate singly, without considering their effects on each other.

Annulling Networks

The question naturally arises as to the flanking of the "end" filters, channels 1 and 12. These channels exhibit

Figure 6. Modulation plan of typical frequency-division multiplex system shows how filter flanking may occur at several levels — channel, group, and supergroup.



characteristics much like those of the unflanked channels 2 and 4 shown in Figure 7. Without adjacent filters, the sharpness of the cutoff on the unflanked sides suffers. To correct this, so-called annulling networks are built to simulate the filters that would be used for channels 0 and 13, if these channels existed. Essentially, these annulling networks provide equal and opposite susceptance to that of the unflanked filter. Sufficient susceptance cancellation can be achieved by using a series tuned circuit to simulate the missing filters. The physical location of these networks is of little consequence so long as they are *electrically* across the input terminals. For example, "filter 0" may be built into the physical container for filter 11—and still provide flanking for filter 1.

The same type of flanking and the same interrelationships occur at other levels in the modulation plan, but the principles involved are the same at the group and supergroup level as they are at the channel level.

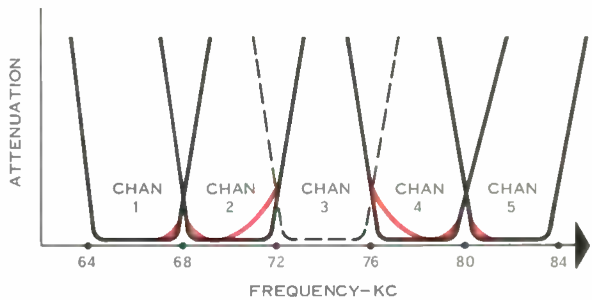
Operational Considerations

When flanking problems arise, it is almost always because a carrier system is operated below design capacity. The installation may be only partially equipped, or a filter may be temporarily removed from a channel bank. Unless the missing filters are simulated in some

inductor and a capacitor — but it is necessary in many cases for satisfactory system performance when only a few channels of a multi-channel system are installed.

Of course it may not be practical to design a network to simulate a single filter which is temporarily removed from the middle of a filter bank. In such a case, adjacent channel performance may be maintained by plugging in a non-operational channel to obtain the flanking effect of its filter.

Figure 7. Removal of channel 3 filter degrades response of all other channels. Most noticeably affected are the near "corners" of the adjacent channels.



way, the result may be degraded performance — at least in the channels immediately adjacent to the gaps left by the missing filters.

This is not to say that multiplex systems must not be operated partially equipped. The manufacturer may specify the minimum number of channels of a specific system which should be installed without using some type of compensating network to take the place of the missing filters. For example, the manufacturer of a 12-channel system might recommend that a partially equipped installation include no fewer than 6 channels (unless a compensating network is used). Such a network is not usually complicated or expensive — a typical one would consist merely of an

It appears that filter flanking and its effects will continue to concern both designers and operators for some time to come. In fact, flanking effects become more important when more complex filters are developed. Various other arrangements such as the use of active elements (amplification) or resistive networks to improve isolation are becoming more common. So-called active filters and phase equalizers achieve much better performance than the conventional passive networks, and this trend may profoundly affect future equipment designs. However, an awareness of the interaction between flanked filters goes far toward forestalling the problems which may arise in operating systems using this technique. •

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N2-Compatible Carrier Described

The Panhandle LN2, a new cable carrier system which interconnects end-to-end with Western Electric N2, has recently been announced by Lenkurt. End-to-end compatibility has been proven in a thorough series of field tests with N2 equipment. System features and performance of the LN2 are described in a new publication, Form LN2-600-P4, available on request from

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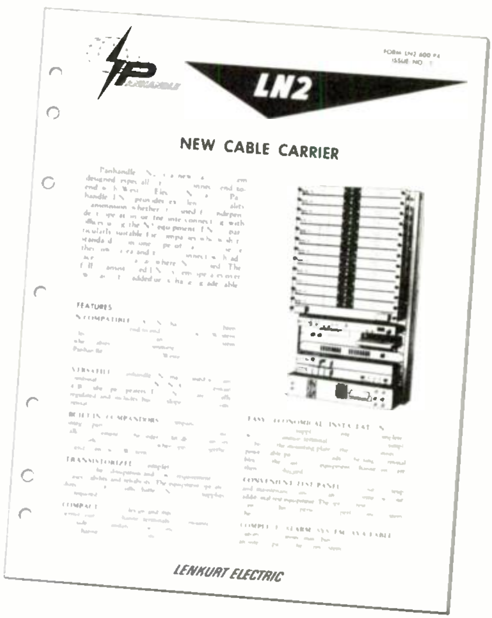

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