U.S. Patent 3,047,660

John P. Costas

Means for Obtaining Character Time in a Radio Communication System Receiver

Application filed in 1960 | Patent issued to *General Electric* in 1962

Until the advent of PSK (phase shift keying) modulation in the late fifties, digital information was modulated on a carrier using FSK (frequency shift keying) modulation. PSK provided higher information content than FSK, permitting information to be conveyed at a spectral efficiency further up Shannon's theoretical curve of Bits/Hz versus E_b/N_o.

Demodulation of PSK and its successors (*e.g.*, QPSK, QAM) presented a new problem, however. Synchronization would now be needed with the modulated carrier (nanosecond timing), not just the underlying digital signal (micro/millisecond timing). As Costas pointed out in his patent, timing information had "to be obtained automatically and accurately even in the presence of fairly large amounts of noise or interference. . . .the timing system must operate properly no matter what message is sent."

The solution to this problem was the Costas loop, an elegant and far-reaching invention that used a control-feedback loop to begin the era of synchronous demodulation by "provid[ing] means for obtaining character time automatically into receiver in a radio Teletype system."

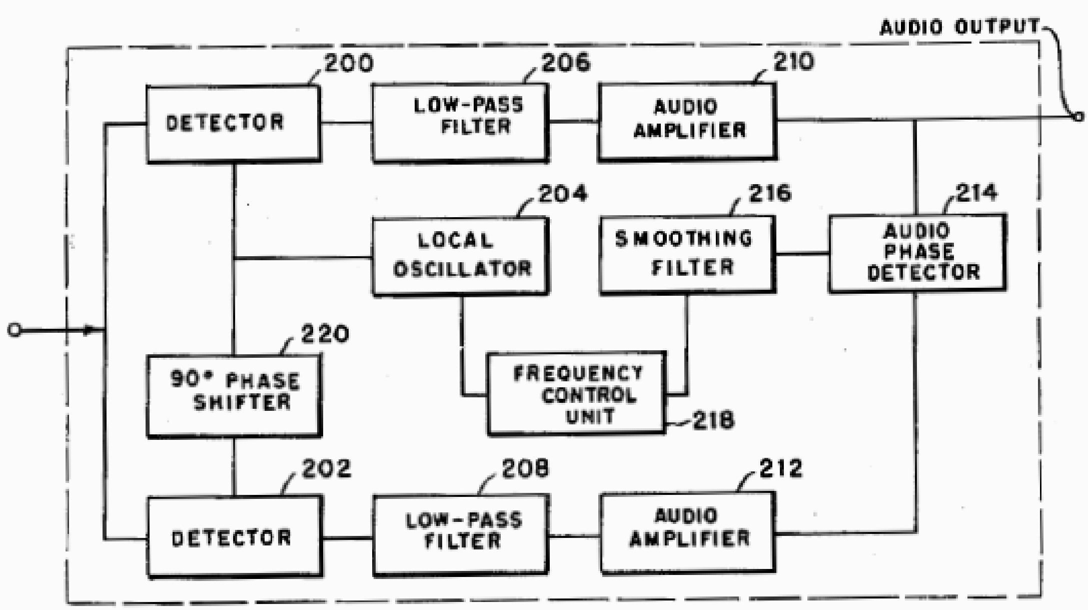

FIG.5

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July 31, 1962 J. P. COSTAS 3,047,660
MEANS FOR OBTAINING CHARACTER TIME IN A RADIO COMMUNICATION SYSTEM RECEIVER
Filed Jan. 6, 1960 7 Sheets-Sheet 1

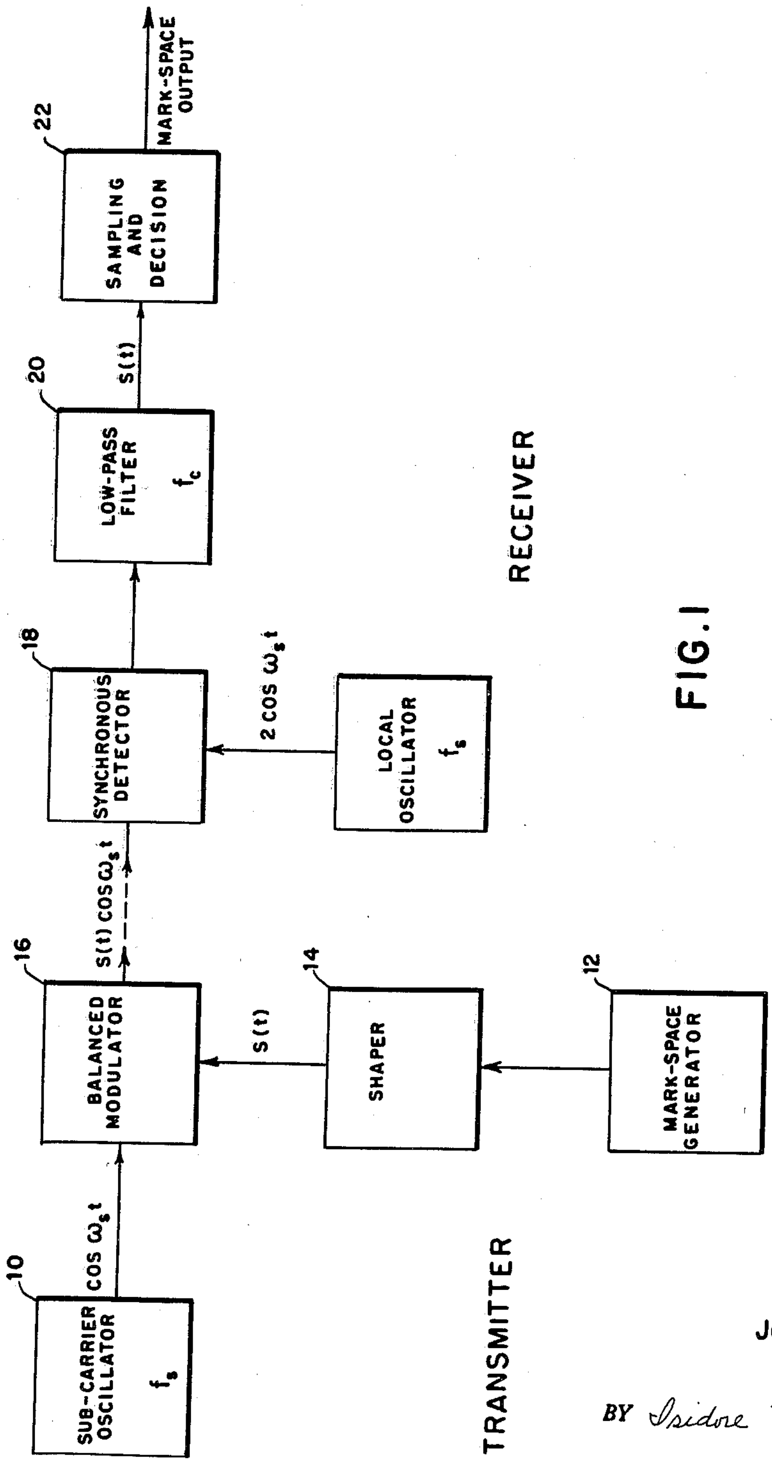

FIG. 1

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July 31, 1962 J. P. COSTAS 3,047,660

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Filed Jan. 6, 1960

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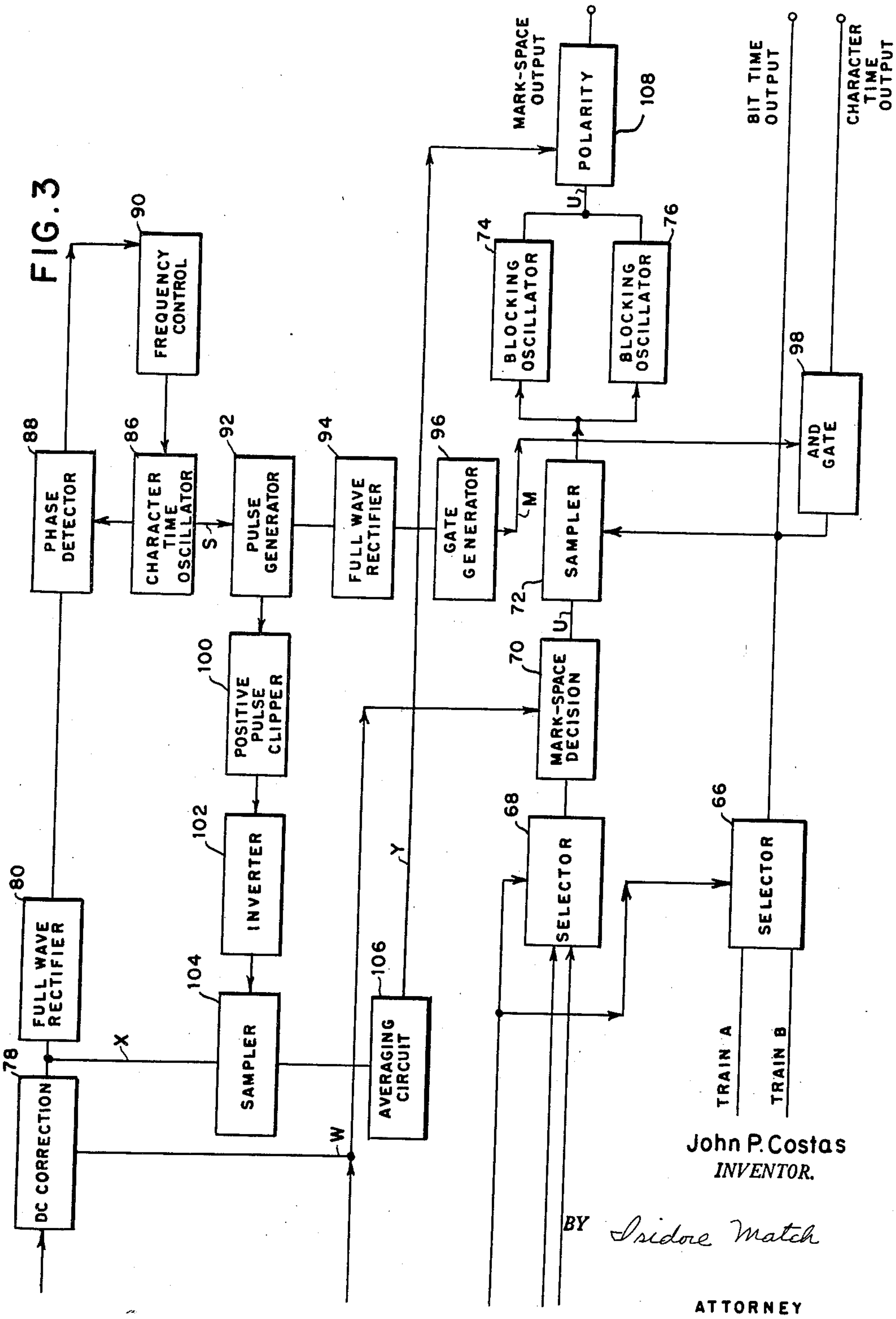

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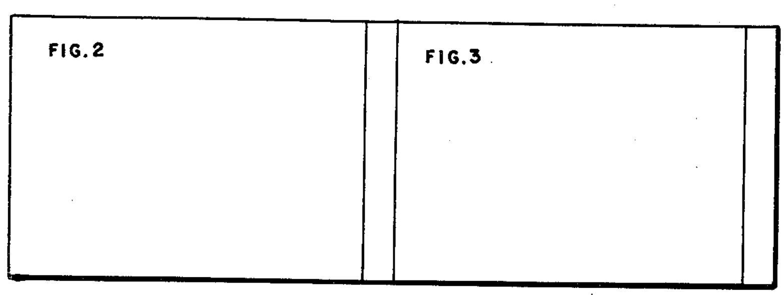
FIG. 4



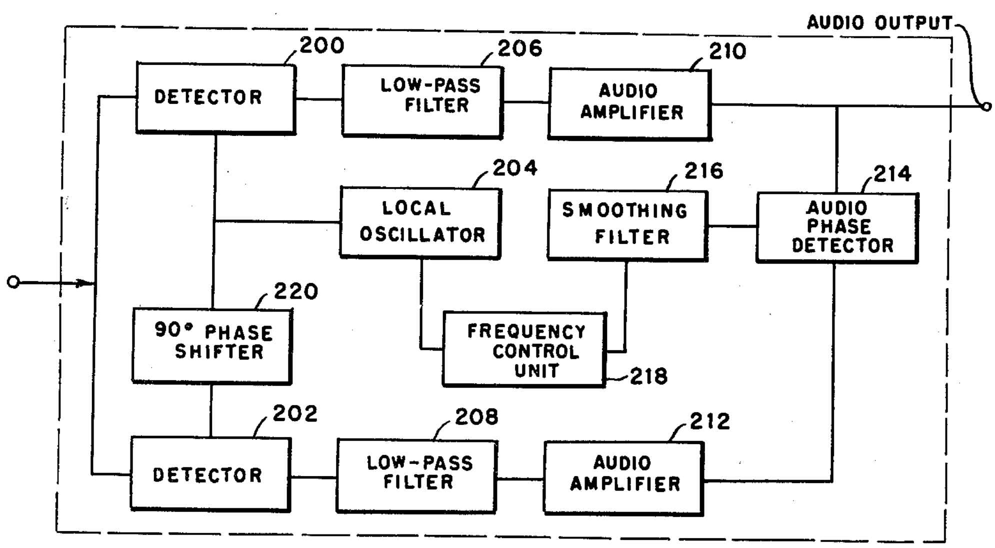


FIG. 5

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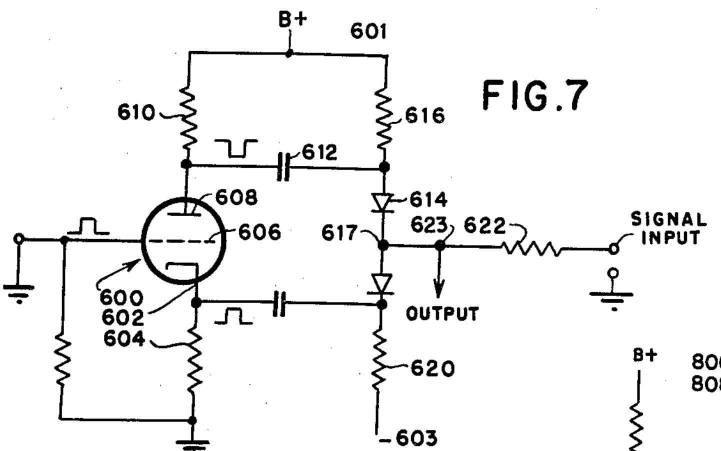

FIG.7

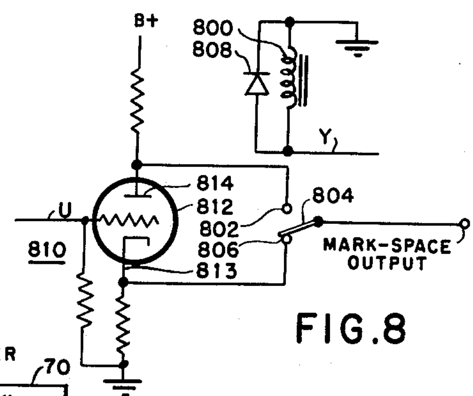

FIG.8

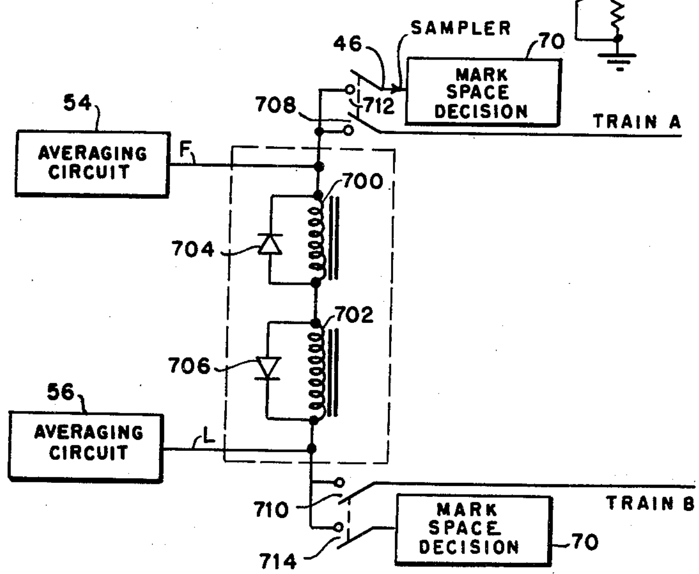

FIG.10

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July 31, 1962 J. P. COSTAS 3,047,660

MEANS FOR OBTAINING CHARACTER TIME IN A RADIO COMMUNICATION SYSTEM RECEIVER

Filed Jan. 6, 1960 7 Sheets-Sheet 7

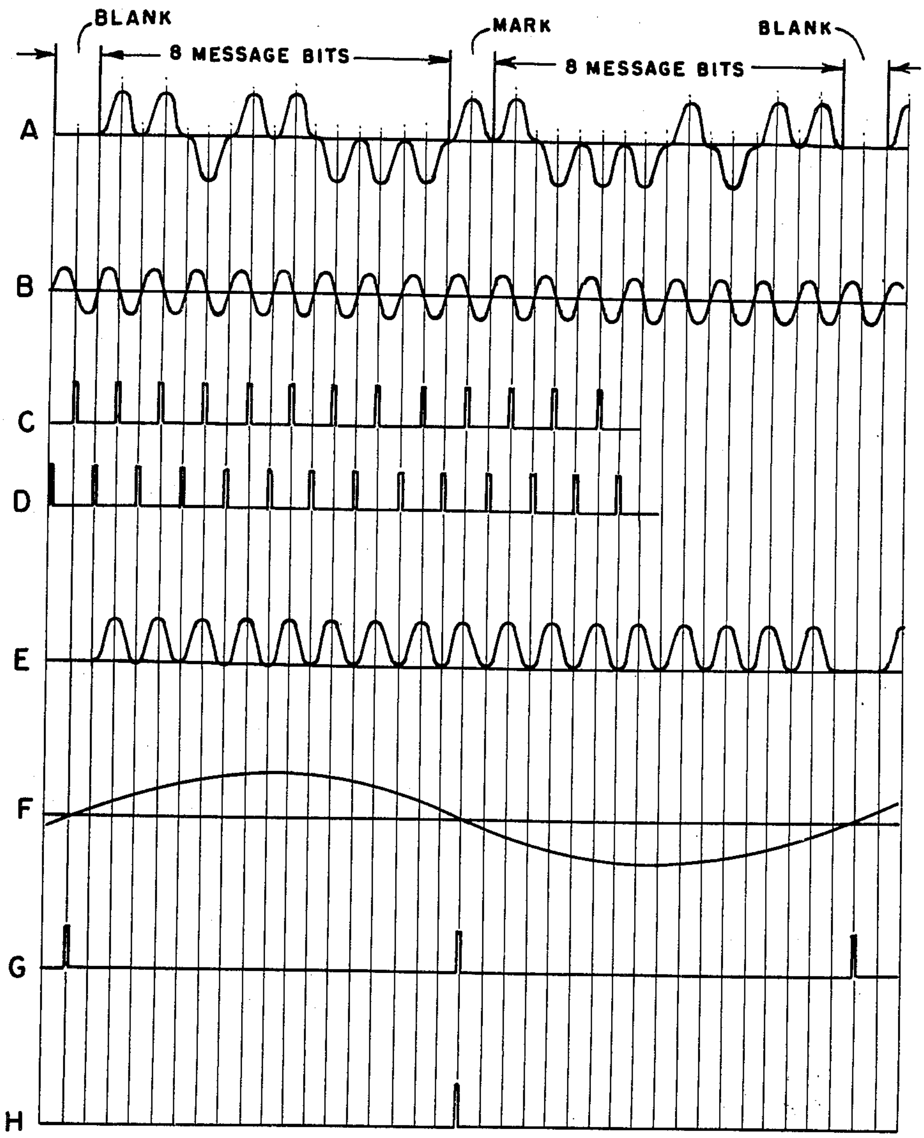

FIG. 9

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MEANS FOR OBTAINING CHARACTER TIME IN A RADIO COMMUNICATION SYSTEM RECEIVER

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Filed Jan. 6, 1960, Ser. No. 858

8 Claims. (Cl. 178—88)

This invention relates to data communication systems. More particularly, it relates to a receiver for an improved radio Teletype communication system which has advantageous gain and improved bandwith requirements.

Heretofore, in radio Teletype systems, frequency shift keying has been utilized for mark-space signal transmission. In a paper by Doelz and Heald entitled "A Predicted Wave Radio Teletype System," 1954 IRE Convention Record, part 8, pp. 63–69, there is described a system which exhibits an 8 db power advantage over a frequency shift keying system. Such "Predicted Wave" system may be regarded as a frequency shift keying system with the exception that the detection technique employed therein is different from conventional techniques. Thus, the mark and space signals are transmitted by frequency shift keying, but at the receiver, a semi-coherent detection and integration technique is employed for both the mark and space channels. A pair of integrators in the receiver provide two outputs, and a comparison of these two outputs determines the mark or space decision for a given baud. In the Doelz and Heald paper, it is pointed out that by the use of such integrator output comparisons, flat fading can be accommodated without the use of limiting amplifiers.

In a paper by John P. Costas entitled, "Phase-Shift Radio Teletype," published in the Proceedings of the IRE, vol. 45, No. 1, January 15, 1957, on pp. 16–20, there is discussed, in theory, a phase shift radio Teletype system and a comparison of its theoretical operation with the "Predicted Wave" radio Teletype system disclosed in the aforementioned Doelz and Heald paper. To make such comparison, a message structure similar to that employed in the Doelz and Heald system is assumed. This message structure is re-timed by storage techniques into a 7 baud character of 156 ms. duration with equal times assigned to each baud. Such time is somewhat shorter than the shortest character time for a sixty word per minute Teletype so that the transmission system stays ahead of the Teletype at all times. The Costas paper shows, essentially through a mathematical analysis, that a phase shift radio Teletype system has a substantial power advantage over both a frequency shift keying system and a predicted wave system.

Thus, if a receiver can be provided which will accurately detect information from a received carrier wave whose frequency remains unchanged but whose phase changes from zero to 180° with a mark-space transition, a substantial gain in power and efficiency and, depending upon the shape of message pulse that is used, a reduction of bandwidth requirements is achieved.

The operational requirements of such a receiver consist in the establishment of timing pulses at the receiver which indicate the beginning of a character and also the center of each bit interval of the bits which make up a character. This timing information has to be obtained automatically and accurately even in the presence of fairly large amounts of noise or interference. Furthermore, the operation of the timing system of the receiver must not be affected by the message structure, i.e., the timing system must operate properly no matter what message is sent, whether it be all marks, all spaces, or an intermixture of each. In addition, it is highly desirable that synchronizing information be contained in the message itself rather than the including in the transmission of special

synchronizing signals either at an out-of-band frequency or in quadrature phase.

It is an important object of this invention to provide means for obtaining character time automatically in a receiver in a radio Teletype system.

It is another object to provide a receiver as in the proceeding object wherein synchronizing information for obtaining character time is not required to be transmitted with the transmitted message.

Generally speaking, and, in accordance with the invention, there is provided a receiver for providing mark-space, bit time and character time information in a radio Teletype system wherein there is utilized a transmitted carrier wave whose phase is shifted by 180° during a mark-space transition. The wave is effectively a suppressed carrier amplitude modulated signal modulated by a message signal comprising bits which are positive and negative pulses, each of the bits having equal widths, a chosen number of bits comprising a single character, an interval of bit width between successive characters, one set of alternate intervals being blanks, the other alternate set of intervals containing a bit pulse of a chosen polarity.

The receiver comprises synchronous detecting means for demodulating the carrier wave and for phase locking the detected message signal with the phase of the carrier wave, the synchronous detecting means having 0° and 180° stable phase lock conditions with respect to the phase of the carrier wave. A generator is provided for producing a first signal having the frequency of the message signal pulse rate and means are included to phase lock the first signal, the latter phase locking means also having 0° and 180° stable phase lock conditions. From the phase-locked first signal, there are produced by suitable pulse generating means, first and second pulse trains, the pulses of one of the trains occurring substantially at the respective centers of the bits of the detected message signal, the pulses of the other of the trains occurring substantially at the respective points between adjacent bits of the detected message signal. First and second sampling means are included for sampling the output of the synchronous detecting means with the first and second pulse trains respectively and first and second substantially unidirectional potentials are derived which are proportional to the average magnitude of the outputs of the first and second sampling means respectively, regardless of the respective polarities of the outputs. Means are provided for comparing these first and second potentials to determine the greater thereof and first and second selecting means responsive to such determination respectively select the pulse train of the first and second pulse trains which comprises pulses occurring at the respective centers of the message signal bits whereby bit time information is provided and the output of either the first or second sampling means which comprise pulsed samples of the detected message signal taken at the respective centers of the message signal bits. Third and fourth substantially unidirectional potentials are derived which are respectively proportional to the average of the outputs of the first and second sampling means and a third selecting means selects the lesser of the third and fourth potentials. This latter selected potential together with the output of the sampling means selected by the second selecting means are applied in additive relationship in a first D.C. correction means, the output of the last named means being samples of the centers of the message bit intervals D.C. corrected for any D.C. shift in the message signal caused in the synchronous detecting means and the latter selected potential is also applied in additive relationship together with the output from the synchronous detecting means in the second D.C. correction means whereby the output of the synchronous detecting means is also corrected for any D.C. shift caused by the detecting means.

Means are provided for generating a second signal having a period equal to the sum of the periods of two characters and two bit intervals and such signal is phase-locked with the phase of the output of the second D.C. correction means. A generator is provided for producing a third pulse train having pulses occurring at the zero crossover points of the second phase locked signal, whereby the pulses comprising the third pulse train occur substantially at the respective centers of the intervals which separate successive characters. These pulses are essentially character time pulses. To insure the accurate occurrence in time of the character time pulses, they may be utilized to generate a gate, i.e. applied to a one-shot multivibrator and the output of the multivibrator may be applied together with pulse train of the first and second pulse train selected by the first selecting means to gate out a character time pulse. A fourth pulse train is provided, suitably from the third pulse train, and comprising pulses occurring at the center of those alternate intervals between characters occupied by a bit pulse and third sampling means is included to sample the output of the second D.C. correction means. A substantially fifth unidirectional potential is derived from the output of the third sampling means and polarity sensing means is provided which controls the polarity of the output of the first D.C. correction means, i.e. if the polarity of the fifth potential is the same as the polarity of the bit pulses occupying alternate intervals between characters, the polarity of the output of the first D.C. correction means is unchanged and if the polarity of the fifth potential is the opposite of that of the interval bit pulses, the polarity of the output of the first D.C. correction means is inverted. By the latter arrangement, the polarity ambiguity existing due to the two stable phase lock conditions of the synchronous detecting means is resolved and true mark-space information is provided.

The features of this invention, which are believed to be new are set forth with particularity in the appended claims. The invention itself, however, may best be understood by reference to the following description when taken in conjunction with the accompanying drawings which show an embodiment of a receiver according to the invention.

In the drawings, FIG. 1 is a functional block diagram of a phase-shift radio Teletype system;

FIGS. 2 and 3 taken together as in FIG. 4 is a block diagram of a receiver in accordance with the invention utilizable in the system of FIG. 1;

FIG. 5 is a block diagram of a synchronous detector suitable for use in the system depicted in FIGS. 2 and 3;

FIG. 6 is a schematic drawing of the detector of FIG.5;

FIG. 7 is a schematic diagram of an example of a sampling circuit suitable for use in the system of FIGS. 2 and 3;

FIG. 8 is a schematic diagram of an example of a circuit suitable for providing the polarity control of the mark-space output of the system of FIGS. 2 and 3;

FIGS. 9A–9H taken together is a timing diagram of the various wave forms respectively occurring at given points in the system of FIGS. 2 and 3; and

FIG. 10 is a suitable example of a D.C. voltage comparator and selecting means utilized in the system of FIGS. 2 and 3.

Referring now to FIG. 1, there is shown in brief functional outline, a synchronous radio Teletype system utilizing phase shift instead of frequency shift, as described in the hereinabove set forth Costas paper.

In this system, a carrier wave is transmitted whose frequency remains unchanged but whose phase changes from zero to 180° with a mark-space transition. Detection of this wave requires a coherent or phase-sensitive detector.

In the system of FIG. 1, the sub-carrier oscillator **10** having a frequency f_s provides an output voltage $\cos \omega_s t$. A mark-space generator **12** together with a shaper **14** provides an output $s(t)$. If it is assumed that the output of shaper **14** is a square wave of $\pm$E volts, the output of the balanced modulator **16**, i.e. the transmitted signal becomes $\pm E \cos \omega_s t$ (the + or − being determined by mark or space). It is to be noted that the use of a balanced modulator indicates that the transmiter is a double-sideband suppressed-carrier transmitter. If the synchronous detector **18** in the receiver is assumed to operate as a multiplier and if the cutoff frequency f_c of the low-pass filter **20** is adjusted to pass only the frequency band occupied by the $s(t)$ square wave, the $s(t)$ wave will appear at the output of low-pass filter **20**. This square wave is sampled and the appropriate mark-space decision is made in the sampling and decision stage **22**. It is to be noted that with this system, pre-detection filtering is not required since receiver selectivity is determined by the low-pass post-detector filter **20**. It is further to be noted that the low-pass filter output noise power is equal to the pre-detector noise power which falls in the frequency band $f_s - f_c$ to $f_s + f_c$. In the presence of noise, the low-pass filter output is sampled at the center of each baud interval. If this sample is positive, a mark decision is made; if the sample is negative, a space decision is made. With such arrangement, flat fading effects are substantially eliminated without the use of limiting circuits. There is, however, an increased probability of error as the signal to noise ratio worsens, but as is well kown, this is inevitable in any system.

The Costas paper explains the required band width for the system of FIG. 1. In this connection, the paper states that since the phase of a wave cannot be changed instantaneously without requiring infinite bandwidth and since instantaneous frequency and amplitude changes also require infinite bandwidth, to permit bandwidth conservation, a shaper circuit and a balanced modulator are employed in the transmitter of FIG. 1 to permit a phase transition of the transmitted signal between mark and space rather than an abrupt change. Shaper **14** converts the output of mark-space generator **12** into a pulse train $s(t)$ composed of individual pulses $p(t)$. A positive $p(t)$ pulse results for a mark and a negative $p(t)$ pulse results for a space. With this arrangement, the output of balanced modulator **16** is a wave having both amplitude variations as well as phase reversals and is a suppressed-carrier AM signal whose modulation consists of the pulse train $s(t)$. It is evident that this prevents the use of class C amplification of this type of signal, but since in the common multiplex operation of Teletype channels, class C amplification would not be possible even if the individual sub-channel signals were of a constant amplitude, phase-shifted variety, no practical advantage is lost by the shaping arrangement of FIG. 1. A bandwidth conservation per sub-channel thus can be realized which permits a closer spacing of sub-carrier frequencies in multiplex operation.

In the system of FIG. 1, if the minimum bandwidth is to be availed of, the pulse shape $p(t)$ preferably should have the form

$$p(t) = E\frac{\sin \omega_c t}{\omega_c t} \quad (1)$$

This pulse shape is the classical one which has no frequency components beyond f_c and permits independent sample values to be transmitted at a rate of $2f_c$. Thus, for a given mark-space transmission rate, the pulse shape defined by Equation 1 results in the minimum bandwidth requirements for binary data transmission.

The considerations determining pulse shape and bandwidth may readily be understood by the following explanation.

If there is considered a signal voltage $S(t)$ composed of a train of pulses $p(t)$ occurring at regular intervals and if the pulses $p(t)$ appear with equal probability of being positive or negative and if each pulse is independent of all other puses, then the autocorrelation function of $S(t)$, $\phi_{ss}(\tau)$, is given by

$$\phi_{ss}(\tau)=m\int_{-\infty}^{\infty}p(t)p(t+\tau)dt \qquad (2)$$

where m is the pulse rate. Further, if the pulse is assumed to be of a duration T_o, Equation 2 may be written as

$$\phi_{ss}(\tau)=m\int_{-T_o/2}^{T_o/2}p(t)p(t+\tau)dt \qquad (3)$$

where zero time represents the center of the pulse duration interval.

The power density spectrum of $S(t)$, $\Phi_{SS}(\omega)$ may be found by taking the Fourier Transform of the autocorrelation function $\phi_{ss}(\tau)$. This yields

$$\Phi_{SS}(\omega)=2\pi m|P(\omega)|^2 \qquad (4)$$

where $P(\omega)$ is the Fourier Transform of $p(t)$ as given by

$$P(\omega)=\frac{1}{2\pi}\int_{-\infty}^{\infty}p(t)\epsilon^{-j\omega t}dt \qquad (5)$$

Since the pulse is assumed to exist only for a time T_o, Equation 5 may be rewritten as

$$P(\omega)=\frac{1}{2\pi}\int_{-T_o/2}^{T_o/2}p(t)\epsilon^{-j\omega t}dt \qquad (6)$$

In the interval $(-T_o/2+T_o/2)$, if the pulse is symmetric about zero time, $p(t)$ may be expressed as

$$p(t)=\frac{a_o}{2}+\sum_{n=1}^{\infty}a_n \cos n\omega_o t \qquad (7)$$

where

$$\omega_o=2\pi/T_o \qquad (8)$$

When Equation 7 is substituted into Equation 5, there results

$$p(\omega)=\frac{T_o}{4\pi}\left\{a_o\frac{\sin \omega T_o/2}{\omega T_o/2}+\sum_{n=1}^{\infty}a_n\left[\frac{\sin (\omega T_o/2-n\pi)}{(\omega T_o/2-n\pi)}+\frac{\sin (\omega T_o/2+n\pi)}{(\omega T_o/2+n\pi)}\right]\right\} \qquad (9)$$

It is to be noted that

$$P(n\omega_o)=T_o a_n/4\pi \qquad (10)$$

signifying that

$$\Phi_{SS}(n\omega_o)=mT_o^2a_n^2/8\pi \qquad (11)$$

Thus of the Fourier Series expansion for $p(t)$ is limited to N terms, the power density spectrum will be zero at $\omega=(N+1)\omega_o$ and for all n greater than $N+1$. The power spectrum will not be zero for frequencies between these points, but it can be shown that very little energy exists beyond $\omega=(N+1)\omega_o$ and that this frequency essentially specifies the bandwidth requirements for the pulse train. (There can be no absolute cutoff frequency since the train is made up of time limited pulses and a pulse which is limited in time cannot be also bandlimited in frequency).

As for pulse shaping, once the bandwidth is determined, the non-zero a_n's may be chosen for pulse-shaping to meet design requirements.

Once the pulse shape is specified, the average power of $S(t)$ can be evaluated by substituting Equation 7 into Equation 2 and letting τ be zero. The result is

$$Pave=\frac{mT_o}{2}\left[\frac{a_o^2}{2}+\sum_{n=1}^{\infty}a_n^2\right] \qquad (12)$$

Thus, assuming that the message structure utilized in the system of FIG. 1 is a 7 baud character of 156 ms. duration with equal times assigned to each band, then the cutoff frequency of low-pass filter **20** has to be made equal to about 22.5 cycles per second if pulses according to Equation 1 are used. From Equation 12, it can be

shown that the average signal power input to the receiver synchronous detector **18** is

$$Pave=E^2/2 \qquad (13)$$

If noise is present at the input to the synchronous detector, the noise power at the low-pass filter output will be equal to the total predetector noise power falling within 22.5 cycles in either side of the local oscillator frequency. In other words, using the above message structure the receiver of FIG. 1 displays an effective predetector bandwidth of 45 cycles which is twice the cutoff frequency value of the low-pass filter.

The pulse-to-pulse time overlap utilizing the pulse shape defined in Equation 1 introduces a problem which can be avoided by a deviation from the classical pulse shape defined by this equation. In the message structure as assumed, the length of the period of each baud is about 22.2 ms. If some time overlap into adjacent baud periods (say 25%) is assumed, each pulse could be permitted a duration of 1.5×22.2 ms. or 33.3 ms. This would still leave the middle 50% of each baud interval free of adjacent pulse voltages and the sampling accuracy requirements of the receiver would be reasonable. Thus, a pulse shape $p(t)$ may be chosen having the form

$$p(t)=\frac{E}{2}(1+\cos \omega_o t),\ \left(-\frac{T_o}{2}<t<\frac{T_o}{2}\right) \qquad (14)$$

where

$$\omega_o=\frac{2\pi}{T_o}\ T_o=0.0333 \text{ sec.} \qquad (15)$$

If T_o is chosen to be 33.3 ms., the pulse defined by Equation 14 has a peak value of E volts and a duration of 33.3 ms. A pulse train $S(t)$ made up of such pulses requires a base-band frequency of 60 c.p.s. and the average *rf* signal power put into the receiver synchronous detector is

$$Pave=0.281E^2 \qquad (16)$$

It is seen that either using the pulse shape defined by Equation 1 or 14, a signal of E volts is produced at the output of low-pass filter **20**. If noise is not considered, the utilization of the pulse shape defined by Equation 14 shows a power advantage over the utilization of the pulse shape defined by Equation 1 of 0.500/0.281 or 2.51 db. However, if noise is present, the 2.51 db advantage is lost due to the increased bandwidth requirements utilizing the pulse shape defined by Equation 14. Thus, returning to the message structure of 22.2 ms. per baud period utilizing a low-pass filter with a cutoff frequency of 60 cycles rather than one of 45 cycles, a filter output noise power increase of 120/45, i.e. 4.27 db results. This leaves 4.27−2.51 or a 1.76 db signal-to-noise ratio advantage using the pulse shape of Equation 1. However, it is seen that a practical design for pulse shape $p(t)$ to be used in the system of FIG. 1 results in a system performance which is within 2 db of the theoretical limit permitted by the use of the pulse shape defined by Equation 1.

Referring now to FIGS. 2 and 3 taken together as in FIG. 4, there is shown a receiver in a synchronous radio Teletype system in accordance with the principles of the invention. The signal received is a carrier wave whose phase is shifted 180° by a mark-space transition. In the interests of bandwidth conservation, abrupt changes do not occur but instead the amplitude as well as the phase are changed for transmission of marks and spaces. When such changes are made in the carrier wave, the net result is a suppressed-carrier AM signal modulated by specially shaped positive and negative pulses. As described hereinabove, the "raised cosine" pulse shape defined by Equation 14 may be advantageously chosen to modulate a double sideband transmitter, i.e., from balanced modulator **16** of FIG. 1, although rectangular pulses may also suitably be utilized, FIG. 9A depicts such a raised cosine modulating message signal. This message signal comprises a pulse train at the baseband frequency comprising raised cosine pulses. Each character has been chosen to comprise 8 message bits but such choice obviously has been made for convenience of illustration and any number of bits per character may be chosen.

The modulated carrier signal is applied to a synchronous detector receiver 30. At this point it is convenient to refer to FIG. 5, which is a block diagram of a synchronous detector receiver and FIG. 6, which is a detailed schematic diagram of the block diagram of FIG. 5. The circuit of FIG. 5 is adapted for the reception and the demodulation of double-sideband signals. It comprises a pair of detectors **200** and **202**. Detectors **200** and **202** are synchronous detectors for developing an output which is proportional to an arithmetic product of the signals applied to a pair of inputs thereof. For example, they may comprise a frequency converter circuit such as the type used commonly in radio receivers for converting radio frequency signals into intermediate frequency signals.

Local oscillator **204** operates to develop a signal of carrier frequency and may be a conventional radio frequency oscillator whose frequency is controlled by a reactance device which in turn is controlled by suitable unidirectional potentials applied thereto. The local oscillator may also be a phase-shift type of oscillator and the frequency control element thereof may include means for varying the phase-shift of the feedback in the oscillator thereby changing its frequency.

The output from local oscillator **204** and the double side band signal to be demodulated are applied to detector **200**, at the output of which there is derived a signal corresponding to the modulating signal and a component of twice the frequency of the original carrier wave modulated by said modulating signal as will be further explained hereinbelow. The modulating signal is recovered by filtering. The output of local oscillator **204** is shifted in phase by 90° and also applied to detector **202** together with the double side band signal.

From the detector **202**, there is produced an ouput having frequency components similar to the frequency components in the output of detector **200**. This output includes a signal representing the modulating signal and and another signal having twice the carrier frequency modulated by the modulating signal. However, the amplitude and polarity of the modulating signal at the output of detector **202** may be different from the amplitude and polarity of the modulating signal at the output of detector **200** by a factor which is a function of the magnitude and direction of departure of the phase of the locally generated signal from local oscillator **204** with respect to the carrier wave as it would have been received had it been transmitted.

The outputs of detectors **200** and **202** are applied respectively to low-pass filters **206** and **208**. These filters remove the components from the respective detector outputs having twice the carrier frequency and signals having the modulating frequency appear at the respective outputs thereof. These modulating signals are amplified respectively by audio amplifiers **210** and **212**, the outputs of amplifiers **210** and **212** being applied to an audio phase detector **214**.

Audio phase detector **214** may be any of a variety of detectors for deriving a signal having one polarity when the signals applied thereto are in phase and another polarity when the signals applied thereto are out of phase with respect to each other, the amplitude of the derived signal depending upon the relative magnitudes of the two input signals. Thus, at the output of audio phase detector **214**, there is obtained a voltage whose polarity and magnitude vary in accordance with the direction and magnitude of departure of the phase of the signal from local oscillator **204** with respect to the phase of the carrier wave (if it were present) of the transmitted double side band signal.

The smoothing filter **216** separates the unidirectional current component from the alternating current components of the output of phase detector **214**. The output from smoothing filter **216** is applied to a frequency control unit **218** which functions to control the frequency of the local oscillator to maintain the output thereof in phase with the carrier wave. Thus, it is seen that with the arrangement of FIG. 5, not only is the modulating voltage recovered at the output of audio amplifier **210** but the channel of audio amplifier **210** is also utilized in conjunction with the channel of audio amplifier **212** to maintain local oscillator **204** in synchronism with the carrier wave to obtain the desired modulating signal without need for any transmitted carrier.

The operation of the system of FIG. 5 is readily understood by considering an example. Let it be assumed that the double side band suppressed carrier amplitude modulated signal is represented by the equation

$$V_1 = f_m(t) \cos \omega_0 t \tag{17}$$

Let it further be assumed that the output of the local oscillator **204** is represented by the equation

$$V_2 = \cos (\omega_0 t + \delta) \tag{18}$$

where δ is the phase error between the local oscillator signal and the carrier signal. In Equation 17, $f_m(t)$ represents the modulating signal which is assumed to have a zero mean value. Since detectors **200** and **202** develop an output proportional to the product of the inputs thereto, the voltage at the output of detector **200** may be represented by the equation

$$V_3 = \frac{f_m(t)}{2}[\cos \delta + \cos (2\omega_0 t + \delta)] \tag{19}$$

Similarly, since the local oscillator input to detector **202** from local oscillator **204** is shifted 90° in phase with respect to the corresponding input to detector **200** such shifted input may be represented by the following equation

$$V_4 = \sin (\omega_0 t + \delta) \tag{20}$$

so that at the output of detector **202**, there is obtained a voltage V_5 represented by the following equation

$$V_5 = \frac{f_m(t)}{2}[\sin \delta + \sin (2\omega_0 t + \delta)] \tag{21}$$

Since the double frequency components $\cos (2\omega_0 t + \delta)$ and and $\sin (2\omega_0 t + \delta)$ of Equations 19 and 21 will not be passed by filters **206** and **208**, at the outputs of these filters there is obtained respectively voltages V_6 and V_7 represented by the following equations

$$V_6 = \frac{f_m(t) \cos \delta}{2} \tag{22}$$

$$V_7 = \frac{f_m(t) \sin \delta}{2} \tag{23}$$

If δ is zero, voltage V_7 will also be zero. Thus, the voltage V_7 is indicative of the phase error. The error sense, i.e. whether δ is positive or negative may be determined at once by comparing the relative polarities of V_6 and V_7.

One way in which the information in Equations 22 and 23 can be used for phase control of local oscillator **204** is by means of audio phase detector **214**, which develops a unidirectional current component of voltage having a polarity and magnitude corresponding to the direction of phase error and magnitude thereof respectively in addition to alternating current components of voltage. The unidirectional current component of voltage is obtained at the output of smoothing filter **216** which removes the aforementioned alternating current components. Thus, the voltage applied to the frequency control unit **218** is a voltage which is zero if no phase error exists and which changes polarity when the phase error changes sign. Accordingly, in the manner described, a stable feedback control is had of the phase of the output of local oscillator **204**.

In the circuit of FIG. 5, described in the preceding equal percentage of marks and spaces over a certain period of time.

It is understood that the message structure shown in FIG. 9A is not mandatory. The character shown therein which is composed of eight bits has been selected for convenience of description in operation and explanation of the invention and it is to be understood a character composed of a greater or smaller number of bits than the eight shown in FIG. 9A may be used. Similarly, as to time for bit duration, this may also be selected depending on the design requirements of the system. For example, a system having bit durations of 0.5 ms. requires a base-band frequency of about 3 kc. Obviously, the bit duration can be varied depending upon the channel capacity desired or the transmission conditions which are expected. With the message structure shown in FIG. 9A and with 0.5 ms. bits, the system of this invention has a capacity of roughly 1,780 bits per second. If properly used, this permits the operation of about 60 teletype machines operating at 60 words per minute.

While there have been described what are considered to be the preferred embodiments of this invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the invention and it is, therefore, aimed in the appended claims to cover all such changes and modifications as fall within the spirit and scope of the invention.

What is claimed and desired to be secured by Letters Patent of the United States is:

1. In a radio Teletype system wherein there is utilized a transmitted wave whose phase is shifted by 180° during a mark-space transition, the wave effectively being a suppressed carrier amplitude modulated signal modulated by a message signal comprising bits which are positive and negative pulses, each of the bits having equal widths, a chosen number of bits comprising a single character, an interval of bit width between successive characters, one set of alternate intervals being blanks, the other set of alternate intervals containing a bit pulse of a chosen polarity; a receiver in said system for providing character time information comprising phase locking synchronous detecting means for demodulating said transmitted wave and for phase-locking the detected message signal with the phase of the carrier contained in the sidebands of the transmitted suppressed carrier signal, means for applying said transmitted modulated wave to said synchronous detecting means, means for generating a signal for a period equal to the sum of two characters and two interval periods, means for phase-locking said generated signal with the phase of said detected message signal, means for applying said generated signal and said phase-locked detected signal to said last named phase-locking means and means responsive to the application thereto of said phase-locked signal for generating a pulse train comprising pulses occurring at the zero crossover points of said generated signal.

2. In a radio Teletype system wherein there is utilized a transmitted wave whose phase is shifted by 180° during a mark-space transition, the wave effectively being a suppressed carrier amplitude modulated signal modulated by a message signal comprising bits which are positive and negative pulses, each of the bits having equal widths, a chosen number of bits comprising a single character, an interval of bit width between successive characters, one set of alternate intervals being blanks, the other set of alternate internate intervals containing a bit pulse of a chosen polarity; a receiver in said system for providing character time information comprising phase locking synchronous detecting means for demodulating the transmitted wave and for phase-locking the detected message signal with the phase of the carrier contained in the sidebands of the transmitted suppressed carrier signal, means for applying said transmitted modulated wave to said synchronous detecting means, in circuit with means for rectifying the output of said synchronous detecting means, means for generating a signal having a period equal to the sum of the periods of two characters and two interval periods, means for phase-locking the phase of said generated signal with the phase of said rectified output of said synchronous detecting means, means for applying said generated signal and said phase-locked detected signal to said last named phase-locking means and means responsive to the application thereto of said phase-locked generated signal for generating a pulse train comprising pulses occurring at the zero crossover points of said generated signal.

3. In a radio Teletype system wherein there is utilized a transmitted wave whose phase is shifted by 180° during a mark-space transition, the wave effectively being a suppressed carrier amplitude modulated by a message signal comprising bits having equal widths, a receiver in said system for providing character time information comprising phase locking synchronous detecting means responsive to the application of said transmitted wave for demodulating said carrier transmitted wave and for phase locking the detected message signal with the phase of the transmitted wave, means responsive to the application thereto of said detected message signal for generating a first signal having the frequency of the detected message signal and for phase locking said first signal with the phase of said detected signal, means for generating first and second pulse trains in response to the application thereto of said first phase locked signal, the pulses of one of said trains occurring substantially at the respective centers of said bits of said detected message signal, the pulses of the other of said trains occurring substantially at the respective points between adjacent bits of said detected message signal, first sampling means for sampling the output of said detecting means with said first pulse train, second sampling means for sampling the output of said detecting means with said second pulse train, means coupled to the output of said first sampling means for deriving a first substantially unidirectional potential which is proportional to the average, regardless of polarity, of the said output of said first sampling means, means coupled to the output of said second sampling means for deriving a second substantially unidirectional potential, which is proportional to the average, regardless of polarity, of the output of said second sampling means, means in circuit with both of said sampling means for comparing said first and second potentials, first selecting means responsive to the greater of said first and second potentials for selecting the output of the sampling means of said first and second sampling means whose pulses occur at the center of the bits of said detected message signal, means in circuit with said first sampling means for deriving a third substantially unidirectional potential which is proportional to the average of the output of said first sampling means, means in circuit with said second sampling means for deriving a fourth substantially unidirectional potential which is proportional to the average of the output of said second sampling means, second selecting means responsive to the one of said third and fourth potentials which is derived from the output of the sampling means whose samples occur between message signal bits, D.C. correction means for adding said one of said third and fourth potentials selected by said second selecting means to the output of said synchronous detecting means, means for generating a second signal having a period equal to the sum of two character periods, means responsive to the application thereto of said second signal and the output of said D.C. correction means for phase locking the phase of said second signal with the phase of the output of said D.C. correction means and means responsive to the application thereto of said phase locked second signal for generating a third pulse train comprising pulses at the zero crossover points of said second signal.

4. In a radio Teletype system wherein there is utilized a transmitted wave whose phase is shifted by 180° during a mark-space transition, the wave effectively being a sup-