

Sept. 3, 1940.

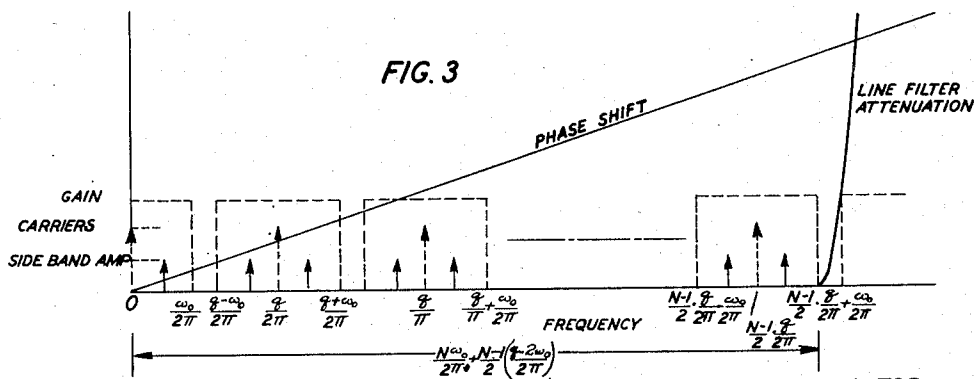
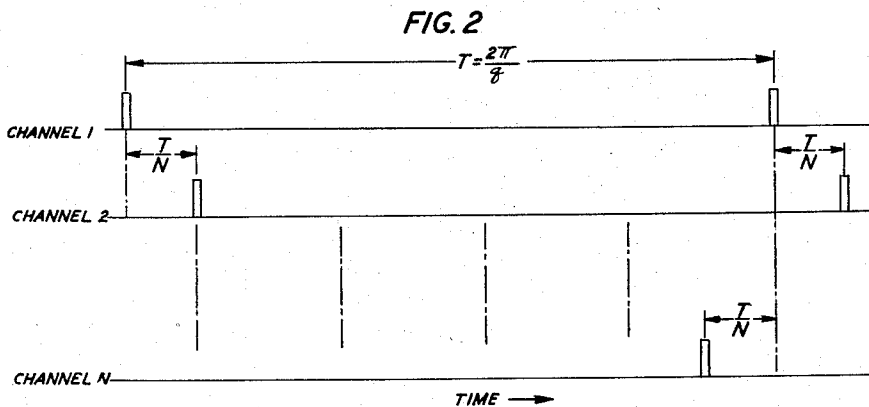
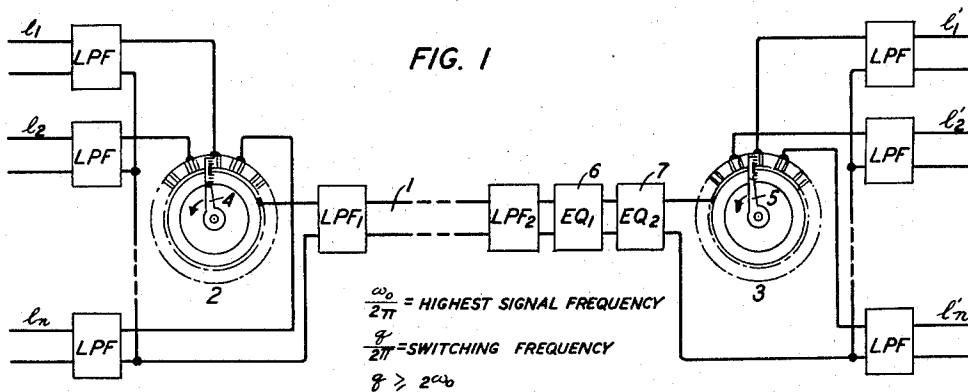
W. R. BENNETT

2,213,938

MULTIPLEX SIGNALING WITH PHASE DISCRIMINATION

Filed July 26, 1938

2 Sheets-Sheet 1



INVENTOR
 W. R. BENNETT
 BY *H. A. Burgess*

ATTORNEY

Sept. 3, 1940.

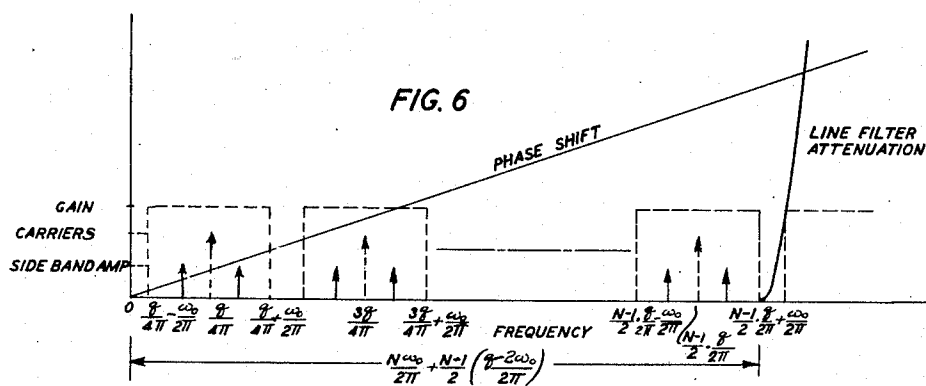
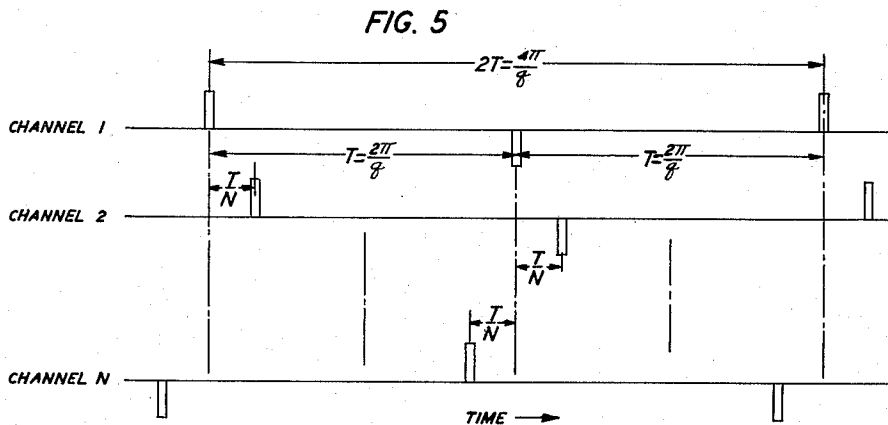
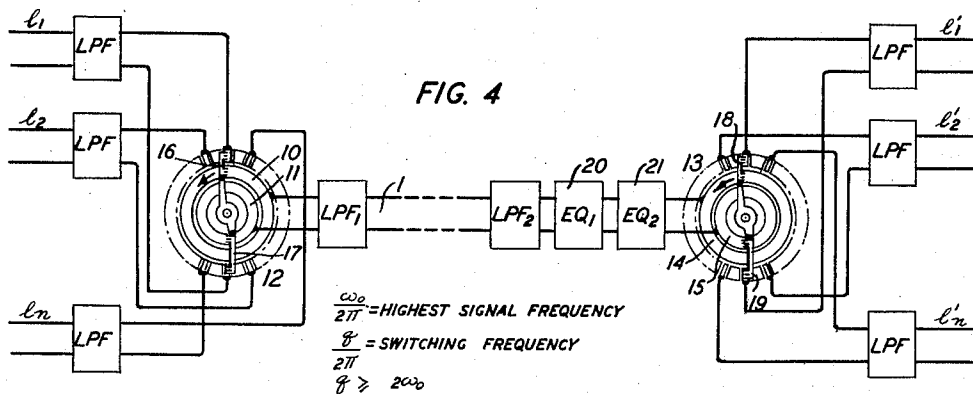
W. R. BENNETT

2,213,938

MULTIPLEX SIGNALING WITH PHASE DISCRIMINATION

Filed July 26, 1938

2 Sheets-Sheet 2



INVENTOR
W. R. BENNETT
 BY *H. A. Burgess*
 ATTORNEY

UNITED STATES PATENT OFFICE

2,213,938

MULTIPLEX SIGNALING WITH PHASE
DISCRIMINATION

William R. Bennett, Maplewood, N. J., assignor to
Bell Telephone Laboratories, Incorporated, New
York, N. Y., a corporation of New York

Application July 26, 1938, Serial No. 221,298

1 Claim. (Cl. 179—15)

The present invention relates to multiplex transmission and reception of signals such as speech, television or other type, on a time division or phase relation basis.

The general object of the invention is to obtain satisfactory quality and sufficiently low level of cross-talk without the necessity of transmitting a wider band of frequencies than is required in other types of multiplex transmission.

While multiplex transmission by time division has been suggested numerous times in the past, an outstanding difficulty has been that a band of excessive width has appeared necessary in order to permit proper separation of the signals at the receiver. The appeal presented in the idea of time division multiplex has been simplicity of terminal apparatus, notably omission of the relatively expensive filters of the ordinary multiplex system. Ideally it was considered that the line or other medium could be apportioned exclusively to each signal in succession for a brief interval of time by synchronously operating switches at the two ends of the system. Prior workers in the art have suggested various types of switching mechanisms for doing this, and it has been realized that the sampling rate should be high compared to the highest signal frequency to be sent. The idea as thus simply envisaged presupposed the transmission of minute fragments of the signals one at a time over the line and their complete separation on a time basis. The Fourier analysis shows, however, that such a concept entails the use of a practically infinite band of frequencies, for only by the use of such a band could there be present at the receiver all of those frequency components that are known to be essential in order for the supposed signal fragment to exist within the allotted reception interval and to be non-existent at all other times. Restriction of the band width means that the received signal fragment will build up slowly and tail off gradually so that it overlaps the time periods supposed to be exclusively allotted to other signals. This results in lack of complete separation or "cross-talk". It should be observed that this is not due to lack of linear phase shift in the line, but is a matter of insufficient band width to satisfy the basic assumption of exclusive use of the line by each signal for a brief interval of time.

The present invention is based on a different concept from having the line exclusively devoted to individual signals in individual times. According to this concept, components of all signals may be present on the line at times other than particular intervals and can in fact be present at all

times. In any one switching interval, however, all signal components except those contributing to the reception of one signal add vectorially to zero in the ideal case because of the phase and amplitude relations produced by the particular frequency-time function or switching function used for sampling at both the transmitter and receiver.

The signal from each channel appears on the line as N side-bands of the various harmonics of the switching function. The receiving process in a channel consists of recovery of the desired signal from these side-bands and rejection from the channel of the signals from the other channels. It may be thought of as a demodulation with harmonic carriers having a specified phase relation such that the components detected from the various side-bands add in phase for the desired signal and form a closed polygon giving zero resultant for the signal from any other channel. Since actually the line will deviate a certain amount from the prescribed attenuation and phase curves, the recovered component from any one side-band in any one channel is the resultant sum of the vector which would be attained if the requirement as to attenuation and phase were met and a small component resulting from this difference between the actual and prescribed characteristics.

The nature and objects of the invention will be more fully understood from the following detailed description taken in connection with the drawings, in which:

Fig. 1 is a simplified diagram of a multiplex system suitable for an odd number of channels in accordance with the invention;

Fig. 4 is a similar diagram of a system suitable for an even number of channels according to the invention; and

Figs. 2, 3, 5 and 6 are diagrams illustrating time and frequency relations to be referred to in the description of the respective systems.

Referring to Fig. 1, the main line l is connected at each end to the rotating arms of the distributors 2 and 3, the segments of which are connected to individual lines such as telephone lines $l_1, l_2 \dots l_N$ at the transmitter and $l'_1, l'_2 \dots l'_N$ at the receiver. Each terminal line includes a low-pass filter LPF as shown to limit the band of signal waves to some definite upper frequency $\omega_0 2\pi$ such as 3,000 cycles per second, for example. It is assumed that the distributors are maintained in synchronism and phase by any suitable method. By way of example the distributors may be of the electronic type disclosed in U. S. patent

application Serial No. 192,471 of P. Mertz filed February 25, 1938 and synchronized in the manner there disclosed. For simplicity they are shown, however, as of mechanical type. The line includes a low-pass filter LPF_1 , and if desired, a second and similar filter LPF_2 for limiting the utilized total band to substantially the product of the number of channels by the band width of one channel. Equalizers 6 and 7 equalize the line to flat attenuation and linear phase shift throughout the used band.

The speed of rotation of the rotating arms 4, 5 is taken as $q/2\pi$ cycles per second so that the period of one revolution is $T=2\pi/q$. For N channels the arm passes over successive contacts at the rate of T/N . The rotation speed is such that the highest frequency signal component is sampled at least twice per cycle or $q \geq 2\omega_0$.

It is assumed in Fig. 1 that the number of channels, N , is odd. The switching plan is then as shown in Fig. 2 where, however, no attempt is made to indicate the exact duration of the contact between the rotating arm and distributor segment. As indicated, however, the contact time is short in comparison to the time allotted to a channel.

The switching function for ideally zero cross-talk assuming uniform transmission over the utilized band is (for the j th channel)

$$\phi_j(t) = a \left(1 + 2 \sum_{n=1}^h \cos \left[nqt - (j-1) \frac{2\pi n}{N} + \theta_n \right] \right)$$

where h is the highest harmonic used, the higher ones being suppressed by the line filter. θ_n is an arbitrary component of the phase angle of the n th harmonic, which may have any value for a given harmonic provided that it does not change for the different values of j . a is a constant which determines the amplitude of the output wave.

As a result of using this type of switching function groups of side-band frequencies are produced as indicated in Fig. 3 based upon carrier frequencies harmonically related. The lowermost side-band is at speech frequency and may extend from zero frequency to $\omega_0/2\pi$ cycles. This may be viewed as having zero frequency carrier. This figure indicates the preferred phase shift characteristic (linear) throughout the used band, and the cut-off of the line filters LPF_1 and LPF_2 . These filters are preferably designed to introduce large attenuation to the lower side-band of the first harmonic above the used band and to all higher frequencies without cutting down the highest utilized side-band.

It is seen that for an odd number of channels the appropriate switching function is composed of

$$\frac{(N-1)}{2}$$

harmonics of equal amplitude and a direct current term of one-half the typical harmonic amplitude.

The band width

$$\frac{q-2\omega_0}{2\pi}$$

appearing between side-bands of adjacent channels represents wasted frequency band and should be made small if frequency range is to be conserved. If, however, the band width used is of less importance than other requirements, it may be desirable to allow a considerable value for this interval since it allows a region in which attenuation and phase are immaterial and thus simplifies the equalization problem.

The switching arrangement appropriate for an even number of channels differs from that of an odd number in that the direction of current flow must be reversed at alternate contacts between a given signal circuit and the multiplex path. For an even number of channels the proper switching function has

$$\frac{N}{2}$$

odd harmonics of half the switching frequency.

Fig. 4 shows an arrangement generally similar to that of Fig. 1 but adapted for an even number of channels. As before, the main line 1 terminates at opposite ends in slip rings 10, 11 and 14, 15 of distributors 12 and 13, the segments of the distributors being connected to the low frequency signal lines at respective stations. In this case, however, two rotating arms, 16, 17 or 18, 19 are used on each distributor, one effectively connected to each side of the main line via the slip rings. This arrangement gives a reversal of the line connection at each half cycle.

The switching plan for the case of N even channels (Fig. 4) is indicated in Fig. 5. The reversal at each half revolution results in zero direct current. The lowest harmonic indicated (see Fig. 6) is $q/4\pi$ cycles per second. The other harmonics are odd multiples of $q/4\pi$. As in the previous case, each of the harmonics is accompanied by upper and lower side-bands of all of the messages. The line is equalized if necessary to flat attenuation and linear phase shift by the equalizers 20, 21 shown in Fig. 4. The low-pass filters in the main line are preferably designed to have sharp cut-off as explained in connection with Fig. 3.

The switching function for an even number of channels is given by

$$\phi_j(t) = 2a \sum_{n=1}^h \cos \left[(2n-1) \frac{qt}{2} - \frac{(j-1)\pi}{N} (2n-1) + \theta_n \right]$$

This wave contains odd harmonics of $q/2$ (radians per second) instead of even and odd harmonics of q . The necessary value of h is then found to be $N/2$ where h is the highest harmonic used.

It is not necessary to use the first $N/2$ harmonics since certain other successions of $N/2$ harmonics will serve. The lowest harmonic selected may be of the form $rN+1$, where r is zero or an integer. In case the first $N/2$ harmonics do not have equal amplitude whereas some other succession of $N/2$ harmonics do, or in case it is desired for some other reason to use the band of frequencies embraced by a particular succession of harmonics, the more preferable range may be used. The low-pass filters LPF_1 and LPF_2 would then be replaced by band-pass filters to suppress all of the side-bands except those based on the desired $N/2$ harmonics. On account of the difficulty of providing requisite sharpness of cut-off in such a filter, advantage may be taken of the principle of design disclosed in Nyquist patent 1,748,186 dated February 25, 1930, according to which the cut-off is made gradual and at such a rate that the resulting distortion of the wanted frequencies near the edge of the band is compensated by frequencies lying on the other side of the desired limiting frequency of the selected band.

Whatever switching mechanism is used, the character of the sampling impulse should be such as to produce the requisite number of harmonics of equal amplitude. The switching plans dia-

grammed in Figs. 2 and 5 indicate that the impulse is preceded and followed by an idle period. In other words, the period of actual contact with a particular channel segment is short compared to the time allotted to that channel. This may not be a necessary condition since the only requisite is the production of the necessary number of harmonics of sufficiently nearly equal amplitude. The use of short impulses is one way of meeting the requirement, however.

The relation between length of impulse and amplitude of harmonics is indicated by the following. If the ratio of the length of the impulse to the time allotted to the switching of one channel is

$$\frac{N}{2m}$$

the m th harmonic is 4 decibels less in amplitude than the fundamental or switching frequency wave. If the ratio is

$$\frac{N}{4m}$$

the m th harmonic is .9 decibel down and if the ratio is

$$\frac{N}{8m}$$

the m th harmonic is .2 decibel down from the fundamental. In a twelve-channel system, for example, six harmonics are required. If the impulse is equal to the duration of the switching time allowed one channel,

$$1 = \frac{12}{2m}$$

and the sixth harmonic is 4 decibels smaller in amplitude than the fundamental. If the impulse is only half as long,

$$\frac{1}{2} = \frac{12}{4m}$$

and the sixth harmonic is now .9 decibel down from fundamental. By using an impulse only one-fourth the channel switching time,

$$\frac{12}{8m} = \frac{1}{4}$$

and the sixth harmonic is only .2 decibel less in amplitude than the fundamental.

The manner in which the signals are separated may be illustrated by a simple example. In a four-channel system there would be two carrier frequencies, for example p and $3p$, and four side-bands based on these carriers. Due to the fact that each carrier is modulated in successive phase by the different signals, however, the carrier of frequency p will appear on the line at any instant as modulated in zero phase by the first signal, as modulated after a phase shift of 45 degrees by the second signal, as modulated

after a phase shift of 90 degrees by the third signal and as modulated after a phase shift of 135 degrees by the fourth signal. Similarly, the carrier of frequency $3p$ will be modulated by the same four signals in successive phases of 0, 135 degrees, 270 degrees and 405 degrees. When these waves are received, with the receiving switching mechanism in a phase position corresponding to the zero phase of the transmitter, it will be noted that the side-bands representing the first signal are in effect demodulated to yield maximum signal. At this instant the side-bands representing the second signal are demodulated to yield four signal frequency components of phases, +45 degrees, -45 degrees, +135 degrees and -135 degrees, which give a resultant of zero. In similar fashion the third and fourth signals are reduced to zero also. In the case of the first or wanted signal the four vectors representing recovered signal add arithmetically.

The invention is not to be construed as limited to the means actually disclosed herein since it is applicable to radio as well as line transmission and to any type of signals, and may be otherwise varied within the scope of the appended claim.

What is claimed is:

A multiplex signaling system comprising at each of two communicating stations a plurality of separate signal circuits, a multiplex transmission path terminating at said stations, means at each station operating cyclically in synchronism with each other for establishing in rapid succession signal transmitting relationship between each of said signal circuits at such station and said transmission path, said means operating at such rate that the frequency of establishment of transmitting relationship between any one signal circuit and said path is at least as high as twice the highest frequency of the signal, such means including means operating to restrict the duration of establishment of any single such transmitting relationship to a small fraction of the interval existing between the establishment of one such relationship for one signal circuit and the establishment of the next following such relationship for the next signal circuit at the same station, whereby the waves transmitted over said path comprise signal side-bands based upon frequencies which are harmonics of the said frequency of establishment of said transmitting relationships, and means to restrict the frequency band transmitted over said path to substantially the product of the number of said signal circuits at each station by the width of one side-band, the value of said fraction bearing a predetermined relation to the value of cross-talk factor between the separate signals so transmitted.

WILLIAM R. BENNETT.