DOPPLER-CORRECTED DIFFERENTIAL DETECTION SYSTEM

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The United States Patent Office

Doppler in a communication system operating with a multiple differential phase-shift-keyed format ("MDPSK") creates an adverse phase shift in an incoming signal. An open loop frequency estimation is derived from a Doppler-contaminated incoming signal. Based upon the recognition that, whereas the change in phase of the received signal over a full symbol contains both the differentially encoded data and the Doppler effect, a symbol (within a given symbol interval) contains only the Doppler induced phase shift, the same change in phase over half a symbol (within a given symbol interval) contains only the doppler induced phase shift, and the Doppler effect can be estimated and removed from the incoming signal. Doppler correction occurs prior to the receiver's final output of decoded data. A multiphase system can operate with samplings per symbol interval at no penalty in signal-to-noise ratio provided that an ideal low pass pre-detection filter is employed, and two samples, at \( \frac{1}{2} \) and \( \frac{3}{2} \) of the symbol interval \( T_s \), are taken and summed together prior to incoming signal data detection.

31 Claims, 13 Drawing Sheets
FIG. 5
FIG. 7A

FIG. 7B

FIG. 7C
FIG. 10
FIG. 13

- ANALYSIS
- X X X SIMULATION (AWGN)
- ■ ■ ■ SIMULATION (FADING)
SIMULATION WITH 20% TIME JITTER (AWGN)
• SIMULATION WITH 20% TIME JITTER (FADING)
X SIMULATION WITH 10% TIME JITTER (AWGN)
■ SIMULATION WITH 10% TIME JITTER (FADING)

\[ \sigma_{\Delta \omega_T} \]

\[ \frac{E_b}{N_0}, \text{dB} \]

**FIG. 14**
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DOPPLER-CORRECTED DIFFERENTIAL DETECTION SYSTEM

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected not to retain title.

TECHNICAL FIELD

This invention relates to an improved communication system which is provided with a Doppler-corrected differential detector located in the communication system's receiver.

BACKGROUND ART

Digital data communication systems employing a carrier that is modulated by data at a transmitter and demodulated at a receiver to decode the transmitted data are well known. Several different types of modulation and demodulation are known and used. This invention pertains to a type of modulation-demodulation which employs data transmission through multiple differential phase-shift-keying ("MDPSK") at the modulator and a comparable differential detection at the system's receiver or demodulator.

Modems, a contraction for modulators and demodulators, are commonly used at both ends of a data communication transmission system. When one modem physically moves relative to another modem in a transmission link, the transmitted signals experience a Doppler effect. Typically Doppler effects are experienced in an earth to space satellite link and cause an effective change of frequency of a received signal due to the relative velocity of the link's transmitter with respect to the link's receiver. The Doppler effect must be rectified in order to achieve efficient data transmission and reception.

A prior art search related to the invention discloses some typical approaches to Doppler correction. Not one of the references located in the search, however, discloses or suggests an open-loop Doppler frequency estimation derived from an incoming signal. Moreover, open-loop correction for a Doppler effect in a MDPSK system having an improved filtering and differential detection configuration is not disclosed in the prior art.

The following search-located U.S. Pat. Nos. include: Heard et al 4,520,493, Poklemba 4,419,759, Poklemba et al 4,472,817 and Mehrgardt et al 4,663,595. Heard '493 discloses a complex closed-loop Doppler correction scheme that decodes and then attempts to correct for the next expected Doppler effect. Such closed loop tracking is not feasible in certain Doppler-related applications e.g., a multipath fading environment. Poklemba et al '817 discloses open loops but does not disclose Doppler correction in a differential detection system. Poklemba '759 is a typical phase-locked loop system. Mehrgardt '959 is of marginal interest only in that it discloses delays and summers in a form typically known in the modulator/demodulator art.

A multipath fading environment creates uncertainties in the carrier phase and/or frequency. These uncertainties essentially eliminate the known techniques which use a phase and/or frequency tracking synchronization loop. Moreover, the above-noted uncertainties may be further masked by phase jitter on the carrier reference. This additional transmission impairment adds further complexity to the system operation. Differential detection employs, as a demodulation reference, the phase and frequency of the carrier corresponding to the previous transmitted data symbol. The deleterious effects in a multipath fading environment are largely avoided by that differential system approach because there is no requirement that the carrier must be synchronized during each present symbol interval. Another known transmission impairment is intersymbol interference (ISI). It is known to use pulse shaping so that the ISI at a receiver is at a minimum at the sampling point at the receiver. Such a scheme filtering between the transmitter and receiver locations is a known way of achieving pulse shaping and minimum ISI.

For MDPSK systems it is common to strive for what is known as a 100% raised-cosine spectrum at the decoder's input. In an MDPSK system such shaping will achieve a satisfactory signal to noise ratio for center sampling at the decoder or demodulator. Various types of multilevel coding and decoding schemes have been introduced in efforts to achieve an optimum signal to noise ratio for such center sampling. Included within these multilevel schemes is the so-called duobinary signaling, a partial response signaling scheme as taught in A. Lender, "The Duobinary Technique for High Speed Data Transmission," IEEE Transactions on Communication Electronics, Vol. 82, May 1963, pp. 214-218.

STATEMENT OF THE INVENTION

The invention features an open loop frequency estimation derived from a Doppler-contaminated data-modulated input signal. A Doppler estimate is obtained in a doppler-estimating circuit and that estimate is followed by Doppler correction prior to the receiver's decoding of the modulated data. An overall Doppler-corrected differential detection system of simple and efficient design is thus provided.

One of the key features of the invention is based upon the inventor's recognition that whereas the change in phase of the received signal over a full symbol contains the sum of the differentially encoded data and the Doppler induced phase shift, the same change in phase over half a symbol (within a given symbol interval) contains only the Doppler induced phase shift. Thus, by proper open-loop processing, including post-detection integration (whose duration is related to the rate of change of the Doppler), the Doppler effect can be estimated and removed from the incoming signal. It has been further discovered that a multiphase system can operate with two samplings per symbol interval at no penalty in signal-to-noise ratio. This discovery is possible provided that an ideal low pass pre-detection filter is employed, and two samples, at $\frac{1}{2}$ and $\frac{3}{2}$ of the symbol interval $T_s$ are taken and summed together prior to decoding.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 depicts a prior art differentially coherent receiver employing a full symbol delay;

FIG. 2 is a basic block diagram of an open-loop Doppler-corrected differentially coherent receiver system in accordance with the invention;

FIG. 3 depicts an I-F implementation of the invention of FIG. 2;
FIG. 4 depicts a baseband implementation of the invention of FIG. 2; FIG. 5 is a set of curves useful in demonstrating the performance of the invention; FIG. 6 is another set of curves also useful for demonstrating the invention's performance; FIG. 7 is a simple building-block diagram depicting the Doppler-corrected receiver in complex form, in a tracking mode; FIG. 7A supplies a more detailed form of the Doppler estimator of FIG. 7; FIG. 7B depicts a fast acquisition circuit for Doppler correction; FIG. 7C depicts a fast acquisition circuit which is equivalent to that depicted in FIG. 7B; FIG. 8 is a block diagram, employing the building blocks of FIG. 7, 7A and 7C, to form a dual mode Doppler-corrected differential detector in complex form.

FIG. 9 is the dual mode Doppler-corrected MDPSK receiver of the invention using quadrature components of a received baseband signal; FIG. 10 is an eye diagram that shows sample points for zero intersymbol interference for the system of FIG. 9; FIG. 11 is a mathematical model which is useful in describing a more complex feature of the invention; FIG. 12 is a mathematical equivalent of FIG. 11; FIG. 13 is a graph depicting the improvement in results achieved by the invention in the absence of time jitter; and FIG. 14 is a graph similar to that of FIG. 13 depicting results in the presence of ten and twenty percent time jitter.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 is a typical block diagram of a known differential detector in a MDPSK receiver. At input terminal 5 an input signal s(t) which may include modulated data and Gaussian noise is split into an in-phase (I) and a quadrature phase (Q) channel 10 and 20 respectively. The quadrature phase channel 20 includes a 90 degree phase shifter 15.

Each channel includes a full symbol interval delay provided by two half-symbol delay networks 31, 32 and 41, 42. Each network thus provides a one-half symbol delay time. Multiplying junctions 35, 45 multiply the undelayed and delayed signals together to form a basis for comparing two different time-related phase angles of the input signals applied to those multiplying junctions 35, 45. The output of each multiplying junction is applied to a detector 50, which detector determines the angular difference between s(t) and s(t) delayed by one symbol and applies a decoded output signal an output lead 6. Both in-phase (I) and quadrature phase (Q) channels 10, 20 are required to represent the well-known phasor diagrams of the prior art.

FIG. 2 includes the broad concept of the Doppler-corrected differential phase detection of the invention. A key feature of the invention is provided by a Doppler estimator circuit 100 which requires input signals from both the in-phase channel 10 and the quadrature channel 20. The in-phase channel 10 supplies a pair of input signals to circuit 100 in the form of an incoming signal s(t) and a delayed version thereof. Doppler estimator circuit 100 receives the incoming signal s(t) over lead 90 and also receives a one-half (T/2) delayed version of that incoming signal over lead 101, which lead connects the output of the T/2 delay circuit 31 to Doppler estimator 100. Simultaneously the quadrature channel 20 applies an input signal to circuit 100 in the form of a phase shifted s(t) and a delayed version thereof. Being delayed by less than a full symbol interval, the input signals from channels 10 and 20, into Doppler estimator 100 have the same data-representing phase; but, with proper processing, the Doppler-induced change in phase in the incoming signal s(t) can be estimated in circuit 100.

Multipliers 35 and 45, operating as before, are connected as in FIG. 1. Doppler removal is done in both the channels and it will now be described.

Between the multipliers 35, 45 and decoder 50 are located Doppler removal circuits 125 and 150. Each Doppler removal circuit receives the estimated Doppler signal from estimator 100 and that estimated signal, prior to signal decoding in detector 50, is removed by Doppler removal circuits 125, 150 in the (I) and (Q) channels 10, 20 respectively. With the Doppler effect nullified, detector 50, in known fashion, delivers a data-representing output signal on lead 6 in accordance with standard MDPSK decoding techniques.

The detector 50 may be of any suitable and known type. Such detectors include the type which employ a maximum-likelihood decoding algorithm. Further processing of the output signal on lead 6 depends upon whether the transmitted data is coded or uncoded. In the case of uncoded data, a decision on the output is conventional as known for FIG. 1. For coded transmission, the output is used directly (in practice, it is Q-BIT quantized) as a soft decoding metric.

A more detailed and rigorous description of the invention is now presented with reference to FIG. 3. In FIG. 3, the Doppler-contaminated input signal s(t) is shown at input terminal 5. That signal is defined as:

\[ s(t) = \sqrt{2P} \sin [(\omega_0 + \Delta \omega_0 + \theta(t)] \tag{1} \]

where \( \omega_0 \) is the carrier, and \( \Delta \omega_0 \) the Doppler shift and \( \theta(t) \) is the data modulated phase information in the form of a predetermined angle shift and some arbitrary phase shift that may be neglected. The input signal will also contain Gaussian noise \( n(t) \) at lead 7, which noise is defined as:

\[ n(t) = \sqrt{2P} \cos (\omega_0 + \Delta \omega_0 + \phi(t)] \sin (\omega_0 + \Delta \omega_0 + \phi(t)] \tag{2} \]

where \( P \) denotes the average signal power in watts, \( \Delta \omega = 2\pi f_\text{IF} \) is the radian Doppler shift, \( B(t) \) is MPSK modulation with symbol rate \( 1/T_s \), and \( n(t), n_s(t) \) are low-pass Gaussian noise processes with one-sided power spectral density \( N_0 \) W/Hz.

Input leads 5 and 7 are connected to summing junction 14, which junction, in turn, is connected to a band pass IF filter 33 which functions to limit the noise in the summed signal. After passing the sum of \( s(t) \) and \( n(t) \) through the IF filter 33 (which for simplicity of analysis is assumed not to distort \( s(t) \), the resulting signal, \( y(t) \), is then processed in parallel by the in-phase (I) and quadrature phase (Q) channels 10 and 20. These two channels produce signals suitable for data detection and Doppler estimation in accordance with the present invention.
In the Doppler estimation circuit 100 of the receiver, the in-phase and quadrature input components (delayed $T_s/2$ by delay circuits 31, 41) are multiplied at multipliers 21, 22 with the undelayed input itself. After zonal filtering by IF filters 34, 36 the second harmonic of the carrier has been removed, leaving the following signal:

\[
x_k(t) = \frac{1}{\sqrt{2}} \sin(\omega_c t - \phi_k - \Omega t) + \frac{1}{\sqrt{2}} \cos(\omega_c t - \phi_k - \Omega t)
\]

where \(\omega_c\) is the carrier frequency, \(\Omega\) is the Doppler frequency, and \(\phi_k\) is the phase of the kth data symbol.

The signals \(x_k\) and \(x_{sk}\) are sampled by switches 81, 82 respectively, and these samples are amplified by gain \(G\) and multiplied by the in-phase and quadrature input components (delayed by \(T_s/2\)), \(A_{sk}\) and \(A_{sk}'\), respectively. After zonal filtering in circuits 81, 82 and amplification by gain \(G\), the desired Doppler term, and \(N'_k\) and \(N'_k'\) are input noise terms. The noise free sample values at the output inputs are respectively applied as one of the inputs to the multiplier circuit 96, and the output signal \(x_k'\) is given by:

\[
x_k' = P \sin(\omega_c T_s + \Omega t) + n(t)(\omega_c t - T_s) + n(t) \sin(\omega_c t - T_s) + n(t) \sin(\omega_c t - T_s)
\]

and, in accordance with our previous assumption, we have made use of the fact that \(\Delta T_s\) is an integer multiple of \(2\pi\). Switches 53, 54 are used to sample \(x_k(t)\) and \(x_{sk}(t)\) at the midpoint of the symbol intervals. See FIG. 10 for the location of midpoint sampling.

The signals \(x_k\) and \(x_{sk}\) are sampled by switches 81, 82 respectively, and these samples are amplified by gain circuits 91, 92 each of which provide a gain term of \(1 - \alpha\). Equation 6 shows that the data term has disappeared and we are left with the Doppler estimation signal. Finally, filtering each sample sequence to reduce undesired phase noise, an estimate \(\Delta T_s\) of the normalized Doppler \(\Delta T_s\) can be obtained. The required filtering is performed using digital filters 93, 94 with gain coefficient \(\alpha (0 < \alpha < 1)\). In such a case, the Doppler estimate, \(\Delta T_s\), is given by:

\[
\Delta T_s = 2 \sin^{-1} \left( \frac{1 - \alpha}{2} \sum_{k=0}^{\infty} a_{x_k}_{l, k} \right)
\]

Taking the sine and cosine of this estimate, namely,

\[
y_s = \cos \Delta T_s\]

gives a pair of quadrature signals that can be further processed and used to remove the Doppler content from the in-phase and quadrature data detection channels, 10, 20 respectively. Before describing that removal, however, the data detection portion of the system will be described in further detail.

In the data detection portion of the receiver, the in-phase and quadrature input components (delayed by \(T_s\) via circuits 31, 32 and 41, 42) are correlated with the input itself to produce (after zonal filtering in circuits 51, 52)

\[
x_k(t) = \frac{1}{\sqrt{2}} \sin(\omega_c t - \phi_k - \Omega t) + \frac{1}{\sqrt{2}} \cos(\omega_c t - \phi_k - \Omega t)
\]

where \(\omega_c\) is the carrier frequency, \(\Omega\) is the Doppler frequency, and \(\phi_k\) is the phase of the kth data symbol.

The signals \(x_k\) and \(x_{sk}\) are sampled by switches 81, 82 respectively, and these samples are amplified by gain circuits 91, 92 each of which provide a gain term of \(1 - \alpha\). Equation 6 shows that the data term has disappeared and we are left with the Doppler estimation signal. Finally, filtering each sample sequence to reduce undesired phase noise, an estimate \(\Delta T_s\) of the normalized Doppler \(\Delta T_s\) can be obtained. The required filtering is performed using digital filters 93, 94 with gain coefficient \(\alpha (0 < \alpha < 1)\). In such a case, the Doppler estimate, \(\Delta T_s\), is given by:

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\]

Taking the sine and cosine of this estimate, namely,

\[
y_s = \cos \Delta T_s\]
ever, is that here, in the baseband configuration, we are dealing with baseband signals rather than IF signals and is a transport or TI-sec delayed version of the received signals alone. This difference is a consequence of multi-plexed signals are formed from the I signal as appropriate). In the IF configuration, the received signals are processed using delay and multiply operations, we can write

\[ y_i = Z_{iK} \cos \frac{2\pi i}{M} + Z_{iK} \sin \frac{2\pi i}{M} \]

which then goes to a decision device. If the modulation is coded, then the Doppler-corrected signals I_t and Q_t would be input to a maximum-likelihood decoder over leads 123, 124. Multipliers 125 and 130 receive the cosine and sine of the various possible phase angles that are available in the coding format. These reference phasors for the decision making process are applied to leads 121 and 122 connected to an input of multipliers 125 and 130. Component 135 is a summer for summing the two outputs of multipliers 125 and 130. Summer 135 is connected to a decision device as is shown which selects the phase angle that is closest to the various reference angles.

FIG. 4 is a baseband implementation of the invention. The primary differences between the IF and baseband implementations (FIGS. 3 and 4, respectively with like numerals designating like components and functions) is described as follows. In the IF operation signals are delay and multiplied (31, 32, 28 and 41, 42, 29) at the carrier frequency producing sum and difference terms. The difference terms represent the desired signals which contain either the Doppler alone (Eqs. (5) and (6)) or the sum of the data and Doppler (Eq. (9)). The sum terms represent second harmonics of the carrier which do not have zero mean and variance

\[ \sigma^2 = \beta N_B \left( 1 + \frac{N_B \beta}{2c^2} \right) \]

where B is the input IF filter bandwidth.

Using (14) in (6) and applying straightforward trigonometric operations, we can write (7) in the normalized form

\[ \Delta_2 T_s - \Delta_2 T_2 = 2 \tan^{-1} \left( \frac{\xi}{2p + \xi} \right) \]

where

\[ \xi = \sqrt{1 - a_2^2} \sum_{k=0}^{\alpha} a^{k} \frac{A_{2k}}{\sigma} ; \sigma_2 = 0, \sigma_2^2 = 1 \]

common to all baseband and IF equivalent circuitry. FIG. 4 requires no further discussion because it uses the features and principles described in connection with FIG. 3 hereinafter.

**PERFORMANCE OF THE DOPPLER ESTIMATOR**

To assess the performance of the Doppler estimator 100 operating in accordance with this invention as described in equation (7), we must characterize the statistical properties of the noise samples N_t and N_t. Using terms (1) and (2) in equation (4), it is straightforward to show that

\[ N_{tK} = A_{tK} \cos \Delta_2 T_2 - A_{tK} \sin \Delta_2 T_2 \]

where A_tK and A_tK are, respectively, samples (at t_k=([4k+3]/4)T_2) of A_t(t) and A_t(t) defined by

\[ A_t(t) = \overline{N_t} \sin \theta(t - T_2) + \overline{N_t} \sin \theta(t + T_2) + \overline{N_t} \sin \theta(t - T_2) \]

and

\[ A_{tK} = \overline{N_t} \sin \theta(t - T_2) - \overline{N_t} \sin \theta(t + T_2) - \overline{N_t} \sin \theta(t - T_2) \]

The non-Gaussian orthogonal components A_tK and A_tK are uncorrelated. Furthermore, B_tK and A_tK both have zero mean and variance

\[ \sigma^2 = \beta N_B \left( 1 + \frac{N_B \beta}{2c^2} \right) \]

where B is the input IF filter bandwidth.

Using (14) in (6) and applying straightforward trigonometric operations, we can write (7) in the normalized form

\[ \Delta_2 T_s - \Delta_2 T_2 = 2 \tan^{-1} \left( \frac{\xi}{2p + \xi} \right) \]

where

\[ \xi = \sqrt{1 - a_2^2} \sum_{k=0}^{\alpha} a^{k} \frac{A_{2k}}{\sigma} ; \sigma_2 = 0, \sigma_2^2 = 1 \]

\[ \xi = \sqrt{1 - a_2^2} \sum_{k=0}^{\alpha} a^{k} \frac{A_{2k}}{\sigma} ; \sigma_2 = 0, \sigma_2^2 = 1 \]
Thus, $\Delta \phi T_s$ is an unbiased estimator of $\Delta \phi T_s$. Making the practical assumption that $K_a$ is large enough (say $K_a=10$ is sufficient) and applying central limit theorem-type arguments, then $\phi_d$ (are approximately Gaussian distributed. Under this condition, the probability density function of $\nu \Delta \Phi/2=(\Delta \phi-\Delta \phi)T_s/2$ is given by

$$p_d(v) = \frac{\exp\left(-\rho \sin^2 \nu \cos \nu \left[1+\exp\left(1+\cos \nu \right)\right]\right)}{2\pi}.$$  

The variance of the estimator can be computed from the second moment of (19) which for $K_a$ large becomes

$$\sigma_a^2 = \frac{1}{K_a} \left(1+N_0B/2P\right)$$


EVALUATION OF THE AVERAGE SYMBOL ERROR PROBABILITY

In R. F. Pawula, S. O. Rice, and J. H. Roberts, "Distribution of the Phase Angle Between Two Vectors Perturbed by Gaussian Noise," IEEE Transactions on Communications, Vol. COM-30, No. 8, August 1982, pp. 1828–1841, it was shown that for uncoded "ideal" (no Doppler) MDPSK, the average symbol error probability is given by

$$p_s = \frac{1}{2} \left[1 - \cos \frac{\pi}{M} \cdot \cos \alpha\right]$$

where $E_b=(\log_2 M)E_s$ is the energy per symbol with $E_b$ the bit energy.

When Doppler is present, which results in a noisy phase $\Delta \Phi=(\Delta \phi-\Delta \phi)T_s$ being added to the decision variable (see [13]), then using Eqs. (11) and (43) of the above-noted Pawula et al. article, equation (21) is modified to

$$p_s = \int_0^{\pi/2} \exp\left[-\frac{E_b}{N_0} \left(1-\cos \left(\frac{\pi}{M} - \Delta \Phi\right) \cos \alpha\right)\right] \, d\alpha +$$

$$\frac{1}{4\pi} \sqrt{\frac{\rho}{\pi}} \int_{-\pi/2}^{\pi/2} \exp\left(-\rho \sin^2 \nu \cos \nu \left[1+\exp\left(1+\cos \nu \right)\right]\right) \, d\nu$$

where $p_s(v)$ is given by (19).

EVALUATION OF THE AVERAGE BIT ERROR PROBABILITY

To evaluate the average bit error probability, we follow the procedure derived by Lee in "Computation of the Bit Error Rate of Coherent Mary PSK with Gray Code Bit Mapping," IEEE Transactions on Communications, Vol. COM-34, No. 5, May 1986, pp. 488-490 for ideal MPSK and MDPSK and extend it to the case where a noisy phase is added to the decision variable. In particular, we define

$$A_s(\Delta \Phi) = \frac{\sin \left(\Delta \Phi - (2i+1) \frac{\pi}{M}\right)}{4\pi} \times \int_{-\pi/2}^{\pi/2} \exp\left[-\frac{E_b}{N_0} \left(1-\cos \left(\Delta \Phi - (2i+1) \frac{\pi}{M}\right) \cos \alpha\right)\right] \, d\alpha -$$

$$\frac{1}{4\pi} \sqrt{\frac{\rho}{\pi}} \int_{-\pi/2}^{\pi/2} \exp\left(-\rho \sin^2 \nu \cos \nu \left[1+\exp\left(1+\cos \nu \right)\right]\right) \, d\nu$$

which represents the probability that the detector output phase is in the region $[2i-1]/M$, $[2i+1]/M$ under the hypothesis that the input phase $\Delta \theta_d=0$. Then, the
conditional symbol error probability of (22) can be expressed as

\[ P_d(\Delta \Phi) = \frac{M-1}{M} \sum_{i=1}^{M-1} A_i(\Delta \Phi) \]  

(25)

with

\[ F(\omega, \beta) = \frac{\sin (\beta - \omega)}{4\pi} \int_{-\pi}^{\pi} \frac{\exp \left[ - \frac{E_i}{N_0} (1 - \cos (\beta - \omega) \cos \alpha) \right]}{1 - \cos (\beta - \omega) \cos \alpha} d\alpha \]  

(32)

and assuming a Gray code bit assignment with Hamming weights \( w_m \), the conditional bit error probability is given by

\[ P_d(\Delta \Phi) = \frac{1}{\log_2 M} \sum_{m=1}^{M-1} w_m A_m(\Delta \Phi) \]  

(26)

Here \( w_m \) represents the number of bit errors that occur if the detector output phase lies in the region corresponding to \( A_m(\Delta \Phi) \).

Recognizing from (24) that \( A_m(\Delta \Phi) = A_0(-\Delta \Phi) \), and since \( \Delta \Phi(\Delta \Phi) \) is a symmetric probability density function then \( A_{m+1} = A_m \), where the overbar denotes averaging over \( P(\Delta \Phi) \). Hence, when the same average is performed on (25) and (26), we get

\[ P_b = \frac{1}{M} \sum_{m=1}^{M-1} A_m - A_M/2 \]  

(27)

and

\[ P_b = \frac{1}{\log_2 M} \left[ \sum_{m=1}^{M/2} (w_m + w_{M-m})A_m - w_{M/2} A_{M/2} \right] \]  

(28)

Lee, in the above-cited article, showed that for \( M=4 \) and \( M=8 \), simple closed form expressions could be obtained for the bit error probability of ideal MDPSK. The analogous expressions for the case of corrected Doppler present are

\[ P_b = F \left( \frac{3\pi}{4} \right) - F \left( \frac{\pi}{4} \right) \]  

(29)

and

\[ P_b = \frac{1}{2} \left[ F \left( \frac{13\pi}{8} \right) - F \left( \frac{5\pi}{8} \right) \right] \]  

(30)

where

\[ F(\omega, x) = \frac{\pm (2x \sqrt{1 - x^2}) \cos \psi - (2x^2 - 1) \sin \psi}{4\pi} \times \]

(38)

For any fixed \( \beta \), \( F(\omega, \beta) \) is easily evaluated using a Gauss-Chebyshev formula. In particular,

\[ I = \int_{-1}^{1} f \left( \frac{1 + x}{2} \right) dx = \frac{\pi N}{\sqrt{1 - z^2}} \]  

(34)

where \( N \) is chosen large enough to give the amount of accuracy desired and

\[ z_k = \cos \left( \frac{(2k-1)\pi}{2N} \right) \]  

(35)

i.e., the zeros of the \( N \)th degree Chebyshev polynomials \( T_N(x) = \cos (N \cos^{-1} x) \).

Similarly \( F(\omega) \) of (31) can also be evaluated using a Gauss-Chebyshev formula. First breaking the integral on \( (-\pi, \pi) \) into two integrals, one on \( (-\pi, 0) \) and one on \( (0, \pi) \), and then using double angle trigonometric identities, we arrive at the desired result, namely,

\[ F(\omega) = \frac{\pi}{N} \sum_{k=1}^{N} g(z_k) \]  

(36)

where \( z_i \) is given by (35) with the index \( k \) replaced by \( i \), and

\[ g(z) = p_0(\omega) [F_+ (\omega, z) + F_- (\omega, z)] \]  

(37)

with \( p_0(z) \) obtained by replacing \( \cos \psi \) with \( z \) in (19) and
Illustrated in FIGS. 5 and 6 are the average bit error probability performances of 4DPSK and 8DPSK as a function of bit energy-to-noise ratio, $E_b/N_0$, in dB with $K_p$ as a parameter. These numerical results were obtained from equations (29) and (30), respectively. For the purpose of comparison, the bit error probability performance for perfect Doppler compensation (i.e., $K_p = \infty$) is also illustrated in these figures. It should be observed that to achieve about 0.5 dB requires a value of $K$ on the order of eighty (80). This seemingly high value of $K$ comes from the fact that the Doppler estimator must be multiplied by 2 (see the multiplier 96 in FIGS. 3 and 4) before using that estimate to remove the Doppler from the data detection signals. This, unfortunately, increases the variance of the estimator by a factor of 4 (see Eq. (20)). The requirement for multiplying the Doppler estimate by a factor of 2 is tied to the fact that within a given symbol interval, the change in phase over half a symbol interval is independent of the data symbol itself and contains only the Doppler-induced phase shift, thus allowing its estimation.

**PRACTICAL CONSIDERATIONS**

In bandlimitied applications, the rectangular baseband pulses assumed thus far should be shaped to limit adjacent channel interference (ACI) and control intersymbol interference (ISI). Since $\theta(t)$ is no longer constant over a symbol time, then in order to still achieve $x_{dk}$ i.e., $x_{dk}$ of the form in (6), i.e., $I$ and $Q$ Doppler estimation samples which are independent of the data modulation, we must impose a requirement on the pulse shaping such that $\theta(k + 1)T_s - \theta(k + 1)T_s = 0$.

\[ \sin \theta(k + 1)T_s = \sin \theta(k + 1)T_s \]
\[ \cos \theta(k + 1)T_s = \cos \theta(k + 1)T_s \]

Assuming that one chooses a pulse shaping to satisfy (39), then, in general, the samples taken at $t = (k + 1/2)T_s$ (i.e., the midpoints of the symbol interval for data detection purposes) will be subject to ISI. Thus, the question may arise: Can we choose a pulse shaping that satisfies (39) yet still allows data detection without any penalty due to ISI? This question has a fortuitously increases the variance of the estimator by a factor of 4 (see Eq. (20)). The requirement for multiplying the Doppler estimate by a factor of 2 is tied to the fact that within a given symbol interval, the change in phase over half a symbol interval is independent of the data symbol itself and contains only the Doppler-induced phase shift, thus allowing its estimation.

Suppose that we consider an overall (transmitter plus receiver) pulse shaping of the 100% excess bandwidth root raised cosine type. Such pulse shaping is known and has a transfer characteristic of the form

\[ P(o) = P_r(o)P_r(o) = \left\{ \begin{array}{ll} T_s \cos oT_s/4, \ |o| \leq 2\pi/T_s \\ 0, \ \text{otherwise} \end{array} \right. \]

with a corresponding impulse response of

\[ p(t) = \frac{1}{\pi} \left[ \frac{\cos 2\pi t}{T_s} \right] \]

Since the zero crossings of $p(t)$ occur at $t = \pm (2k + 1)T_s/4; k = 1, 2, 3, \ldots$, then if $p(t)$ were used as the underlying pulse shape in a digital pulse train of the form $m(t) = \sum a_{dk}(t - nT)$ with $\{a_{bk}\}$ representing a multilevel data sequence, then $m(t)$ taken at $t = -(n + 1/4)T_s$ and $(n + 3/4)T_s$ would be ISI free and equal in amplitude. Thus, using such an $m(t)$ for the I and Q data signals $sin \theta(t)$ and $cos \theta(t)$ allows (40) to be satisfied.

The question remains as to where to sample and how to process the I and Q data signals for data signals for data detection purposes. Since, as pointed above, samples of $\sin \theta(t)$ and $\cos \theta(t)$ taken at $t = -(n + 1/4)T_s$ and $(n + 3/4)T_s$ are ISI free, then it seems reasonable to sum these two samples prior to differential detection. Since $p(t)$ has value unity at these sample points, i.e., the same value as a unit rectangular pulse, then compared to a single sample of this rectangular (ISI free) pulse, the above sum yields a 6 dB increase in power of the predetection sample in the absence of noise.

Ordinarily from the standpoint of maximizing the SNR of a single sample of I or Q, one would split the total pulse shaping $P(o)$ equally between the transmit and receive filters with the filters at each location taking the form of a square root raised cosine characteristic. Note that from an overall system standpoint the filters multiply and thus yield an equivalent raised cosine system response. Such a split would result in the noise samples at $t = -(n + 1/4)T_s$ and $(n + 3/4)T_s$ being correlated. Suppose instead that half of the filtering (square root raised cosine) is placed at the transmitter and a root raised cosine filter.

For a summer and 3Td4 supplied to a summer and 3Td4 yielded an equivalent operation to a 100% root raised cosine filter.
the pre-detection sample formed from the sum of samples taken at \( t = (n + 1/4)T \) and \( (n + 3/4)T \) is identical to that of a single sample of a rectangular pulse and thus there is no ISI penalty.

In fact, the above-noted result, which appears rather surprising at first, can be supported quite easily by showing that, in the absence of Doppler, the split filtering with an ideal low pass filter at the receiver is indeed the optimum filter split for Nyquist-type signaling with two nonzero uniform sample points (as is proved by Appendix A). In this context, the above scheme bears resemblance to the duobinary approach discussed earlier but is entirely binary and does not depend upon the three level complexity of the duobinary approach.

When Doppler is present, \( G(\omega) \) of FIG. 12 is replaced by

\[
G(\omega - \Omega_0) = 1 + \exp \left(-j\omega T/2\right)
\]

\[
= 1 + a \exp \left(-j\omega T/2\right) a = \exp \left(j\Omega_0 T/2\right)
\]

thus requiring knowledge of the Doppler frequency shift. What is used is the Doppler estimate \( \Delta \omega \) in the implementation of equation (42) analogous to the use of \( \Delta \omega \) instead of \( \omega \) for the final Doppler removal.

If the matched filter follows the differential detector, the circuit operation is once again \( G(\omega) \) of FIG. 12. It should be noted that one could indeed also use a differential detector followed by the \( G(\omega) \) combination for the data detection portion of the receiver in an effort to produce some commonality in structure. However, this later approach is suboptimal and leads to a degradation in output SNR. Also, in this case, the probability density function of the differential detector output (which is not Gaussian) is changed by the matched filter and hence, the bit error probability performance expressions of equations (24) through (28) are no longer valid.

One additional point, alluded to above, needs to be discussed. Since in the ACQ mode, the differential detector operates over a \( T \) sec. interval, the output of the digital filter will proportional to \( \exp \left(-j\Delta \omega T\right) \) rather than \( \exp \left(-j\Delta \omega T/2\right) \) as in the tracking (TRK) mode where the differential detector operates over \( T \) sec. Since implementation of the matched filter for data detection requires the complex quantity “a” of equation (42), then in the ACQ mode, one must take the square root of the digital filter output in order to make this quantity available. On the other hand, in the TRK mode, where “a” is directly available, then to achieve the quantity \( \exp \left(-j\Delta \omega T\right) \) which is needed for Doppler removal, we square the digital filter output.

FIG. 7, described below, relates to differential detection with Doppler estimation. This FIG. 7 includes, in a practical implementation, the theory discussed above concerning data detection and Doppler correction. A review of equation 43 shows that if the Doppler amount is zero then the matched filter of FIG. 7 is in accordance with FIG. 12.

In FIG. 7, the box legend “C” represents a conjugate operation. Pseudo-matched filter 710 includes brickwall filter 740, multiplier 750, a half symbol delay 760 and a summer 770. Multiplier 750 requires two signals, (1) a filtered output signal from brickwall filter 740 and (2) an input signal in the form of the complex quantity \( a = \exp(j \Delta \omega T/2) \). The complex quantity \( \exp(j \Delta \omega T/2) \), obtained by Doppler estimator 790, is required for Doppler removal in the pseudo-matched filter prior to differential detection in detector 720. In the absence of Doppler, \( a = 1 \) and the pseudo-matched filter becomes a true matched filter, i.e., a root raised cosine filter. Furthermore, the bandwidth of the brickwall filter is narrowed to the symbol rate. Differential detector 720 of FIG. 7 operates in the manner described previously and requires no further discussion.

A practical implementation of the receiver of FIG. 7 requires an understanding and use of acquisition ("ACQ") and tracking ("TRK") modes which will be discussed in connection with additional figures such as FIGS. 7A through 7C. If \( \Delta \omega = \Omega_0 = 0 \) and the bandwidth of the brickwall filter 740, FIG. 7, is equal to \( 1/T \), then filter 740 is exactly a matched filter for a root raised cosine filter with 100% excess bandwidth at the transmitter. If \( \Delta \omega \) is not equal to zero then filter 740 represents a pseudo-matched filter (e.g., an approximately matched filter). The bandwidth of brickwall filter 740, in the presence of Doppler frequency shift, should be equal to \((1/T) + \Omega_0 \).

FIG. 7A presents additional details of the circuitry and operation of the Doppler estimator 790 shown simply as a block diagram in FIG. 7. A tracking mode for the Doppler estimator circuit 790 of FIG. 7A will be described. An output from the brickwall filter 740 is applied as an input signal to another differential detector 781 which operates in the manner previously described, i.e., that differential detector 781 of FIG. 7A differentially detects two samples within each full symbol interval. The samples are separated by \( T/2 \) in order to "wipe off" the data phase, and thus result in a complex signal of Doppler induced phase \( T/2 \). The sampled output from detector 781 is applied to a digital low pass filter 782. This digital low pass filter is comparable to those described earlier in connection with FIG. 3 and is employed to improve the estimate of the Doppler by removing the effect of noise on \( \Delta \omega T/2 \). An amplitude normalizer 783 normalizes the envelope of digital filter output 782 to unity. This normalized output from 783 is provided both to the pseudo-matched filter 710, FIG. 7, and to a squaring circuit 784. A squared output from 784 is applied to the residual Doppler corrector 730, FIG. 7. As previously explained, the residual Doppler is removed at the output of 730 and the output signal on lead 731 contains only the differential detected phase data which is recovered in standard operation by differential detector 720, FIG. 7.

In many applications, Doppler estimation, such as that achieved by estimator 790, first takes place via a coarse Doppler estimate which is obtained in the presence of a known data sequence, e.g., all zeros. FIG. 7B depicts a fast acquisition circuit that is used when the data sequence is known to the receiver. Such predetermined knowledge at the receiver is accomplished by having the transmitter send a constant phase for a short time in the order of about twenty symbols as a preamble to every data packet. Such a preamble results in a fast acquisition of the Doppler estimate. After that fast acquisition the receiver can switch to the tracking mode for open loop Doppler estimation where the data phase is not known by the receiver.

In the above-noted acquisition (ACQ) mode, the change in \( \dot{\delta}(t) \) is known (for the all zeros sequence, this change is indeed zero) and thus one would expect that the differential detector output samples could be used as inputs to a digital filter in the Doppler estimator. Unfortunately, as we have just pointed out above, the differential detector output samples are themselves functions of the Doppler estimate and thus implementing the
been made in regard to the manner in which the tan-
operation is performed. In particular, the quadrature
rated in the simple illustration of FIG. 6. The eye diagram (FIG. 10) of the brickwall filter out-
signals necessary to remove the Doppler (see FIG.
the Doppler-corrected differential detector analogous
the residual Doppler correction circuit 730 of FIG. 7. Cosine filter, the overall channel response remains root
cosine, the pseudo-matched filter 710 of FIG. 7. Components of the circuit shown in FIGS. 7A and 7C, Over the Nyquist bandwidth) and comparison of a single
symbol interference (ISI) due to timing jitter on the
performance of the system under consideration. The
Simulation and analytical results were in excellent
agreement as shown by FIGS. 13 and 14 included
herein.

APPENDIX A

On the Optimal Filter Split for Nyquist-Type Signaling
Two Nonzero Sample points

In the foregoing, it was shown that 100% excess
bandwidth root raised cosine signaling could be used to
satisfy the Doppler estimation requirement of equal,
zero ISI sampling points spaced T/2 apart and symmet-
trically placed with respect to the midpoint of the sym-
bol interval. From the standpoint of optimum data de-
tection, the conventional Nyquist approach is to use an
equivalent flat channel (i.e., the sum of all translates of
the overall frequency response should be a constant
over the Nyquist bandwidth) and comparison of a single
to a threshold. Raised cosine signaling achieves such
an equivalent Nyquist channel with a single ISI-
free sampling point. Thus, to use this technique in com-
bination with the above Doppler estimation circuit, one
would require an additional root raised cosine filter at
the receiver. (Actually, for the baseband implementa-
tion, two such additional filters would be required; one
for the I channel and one for the Q channel).

To avoid the necessity of this additional root raised
cosine filter, the overall channel response remains root
raised cosine, as required for the Doppler estimate, and
for data detection the pair of samples taken per symbol
are algebraically summed and used as a single sample
for comparison with a threshold. Using the above filter
split (i.e., all of the filtering at the transmitter and none
at the receiver), it was shown that the error probability
performance achieved was indeed equal to that using
the conventional Nyquist approach (i.e., raised cosine
signaling with single sample per symbol detection) as
described above.

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the conventional Nyquist approach (i.e., raised cosine
signaling with single sample per symbol detection) as
described above.

SYSTEM MODEL

Consider the mathematical model of the system illus-
trated in FIG. 11. Actually, this system represents only
the in-phase (I) or quadrature channel (Q) of the base-
The above description presents the best mode contemplated in carrying out our invention. Our invention is, however, susceptible to modifications and alternate constructions from the embodiments shown in the drawings and described above. Consequently, it is not the intention to limit the invention to the particular embodiments disclosed. On the contrary, the invention is intended and shall cover all modifications, sizes and alternate constructions falling within the spirit and scope of the invention, as expressed in the appended claims when read in light of the description and drawings.

What is claimed is:

1. A receiver in a communication system which produces a Doppler effect in an incoming multiple differential phase-shift-keyed signal having a given symbol interval, with the receiver for the incoming signal having a differential detector for restoring the data by multiplying the incoming signal with a full symbol interval delayed version of itself (or an equivalent sampled version thereof) and applying the restored signal to the detector's output, said receiver comprising:
   - means for delaying the incoming data signal (which has the Doppler effect therein) by a half symbol interval;
   - means in an open-loop forward acting circuit for estimating the amount of the Doppler effect from the incoming data signal and the half-symbol delayed signal; and
   - means for subtracting the estimated Doppler amount from the detector's output.

2. A communication system having a transmitter and the receiver of claim 1 separated by a bandlimited medium over which the transmitter sends to the receiver, a data modulated multiple differential phase-shift-keyed signal having a predetermined symbol interval, Ts contaminated by said Doppler effect, said system comprising:
   - signal shaping split between the transmitter and the receiver to yield an impulse response at the receiver in the form of
   \[
   p(t) = \frac{1}{\pi} \frac{\cos 2\pi \frac{t}{T_s}}{1 - \left(\frac{4t}{T_s}\right)^2}
   \]
   where \(t\) is time and \(T_s\) is the symbol duration.

3. A communication system in accordance with claim 2 wherein said differential detector for decoding the data represented in the received signal has the Doppler effect in the detector's output, said system further comprising:
   - means in the detector including said receiver's signal shaping for sampling the received signal at times \(t=(n+1/4)T_s\) and \(t=(n+3/4)T_s\) to obtain intersymbol interference-free ("ISI") data signal samples, wherein "n" corresponds to the nth symbol interval of duration \(T_s\) and \(n\) is any arbitrarily selected integer.

4. A communication system in accordance with claim 3 wherein said means for removing the Doppler effect from the differential detector output, further comprises:
   - means for multiplying said ISI samples with the Doppler estimating amount from said subtracting means as a Doppler-correcting error to cancel the Doppler effect from the differential detector's output.

5. A communication system in accordance with claim 1 wherein the Doppler effect introduces a Doppler-induced phase change that tends to mask differential phase changes encoded in said incoming data signal, and said system includes a receiver which is further characterized in that:
   - said Doppler effect estimating means is responsive to the change in phase of said incoming signal over a full symbol interval, which incoming signal con-
tains both the differentially encoded data and the Doppler-induced phase change, whereas the same phase change over half a symbol interval contains only the Doppler-induced phase change.

6. A communication system in accordance with claim 2 wherein said signal processing is provided by transmit and receive filters with the transmitter filter taking the form of a square root raised cosine characteristic, the improvement in said system comprising:

a filter at the receiver having a characteristic matched to the transmitter's filter and also exhibiting a square root raised cosine characteristic that is formed from an ideal low pass filter with its output connected in tandem to a summer, which summer receives the low pass filter's output, and a half symbol delayed version of that filter's output.

7. A communication system in accordance with claim 6 wherein the symbol interval is expressed as \( T_s \) and the transmitter's filter has 100% excess bandwidth and further wherein said receiver's ideal low pass filter has a bandwidth equal to \( 1/T_s \) expressed in Hertz.

8. A communication system in accordance with claim 6 wherein the symbol interval is expressed as \( T_s \) and wherein the transmitted signal experiences a maximum Doppler frequency shift ("\( f_d, \text{MAX} \)) and further wherein said receiver's ideal low pass filter has a bandwidth of \( 1/T_s \) (in Hz) plus \( f_d, \text{MAX} \).

9. A communication system in accordance with claim 6 wherein the low pass filter's output is connected to a Doppler correcting circuit, and wherein said system is further characterized:

said means in an open loop forward acting circuit which receives the low pass filter's output, for estimating said Doppler-correcting error signal, which error signal is indicative of the amount of Doppler correction that is required at the detector's output.

10. A communication system in accordance with claim 9 wherein the data at the transmitter is encoded as multiple differential phase-shift-keyed changes on a transmitted carrier as an output signal and an output terminal, for supplying decoded data, and comprising:

a modulator at the system's transmitter for impressing information as differential phase-shift-keyed changes on a transmitted carrier as an output signal; a Doppler-inducing communication medium that causes a Doppler phase error to become embedded in the transmitted signal; a system receiver operative on the incoming signal which still has the Doppler phase error in the transmitted signal; means for removing the Doppler phase error and restoring the information from the differential phase changes on a transmitted carrier as an output signal; and a forward acting open loop correction circuit connected to said sensing circuit for removing the Doppler phase error from said restored signal.
that information only is available at the receiver's output terminal.

16. An improved communication system for communicating information, encoded by differential phase changes in symbol intervals, over a communication link which introduces a Doppler-induced phase change that tends to mask the encoded differential phase changes, said system improvement being based upon the recognition that, at a receiver, the change in phase of a received incoming signal over a full symbol interval contains both the differentially encoded data and the Doppler-induced phase change, whereas the same phase change over half a symbol interval contains only the Doppler-induced phase change, and said system improvement comprising at the system's receiver:

a. an input signal receiving terminal; means connected to said terminal and operative over a half symbol interval in response to said input signal for deriving therefrom a Doppler estimate signal that is indicative of the Doppler-induced phase change which is present in the incoming signal;

b. means connected to said input terminal and operative over a full symbol interval in response to said input signal for deriving therefrom a detected output signal which is indicative of the data encoded phase change and including the Doppler-induced phase change as an undesired part of the detected output signal; and

c. means applying the Doppler estimate to the detected output signal for canceling the undesired Doppler-induced phase change from the detected output signal.

17. A communication system for symbol interval data in an environment with Doppler frequency shift and having a signal transmitter and a signal receiver connected together via a communication medium, and having transmit and receive filters with the transmitter filter taking the form of a square root raised cosine characteristic, the improvement in said system comprising:

a. a filter at the receiver having a characteristic pseudo matched to the transmitter's filter and also exhibiting a square root raised cosine characteristic only in absence of Doppler shift, said filter being formed from an ideal low pass filter with its output connected in tandem to a summer, which summer receives the low pass filter's output, and a half symbol delayed version of itself, said receiver comprises:

b. a data detector for restoring data at the receiver and means for removing the Doppler from the restored data of said detector by applying said Doppler error signal to the detector's output; and

c. means for delaying the incoming data signal by a delay time of one-half of the symbol interval's means for multiplying that half delayed signal with its output connected in tandem to a summer, which summer receives the low pass filter's output, and a half symbol delayed version of that filter's output, which half symbol delayed version is corrected by said Doppler estimate.

18. An improved communication system of claim 17 and further comprising:

a. means at the transmitter for transmitting, as part of a data signal, a known sequence of phase shifts; and

b. means at the receiver responsive to that known sequence for acquiring a Doppler error signal during the time of receipt of that known sequence.

19. An improved communication system of claim 18 and further comprising:

a. means at the receiver responsive to said Doppler error signal for condition achieving Doppler correction during the receipt of unknown phase shifts by said receiver.

20. A communication system in accordance with claim 17 wherein the symbol interval is expressed as T_s, and the transmitter's filter has 100% excess bandwidth and further wherein said receiver's:

a. ideal low pass filter has a bandwidth equal to 1/T_s (expressed in Hz);

b. ideal low pass filter has a bandwidth of 1T_s (in Hz per second) plus f_{D_MAX}.

21. A communication system in accordance with claim 17 wherein the symbol interval is expressed as T_s and wherein the transmitted signal experiences a maximum Doppler frequency shift ("f_{D_MAX}") and further wherein said receiver's:

a. ideal low pass filter has a bandwidth equal to 1/T_s (expressed in Hz);

b. ideal low pass filter has a bandwidth of 1T_s (in Hz per second) plus f_{D_MAX}.

22. A communication system in accordance with claim 21 wherein the low pass filter's output is connected to a Doppler correcting circuit, and further wherein said Doppler correcting circuit is characterized by:

a. means in an open loop forward acting circuit which receives the low pass filter's output for estimating therefrom, a Doppler error signal, which error signal is indicative of the amount of Doppler correction that is required;

b. a data detector for restoring data at the receiver and making the restored data available at the detector's output; and

c. means for removing the Doppler from the restored data of said detector by applying said Doppler error signal from said estimating means to the detector's output.

23. A communication system in accordance with claim 22 wherein the data is encoded as multiple differential phase changes in said symbol intervals, and further wherein:

a. a data detector is a multiple differential phase decoder for restoring the data in a data output signal that is formed by multiplying, at a multiplier circuit, the incoming data signal with a full symbol interval delayed version of itself.

24. A communication system in accordance with claim 23 wherein the Doppler correcting circuit further comprises:

a. means for delaying the incoming data signal by a delay time of one-half of the symbol interval's means for multiplying that half delayed signal with the incoming data signal; and

b. means for further processing the multiplied signal from said multiplying means before said signal is applied to said detector's output as a Doppler error correction signal.

25. The communication system of claim 23 wherein the processing means further comprises:

a. means for sampling the multiplied signal at times t = (n + 1/4)T_s and (n + 3/4)T_s, where "n" corresponds to the nth symbol interval of duration T_s and n is any arbitrarily selected integer; and

b. means for multiplying the sampled signals from said sampling means with said detector's output.

26. A receiver in a communication system which produces a Doppler effect in an incoming multiple differential phase-shift keyed signal having a given symbol interval, with the receiver for the incoming signal having a differential detector for restoring the data by multiplying the incoming signal with a full symbol interval delayed version of itself (or an equivalent sampled version thereof), said receiver comprising:

a. means for delaying the incoming data signal (which has an unwanted Doppler effect therein) by a half symbol interval; and
an open-loop forward acting circuit means connected to said delaying means for deriving an estimated amount of the Doppler effect from the signal to be restored, the estimated amount then being used to cancel the unwanted Doppler.

27. A communication system having a transmitter and the receiver separated by a bandlimited medium over which the transmitter sends to the receiver, a data modulated multiple differential phase-shift-keyed signal or a multiple phase-shifted-keyed signal, with each signal having a predetermined symbol interval, T_d, contaminated by an unwanted Doppler effect that may be removed by samples, a half symbol-interval apart, from the incoming signal, said system comprising:

signal shaping split between the transmitter and the receiver to yield an impulse response at the receiver, where said signal shaping is connected, with said impulse being in the form of

$$p(t) = \frac{4}{\pi} \left[ \frac{\cos \frac{2\pi}{T_s} \frac{t}{T_s}}{1 - \left( \frac{4t}{T_s} \right)^2} \right]$$

where t is time and T_s is the symbol duration, and said signal shaping yields samples for Doppler removal that are a half symbol duration apart; and

means connected to said signal shaping means and responsive to said samples yielded thereby for correcting for said unwanted Doppler effect.

28. The communication system of claim 27 wherein the Doppler error is removed by samples taken a half symbol duration apart for Doppler correction, said system comprising:

means for sampling the multiplied signal at times \( t = (n + 1/4)T_s \) and \( (n + 3/4)T_s \), where n corresponds to the nth symbol interval of duration T_s, and n is any arbitrarily selected integer, in order to obtain two independent samples; and

Doppler correcting means responsive to said independent samples for correcting for said unwanted Doppler error.

29. A receiver in a communication system which produces a Doppler effect in an incoming multiple phase-shift-keyed signal having a given symbol interval, with the receiver for the incoming signal having a matched filter detector for restoring the data after Doppler removal, said receiver comprising:

means for delaying the incoming data signal (which has the Doppler effect therein) by a half symbol interval; and

an open-loop forward acting circuit means connected to said delaying means for removing the amount of the Doppler effect from the signal to be restored, the estimate of which is then used to cancel the Doppler.

30. A communication system for symbol interval data having a signal transmitter and a signal receiver connected together via a communication medium, and having transmit and receive filters with the transmitter filter taking the form of a square root raised cosine characteristic, the improvement in said system comprising:

a filter at the receiver having a characteristic matched to the transmitter’s filter and also exhibiting a square root raised cosine characteristic that is formed from an ideal low pass filter with its output connected in tandem to a summer, which summer receives the low pass filter’s output, and a half symbol delayed version of that filter’s output, means at the transmitter for transmitting, as part of a data signal, a known sequence of phase shifts; and

means at the receiver responsive to that known sequence for acquiring (“ACQ”) a Doppler error signal during the time of receipt of that known sequence.

31. An improved communication system of claim 30 means at the receiver responsive to the acquisition of the Doppler correction by said Doppler error acquiring means for assuming a tracking condition wherein the Doppler correction takes place during the receipt of unknown data phase shifts by said receiver.