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A New Method for Frequency-Division Multiplexing, and Its Integration with Time-Division Switching*

A new method to achieve frequency-division multiplexing has been determined. The basis of this method is a new heterodyning scheme, which operates in conjunction with a generalized concept of resonant transfer. Besides achieving frequency-division multiplexing, these concepts, in combination with time-division switching, are the basis for a system that seems to be more economical than conventional combinations of these capabilities. Such a combination is required to effect time-division switching into and out of frequency-divided trunk lines. The basic reason that this integrated system offers the potential of such economy is that the time-division switches are made to serve two purposes. In addition to performing their normal switching function, they also serve a purpose in the frequency multiplexing and demultiplexing operations. Laboratory analysis and development have thus far validated the feasibility of these concepts.

To understand the frequency multiplexing and switching operations, first examine the new modulation-demodulation process, which is basic to the system operation (see Fig. 1). Suppose a continuous function of time with an associated spectrum in the low frequency region, such as a voice signal, is applied to the input of Fig. 1. This signal is fed to the lowpass filter for the purpose of band limiting before sampling by the linear sampling gate 1. Assuming a sampling rate of f_s, this filter must not pass components greater than $f_s/2$ to prevent distorting the input spectrum due to the folding phenomena. After bipolar sampling by gate 1, the spectrum associated with the resulting pulse train will consist of a baseband and upper and lower sidebands of the input signal placed about points on the frequency axis of $0, f_s, 2f_s, 3f_s, \cdots$. It can be shown that if the sampling pulse width, τ, is much less than the pulse repetition period, T, there will be many sidebands with an amplitude approximately that of the baseband. For the application to be discussed here τ will be much less than T, since this fact makes it possible to accommodate a large number of channels in a multichannel system comprised of a number of channels like the one illustrated in Fig. 1. This will become evident later when these applications are mentioned. Thus, there will be many such sidebands, and, further, the amplitudes of the baseband signal and these sidebands will be quite small, since these amplitudes depend on the duty factor, τ/T. For example, assuming a voice-band type signal with a frequency range from zero to 4 kc/sec and a sampling rate, f_s, of 8 kc/sec a realistic value for this duty factor could be of the order of 1/125. Thus, in this case the loss represented by this sampling procedure is considerable, i.e., 20 log 125 $\approx$ 42 dB.

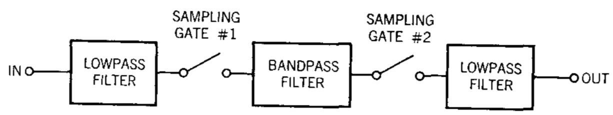

Figure 1 Scheme for new modulation-demodulation process.

When the train of pulses is applied to the bandpass filter, which is set to be coextensive with one of the sideband regions in the frequency domain, the continuous function associated with that sideband will be recovered, but, as indicated above, at a greatly reduced amplitude level as compared to the input baseband signal. This signal is then sampled by the linear sampling gate 2 at the same rate as the band limited input function was originally sampled by gate 1. Note that the sampling rate

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for this second gate is in accord with the bandwidth of the signal spectrum. It is independent of the particular upper or lower sideband region chosen by the filter. The resulting pulse stream will have a spectrum of baseband and upper and lower sidebands distributed just like the original sampled signal after the first gate. The amplitudes of these various components will be further reduced by a factor approximating τ/T because of the second sampling stage. This pulse stream is finally applied to the output lowpass filter which will recover the original function at the output point.

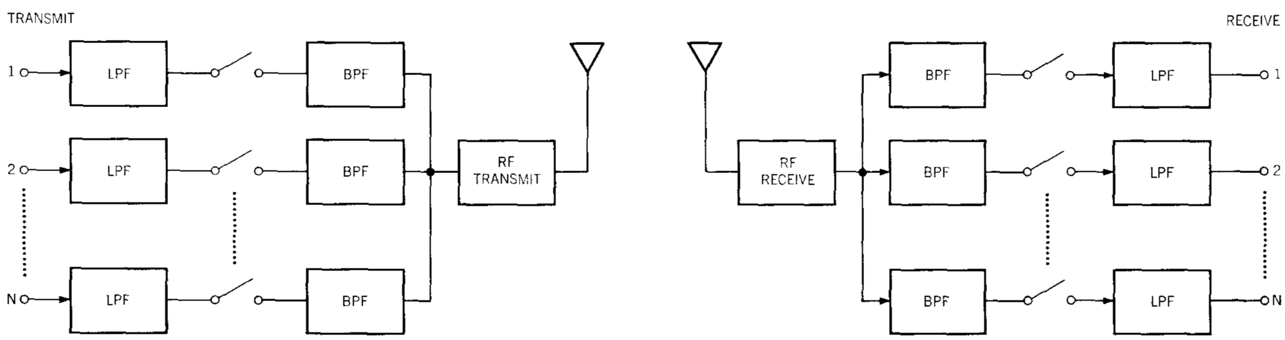
Two primary problems are connected with this process. The first of these is the large amplitude loss incurred, and the second is that a constant phase shift occurs unless certain precautions are taken with respect to synchronizing the input and output sampling stages. Interestingly, transmission through such a circuit can be accomplished without loss, under ideal circumstances, by utilizing a generalization of the technique commonly referred to as "resonant transfer." Conventionally this technique is applied only to transmission between lowpass filters via a gate. The topic of resonant transfer as applied to this lowpass-to-lowpass case has received extensive coverage in the literature during the last 10 years.[1-9] For the situation at hand, the transmission is between a lowpass filter and a bandpass filter. Resonant transfer is applicable, in general, to transmission between bandpass filters via a gate; the cases of Fig. 1 and the conventional lowpass to lowpass transmission are just special cases of this more general concept. By designing the filters to incorporate resonant transfer in this generalized sense, losses of less than 2 dB have been attained. Resonant transfer has the effect of concentrating all of the energy of the sampled pulse stream, that is spread out from zero to infinity along the frequency axis, into the region of the bandpass, or baseband, filter accepting the pulses. Thus, the application of this technique overcomes the problem of the amplitude loss inherent in sampling. In general, it may be said that this system is ideally lossless from the standpoint of power by virtue of the application of this generalized concept of resonant transfer, and, further, it is ideally lossless from the standpoint of information by virtue of the new modulation-demodulation scheme used.

Lack of synchronism between the input and output sampling gates in Fig. 1 produces "phase intercept distortion." This would have very little detrimental effect on voice transmission through the circuit since the ear is relatively insensitive to this type of distortion. However, it could not be tolerated for data. In some applications, the distortion could be eliminated by operating the input and output sampling gates in phase synchronization, while in others it would be necessary to use data modems that are designed to be insensitive to this type of distortion.

The procedure illustrated in Fig. 1 has the effect of heterodyning the baseband spectrum to a position along the frequency axis, as determined by the position of the bandpass filter, and then back again. This is exactly the kind of process required to effect frequency-division multiplexing, in which case a number of parallel channels must each have its spectrum heterodyned to an appropriate position along the frequency axis for transmission and then shifted back down for recovery purposes. Figure 2 illustrates a system configuration that could be used to effect a frequency-division multiplexing system. Note that gates replace the conventional combinations of balanced modulators and carriers that are normally used to achieve such a system. For this reason, it would seem that the configuration of Fig. 2 would have the potential of being simpler than the conventional configuration.

An application for which it is more apparent that significant savings could be gained is that of time-division switching centers operating in conjunction with input and output multiplex-demultiplex equipment. Figure 3 shows a typical conventional arrangement for such a distribution

Figure 2 New frequency-division multiplexing system.



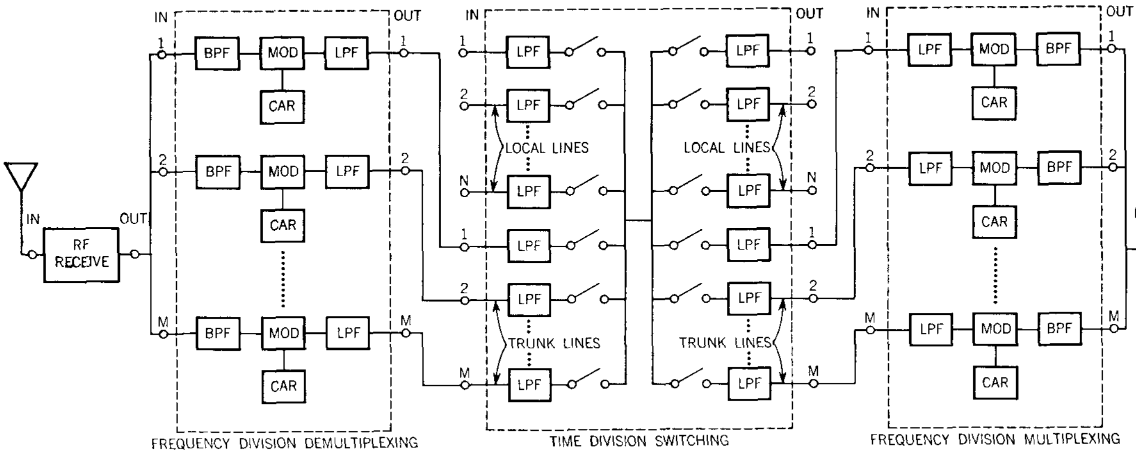


Figure 3 Conventional frequency-division multiplexing, time-division switching system.

and frequency multiplexing center. The basic functions that must be performed are:

(a) Multiplex the individual channels into an outgoing wideband frequency-divided signal.

(b) Demultiplex incoming wideband frequency-divided signal into individual channels.

(c) Effect the following connections:
1. An incoming local line to an outgoing local line.
2. An incoming local line to an outgoing trunk.
3. An incoming trunk to an outgoing local line.
4. An incoming trunk to an outgoing trunk.

A variation of the arrangement of Fig. 1 results in integrating the switching and multiplexing into one common operation. This is shown in Fig. 4. Note that this has the effect of completely eliminating the input and output multiplex-demultiplex equipment, at the expense of only slightly changing the time-division switching facility. The only basic change in this facility is that the trunks employ bandpass instead of lowpass filters. 4 kc/sec bandpass filters in the range of the basic trunk group, 60 to 104 kc/sec, incorporating generalized resonant transfer have been successfully designed.

The conclusions to be drawn are that the successful application of these methods could result in a completely different method of achieving frequency-division multiplexing, and when combined with time-division switching could result in a major improvement in automatic electronic switching exchanges and the associated multiplexing equipment. Currently, two experimental laboratory models involving twelve local lines and twelve trunk channels, comprising a standard group, are being developed.

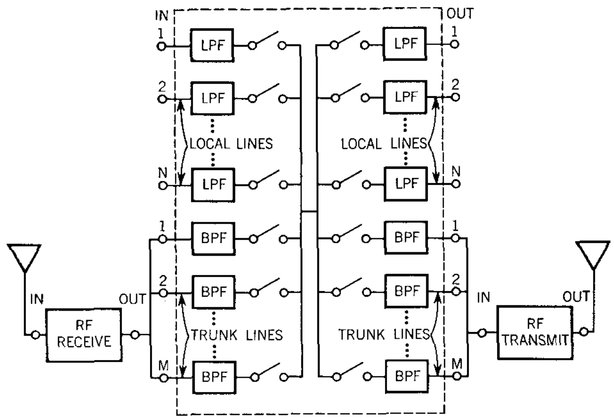


Figure 4 New frequency-division multiplexing, time-division switching system.

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