

PHASE JITTER ESTIMATION OR CORRECTION

5 This invention relates to phase jitter estimation or correction.

 In a communications system where signals are transmitted over a communications channel, the transmitted signals are normally corrupted by imperfections in the channel. In order to properly recover the transmitted signals, circuits which correct various signal impairments are employed in a receiver. Phase jitter is one such signal impairment. It is typically modeled as a set of sinusoids of different frequencies and is attributed to power line harmonics and ringing voltages present in the channel.

 Phase-jitter-correction techniques typically call for an estimation of the phase jitter before the jitter can be effectively removed. One such technique involves the use of an adaptive finite-impulse-response (FIR) filter for the phase jitter estimation, as described in U.S. Patent 4,320,526 issued March 16, 1982 to R. D. Gitlin. Disadvantageously, such an FIR filter is relatively slow in converging on each of the phase jitter frequencies during an adaptation process. Moreover, this FIR filter does not provide the estimate accurate enough to effect a substantial removal of the phase jitter.

 Another technique involves the use of an adaptive IIR filter for estimating the phase jitter, as described in U.S. Patent 4,847,864 issued July 11, 1989 to R. L. Cupo. The coefficients of such an IIR filter are selected, using a well-known least-mean-square (LMS) optimization method, to minimize a phase error indicative of the difference between the phase jitter estimate and the actual phase jitter present in the received signal. Stemming from certain limitations of the optimization method used, this IIR filter can only provide an estimate, although accurate, of a particular frequency component of the phase jitter. However, in practice, the phase jitter oftentimes consists of a plurality of frequency components. This being so, in order to remove the phase jitter completely, a multiplicity of these IIR filters (i.e., one filter for each frequency component) must be incorporated in the receiver. Notwithstanding such, the actual number of jitter frequency components incurred in a channel varies from one channel to another and, therefore, cannot be determined in advance. Overestimating the number of the jitter frequency components results in incorporating too many such filters and adds an unnecessary,

substantial cost to the system. On the other hand, underestimating the number results in too few such filters and undesirably degrades the system's performance.

According to a first aspect of this invention there is provided apparatus for estimating phase jitter in a received signal, said apparatus comprising means for receiving a phase error signal which is representative of a difference between said
5 phase jitter and an estimate thereof, and means for providing said estimate in response to said phase error signal, said providing means having an impulse response of infinite duration and a transfer function which is determined by an autocorrelation of said phase error signal.

10 According to a second aspect of this invention there is provided receiver apparatus for processing a signal which includes phase jitter, said receiver apparatus comprising means for generating a phase error indicative of a difference between said phase jitter and an estimate thereof, means for providing said estimate, said
15 providing means having an impulse response of infinite duration and a transfer function which is determined by an autocorrelation of said phase error, and means for removing said phase jitter from said signal in response to said estimate.

According to a third aspect of this invention there is provided apparatus for receiving a signal, said apparatus comprising means for demodulating samples of said signal which include phase jitter, said demodulating means using an estimate of
20 said phase jitter as a carrier frequency so that said phase jitter is removed from said samples, and means for providing said estimate in response to a phase error signal, said providing means having an impulse response of infinite duration and a transfer function which is a function of an autocorrelation of a phase error, said phase error being indicative of a difference between said estimate and said phase jitter.

25 According to a fourth aspect of this invention there is provided a communication system having a transmitter which transmits a signal, said communication system comprising means for recovering said signal based on samples of a received signal associated with said signal, said samples including phase jitter, means for providing an estimate of said phase jitter in response to a
30 received signal sample, said providing means having an impulse response of infinite duration and a transfer function which is a function of an autocorrelation of a phase error, said phase error being indicative of a difference between said estimate and said phase jitter, and means for removing said phase jitter from said samples in response to said estimate.

According to a fifth aspect of this invention there is provided a method for estimating phase jitter in a received signal, said method comprising the steps of receiving a phase error signal which is representative of a difference between said phase jitter and an estimate thereof, and providing said estimate using a filter having
5 an impulse response of infinite duration and a transfer function which is determined by an autocorrelation of said phase error signal.

According to a sixth aspect of this invention there is provided a method for use in receiver apparatus for processing a signal which includes phase jitter, said method comprising the steps of generating a phase error indicative of a difference
10 between said phase jitter and an estimate thereof, providing said estimate using a filter whose impulse response has an infinite duration and whose transfer function is a function of an autocorrelation of said phase error, and removing said phase jitter from said signal in response to said estimate.

According to a seventh aspect of this invention there is provided a
15 method for use in apparatus for receiving a signal, said method comprising the steps of demodulating first and second samples of said signal which includes phase jitter, said first sample preceding said second sample in time, said demodulating means using an estimate of said phase jitter as a carrier frequency so that said phase jitter is removed from said second sample, and providing said estimate in response to said
20 first sample using a filter whose impulse response has an infinite duration and whose transfer function is a function of an autocorrelation of a phase error, said phase error being indicative of a difference between said estimate and said phase jitter.

According to an eighth aspect of this invention there is provided a method for use in a communications system having a transmitter which transmits a
25 signal, said method comprising the steps of recovering said signal based on samples of a received signal associated with said signal, said samples including phase jitter, providing an estimate of said phase jitter in response to a received signal sample using a filter whose impulse response has an infinite duration and whose transfer function is a function of an autocorrelation of a phase error, said phase error being
30 indicative of a difference between said estimate and said phase jitter, and removing said phase jitter from said samples in response to said estimate.

Advantageously, embodiments of the invention adapt to a phase jitter having a plurality of frequency components and provide an accurate phase jitter estimate, which is conducive to a substantial removal of the jitter.

The invention will now be described with reference to the accompanying drawings, in which:

FIG. 1 illustrates a block diagram of a communications system embodying the invention: and

5 FIG. 2 illustrates a block diagram of a phase predictor for estimating phase jitter present in a received signal in the communications system of FIG. 1.

FIG. 1 illustrates a system 10 which includes a data source 100 configured to communicate information to data sink 104. For example, data source 100 may be a mainframe, a minicomputer, etc., and data sink 104 may be a data
10 terminal, a printer, and such. Digital bits representative of the information from data source 100 are fed to transmitter 101 of conventional design. These bits are collected in transmitter 101 in groups of twenty-eight. Each group is trellis coded into 8-dimensional symbols selected from a predetermined signal constellation (not shown). In a well known manner, each 8-dimensional symbol is mapped to four 2-
15 dimensional signal points, which are transmitted as four respective quadrature-amplitude-modulated (QAM) signals, each having a spectrum centered at a carrier frequency ω_c . During each baud interval of $T = 1/2742.8571$ sec, one such QAM signal is transmitted through channel 103. Thus the digital bits are communicated at a rate of $T/4 = 685.7142$ 8-dimensional symbols per second, or a data transmission
20 rate of 19.2 Kbps.

In this particular illustrative embodiment, channel 103 is furnished by a standard private line network. The transmitted signal is corrupted in channel 103 by various impairments including phase jitter. The present invention is directed to the correction for such phase jitter. Phase jitter normally includes a plurality of
 5 frequency components and, in fact, it may be mathematically expressed as follows:

$$\theta(t) = \sum_{q=0}^Q \alpha_q \sin \omega_q t, \quad (1)$$

where Q is the number of frequency components in phase jitter $\theta(t)$ at time t, α_q is the phase jitter amplitude of the q^{th} sinusoidal component, and ω_q is the frequency of that component. Phase jitter is mainly attributed to power line harmonics and
 10 ringing voltages present in channel 103. For example, the fundamental frequency of power line voltages, i.e. 60 Hz, is usually the dominant cause of the phase jitter. In certain situations, the second harmonic of the fundamental frequency, i.e., 120 Hz, also substantially contributes to the phase jitter. It is noteworthy, however, that the phase jitter frequencies need not be harmonically related.

15 Receiver 102 receives a signal $r(t)$ which represents the transmitted signal subjected to impairments including phase jitter. Anti-aliasing filter 11, which is a standard, low-pass filter, filters out energy in the signal $r(t)$ at frequencies above 4000 KHz. The filtered signal is supplied to A/D converter 13 which generates passband samples of the received signal at a rate of $4/T$ samples per second. The
 20 passband samples are fed to Hilbert filter 15 which provides, during each baud interval, a pair of signals representing the Hilbert transform of the passband samples on leads 16 and 17. These leads extend to the input of linear equalizer 20 which is of conventional design. Linear equalizer 20 may be of the type disclosed in U. S. Patent 3,868,603 issued February 25, 1975 to Guidoux. It is also referred to as a
 25 "fractionally spaced" equalizer since it receives and processes more than one input during each symbol interval. The function of linear equalizer 20 is to eliminate, from the passband samples, intersymbol interference caused by channel 103.

The output of linear equalizer 20 is a complex signal and is generated once per baud interval. The complex signal generated during the n^{th} baud interval is
 30 denoted Z_n . This complex signal Z_n , including a real component z_n and an imaginary component $\hat{z}_n$, is passed to demodulator 30. In a well known manner, demodulator 30 demodulates the passband signal Z_n based on the aforementioned carrier frequency ω_c to generate a complex baseband signal Y_n having real and imaginary components y_n and $\hat{y}_n$.

It should be pointed out at this juncture that the baseband signal Y_n is subjected to the aforementioned phase jitter impairment. In order to correct for the phase jitter, a second demodulator 35 demodulates the signal Y_n as if its components, y_n and $\hat{y}_n$, had respectively been modulated by $\cos(\theta(nT))$ and $\sin(\theta(nT))$ in channel 103. Demodulator 35 receives the values of $\cos(\hat{\theta}_{n-1})$ and $\sin(\hat{\theta}_{n-1})$ which are provided by sin-cos calculator 85. Here, $\hat{\theta}_{n-1}$ is a predictive estimate of the phase jitter $\theta(nT)$ present in Y_n . This estimate is supplied by phase predictor 70, operating in conjunction with phase difference estimator 55. To this end, phase difference estimator 55 provides a phase error signal having a value ψ_n which is indicative of the difference between $\theta(nT)$ and $\hat{\theta}_{n-1}$. As shown in the following formula, ψ_n is a function of D_n and S_n , which are respectively the complex values of the signals from demodulator 35 and slicer 40.

$$\psi_n = \text{Im} \left[\frac{D_n S_n^*}{|S_n|^2} \right], \quad (2)$$

where Im denotes the imaginary component of its argument; S_n^* is the complex conjugate of S_n ; and $|S_n|$ represents the modulus of S_n .

The operation of phase predictor 70 is fully described hereinbelow. It suffices to know for now that phase predictor 70 is an infinite-impulse-response (IIR) filter having a plurality of reflection coefficients. (By definition, an IIR filter is a filter whose impulse response has an infinite duration.) The values of these reflection coefficients are provided by processor 67 after an initialization process occupying the first N baud intervals. (N is experimentally determined to be on the order of 100 and is equal to 64 in this instance.) During this process, processor 67 determines the coefficient values based on $\psi_1, \psi_2 \dots \psi_N$ collected from phase difference estimator 55.

The output of phase predictor 70, $\hat{\theta}_{n-1}$, is fed back to the phase predictor through adder 60 which adds the value of ψ_n to the value of $\hat{\theta}_{n-1}$. The resulting sum, ϕ_n , is supplied to phase predictor 70 for predicting the value of $\theta((n+1)T)$. In the steady state, the real and imaginary components of the complex signal D_n , respectively denoted as d_n and $\hat{d}_n$, are virtually free of the phase jitter, and the phase error signal value, ψ_n , at the output of phase difference estimator 55 is substantially zero.

Slicer 40 provides the complex signal S_n whose real and imaginary components (s_n and $\hat{s}_n$) are the quantized versions of d_n and $\hat{d}_n$. S_n represents the so-called "tentative" decisions as to what the transmitted 2-dimensional signal points

actually were. These tentative decisions are used for equalizer adaptation purposes. To this end, subtracter 65 provides a complex baseband error signal by subtracting the real and imaginary components of S_n from the corresponding components of D_n . The resulting real and imaginary components are respectively modulated by
 5 modulator 80 with quadrature carriers, $\cos(\omega_c nT + \hat{\theta}_{n-1})$ and $\sin(\omega_c nT + \hat{\theta}_{n-1})$. The output of modulator 80 is, accordingly, a complex passband error signal which is supplied to linear equalizer 20 for updating its coefficients in a conventional manner.

Based on a sequence of the signals provided by demodulator 35, Viterbi
 10 decoder 41, in a standard way, determines the most likely sequence of 8-dimensional symbols which were communicated from transmitter 101. Bit converter 43 translates each of these 8-dimensional symbols into a group of twenty-eight digital bits which the symbol represents. The digital bits are thereupon received by data sink 104.

15 We turn now to a full description of phase predictor 70.

Phase predictor 70 is an IIR filter having a transfer function $H(z)$ as follows:

$$H(z) = \frac{G z^{-1}}{1 + \sum_{i=1}^p \beta_i z^{-i}}, \quad (3)$$

where G is the square root of the total energy in the phase error signal whose value is
 20 ψ_n ; and p is the order of the IIR filter. (In this particular embodiment, p is experimentally determined to be 10.) The values of β_i 's, for $1 \leq i \leq p$, are selected so as to minimize ψ_n to substantially zero. This minimization is achieved by using the Durbin recursion technique as set forth in J. Makhoul "Linear Prediction: A Tutorial Review," Proc. IEEE, vol. 63, April 1975, pages 561 - 580. In accordance
 25 with this technique, the values of β_i 's are determined based on the autocorrelation of ψ_n . Specifically, they are obtained by solving the following equations (4) through (8) recursively for $i = 1, 2, \dots, p$. Given $E_0 = R(0) = \sum_{n=0}^N \psi_n^2$,

$$R(i) = \sum_{n=0}^N \psi_n \psi_{n-i}; \quad (4)$$

$$k_i = - \left[R(i) + \sum_{j=1}^{i-1} a_j^{(i-1)} R(i-j) \right] / E_{i-1}; \quad (5)$$

$$a_i^{(1)} = k_i; \quad (6)$$

$$a_j^{(i)} = a_j^{(i-1)} + k_i a_{i-j}^{(i-1)}, \text{ where } 1 \leq j \leq i-1; \quad (7)$$

$$E_i = (1 - k_i^2) E_{i-1}; \quad (8)$$

and finally $\beta_i = a_i^{(p)}$ for $i = 1, 2, \dots, p$. It should be pointed out that $R(i)$ is the autocorrelation of ψ_n . It should also be pointed out at this juncture that the aforementioned G in equation (3) is defined as follows:

$$G = \sqrt{E_0 + \sum_{i=1}^p \beta_i R(i)}. \quad (9)$$

With the foregoing in mind, we now turn to FIG. 2 which is a realization of phase predictor 70. In this preferred embodiment, phase predictor 70 is realized as a lattice structure. Advantageously, this lattice structure incurs less quantization error than other realizations of phase predictor 70 such as a standard direct form.

- 10 This quantization error is attributed to a truncation or rounding off of the products formed by multiplications involved in each realization.

As shown in FIG. 2, phase predictor 70 in the lattice structure includes reflection coefficients, k_i 's (where $1 \leq i \leq p$), as opposed to the aforementioned β_i 's which are actually the tap coefficients used in the standard direct form. A careful
15 reading reveals that these k_i 's are the byproducts of the above-described recursive process through which the β_i 's are determined. Specifically, in each iteration of the process, equation (5) yields a k_i . In fact, processor 67 of FIG. 1 runs this recursive process to provide a set of k_i 's for phase predictor 70 during the initialization process.

20 Specifically, phase predictor 70 includes p stages. A signal having a value ϕ_n on lead 61 is applied to the first stage of phase predictor 70 wherein subtracter 201 subtracts M_1 from ϕ_n . M_1 is derived from I_1 which is provided by the second stage of phase predictor 70. Specifically, M_1 is achieved by delaying I_1 for a period of T with delay element 205 and then scaling, via multiplier 203, the
25 delayed version of I_1 by a reflection coefficient of k_p . The output of subtracter 201, denoted O_1 , is applied to the second stage wherein subtracter 207, like subtracter 201, subtracts M_2 from O_1 . Similarly, M_2 is achieved by delaying I_2 , which is provided by the third stage of phase predictor 70, for a period of T and then scaling the delayed version of I_2 by a reflection coefficient of k_{p-1} . The output of subtracter
30 207, denoted O_2 , is applied to the third stage of phase predictor 70. O_2 is also scaled by a reflection coefficient of k_{p-1} via multiplier 209. Adder 213 sums the scaled version of O_2 and the delayed version of I_2 to form the aforementioned I_1 .

The third through $(p-1)^{th}$ stages of phase predictor 70 are structurally similar to the second stage as just described. The only difference lies in the value of
35 the reflection coefficient used in each of those stages. Specifically, the reflection

coefficient in the m^{th} stage has a value of k_{p-m+1} , where $3 \leq m \leq p-1$. The p^{th} stage, i.e., the last stage of phase predictor 70, is also very similar to the second stage. It differs from the second stage in that, besides using a different value of reflection coefficient k_1 , the output of the p^{th} stage is looped back to delay element 215 in that same stage. Phase predictor 70 generates, on to lead 71, a signal of the aforementioned value $\hat{\theta}_{n-1}$, which is formed by scaling the output of delay element 215 by a factor G.

The foregoing merely illustrates the present invention. It will thus be appreciated that those skilled in the art will be able to devise numerous other arrangements.

For example, although the disclosed system is embodied in the form of various discrete electronic building blocks and components, the invention could equally as well be embodied in a system in which the functions of any one or more of those building blocks and components or indeed, all of the functions thereof, are realized, for example, by one or more appropriately programmed processors.

**Claims:**

1. Apparatus for estimating phase jitter in a received signal, said apparatus comprising means for receiving a phase error signal which is representative of a difference between said phase jitter and an estimate thereof, and
5 means for providing said estimate in response to said phase error signal, said providing means having an impulse response of infinite duration and a transfer function which is determined by an autocorrelation of said phase error signal.
2. Receiver apparatus for processing a signal which includes phase jitter, said receiver apparatus comprising means for generating a phase error indicative of a
10 difference between said phase jitter and an estimate thereof, means for providing said estimate, said providing means having an impulse response of infinite duration and a transfer function which is determined by an autocorrelation of said phase error, and means for removing said phase jitter from said signal in response to said estimate.
- 15 3. Apparatus for receiving a signal, said apparatus comprising means for demodulating samples of said signal which include phase jitter, said demodulating means using an estimate of said phase jitter as a carrier frequency so that said phase jitter is removed from said samples, and means for providing said estimate in response to a phase error signal, said providing means having an impulse response of
20 infinite duration and a transfer function which is a function of an autocorrelation of a phase error, said phase error being indicative of a difference between said estimate and said phase jitter.
4. A Communication system having a transmitter which transmits a signal, said communication system comprising means for recovering said signal
25 based on samples of a received signal associated with said signal, said samples including phase jitter, means for providing an estimate of said phase jitter in response to a received signal sample, said providing means having an impulse response of infinite duration and a transfer function which is a function of an autocorrelation of a phase error, said phase error being indicative of a difference
30 between said estimate and said phase jitter, and means for removing said phase jitter from said samples in response to said estimate.
5. Apparatus as claimed in claim 2, or a system as claimed in claim 4,



11.

wherein said removing means comprises means for demodulating said samples using said estimate as a carrier frequency.

6. Apparatus as claimed in claim 1,2,3 or 5, or a system as claimed in claim 4 or 5, wherein said transfer function is determined using a recursive
5 technique.

7. Apparatus as claimed in claim 1,2,3,5 or 6, or a system as claimed in claim 4,5 or 6, wherein said providing means is realized as a lattice structure.

8. A method for estimating phase jitter in a received signal, said method comprising the steps of receiving a phase error signal which is representative of a
10 difference between said phase jitter and an estimate thereof, and providing said estimate using a filter having an impulse response of infinite duration and a transfer function which is determined by an autocorrelation of said phase error signal.

9. A method for use in receiver apparatus for processing a signal which includes phase jitter, said method comprising the steps of generating a phase error
15 indicative of a difference between said phase jitter and an estimate thereof, providing said estimate using a filter whose impulse response has an infinite duration and whose transfer function is a function of an autocorrelation of said phase error, and removing said phase jitter from said signal in response to said estimate.

10. A method for use in apparatus for receiving a signal, said method
20 comprising the steps of demodulating first and second samples of said signal which includes phase jitter, said first sample preceding said second sample in time, said demodulating means using an estimate of said phase jitter as a carrier frequency so that said phase jitter is removed from said second sample, and providing said estimate in response to said first sample using a filter whose impulse response has an
25 infinite duration and whose transfer function is a function of an autocorrelation of a phase error, said phase error being indicative of a difference between said estimate and said phase jitter.

11. A method for use in a communications system having a transmitter which transmits a signal, said method comprising the steps of recovering said signal
30 based on samples of a received signal associated with said signal, said samples



12.

including phase jitter, providing an estimate of said phase jitter in response to a received signal sample using a filter whose impulse response has an infinite duration and whose transfer function is a function of an autocorrelation of a phase error, said phase error being indicative of a difference between said estimate and said phase jitter, and removing said phase jitter from said samples in response to said estimate.

12. A method as claimed in claim 9 or 11 wherein said removing step comprises the step of demodulating said samples using said estimate as a carrier frequency.

13. A method as claimed in any one of claims 8 to 12 wherein said transfer function is determined using a recursive technique.

14. A method as claimed in any one of claims 8 to 13 wherein said filter is realized as a lattice structure.
