Nov. 24, 1964 J. L. FLANAGAN 3,158,693

SPEECH INTERPOLATION COMMUNICATION SYSTEM

Filed Aug. 7, 1962 5 Sheets-Sheet 1

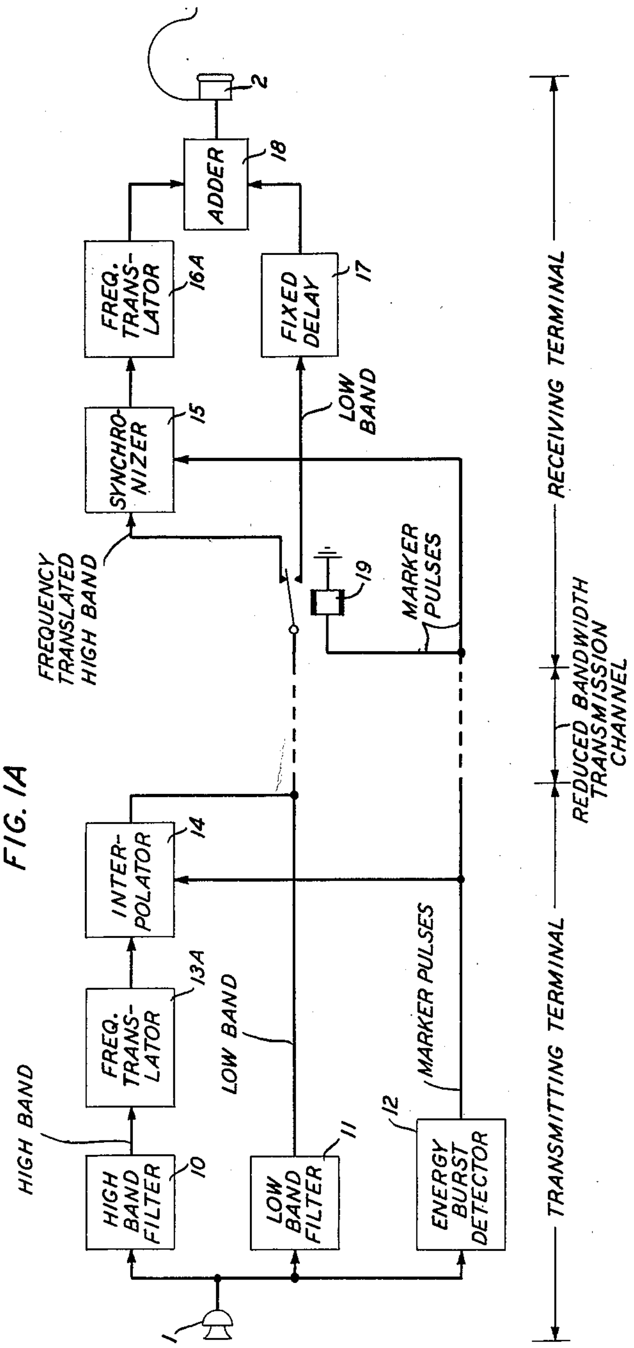

FIG. 1A

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SPEECH INTERPOLATION COMMUNICATION SYSTEM

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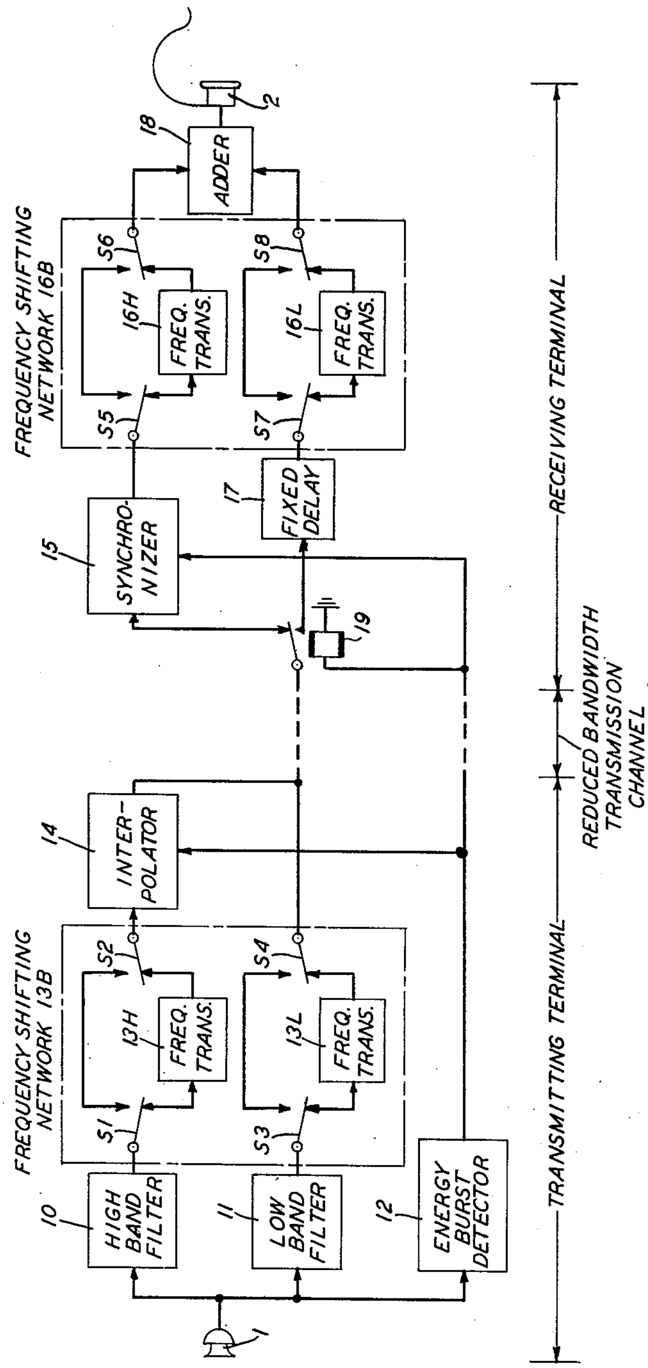
FIG. 1B



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SPEECH INTERPOLATION COMMUNICATION SYSTEM

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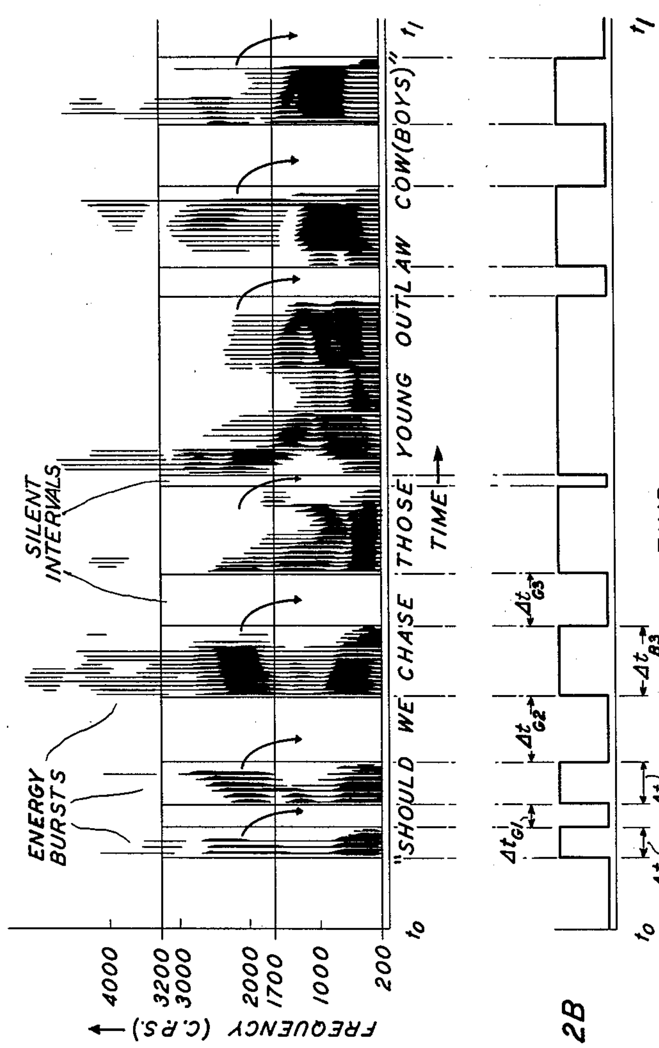

FIG. 2A

FIG. 2B

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SPEECH INTERPOLATION COMMUNICATION SYSTEM

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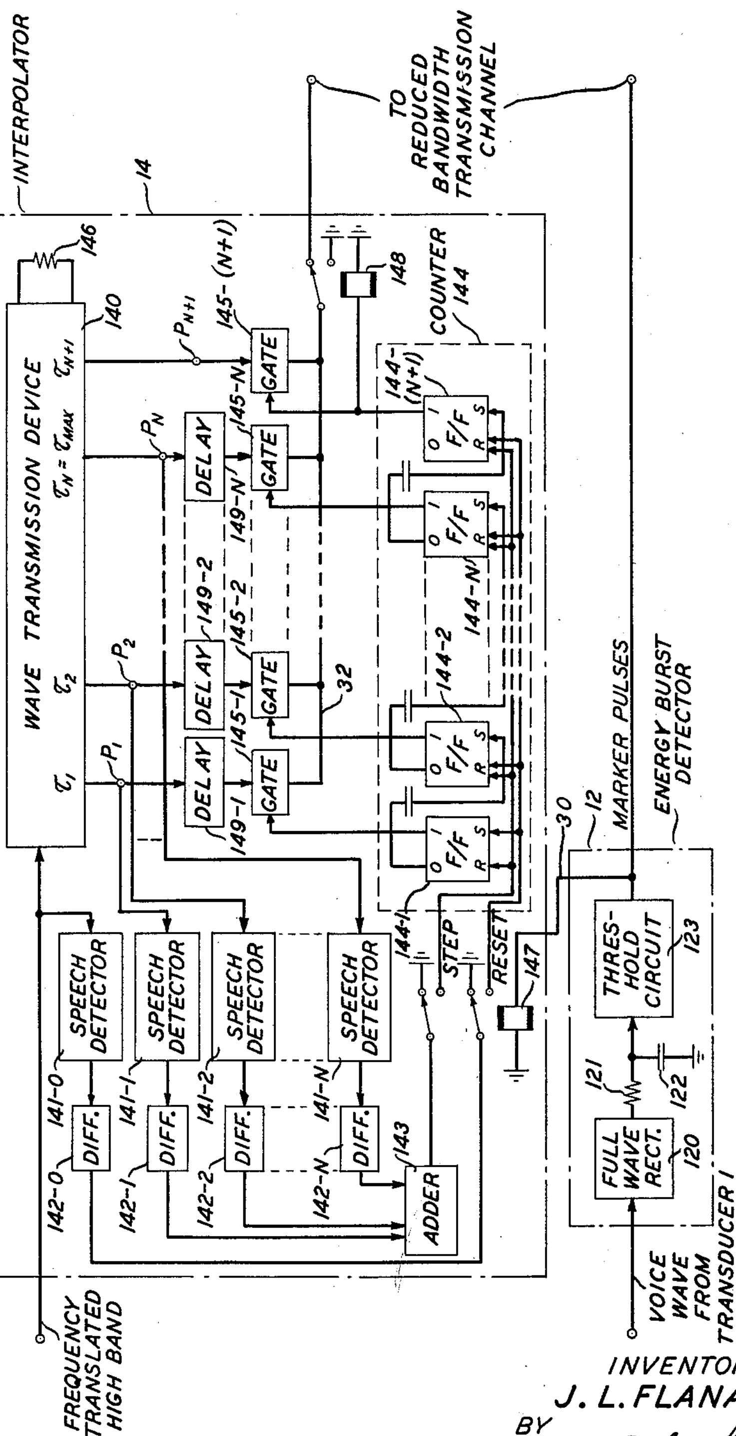

FIG. 3

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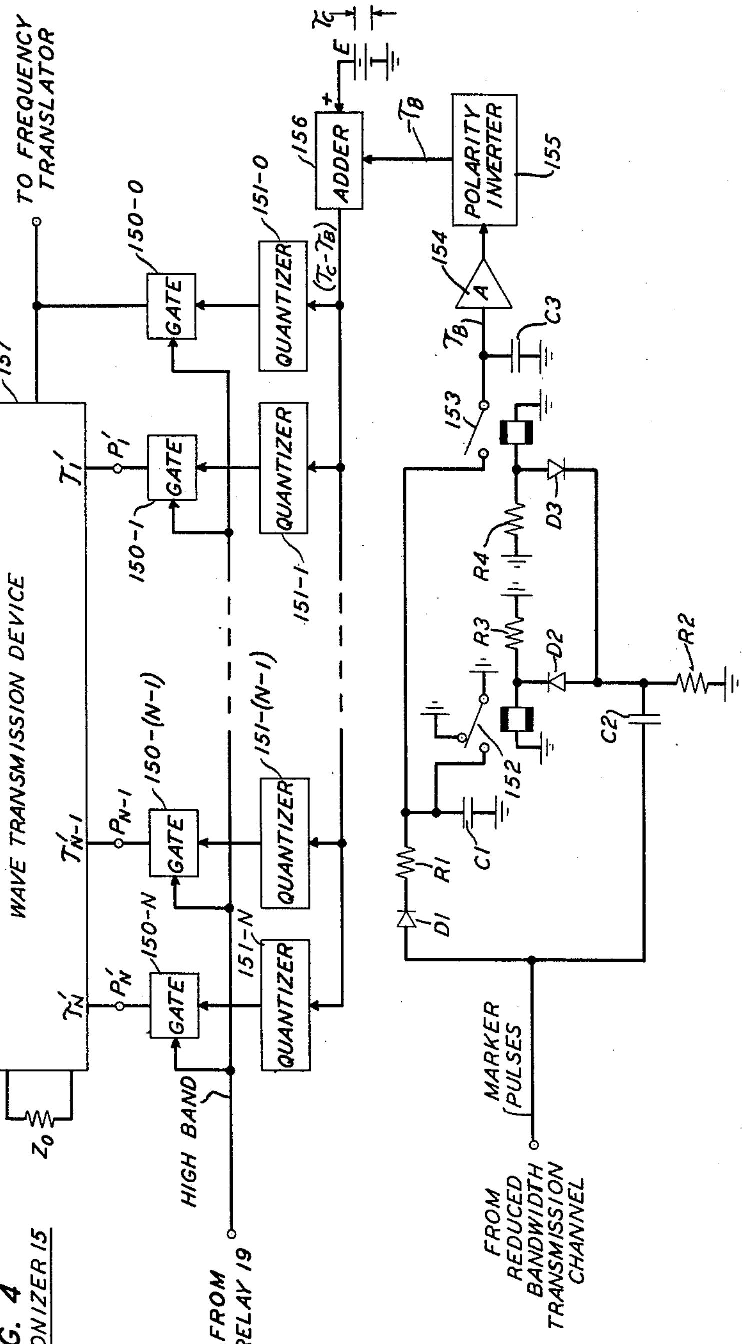

FIG. 4
SYCHRONIZER 15

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SPEECH INTERPOLATION COMMUNICATION SYSTEM

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8 Claims. (Cl. 179—15.55)

This invention relates to systems for reducing the frequency bandwidth required to transmit speech information, and particularly to systems in which bandwidth is reduced by interpolating speech information into the silent intervals that normally separate bursts of energy in human speech sounds.

In an effort to make more economical use of speech transmission facilities, a number of arrangements have been devised to reduce the amount of frequency bandwidth required to transmit speech information. One approach to bandwidth reduction is to turn to advantage the silent intervals that separate energy bursts in normal speech sounds. In prior art systems embodying this approach, additional speech information is interpolated into these silent intervals so that a greater amount of information may be carried by a given amount of frequency bandwidth. Two examples of systems for reducing transmission channel bandwidth by speech interpolation are described in A. E. Melhose Patent 2,541,932, issued February 13, 1951, and R. Guenther Patent 2,870,260, issued January 20, 1959.

A feature common to prior art bandwidth reduction systems of the type described in the above-identified Melhose and Guenther patents is the interpolation of an energy burst from the voice signal of one talker into a time-coincident silent interval in the voice signal of another talker. By utilizing silent intervals in this fashion, a number of transmission channels between two points may accommodate a larger number of talkers. Speech interpolation systems therefore reduce the amount of bandwidth required to provide communication service between two points for a given number of talkers because in conventional speech transmission systems the number of talkers typically cannot exceed the number of channels. It is evident, however, that in speech interpolation arrangements of the sort shown in the Melhose and Guenther patents, transmission channel economy is realized only during those periods in which the number of talkers exceeds the number of channels, for only in such periods does the use of silent intervals enable the channels to transmit more speech information than conventional systems where the number of talkers does not exceed the number of channels.

The present invention also interpolates speech energy bursts into silent intervals in order to reduce transmission channel bandwidth, but it does so by interpolating selected portions of a talker's voice signal into the same talker's silent intervals. As a result, the bandwidth reduction effected by this invention is not dependent upon the number of talkers exceeding the number of transmission facilities between two points; instead, this invention realizes the same bandwidth reduction for each talker's voice signal, regardless of the number of talkers at a given instant.

In the present invention, a talker's voice signal is individually reduced in bandwidth before transmission by interpolating the high-frequency portion of each energy burst into the next following silent interval in the talker's own voice signal. This is achieved by first dividing each energy burst into two frequency bands, a high band and a low band, and then translating one or both of the bands to the frequency range accommodated by a reduced bandwidth transmission channel. After frequency translation, the low band is transmitted directly from a transmitting terminal to a receiving terminal over the reduced bandwidth channel, while the high band is delayed for the duration of its own energy burst. At the end of an energy burst, all of the low band has been transmitted, and transmission of the delayed high band during the next following silent interval is commenced. At the receiving terminal, the low band and the next following high band are adjusted on the time scale to bring the two bands into time-coincidence. After translation of one or both of the now time-coincident bands to their original frequency ranges, the two bands are combined to reconstruct a replica of the original energy burst of the voice signal.

An important feature of the present invention is the maintenance of uninterrupted service even when a silent interval is too short to accommodate all of the high band of a preceding energy burst. Both energy bursts and silent intervals vary in duration, with the average duration of energy bursts exceeding the average duration of silent intervals, according to the speech statistics published by R. H. Bolt and A. D. MacDonald in "Theory of Speech Masking by Reverberation," volume 21, Journal of The Acoustical Society of America, page 577 (1949). The difference in average duration between energy bursts and silent intervals means that occasionally the silent interval separating two bursts will be too short to accommodate all of the high band of the preceding burst. In such a situation, the present invention transmits only as much of the high band of the preceding burst as there is time for during the next following silent interval, and discards the untransmitted portion of the high band to give preference to the low-frequency components of the next occurring energy burst.

The occasional loss of even a large portion of the high band of an energy burst does not seriously impair the intelligibility of the received voice signal because only a relatively small amount of speech information is contained in the high band of an energy burst. Correspondingly, transmission of all of the low band of each energy burst maintains uninterrupted service, since the low bands contain a sufficiently large amount of speech information to constitute an intelligible voice signal even in the absence of the high bands.

It is another feature of this invention that except for the limitations mentioned above, the voice signal reconstructed at the receiving terminal is an undistorted replica of the original voice signal at the transmitting terminal despite wide variations in the durations of energy bursts in normal speech sounds. As previously mentioned, the high band of each energy burst is delayed at the transmitting terminal for the duration of its own energy burst, at which point the delayed high band is transmitted during the silent interval next following the energy burst. Because energy bursts vary widely in duration, both low bands and high bands also vary in duration, hence the amount of time by which each high band is delayed at the transmitting terminal varies from burst to burst. It is therefore apparent that before each directly transmitted low band can be combined with its delay high band at the receiving terminal, each low band must also be delayed by an amount of time at least equal to the duration of its own energy burst in order to synchronize each low band with its following high band. It has been determined, however, that synchronization is not the sole criterion in determining the delay of the low bands at the receiving terminal, because delaying the low bands as well as the high bands by varying amounts introduces between the original voice signal and the reconstructed voice signal a variable transmission delay that is subjectively undesirable. On the other hand, it is well known that a constant transmission delay between transmitting terminal and receiving terminal is subjectively tolerable provided that the delay is not excessive.

The present invention satisfies the dual criteria of synchronization and constant transmission delay in the following manner. At the receiving terminal, each low band is delayed by a constant amount that is selected to be equal to or greater than the longest anticipated burst duration but shorter than the maximum tolerable transmission delay. In addition, because the constant delay of the low band at the receiving terminal is selected to be longer than most burst durations, the delay of most high bands at the transmitting terminal is shorter than the delay of the corresponding low bands at the receiving terminal. Accordingly, to bring each pair of corresponding high and low bands into time-coincidence, this invention also delays each high band at the receiving terminal by an amount equal to the difference between the constant delay of the low band and the duration of the energy burst from which each high band and low band are derived.

In the relatively rare event that the duration of an energy burst exceeds the constant delay of the low band at the receiving terminal, the high band of such a burst is discarded in its entirety at the transmitting terminal in order to prevent the distortion that would result from combining the high band with the low band in improper synchrony. The occasional loss of the high band in this situation does not significantly impair the reconstructed voice signal, since sufficient speech information is contained in the low band to maintain intelligibility.

The invention will be fully understood from the following detailed description of illustrative embodiments thereof taken in connection with the appended drawings, in which:

FIGS. 1A and 1B are schematic block diagrams of complete bandwidth reduction systems embodying the principles of this invention;

FIG. 2A is a replica of the spectrogram of connected speech sounds;

FIG. 2B is a signal waveform indicative of certain features of the sound spectrogram of FIG. 2A; and

FIGS. 3 and 4 are circuit diagrams showing details of certain of the components of FIGS. 1A and 1B.

Referring first to FIG. 2A, there is illustrated a replica of a sound spectrogram of the utterance "Should we chase those young outlaw cowboys?" The shaded areas represent varying amounts of energy, with the darker areas representing greater amounts of energy than the lighter areas, and the unshaded or blank areas representing zero energy or silent intervals. It is observed that this seemingly continuous utterance is in fact composed of a succession of energy bursts separated by silent intervals. This invention takes advantage of the silent intervals to reduce the bandwith required to transmit voice signals by interpolating a selected high-frequency portion of each energy burst into the next following silent interval, as indicated by the curved arrows in FIG. 2A.

Turning now to FIG. 1A, there is illustrated a complete system for reducing the bandwith required to transmit speech information in accordance with the principles of this invention. The system comprises transmitting terminal apparatus, a reduced bandwith transmission channel, and receiving terminal apparatus. At the transmitting terminal, incoming speech sounds are converted by transducer **1** into a voice wave, where transducer **1** may be a conventional telephone transmitter microphone, if desired. From transducer **1**, the voice wave is applied simultaneously to high-band filter **10**, low-band filter **11**, and energy-burst detector **12**.

High-band filter **10** and low-band filter **11** may be conventional bandpass filters and serve to divide the frequency components of each energy burst of the voice wave into two selected bands, a band of high-frequency components and a band of low-frequency components. Selection of suitable limits for the two frequency bands depends upon a number of factors, for example, the total bandwidth of the voice wave, the bandwidth of the available transmission channel, and the quality desired in the voice wave after transmission. In the case of a voice wave of commercial telephone quality, for example, where the bandwith is on the order of 3,000 cycles per second, the present invention permits a channel of about 1,500 cycles per second bandwith to be utilized to transmit a voice wave of good quality by dividing the frequency components of the voice wave into two 1,500 cycles per second bands. This example is illustrated graphically by the three horizontal lines in FIG. 2A which divide a telephone quality voice wave whose lower and upper frequency limits are respectively 200 cycles per second and 3,200 cycles per second into a low band from about 200 to 1,700 cycles per second and a high band from about 1,700 to 3,200 cycles per second. Transmission of these two bands over a channel of about 1,500 cycles per second bandwidth in accordance with the principles of this invention produces a good quality voice wave at the receiving terminal. This example also illustrates that if conservation of bandwidth is of primary importance, a voice wave of given bandwidth may be transmitted over the narrowest possible channel by dividing the frequency components of the voice wave into two bands of equal width.

Returning to FIG. 1A, at the same time that filters **10** and **11** are dividing energy bursts of the voice wave from transducer **1** into two bands of frequency components, energy-burst detector **12** is deriving from the voice wave a succession of marker pulses indicative of the beginning, end, and duration of each energy burst. Detector **12** is illustrated in detail in FIG. 3 and described further below, and FIG. 2B shows the succession of marker pulses corresponding to the utterance whose spectrogram is depicted in FIG. 2A. It is observed in FIG. 2B that the marker pulses are of uniform amplitude but variable length. The variable pulse lengths, denoted Δt_{B1}, Δt_{B2}, Δt_{B3} . . . correspond to the variable durations of the energy bursts, and the intervals between pulses, denoted Δt_{G1}, Δt_{G2}, Δt_{G3}, correspond to the durations of the silent intervals between successive bursts.

The low-frequency components passed by filter **11** are transmitted directly from the transmitting terminal to the receiving terminal over a reduced bandwidth channel, the channel being indicated by broken lines. The high-frequency components passed by filter **10** are delayed by interpolator **14** in order to be transmitted over the reduced bandwidth channel during the silent intervals between successive energy bursts, the operation of interpolator **14** being controlled by marker pulses from detector **12**. The details of interpolator **14** are shown in FIG. 3 and described fully below. Before the high bands are passed to interpolator **14**, however, the frequency range of the high bands is shifted to the frequency range accommodated by the transmission channel. Accordingly, frequency translator **13A** is interposed between filter **10** and interpolator **14**, where translator **13A** may be any one of a number of well-known devices for shifting the components of the high-band signal from their original range of frequencies to the range of frequencies accommodated by the reduced bandwidth channel. An example of a suitable translator is shown in FIG. 3 of J. C. Steinberg Patent 1,836,824, issued December 15, 1931.

It is to be understood, however, that it may be desirable to shift the frequency range of the low bands, either as an alternative to shifting the frequency range of the high bands or in addition to shifting the frequency range of the high bands. An arrangement for shifting the frequency range of one or both of the two bands is illustrated by frequency shifting network **13B** in FIG. 1B. Between filter **10** and interpolator **14** two subpaths are provided, one for delivering the high bands from filter **10** directly to interpolator **14**, and the other for delivering the high bands to interpolator **14** through frequency translator **13H**. The construction of translator **13H** may be similar to that of translator **13A** of FIG. 1A, and the desired subpath is selected by setting switches S1 and S2 to the appropriate positions. Similarly, two subpaths are provided between filter 11 and the reduced bandwidth channel, with one subpath serving to deliver the low bands from filter 11 directly to the channel, and the other subpath serving to deliver the low bands to the channel through frequency translator 13L. Translator 13L is similar in structure to translator 13H, and the desired subpath is chosen by setting switches S3 and S4 to the appropriate positions.

In the present invention, therefore, the reduced bandwidth channel carries a succession of bands of low-frequency components alternating with delayed bands of high-frequency components, with each band of low-frequency components and the next following band of high-frequency components being derived from the same original energy burst of the incoming voice wave. In addition to carrying the succession of high and low bands, it is also necessary for the channel to have sufficient bandwidth to carry the marker pulses in order to reconstruct from the high and low bands a replica of the original voice wave at the receiving terminal; however, the bandwidth required to carry the marker pulses is relatively small compared to the total bandwidth of the channel.

At the receiving terminal, as shown in FIG. 1A, a replica of the original voice wave is constructed from the transmitted high and low bands by combining each pair of high and low bands to form a succession of reconstructed energy bursts separated by silent intervals which closely follows the succession of energy bursts and silent intervals of the original voice wave. The transmitted low bands and high bands are first separated from each other by relay 19, which is controlled by the marker pulses to pass the low bands to fixed delay 17 and the high bands to synchronizer 15. Relay 19 is energized by the marker pulses so that the relay armature makes contact with the input terminal of fixed delay 17 whenever an energy burst is present. During silent intervals, the absence of marker pulses de-energizes relay 19, thereby causing the armature to make contact with the input terminal of synchronizer 15 for receiving high bands during silent intervals. Synchronizer 15, which is described in full below in connection with FIG. 4, operates together with fixed delay 17 to synchronize the high and low bands from each energy burst so that the two bands may be combined to form an accurate replica of the original energy burst. The need for synchronization arises from variations in the amount of delay of each high band at the transmitting terminal, and the exact manner in which synchronization is achieved by synchronizer 15 and delay 17 is explained in detail below in the description of FIG. 4.

As a result of the synchronizing operation performed by synchronizer 15 in conjunction with fixed delay 17, each high band appearing at the output terminal of synchronizer 15 is in time-coincidence with its corresponding low band appearing at the output terminal of delay 17. From synchronizer 15, each high band is then passed through frequency translator 16A to restore its frequency components to their original range of frequencies, and each frequency-translated high band is combined with its corresponding low band in adder 18 to reconstruct a replica of the original voice wave. A suitable reproducer 2, for example, a telephone receiver, converts the reconstructed voice wave into audible speech sounds of good quality.

In the event that the transmitting terminal apparatus shown in FIG. 1B is utilized for shifting the frequency range of one or both of the two bands before transmission, restoration of the original frequency range of each band may be accomplished by frequency shifting network 16B of the receiving terminal apparatus shown in FIG. 1B. Two subpaths are interposed between synchronizer 15 and adder 18, one of which serves to deliver the synchronized high bands directly to adder 18, while the other serves to deliver the synchronized high bands to adder 18 through frequency translator 16H. Selection of the desired subpath is obtained by setting switches S5 and S6 to the appropriate positions, and frequency translator 16H is designed to introduce a frequency shift that offsets the frequency shift introduced by translator 13H at the transmitting terminal, thereby restoring the high bands to their original frequency range. A similar pair of subpaths is provided between fixed delay 17 and adder 18 so that by setting switches S7 and S8 to the appropriate positions, the low bands may be delivered to adder 18 either directly or through frequency translator 16L. Translator 16L is constructed to shift the low bands back to their original frequency range from the frequency range utilized during transmission and introduced by translator 13L at the transmitting terminal.

Referring now to FIG. 3, this drawing illustrates the circuit details of energy-burst detector 12 and interpolator 14. Energy-burst detector 12 derives a marker pulse of the type shown in FIG. 2B from each energy burst of the voice wave by means of a full-wave rectifier 120 connected to a threshold circuit 123 through resistor 121 and shunt capacitor 122. Rectifier 120 converts the incoming voice wave into a unidirectional wave, resistor 121 and capacitor 122 smooth the unidirectional wave, and threshold circuit 123, which may be a conventional squaring amplifier or Schmidt trigger circuit, derives from the smoothed unidirectional wave a succession of rectangular marker pulses of uniform amplitude but variable length. As illustrated in FIGS. 2A and 2B, each marker pulse corresponds to an energy burst in the voice wave, with the length of each pulse indicating the duration of the corresponding energy burst.

The marker pulses from detector 12 are transmitted, as stated above, over a reduced bandwidth channel to a receiving terminal for use in synchronizer 15 as described below. The marker pulses are also transmitted by way of a conductor 30 to energize relay 147 of interpolator 14 during each energy burst and thereby control the amount of time by which the band of high-frequency components from each energy burst is delayed before being transmitted in the silent interval next following the burst.

At the onset of an energy burst, the band of frequency-translated, high-frequency components of the burst is applied to the input terminal of a wave transmission device 140 such as an electromagnetic or acoustic delay line. Device 140 is terminated at its far end in an impedance 146 to prevent reflections, and is provided with a number of lateral taps $P_1, P_2 \ldots P_N, P_{N+1}$ so located that the incoming signal appears at each tap in succession after progressively larger amounts of preassigned delay, denoted $\tau_1, \tau_2 \ldots \tau_N, \tau_{N+1}$, respectively. It is evident that the taps quantize the burst durations by delaying each high band by a discrete quantum of time. However, the spacing between taps is sufficiently small so that the effect of the discrete delay times is subjectively equivalent to a continuously variable delay. The preassigned delay times of the taps of device 140 may start, for example, with a delay τ_1 as much as 5 milliseconds and proceeding at approximately 5 millisecond intervals to a delay τ_{N+1} of about 505 milliseconds.

At the beginning of an energy burst, the high band is applied to speech detector 141–0 as well as to wave transmission device 140. Detector 141–0, which may be of a construction similar to that of detector 12, converts the high band into a rectangular pulse, and differentiator 142–0 develops from the leading edge of this rectangular pulse a so-called reset pulse indicative of the onset of an energy burst. The output terminal of differentiator 142–0 is connected to one of the two armatures of relay 147 so that when relay 147 is energized by a marker pulse from detector 12 at the beginning of an energy burst, the two armatures of relay 147 are closed and the reset pulse from differentiator 142–0 is delivered to the reset terminal of counter 144.

Counter 144 may take various forms, a suitable form being a ring counter composed of a series of intercoupled bistable devices, as described by R. K. Richards in Arithmetic Operations in Digital Computers, page 205 (1955). The bistable devices, which may be flip-flops of well-known design, are arranged so that the delivery of a reset pulse from differentiator 142–0 at the beginning of a high band causes flip-flop 144–1 to be turned "on," or to conduction state "one" and flip-flops 144–2 through 144–(N+1) to be turned "off" or to conduction state "zero." The output terminal of the "one" conduction stage of each bistable device 144–1 through 144–(N+1) is connected to the control terminal of a gate 145–1 through 145–(N+1), respectively, where gates 145 are preferably of the linear or transmission variety described by L. W. Hussey in "Semiconductor Diode Gates," volume 32, Bell System Technical Journal, page 1137 (1953). The input terminals of gates 145–1 through 145–(N+1) are connected to the taps of wave transmission device 140, with delay elements 149–1 through 149–N being interposed between taps P_1 through P_N and gates 145–1 through 145–N, and the output terminals of the gates are connected to bus 32. The delay introduced by elements 149–1 through 149–N is just short enough to permit each of the gates 145 to be disabled, in the manner described below, before the leading edge of the high band reaches the input terminal of a gate.

By the arrangement described above, gate 145–1 is enabled at the onset of an energy burst as a result of flip-flop 144–1 being set to the "one" conduction state by the reset pulse from differentiator 142–0 and gate 145–1 remains enabled until flip-flop 144–1 is changed to the "zero" state. Gate 145–1 remains enabled until a time τ_1 after the beginning of an energy burst, when the leading edge of a high band appears at tap P_1. When the leading edge of the high band reaches tap P_1, it is immediately detected by speech detector 141–1 and converted into a so-called first stepping pulse by differentiator 142–1; and if the energy burst has not terminated and relay 147 is still closed, the first stepping pulse is delivered through the other closed armature of relay 147 to the step terminal of counter 144. The step pulse is applied to all of the flip-flops of counter 144 to change them from conduction state "one" to conduction state "zero." Since the only flip-flop that is in conduction state "one" is 144–1, only flip-flop 144–1 is changed to the "zero" conduction state by the first stepping pulse from differentiator 142–1. The change of flip-flop 144–1 from conduction state "one" to conduction state "zero" disables gate 145–1, and because of element 149–1 interposed between tap P_1 and gate 145–1, the gate is disabled before the high band reaches it, thereby preventing the high band from passing to bus 32 and thence to the reduced bandwidth transmission channel.

Further, flip-flop 144–1 is intercoupled with flip-flop 144–2 so that the change of flip-flop 144–1 from conduction state "one" to conduction state "zero" causes flip-flop 144–2 to be changed from conduction state "zero" to conduction state "one." Gate 145–2 associated with flip-flop 144–2 is enabled when flip-flop 144–2 is in conduction state "one," and it is therefore observed that as long as an energy burst continues, the "one" conduction state of the bistable devices of counter 144 is stepped along just ahead of the high band moving through device 140. Correspondingly, as the "one" conduction state of counter 144 is stepped along, the gate enabled by this "one" conduction state is also stepped along ahead of the high band moving through device 140. Hence the delay of the high band is successively increased by discrete amounts as long as the energy burst continues.

However, at the end of an energy burst, the marker pulse from detector 12 disappears, thereby de-energizing relay 147 and opening its armatures to block the passage of further stepping pulses from differentiators 142–1 through 142–N to counter 144. By blocking the passage of further stepping pulses to counter 144, the last flip-flop to be changed to conduction state "one" before the end of an energy burst remains in conduction state "one" even after the leading edge of the high band reaches the tap associated with this flip-flop.

As a result of the "one" conduction state of one of the bistable devices of counter 144 remaining stationary at the end of an energy burst, the gate associated with the flip-flop in the "one" conduction state correspondingly remains enabled during the next following silent interval. Hence the high band arriving at the associated tap passes through the delay element to the enabled gate and thence to bus 32 for transmission over the reduced bandwidth channel during the silent interval.

At the beginning of the next energy burst, the corresponding marker pulse energizes relay 147, and the reset pulse from differentiator 142–0 returns flip-flop 144–1 to the "one" conduction state and all of the other flip-flops to the "zero" conduction state. It is therefore evident that in some instances the next energy burst may occur before all of the high band has passed out of device 140, thereby causing some of the high band of the preceding burst to be lost. The loss of a portion of the high-band signal in these instances may result in some loss of quality in the voice wave reconstructed at the receiving terminal, but these instances are comparatively rare and therefore the cumulative effect on intelligibility is negligible.

The maximum time by which a high band may be delayed before interpolating it in the next following silent interval depends upon the maximum anticipated length of the energy bursts, and it is this maximum anticipated length that determines the length of wave transmission device 140 and therefore the location of the Nth tap on device 140. As indicated in FIG. 3 by the equation $\tau_N=\tau_{max}$, the location of the Nth tap corresponds to the maximum anticipated length of the energy bursts, but it is possible that an occasional energy burst will be longer than the anticipated maximum. From the previously described construction and operation of interpolator 14, it is apparent that in the event that the duration of an energy burst does exceed the anticipated maximum, a portion of the high band will have passed to the end of device 140 before the burst is over, and therefore some of the high band will have been lost by the time that the burst is over. Although the occasional loss of a portion of the high band does not seriously impair intelligibility, the problem of synchronizing the remaining portion of the high band with the corresponding portion of the previously transmitted low band is quite complex. One solution is to make device 140 sufficiently long to accommodate the entire high band of all energy bursts, regardless of length, but this solution is accompanied by the introduction of an intolerably long delay between transmitting and receiving terminals. Another solution is to make device 140 long enough to accommodate all of the high bands of most energy bursts, and to discard entirely the high bands of those energy bursts which have durations that exceed the preassigned length of device 140. The second solution is adopted in the apparatus illustrated in FIG. 3 by providing device 140 with an extra tap P_{N+1} located at a delay τ_{N+1} which is greater than the maximum anticipated burst duration. Associated with tap P_{N+1} are gate 145–(N+1), relay 148, and flip-flop 144–(N+1) of counter 144. When a burst exceeds the maximum anticipated duration, the leading edge of the high band arriving at tap P_N is converted by detector 141–N and differentiator 142–N into a stepping pulse that advances the "one" conduction state of counter 144 from flip-flop 144–N to flip-flop 144–(N+1). The output terminal of flip-flop 144–(N+1) is connected to relay 148 as well as to gate 145–(N+1), so that when flip-flop 144–(N+1) is in conduction state "one," the armature of relay 148 makes contact with ground instead of with the reduced bandwidth channel. Hence, upon the high band reaching tap P_{N+1}, it is discarded because gate 145–(N+1) passes the high band to ground regardless of how much longer the energy burst continues beyond the maximum duration. When the "one" conduction state of counter **144** is reset to flip-flop **144-1** at the beginning of the next energy burst, relay **148** is de-energized and its armature returns to its normal position connecting bus **32** to the reduced bandwidth channel.

Turning now to FIG. 4, synchronizer **15** of FIGS. 1A and 1B is illustrated in detail. The incoming high band, for example, from relay **19** as shown in FIG. 1A, is applied in parallel to the input terminals of linear gates **150-N** through **150-0**. The output terminal of each gate **150-N** through **150-1** is connected to one of the taps P_N' through P_1' of wave transmission device **157**, and the output terminal of gate **150-0**, together with the output terminal of device **157**, is connected directly to the input terminal of frequency translator **16A** shown in FIG. 1A or to one of the input terminals of frequency shifting network **16B** shown in FIG. 1B, as the case may be.

Wave transmission device **157** may be a delay line of construction similar to that of device **140** of interpolator **14** described above, and is provided with an impedance Z_0 at one end to prevent reflections and with lateral taps P_N' through P_1' located along device **157** to correspond to discrete amounts of delay denoted τ_N' through τ_1' so that discrete delays τ_N' through τ_1' are equal to corresponding discrete delays τ_N through τ_1 of the interpolator apparatus in FIG. 3. The control terminal of each gate **150-N** through **150-0** is connected to the output terminal of a corresponding quantizer **151-N** through **151-0**, where each quantizer may be of the type disclosed in B. M. Oliver Patent 2,773,980, issued December 11, 1956. A control signal generated by one of the quantizers at the end of an energy burst enables its corresponding gate to pass each high band to one of the taps of device **157** so that each delayed high band appearing at the output terminal of device **157** is time-coincident with its corresponding low band. In the event that it is unnecessary to delay a high band in order to synchronize it with its corresponding low band, gate **150-0** and quantizer **151-0** are provided to pass the high band directly to frequency translator **16A** shown in FIG. 1A or frequency shifting network **16B** shown in FIG. 1B.

It is recalled from the foregoing description of FIG. 3 that each high band is delayed at the transmitting terminal by a discrete amount of time, denoted τ_1 through τ_N, in order to permit all of the corresponding low band to be transmitted to the receiving terminal. It is further recalled from the description of FIG. 1A above that each low band is delayed at the receiving terminal by a fixed amount of time, to be denoted τ_C, where τ_C may be chosen to be equal to or greater than the duration of the longest anticipated energy burst, τ_{max}, but short enough to yield a subjectively tolerable constant transmission delay between transmitting terminal and receiving terminal. Since each high band received at the receiving terminal is never delayed by an amount exceeding τ_{max}, high bands of longer delay being discarded at the transmitting terminal in the manner shown in FIG. 3, the additional amount of time by which it is necessary to delay each high band at the receiving terminal is equal to the difference between the fixed delay of each low band at the receiving terminal, τ_C, and the discrete delay of each high band at the transmitting terminal, denoted τ_B, where τ_B may have any one of the discrete values τ_1 through τ_N. Hence the tap of device **157** to which each high band is passed by one of the gates corresponds to a delay equal to the difference $(\tau_C-\tau_B)$.

To select the tap of device **157** corresponding to the difference $(\tau_C-\tau_B)$, each marker pulse transmitted over the reduced bandwidth channel is applied in parallel to diode D1 and capacitor C2. The length of each marker pulse is equal to the duration of an energy burst, and hence is approximately equal to τ_B, since τ_B denotes discrete energy burst durations. Capacitor C2 and resistor R2 differentiate the leading edge and trailing edge of each marker pulse to obtain therefrom a positive-going pulse and a negative-going pulse, respectively. Diode D2 and resistor R3 pass the positive-going pulse to energize relay **152** momentarily at the beginning of an energy burst, while diode D3 and resistor R4 pass the negative-going pulse to energize relay **153** momentarily at the end of an energy burst. Meanwhile, diode D1 passes each marker pulse to resistor R1 and capacitor C1, which operate to integrate each marker pulse by building up a charge on capacitor C1 which is proportional to the length of the marker pulse. Since the length of the marker pulse is proportional to the duration of the corresponding energy burst and is approximately equal to the discrete delay, τ_B, of the high band at the transmitting terminal, the momentary operation of relay **153** at the end of a marker pulse samples the τ_B voltage on capacitor C1. The sampled τ_B voltage from capacitor C1 is held on capacitor C3 and amplified by amplifier **154**, for example, a cathode follower, and the polarity of the τ_B voltage is inverted by a conventional polarity inverter **155** to obtain a signal representative of $(-\tau_B)$. The $(-\tau_B)$ signal is combined in adder **156** with a constant amplitude signal from energy source E, where the constant amplitude signal is proportional to the fixed delay τ_C of the low band at the receiving terminal. The difference signal appearing at the output terminal of adder **156** therefore has an amplitude proportional to the difference $(\tau_C-\tau_B)$. At the beginning of the next energy burst, the momentary operation of relay **152** discharges capacitor C1 to allow integration of the marker pulse for the next energy burst.

From adder **156** the difference signal is applied in parallel to quantizers **151-N** through **151-0**. As described in the above-mentioned Oliver patent, a single state quantizer responds only to signal amplitudes falling within a preselected range of values. For a signal whose amplitude falls within this range, the output condition of the quantizer changes to signify this occurrence. In the present invention, each of the quantizers **151-N** through **151-0** is set to respond to a difference signal whose amplitude falls within a relatively narrow range of values about a selected difference between τ_C and one of the discrete values assumed by τ_B. Thus quantizer **151-N** responds to difference signals whose amplitudes $(\tau_C-\tau_B)$ are approximately equal to τ_N', while quantizer **151-1** responds to difference signals whose amplitudes are approximately equal to τ_1'. Actuating a particular quantizer results in enabling its associated gate, hence the high band is passed to the tap which will cause the high band to be delayed by an amount of time most closely equal to the difference $(\tau_C-\tau_B)$. Since delays τ_N' through τ_1' are equal to corresponding delays τ_N through τ_1 in the interpolator apparatus of FIG. 3, the high-band signal appearing at the output terminal of device **157** is therefore time-coincident with the low band appearing at the output terminal of delay device **17** of FIGS. 1A and 1B.

It is to be understood that the above-described arrangements are merely illustrative of applications of the principles of this invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A communication system that comprises
   a transmitter terminal including means for dividing each energy burst of a voice wave into a first band of selected low-frequency components and a second band of selected high-frequency components, and
   means for transmitting said first and second bands to a receiving terminal over a reduced bandwith channel, said means for transmitting including
   means for sending said first band directly to said receiving terminal, and
   means for delaying said second band for the duration of its energy burst so that said second band is transmitted to said receiving terminal during the silent interval following its energy burst,
   and at said receiving terminal,

means for delaying said first band by an amount of time selected to be equal to or greater than the longest anticipated energy burst but shorter than the maximum tolerable delay in transmission between said transmitter terminal and said receiving terminal,

means for adjusting said second band on the time scale to coincide with said first band, and

means for combining said time-coincident first and second bands to form a replica of the original voice wave.

2. A speech interpolation communication system that comprises

a transmitting terminal including

a transducer for converting speech sounds into a voice wave,

first filter means supplied with said voice wave for obtaining from each energy burst of said voice wave a first band of selected high-frequency components,

second filter means supplied with said voice wave for obtaining from each energy burst of said voice wave a second band of selected low-frequency components,

detector means supplied with said voice wave for obtaining from each energy burst of said voice wave a marker pulse indicative of the duration of each energy burst,

a first frequency translator provided with first and second input terminals and first and second output terminals for shifting the frequency ranges of said first and second bands,

means for connecting said first filter means to the first input terminal of said first translator,

means for connecting said second filter means to the second input terminal of said first translator,

interpolating means provided with a control terminal, an input terminal, and an output terminal, including

means for delaying said first band for the duration of its energy burst when said burst is equal to or shorter than a preassigned maximum duration, and

means for discarding said first band when the duration of said burst exceeds said preassigned maximum duration,

means for applying said marker pulses to the control terminal of said interpolating means,

a reduced bandwidth channel,

means for connecting the first output terminal of said first translator to the input terminal of said interpolating means,

means for connecting the second output terminal of said first translator to said channel,

means for connecting the output terminal of said interpolating means to said channel, and

means for connecting said detector means to said channel, and

a receiving terminal including

means for separating said first band from said second band,

means supplied with said second band for delaying said second band for a fixed interval of time selected to be equal to or greater than the longest anticipated burst duration but shorter than the maximum tolerable delay in transmission between said transmitting terminal and said receiving terminal,

synchronizing means controlled by each marker pulse and supplied with said first band for delaying said first band by an amount of time equal to the difference between the delay of said second band at the receiving terminal and the delay of said first band at the transmitting terminal,

a second frequency translator provided with first and second input terminals and first and second output terminals for returning said first and second bands to their original frequency ranges,

means for connecting said synchronizing means to the first input terminal of said second translator,

means for connecting said delaying means to the second input terminal of said second translator,

an adding means provided with two input terminals and an output terminal,

means for connecting the output terminals of said second translator to the input terminals of said adding means, and

a reproducing means connected to the output terminal of said adding means.

3. A system as defined in claim 2 wherein said detector comprises

a full-wave rectifier, a resistor shunted by a capacitor, and a threshold circuit connected in tandem.

4. A system as defined in claim 2 wherein said interpolating means comprises

a wave transmission device provided with an input terminal, a plurality of (N+1) taps, and an impedance at its far end to prevent reflections,

a plurality of N delay devices,

means for connecting each of the first N taps of said wave transmission device to one of said delay devices,

a plurality of (N+1) gates, each of which is provided with an input terminal, a control terminal, and an output terminal,

means for connecting each of said delay devices to the input terminal of one of the first N of said gates,

means for connecting the (N+1)th tap of said wave transmission device to the input terminal of said (N+1)th gate,

means for connecting the output terminals of all of said gates to a common conductor,

a counter provided with (N+1) stages, a reset terminal and a step terminal,

reset means provided with an input terminal and an output terminal,

means for connecting the input terminal of said reset means and the input terminal of said wave transmission device to a common input point for receiving the first band from said first translator,

a plurality of N stepping means each of which is provided with an input terminal and an output terminal,

means for connecting each of the first N taps of said wave transmission device to the input terminal of one of said stepping means,

adding means provided with N input terminals and an output terminal,

means for connecting the output terminal of each stepping means to one of the input terminals of said adding means,

means responsive to each marker pulse for connecting the output terminal of said reset means to the reset terminal of said counter and for connecting the output terminal of said adding means to the step terminal of said counter,

means for connecting each stage of said counter to the control terminal of one of said gates, and

means controlled by the (N+1)th stage of said counter for connecting said common conductor to said reduced bandwidth channel.

5. A system as defined in claim 2 wherein said synchronizing means comprises

a wave transmission device provided with a plurality of N taps, an output terminal, and an impedance at its far end to prevent reflections,

a plurality of (N+1) gates each of which is provided with an input terminal, a control terminal and an output terminal,

means for connecting the output terminal of each of the first N of said gates to one of the taps of said wave transmission device,

means for connecting the output terminal of said (N+1)th gate and the output terminal of said wave transmission device to a common output point for delivering said first band to said second translator,

means for applying said first band in parallel to the input terminals of all of said gates,
- a plurality of (N+1) quantizers in one-to-one correspondence with said (N+1) gates, each of said quantizers being responsive to a predetermined range of amplitudes and being provided with an input terminal and an output terminal,
- means for connecting the output terminal of each quantizer to the control terminal of its corresponding gate,
- means for connecting the input terminals of said quantizers to a common conductor, and
- means connected to said common conductor for generating from each marker pulse a signal whose amplitude is representative of the difference between the delay of said second band at the receiving terminal and the delay of said first band at the transmitting terminal.

6. Apparatus for reducing the bandwidth of a voice wave which comprises
- a transducer for converting speech sounds into a voice wave,
- means for separating each energy burst of said voice wave into a first narrow band of high-frequency components and a second narrow band of low-frequency components,
- means for shifting said first and second narrow bands to a predetermined narrow range of frequencies,
- means for obtaining from each energy burst of said voice wave a corresponding marker pulse indicative of the duration of its energy burst,
- a reduced bandwidth channel for transmitting said frequency shifted second band directly to a distant point, and
- interpolating means responsive to said marker pulse for delaying the transmission of each frequency shifted first band over said reduced bandwidth channel for the duration of the corresponding energy burst.

7. Apparatus for reconstructing a replica of a voice wave which comprises
- a source of a reduced bandwidth signal comprising selected low-frequency portions of the energy bursts of a voice wave separated by selected high-frequency portions of said energy bursts, each of said low-frequency portions being followed by the high-frequency portion of the same energy burst,
- means for delaying each of said low-frequency portions of said reduced bandwidth signal for a preassigned length of time,
- synchronizing means for bringing the high-frequency portion of each energy burst into time-coincidence with the delayed low-frequency portion of the same energy burst, and
- means for combining said synchronized low-frequency and high-frequency portions to reconstruct a replica of the original voice wave.

8. Apparatus for reconstructing a replica of a voice wave which comprises
- a source of a marker pulse indicative of the duration of an energy burst of a voice wave,
- a source of a reduced bandwidth signal comprising a selected band of low-frequency components of an energy burst of said voice wave followed by a selected band of high-frequency components of said energy burst,
- means under the control of said marker pulse for separating said low-frequency band from said high-frequency band,
- means for delaying said low-frequency band for a predetermined interval of time,
- means responsive to said marker pulse for bringing said high-frequency band into time-coincidence with the delayed low-frequency band,
- means supplied with said time-coincident bands for restoring said bands to their original frequency ranges, and
- means for combining said time-coincident, frequency restored bands.

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