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(54) **METHOD AND APPARATUS FOR REDUCING COUPLING BETWEEN SIGNALS IN A MEASUREMENT SYSTEM**

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A61B 5/00 (2006.01)

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CPC ***A61B 5/14552*** (2013.01); ***A61B 5/14551*** (2013.01); ***A61B 5/7203*** (2013.01); ***A61B 5/7228*** (2013.01); *A61B 5/7221* (2013.01)

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See application file for complete search history.

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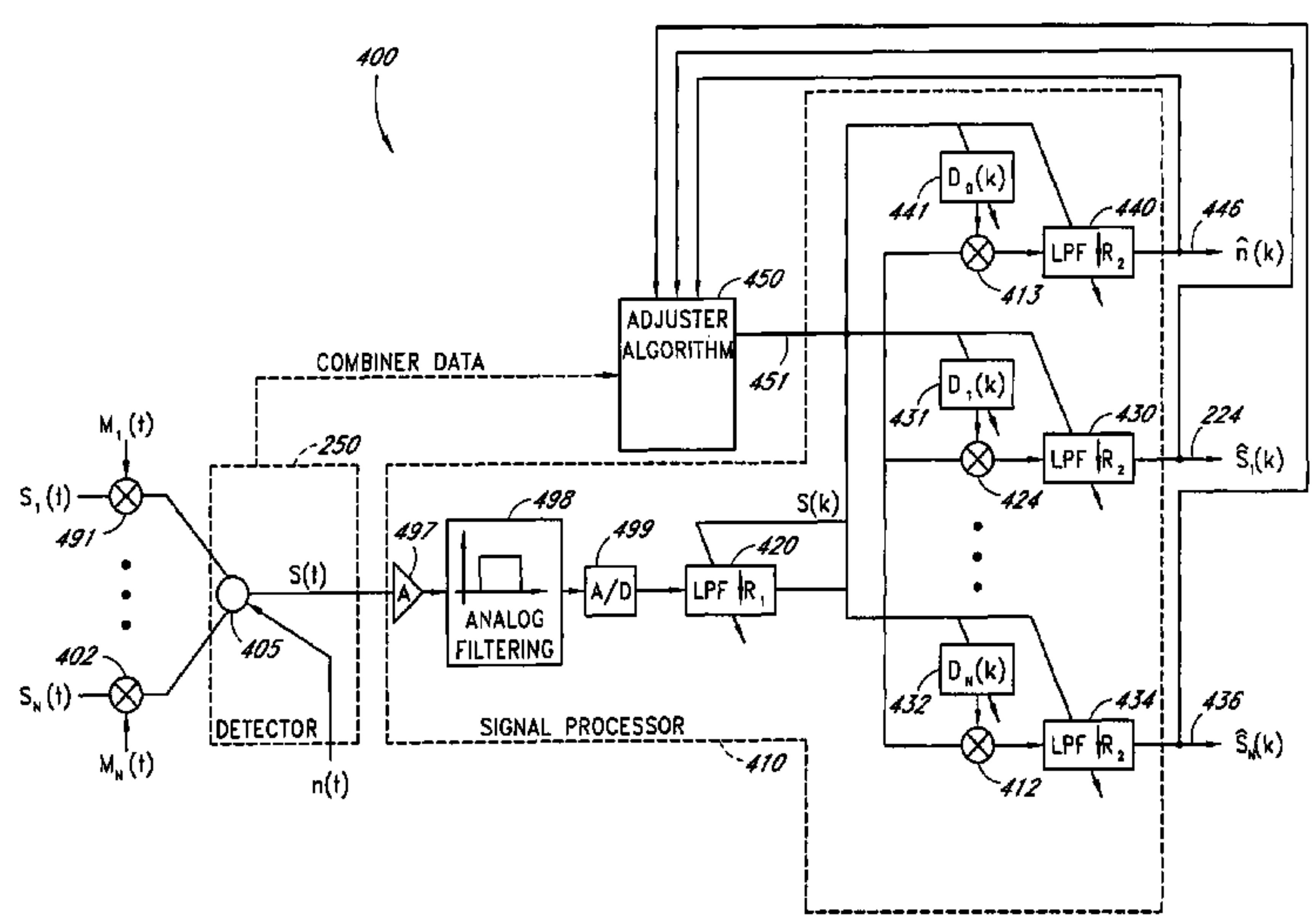
(57) **ABSTRACT**

A method and an apparatus for separating a composite signal into a plurality of signals is described. A signal processor receives a composite signal and separates a composite signal in to separate output signals. Pre-demodulation signal values are used to adjust the demodulation scheme.

20 Claims, 4 Drawing Sheets



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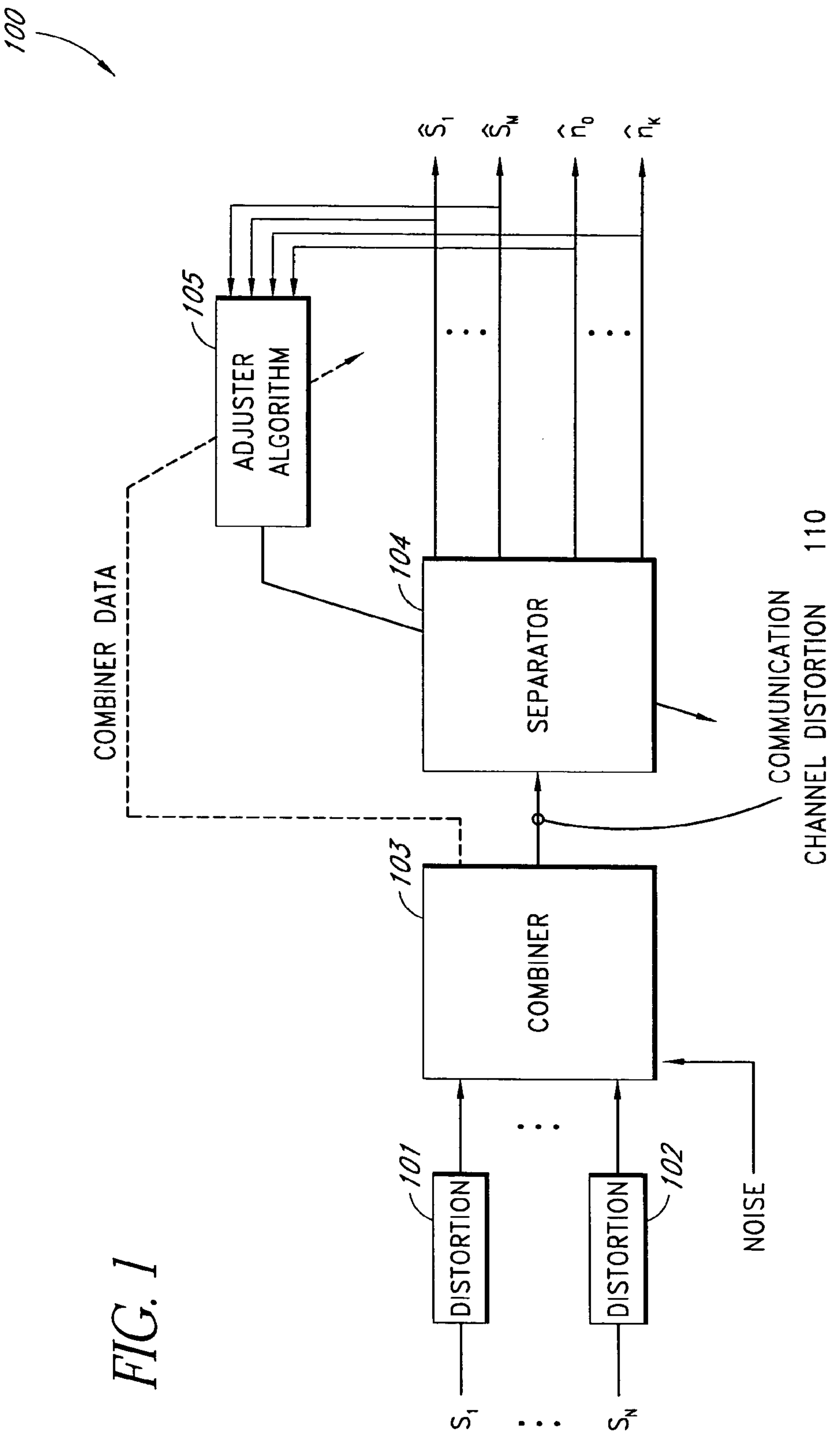
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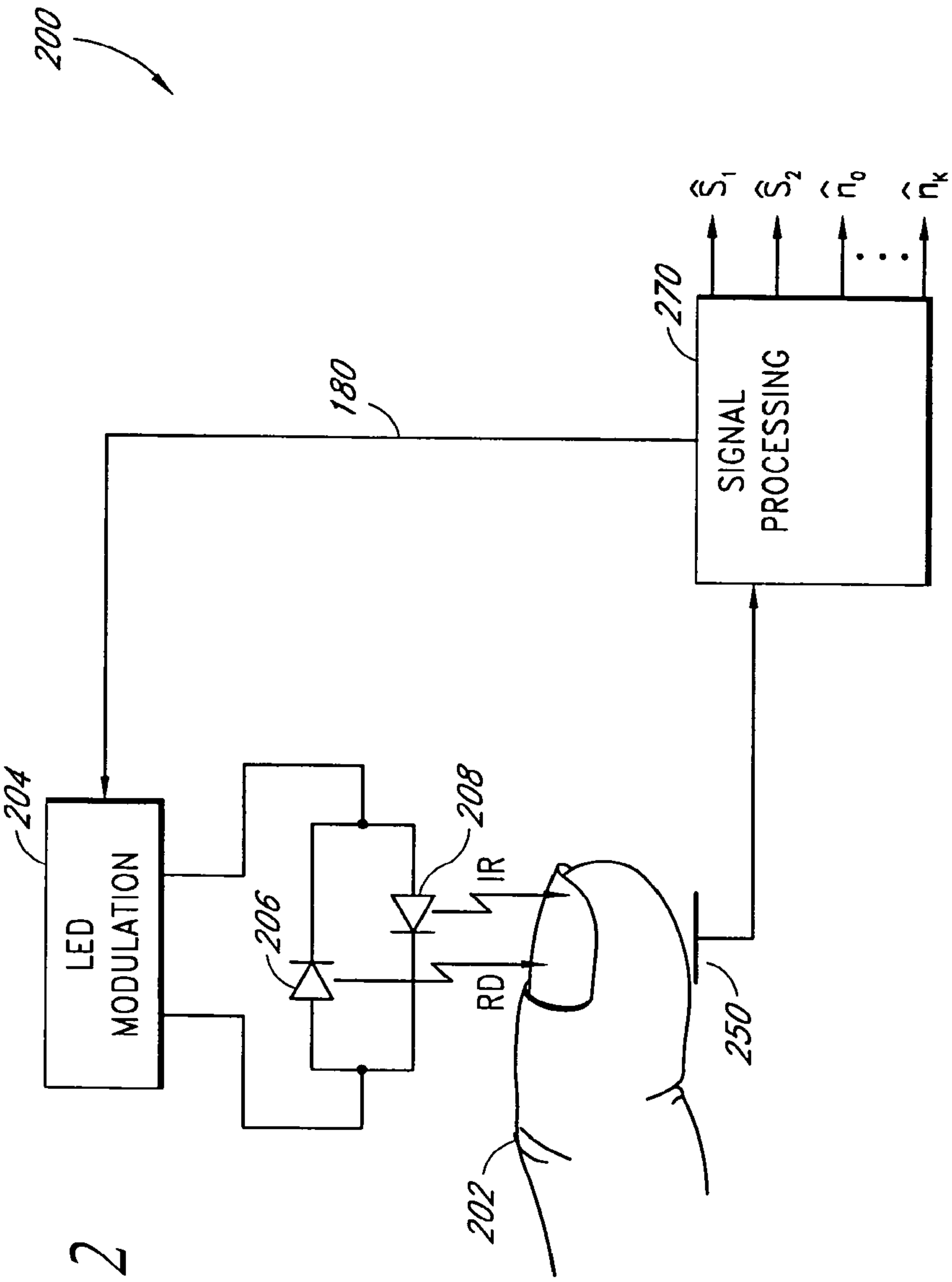
FIG. 1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SIGNAL PROCESSING
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n̂k

FIG. 2

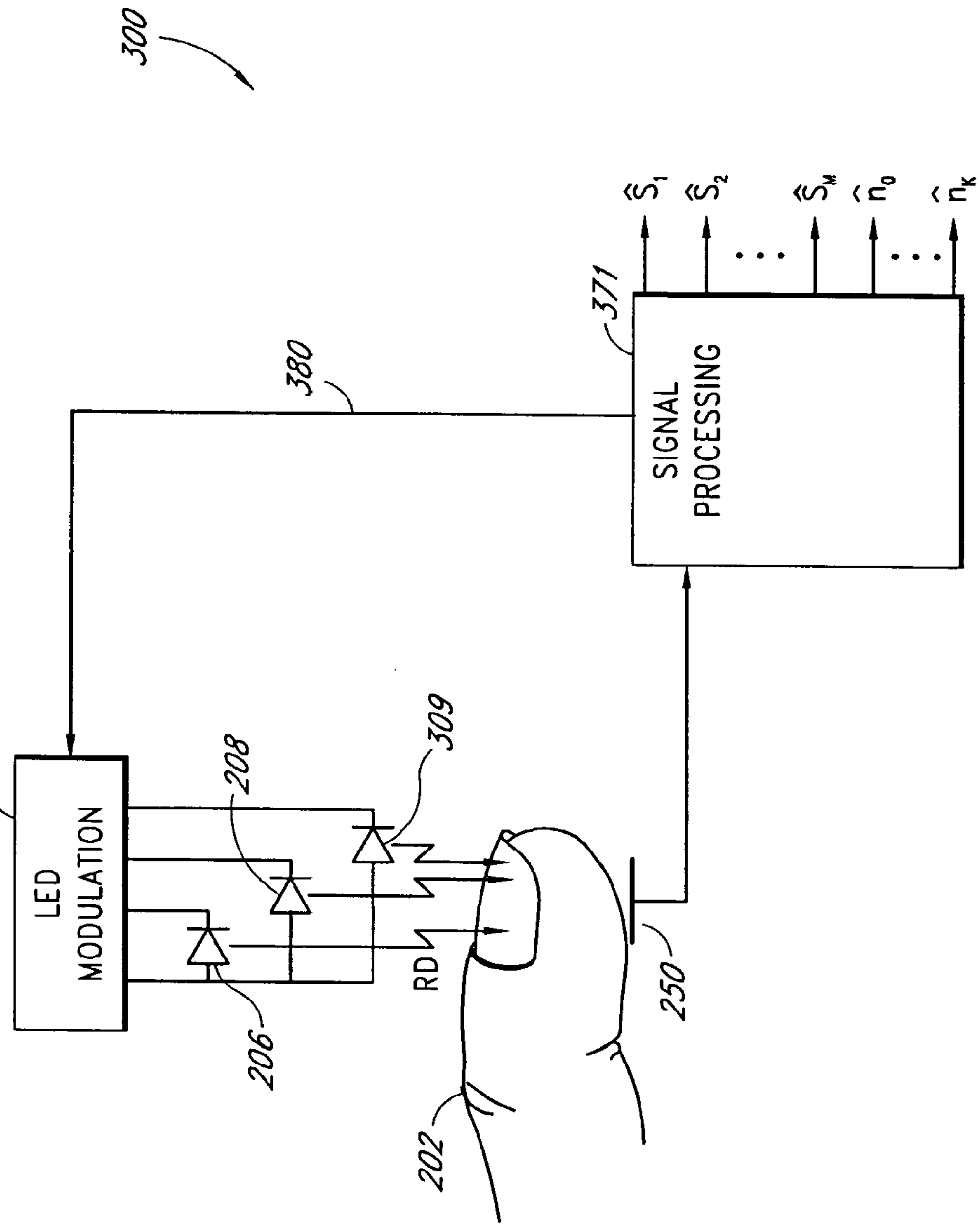
300
380
371
SIGNAL PROCESSING
314
LED MODULATION
208
309
206
RD
250
202

FIG. 3

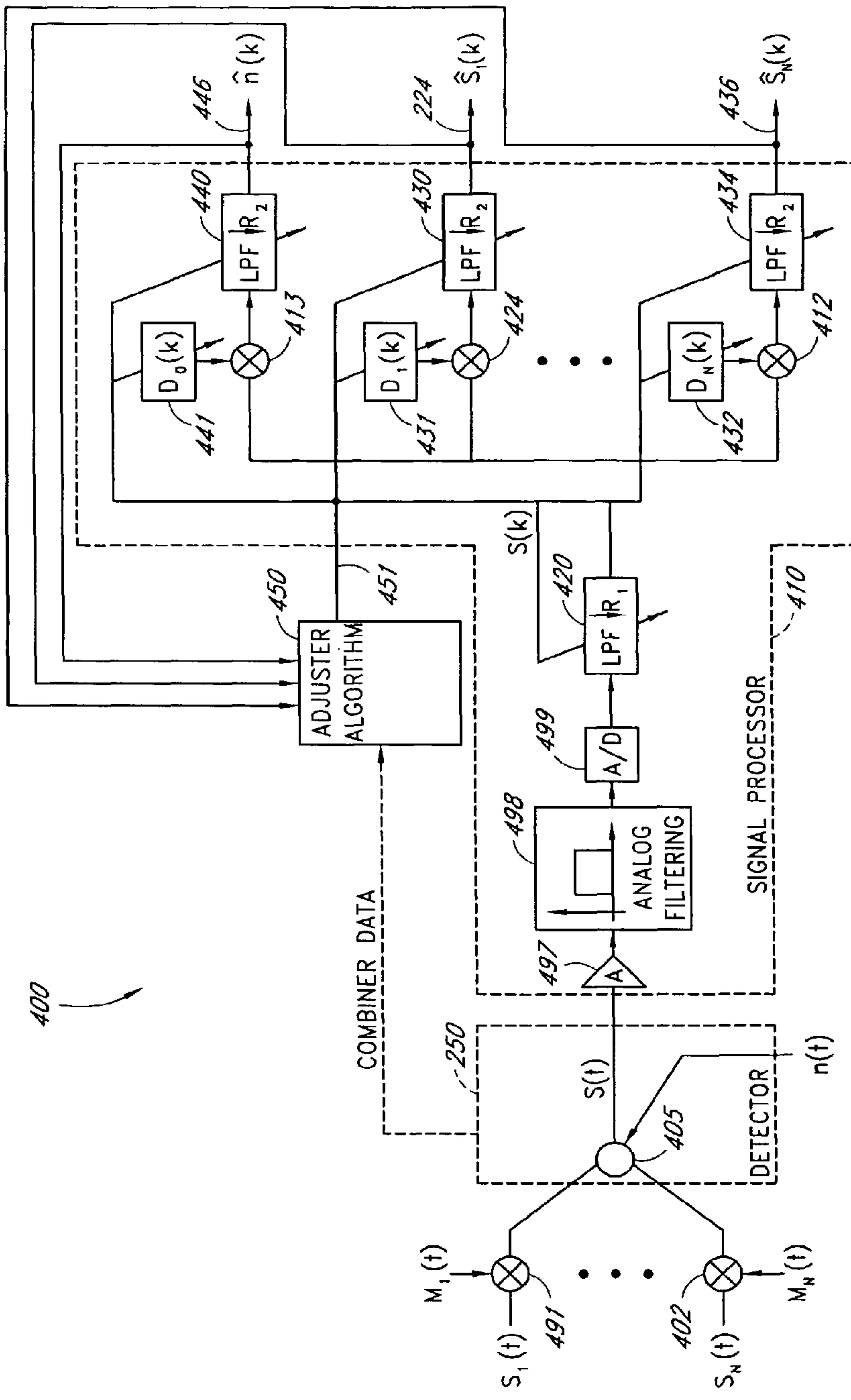
400
ADJUSTER ALGORITHM
450
451
COMBINER DATA
250
DETECTOR
405
n(t)
S(t)
497
A
498
ANALOG FILTERING
499
A/D
420
LPF R1
S(k)
SIGNAL PROCESSOR
410
441
D0(k)
413
440
LPF R2
446
n̂(k)
431
D1(k)
424
430
224
Ŝ1(k)
432
DN(k)
412
434
436
ŜN(k)
S1(t)
M1(t)
491
SN(t)
MN(t)
402

FIG. 4

METHOD AND APPARATUS FOR REDUCING COUPLING BETWEEN SIGNALS IN A MEASUREMENT SYSTEM

REFERENCE TO RELATED APPLICATIONS

The present application is a continuation of U.S. application Ser. No. 12/983,823, filed Jan. 3, 2011, titled "Method and Apparatus for Reducing Coupling Between Signals in a Measurement System," which is a continuation of U.S. application Ser. No. 11/371,242, filed Jan. 23, 2006, titled "Method and Apparatus for Reducing Coupling Between Signals in a Measurement System," which is a continuation of U.S. application Ser. No. 10/615,333, filed Jul. 8, 2003, titled "Method and Apparatus for Reducing Coupling Between Signals," the entire contents of which is hereby incorporated by reference.

BACKGROUND

1. Field

The present disclosure relates to the field of signal processing, and, more particularly, relates to multi-channel demodulators for demodulating mixed signals, such as, for example, signals generated in a pulse oximetry system.

2. Description of the Related Art

In many multi-channel measurement and communication systems, crosstalk between channels and corruption of data within the channels are significant problems. Such problems can arise from variations in manufacturing tolerances, movement, propagation delays, phase shifts, temperature effects, degradation of components due to age or other factors, noise, etc.

A pulse oximetry system is one example of a system where the above-referenced problems are found. In a pulse oximetry system, blood oxygen saturation is determined by transmitting pulses of electromagnetic energy through a portion of a subject having blood flowing therein (e.g., through a finger, through an ear lobe, or other portion of the body where blood flows close to the skin). The pulses of electromagnetic energy comprise periodic pulses of red light having wavelengths of approximately 660 nanometers, for example, and periodic pulses of infrared light having wavelengths of approximately 905 nanometers.

After propagating through the portion of the subject, the red pulses and the infrared pulses are detected by a detector which is responsive to light at both wavelengths and which generates an electrical signal that has a relationship to the intensity of the electromagnetic energy incident on the detector. The detector output is a two-channel signal having a first signal component corresponding to the detected red pulses and a second signal component corresponding to the detected infrared pulses.

The two-channel signal is demodulated to recover separate signals corresponding to the first signal component and the second signal component. However, prior art demodulators are not sufficiently accurate enough to completely separate the two signal components in all cases. Thus, it is not uncommon for the first demodulator output signal (corresponding to the first signal component) to contain residual components of the second signal and vice versa. This crosstalk between the first and second signal components reduces the accuracy of the recovered first and second signals. In multi-channel systems with more than two channels, crosstalk can occur between all of the channels, again reducing accuracy.

SUMMARY

The present disclosure solves these and other problems by separating a combined multi-channel signal into a plurality of output signals in a manner that reduces crosstalk and other contamination in the plurality of output signals. In one embodiment, the separator includes a multi-channel demodulator that is first configured using nominal values for the various components in the signal path. In one embodiment, the multi-channel demodulator is further configured using data obtained from calibration measurements. In one embodiment, the calibration measurements are made during an initialization period. In one embodiment, the calibration measurements are made frequently, continuously, or at selected intervals. In one embodiment, calibrations are performed on at least one of, initialization, on command, on attachment of a new sensor, continuously, and/or interspersed with measurements. In one embodiment of a system for measuring one or more blood constituents, the calibration measurements are made when the system detects that a patient has been connected to the system. In one embodiment, the multi-channel demodulator is further configured at regular intervals by re-running the calibration measurements. In one embodiment, the multi-channel demodulator comprises an optimizing demodulator. In one embodiment, crosstalk in the multi-channel demodulator is reduced by computing an amplitude and/or phase adjustment of one or more demodulation signals that are provided respectively to one or more mixers.

In one embodiment, an apparatus for measuring blood oxygenation in a subject includes a first signal source which applies a first input signal during a first time interval. A second signal source applies a second input signal during a second time interval. A detector detects a first parametric signal responsive to the first input signal passing through a portion of the subject having blood therein and detects a second parametric signal responsive to the second input signal passing through the portion of the subject. The detector generates a detector output signal responsive to the first and second parametric signals. A signal processor receives the detector output signal and demodulates the detector output signal by applying a first demodulation signal to a signal responsive to the detector output signal to generate a first demodulator output signal and applying a second demodulation signal to the signal responsive to the detector output signal to generate a second demodulator output signal. In one embodiment, the first demodulation signal has at least one component comprising a first frequency, a first phase, and a first amplitude; and the second demodulation signal has at least one component comprising a second frequency, a second phase, and a second amplitude. In one embodiment, the first phase and the second phase are chosen to reduce crosstalk from the first parametric signal to the second demodulator output signal and to reduce crosstalk from the second parametric signal to the first demodulator output signal. In one embodiment, the first amplitude and the second amplitude are chosen to reduce crosstalk from the first parametric signal to the second demodulator output signal and to reduce crosstalk from the second parametric signal to the first demodulator output signal. In one embodiment, at least one of the first amplitude, the first phase, the second amplitude, and the second phase are chosen to reduce crosstalk from the first parametric signal to the second demodulator output signal and to reduce crosstalk from the second parametric signal to the first demodulator output signal.

In one embodiment, at least one of the first amplitude, the first phase, the second amplitude, and the second phase is determined by turning off one of the first and second signal sources and measuring the crosstalk between one of the parametric signals and the non-corresponding output signal.

One embodiment includes a method of reducing crosstalk between two signals generated by applying a first pulse and a second pulse to measure a parameter. The first pulse and the second pulse are applied periodically at a repetition rate defining a period. The first pulse is generated during a first interval in each period and the second pulse is generated during a second interval in each period. In one embodiment, the second interval is spaced apart from the first interval. In one embodiment, the second interval overlaps at least a portion of the first interval. The first and second pulses produce first and second parametric signals responsive to the parameter. The first and second parametric signals are received by a detector which outputs a composite signal responsive to the first and second parametric signals. The method includes applying a first demodulation signal to the composite signal to generate a first demodulated output signal. The first demodulation signal includes at least one component having at least a first amplitude and a first phase. The method further includes applying a second demodulation signal to the composite signal to generate a second demodulated output signal. The second demodulation signal includes at least one component having at least a second amplitude and a second phase. The method further includes lowpass filtering the first demodulated output signal to generate a first recovered output signal responsive to the first parametric signal, and lowpass filtering the second demodulated output signal to generate a second recovered output signal responsive to the second parametric signal. The method also includes choosing at least one of the first phase, the first amplitude, the second phase, and the second amplitude to reduce crosstalk components in the first recovered output signal and the second recovered output signal. In one embodiment, the method also includes choosing the first phase and/or the second phase to reduce crosstalk components in the first recovered output signal and the second recovered output signal.

In one embodiment, the first phase and the second phase are chosen by applying a first light pulse pattern during a first time period and measuring the first recovered output during the first time period as a first calibration output, and measuring the second recovered output during the first time period as a second calibration output. The method includes applying a second light pulse pattern during a second time period and measuring the first recovered output during the first time period as a third calibration output and measuring the second recovered output during the second time period as a fourth calibration output. The method further includes computing the first phase and the second phase from at least the first calibration output, the second calibration output, the third calibration output, and the fourth calibration output.

In one embodiment the first phase is computed from a ratio of the first calibration output and the second calibration output.

In one embodiment, the first demodulation signal includes a sum of a first demodulation component having a first amplitude and a second demodulation component having a second amplitude. The second demodulation component is in quadrature with the first demodulation component and the act of choosing the first phase involves choosing the first amplitude and the second amplitude. In one embodiment the quadrature components are sinusoidal and cosinusoidal.

In one embodiment, the first demodulation signal includes a sum of a sinusoidal component having a first amplitude and a cosinusoidal component having a second amplitude. The first amplitude and the second amplitude are chosen by a least squares minimization of an error corresponding to the crosstalk. In one embodiment, the error is integrated over a time period corresponding to an integer number of cycles of the sinusoidal component.

In one embodiment, a first demodulation signal is applied to a composite signal having first and second coefficients to generate a first demodulated signal. The first demodulation signal includes a first component having a first amplitude and a second component having a second amplitude. The first and second components being in quadrature. The second amplitude has a predetermined relationship to the first amplitude. The predetermined relationship is selected to cause the first demodulated signal to have lower frequency components that include a primary component corresponding primarily to the first desired component and a residual component corresponding to the second component. The first demodulated signal is lowpass filtered to generate a first output signal. At least one of the first amplitude and the second amplitude are adjusted to reduce the residual component with respect to the primary component.

In one embodiment, a pulse oximetry system includes a modulation signal generator. The modulation signal generator generates a first modulation signal including a first pulse at a repetition frequency having a first duty cycle. The modulation signal generator generates a second modulation signal including a second pulse which also repeats at the repetition frequency and having a second duty cycle. The second pulse can be non-overlapping with respect to the first pulse, or the second pulse can partially or completely overlap the first pulse. The first and second pulses include a plurality of components wherein a first component has a frequency corresponding to the repetition frequency and a second component has a second frequency corresponding to twice the first frequency. A first transmitter emits electromagnetic energy at a first wavelength in response to the first pulse. A second transmitter emits electromagnetic energy at a second wavelength in response to the second pulse. A detector receives electromagnetic energy at the first and second wavelengths after passing through a portion of a subject. The detector generates a detector output signal responsive to the received electromagnetic energy. The detector output signal includes a signal component responsive to attenuation of the electromagnetic energy at the first wavelength and a signal component responsive to attenuation of the electromagnetic energy at the second wavelength. A first demodulator multiplies the detector signal by a first demodulation signal and generates a first demodulated output signal. A second demodulator multiplies the detector signal by a second demodulation signal and generates a second demodulated output signal. A configuration module configures the first demodulation signal and the second demodulation signal to substantially separate the first demodulator output and the second demodulator output.

In one embodiment, the configuration module selects a phase relationship between the first demodulation signal and the second demodulation signal.

In one embodiment, the configuration module configures the first demodulation signal and the second demodulation signal using, at least in part, data obtained during a calibration period. In one embodiment, the calibration data includes first and second calibration data corresponding to the first and second demodulated output signals during a first time period, and third and fourth calibration data corresponding to the first and second demodulated output signals during a second time period. In one embodiment, the second transmitter is turned off during the first time period, and the first transmitter is turned off during the second time period.

In one embodiment, the configuration module configures the first demodulation signal and the second demodulation signal by adjusting initial parameters that define the first demodulation signal and the second demodulation signal.

The configuration module adjusts the initial parameters using, at least in part, the calibration data obtained during a calibration period.

BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure will be described below in connection with the accompanying figures.

FIG. **1** is a block diagram of a multi-channel processing system that uses feedback from one or more outputs to configure the operation of a signal separator that separates a composite signal into a plurality of output signals.

FIG. **2** is a block diagram of a two-channel signal processing system to determine blood oxygen saturation in a subject, wherein illumination is provided by back-to-back Light-Emitting Diodes (LEDs).

FIG. **3** is a block diagram of a multi-channel signal processing system to determine blood constituents (e.g., oxygen saturation) in a subject, wherein illumination is provided by N diodes or illumination sources.

FIG. **4** is a block diagram of a specific embodiment of the multi-channel processing system of FIG. **1**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. **1** shows a topology of a multi-channel measurement or communication system **100**. The system **100** has a signal combiner **103** for combining one or more input signals $S_1 \ldots S_N$ into a composite signal and a signal separator **104** for separating the composite signal into one or more output signals $\hat{S}_1 \ldots \hat{S}_M$ The output signals $\hat{S}_1 \ldots \hat{S}_M$ can include estimates of the input signals $S_1 \ldots S_N$. The input signals $S_1 \ldots S_N$ are corrupted by pre-combination distortion **101-102** respectively, and, optionally, by combination distortion in the signal combiner **103**. The combiner **103** combines the N input signals into a composite signal (or composite signals). The combiner **401** can combine signals by addition, subtraction, multiplication, division, modulation, non-linear processes, linear processes, estimation, combinations thereof, etc. The composite signal is provided through a communication channel to the separator **104**. The composite signal is distorted by communication channel distortion **110**. The separator **104** separates the composite signal into M output signals, where M can be less than N, greater than N, or equal to N. In one embodiment, the separator also provides one or more additional output signals $\hat{n}_0 \ldots \hat{n}_K$ corresponding to estimates of other signals, such as, for example, noise signals, error signals, etc.

Due to errors in the system **100**, the output signals $\hat{S}_1 \ldots \hat{S}_M$ are typically not exact copies of the input signals, but rather are estimates of the input signals. The accuracy of these estimates is a measure of system performance. The pre-combination distortion **101-102**, the combiner distortion, and/or the channel distortion **110** tend to introduce crosstalk between the channels and thereby corrupt the output signals. The pre-combination distortion **101-102**, combiner distortion, and the channel distortion **110** can be caused by variations in manufacturing tolerances, delay, movement, temperature effects, degradation of components due to age or other factors, noise, etc.

A module **105** is provided to configure the separator **104** to improve the quality of the separation function and thereby improve the quality of the output signals. One or more of the output signals from the separator are provided to the module **105** to provide feedback regarding the quality of the output signals and/or feedback regarding the operation of the separator **104**. The module **105** uses feedback from one or more of the output signals $\hat{S}_1 \ldots \hat{S}_M$ (and, optionally, the output signals $\hat{n}_0 \ldots \hat{n}_K$) to monitor the quality of the separation function and to provide control information to control the operation of the separator. In one embodiment, the module **105** is configured by using configuration data obtained from the combiner **103**. Such configuration data can be obtained by calibration procedures that test the operation of the combiner **103** before or during system use.

In one embodiment, the module **105** configures demodulators in the signal separator **104** using, at least in part, calibration data obtained during a calibration period. For example, in one embodiment involving a two channel system, the calibration data includes first and second calibration data corresponding to the first and second output signals during a first time period, and third and fourth calibration data corresponding to the first and second demodulated output signals during a second time period. In one embodiment, the second transmitter is turned off during the first time period, and the first transmitter is turned off during the second time period. In one embodiment, the module **105** configures the first demodulation signal and the second demodulation signal by adjusting initial parameters that define the first demodulation signal and the second demodulation signal. The configuration module adjusts the initial parameters using, at least in part, the calibration data obtained during a calibration period.

FIG. **2** is a block diagram of a two-channel signal processing system **200** that fits the general topology shown in FIG. **1**. The system **200** is configured to determine one or more blood constituents in a subject, such as, for example, a human subject. In the example presented, the measurements are performed on a portion of the subject, such as a finger **202** illustrated in FIG. **2**A. An LED modulation circuit **204** drives a pair of back-to-back light emitting diodes (LEDs) **206**, **208** by applying a periodic signal to the two light emitting diodes **206**, **208**. Light from the diodes **206**, **208** passes through the finger **202** and is detected by a detector **250**. An output from the detector **250** is provided to a signal processing block **270**. A control output from the signal processing block **270** is provided to the LED modulation circuit **204**. The signal processing block **270** also provides outputs $\hat{S}_1$ and $\hat{S}_2$ corresponding to the light detected from the diodes **206**, **208**, and, optionally, output signals $\hat{n}_0 \ldots \hat{n}_K$ corresponding to estimates of noise or other signals.

In one embodiment, the LED **206** is selected to emit electromagnetic energy in the red visible light range, and has a wavelength of, for example, approximately 660 nanometers. The LED **208** is selected to emit electromagnetic energy in the infrared range, and has a wavelength of, for example, approximately 905 nanometers. The LED modulation circuit **204** supplies current to activate the LEDs **206** and **208**. Each LED is activated for a time period τ which can be different for the different LEDs. The pulses from the LEDs **206** and **208** repeat with a periodicity T.

FIG. **3** is a block diagram of a multi-channel signal processing system **300** that also fits the topology shown in FIG. **1**. Like the system **200**, the system **300** is configured to determine blood oxygen saturation or other blood constituents in a subject, such as, for example, a human subject. In FIG. **3**, an LED modulation circuit **314** drives N diodes, where N is two or greater, thus allowing greater flexibility than the system **200**. In FIG. **3**, the diodes **206** and **208** are shown, along with an N'th diode **309**, it being understood that the diode **309** is omitted if N=2. The LED modulation circuit **314** is configured to allow the diodes **206**, **208**, and **309** to be driven independently such that the diodes can be driven at separate times or in overlapping time periods if desired. Light from the diodes **206**, **208**, **309** passes through the finger **202** and is detected by the detector **250**. The output from the detector **250** is provided to a signal processing block **371**. A control output from the signal processing block **371** is provided to the LED modulation circuit **314**. The signal processing block **371** also provides outputs S_1 through S_M, where M is greater than or equal to one, but need not be equal to N.

FIG. **4** shows one embodiment of an adjustable multichannel modulator/demodulator system **400**. The system **400** is based on the topology of the system **100** and can be used in a system for measuring blood constituents (e.g., pulse oximetry, carboxyhemoglobin, etc.) as shown in FIGS. **2** and **3**. In the system **400**, an input $S_1(t)$ and a modulation input $M_1(t)$ are provided to a first modulator **491**. A signal input $S_N(t)$ and a modulation input $M_N(t)$ are provided to an N^{th} modulator **402**.

The photodetector **250** is modeled as an adder **405**. The outputs of the modulators **491** and **402** are added together in the adder **405**, in the presence of noise n(t) to generate a composite signal M(t) where:

$$S(t)=S_1(t)M_1(t)+\ldots+S_N(t)M_N(t)+n(t) \quad (1)$$

The S(t) signal output of the adder **405** (i.e., the output of the detector **250**) is applied to the input of a signal-processing block **410**. Within the signal-processing block **410**, the signal S(t) is passed through an amplifier **497** and through an analog bandpass filter **498**. The analog bandpass filter **498** provides anti-aliasing and removal of low frequency noise and DC. The desired signal components in the signals $S_i(t)$ are frequency shifted by the operation of the modulation signals $M_i(t)$ and are passed by the analog bandpass filter **498**.

The output of the analog bandpass filter **498** is sampled by an analog-to-digital converter **499** and converted therein to digital signals and provided to an input of an optional decimation block **420**.

The filtered (and, optionally, decimated) signal S(t) is sampled to produce a sampled-data signal S(k) that is provided to the first input of the first mixer **424**, to the first input of the N'th mixer **412**, and to the first input of a noise channel mixer **413**. A first demodulating signal $D_1(k)$ is provided to a second input of a first mixer **424** from a signal generator **431**. The N^{th} demodulating signal $D_N(k)$ is provided to an N^{th} mixer **412** from an output of a signal generator **432**. The noise demodulating signal $D_0(k)$ is provided to the noise channel mixer **413** from an output of a signal generator **441**. A control input to each of the signal generators **431**, **432**, and **441** is provided by the output of the adjuster algorithm **450**. In yet another embodiment, the adjuster algorithm **450** may also be controlled by other signal processing elements downstream of the signal processor **400**.

The outputs of the mixers **413**, **424**, and **412** are provided as respective inputs to decimation blocks **440**, **430**, and **434** respectively. Each of the decimation blocks **440**, **430**, and **434** has a control input provided by the output of the adjuster algorithm block **450**. The output of the decimation block **440** is an estimate of the signal n(t) and it is provided to an input of the adjuster algorithm block **450**. In an alternate embodiment, the signal estimates $\hat{S}_i(k)$ are also provided to the adjuster algorithm block **450**.

An output of the decimator **430** is a signal $\hat{S}_1(k)$, which, as discussed above, is an estimate of the signal $S_1(k)$ (where $S_1(k)$ corresponds to a sampled-data representation of $S_1(t)$). Likewise, the output of the decimation block **434** is an estimate of the signal $S_N(t)$. As shown above, the selection of the demodulating signals $D_i(t)$ for i=0 . . . N in accordance with the present disclosure substantially reduces or eliminates the effects of noise in the output signals $\hat{S}_i$ (k) and n(k), and also substantially reduces or eliminates crosstalk between the signals.

When the system **400** is used in connection with a blood constituent measurement system as shown in FIGS. **2** and **3** the red LED **206** provides a light intensity represented as I_{RD}, and the infrared LED **208** provides a light intensity represented as I_{IR}. The effects of turning the LEDs **206**, **208** on and off on a periodic bases are modeled by the first multiplier or modulator **290** which applies a first modulation signal $M_1(t)$ to the red light intensity to generate a modulated red signal $I_{RDMOD}(t)$ and by a second multiplier the modulator **292** which applies a second modulation signal $M_2(t)$ to the infrared light intensity to generate a modulated infrared signal $I_{IRMOD}(t)$. The modulated light red signal and the modulated infrared signal are applied to the finger **202**, or other body portion, as described above. The blood in the finger **202** has a volume and scattering components, which vary throughout each cardiac cycle. The blood carries oxygen and other materials therein. The oxygen content is a function of both the blood volume and the concentration of the oxygen in the blood volume. The concentration of the oxygen in the blood volume is generally measured as blood oxygen saturation for reasons which are described in full in U.S. Pat. Nos. 5,482,036 and 5,490,505, both of which are hereby incorporated by reference in their entirety. As further described in the two referenced patents, the blood oxygen saturation is determined by comparing the relative absorption of the red light and the infrared light in the finger **202**. The comparison is complicated by the noise caused by movement, ambient light, light scattering, and other factors. The signals $S_1(t)$ and $S_2(t)$ represent the effect of the time-varying volume and scattering components of the blood in the finger **202** on the red light and the infrared light, respectively, passing through the finger **202** from the LEDs **206**, **208** to the detector **250**.

As shown in FIG. **4**, a set of N+1 signals $S_i[k]i=1\ldots N$, and n(k) are sampled at a desired sample rate. The signals are combined according to the formula:

$$S(k)=M_1(k)S_1(k)+\ldots+M_N(k)S_N(k)+n(k) \quad (2)$$

In one embodiment, each of the decimators **420**, **440**, **430**, and **434** includes a digital lowpass filter and a sample rate compressor. In one embodiment, the characteristics of the digital lowpass filters (e.g., the number of filter coefficients and values of the filter coefficients) and the sample rate compression factor of each decimator are fixed. In one embodiment, the characteristics of the digital lowpass filters (e.g., the number of filter coefficients or values of the filter coefficients) and the sample rate compression factor of each decimator are provided by the adjustment algorithm **450**. The signal generators **431**, **432** and **441** generate the demodulation sequences for the demodulators **424**, **412**, and **413** respectively. The demodulation sequences produced by the signal generators **431**, **432** and **441** are controlled by the adjuster algorithm **450**.

In one embodiment, the adjuster algorithm **450** adjusts the pre-demodulation decimation rate R_1 (in the demodulator **420**), and the post-demodulation decimation rate R_2 (in the demodulators **430**, **434** and **440**) according to the noise in the noise estimate $\hat{n}(k)$ and (optionally) according to the signals $\hat{S}_i(k)$. The product R_1R_2 is the total decimation rate from the signal S(k) at the output of the A/D converter **499** to the signals $\hat{S}_i(k)$ at the output of the signal processing block **400**. The adjuster algorithm may adjust R_1 and R_2 such that the product R_1R_2 varies, or the adjuster algorithm may adjust R_1 and R_2 such that the product R_1R_2 is substantially constant. Typically, the adjuster algorithm will keep the R_1R_2 product constant so that the signal processing blocks downstream of the signal processor **400** will operate at a substantially constant sample rate.

In one embodiment, the adjuster algorithm **450** adjusts the demodulation signals $D_i(k)$ to reduce or eliminate crosstalk. In one embodiment, the adjuster algorithm **450** reduces crosstalk by configuring the demodulators, as discussed in more detail below.

One skilled in the art will recognize that the lowpass filters provided in connection with the decimation blocks can provide other filter functions in addition to lowpass filtering. Thus, for example, the lowpass filters **420**, **430**, **440**, and **450**, and the decimators **420**, **430**, **434**, and **440** can provide other filter functions (in addition to lowpass filtering) such as, for example, bandpass filtering, bandstop filtering, etc. Moreover, the post-demodulation decimation rate R_2 need not be the same for each output channel. Thus, for example, in FIG. **4**, the decimator **440** can have a first decimation rate $R_2=r_1$ while the decimators **430** and **434** have a second decimation rate $R_2=r_2$.

The demodulators above are described in terms of digital signal processing on sampled data. Thus, the demodulator signals are written $D_i(k)$. The demodulators and the filtering associated with the demodulators can be done in using analog processing (using time-domain demodulator signals $D_i(t)$) or on sampled data signals (using digital-domain demodulator signals $D_i(k)$). For convenience, the following development describes the demodulator signals primarily in the time domain, with the understanding that the modulators can be implemented using digital signal processing or analog processing.

The characteristics of the demodulation signals $D_1(t)$ and $D_2(t)$ affect how much crosstalk is seen in the output signals. In an diagonal system, that is, when the demodulator has been diagonalized, there is, ideally, no crosstalk. The first output signal $\hat{S}_1(t)$ is an estimate (or approximation) to the signal $S_1(t)$. Similarly, the second output signal $\hat{S}_2(t)$ is an estimate (or approximation) to the signal $S_2(t)$. When the composite signal S(t) is a linear combination of the signals $S_i(t)$, then the relationship between the signals $S_i(t)$ and the signals $\hat{S}_i(t)$. When $M_1=\cos\omega t$, $M_2=\sin\omega t$, $n(t)=0$, and there is no distortion (e.g., no pre-combination, combiner, or channel distortion) then:

$$S(t)=S_1(t)\cos\omega t+S_2(t)\sin\omega t \tag{3}$$

Then:

$$\hat{S}_1(t)=LP[D_1(t)S(t)] \tag{4}$$

$$\hat{S}_2(t)=LP[D_2(t)S(t)] \tag{5}$$

If:

$$D_1(t)=2\cos\omega t \tag{6}$$

$$D_2(t)=2\sin\omega t \tag{7}$$

then

$$\begin{aligned} D_1(t)S(t) &= 2S_1(t)\cos^2\omega t + 2S_2(t)\sin\omega t\cos\omega t \\ &= S_1(t) - S_1(t)\cos 2\omega t + S_2(t)\sin 2\omega t \end{aligned} \tag{8}$$

After lowpass filtering to remove the terms with a frequency of 2 ωt and higher

$$\hat{S}_1(t)=S_1(t) \tag{9}$$

Similarly for

$$\hat{S}_2(t)=LP[D_2(t)S(t)] \tag{10}$$

then

$$\begin{aligned} D_2(t)S(t) &= 2S_1(t)\sin\omega t\cos\omega t + 2S_2(t)\sin^2\omega t \\ &= S_2(t) - S_2(t)\cos 2\omega t + S_1(t)\sin 2\omega t \end{aligned} \tag{11}$$

After lowpass filtering to remove the terms with a frequency of 2 ωt

$$\hat{S}_2(t)=S_2(t) \tag{12}$$

In the above analysis, it was assumed that there are no time delays or phase shifts in the signal S(t), and thus, configuration is relatively straightforward

When an unknown delay (or phase error) is introduced, then the signals are no longer diagonal. Consider, for example, the situation when a delay Δ is introduced into the composite signal. Then:

$$S(t)=\cos\omega(t-\Delta)S_1(t-\Delta)+\sin\omega(t-\Delta)S_2(t-\Delta)$$

It then follows that:

$$\begin{aligned} \hat{S}_1(t) &= LP[2\cos\omega t(\cos\omega t(t-\Delta)S_1(t-\Delta) + \sin\omega(t-\Delta)S_2(t-\Delta))] \\ &= LP[2\cos\omega t(\cos\omega t\cos\omega\Delta + \sin\omega t\sin\omega\Delta)S_1(t-\Delta)] + \\ &\quad LP[2\cos\omega t(\sin\omega t\cos\omega\Delta - \cos\omega t\sin\omega\Delta)S_2(t-\Delta)] \\ &= \cos\omega\Delta S_1(t-\Delta) - \sin\omega\Delta S_2(t-\Delta) \end{aligned}$$

The above equations can be expressed in matrix form as:

$$\begin{bmatrix} \hat{S}_1(t) \\ \hat{S}_2(t) \end{bmatrix} = \begin{bmatrix} \cos\omega\Delta & -\sin\omega\Delta \\ \sin\omega\Delta & \cos\omega\Delta \end{bmatrix} \begin{bmatrix} S_1(t-\Delta) \\ S_2(t-\Delta) \end{bmatrix} \tag{13}$$

Then

$$\begin{bmatrix} S_1(t-\Delta) \\ S_2(t-\Delta) \end{bmatrix} = \begin{bmatrix} \cos\omega\Delta & \sin\omega\Delta \\ -\sin\omega\Delta & \cos\omega\Delta \end{bmatrix} \begin{bmatrix} \hat{S}_1(t) \\ \hat{S}_2(t) \end{bmatrix} \tag{14}$$

The above equation can be expressed as

$$\begin{aligned} \begin{bmatrix} S_1(t-\Delta) \\ S_2(t-\Delta) \end{bmatrix} &= \begin{bmatrix} \cos\omega\Delta & \sin\omega\Delta \\ -\sin\omega\Delta & \cos\omega\Delta \end{bmatrix} \cdot LP \begin{bmatrix} D_1(t)S(t) \\ D_2(t)S(t) \end{bmatrix} \\ &= LP\left[\begin{bmatrix} \cos\omega\Delta & \sin\omega\Delta \\ -\sin\omega\Delta & \cos\omega\Delta \end{bmatrix} \begin{bmatrix} D_1(t) \\ D_2(t) \end{bmatrix} S(t)\right] \\ &= LP\left[\begin{bmatrix} \overline{D}_1(t) \\ \overline{D}_2(t) \end{bmatrix} S(t)\right] \end{aligned} \tag{15}$$

where

$$\begin{aligned} \overline{D}_1(t) &= \cos\omega\Delta D_1(t) + \sin\omega\Delta D_2(t) \\ &= 2\cos\omega\Delta\cos\omega t + 2\sin\omega\Delta\sin\omega t \end{aligned}$$

and similarly for $\overline{D}_2(t)$. Thus the modified demodulation functions $\overline{D}_1(t)$ and $\overline{D}_2(t)$ can be expressed as a linear combination of basis functions. If the time delay Δ can be predicted, then the demodulator functions can be calculated and programmed into the communication system. However, in many cases the time delay Δ is not known or changes over time. As described below, the demodulator functions can be determined by system calibration procedures.

When an unknown phase shift (or phase error) is introduced, then there may be crosstalk in the system. Consider, for example, the situation when a phase error ϕ_1 occurs in the signal $S_1(t)$ and a phase error ϕ_2 occurs in the signal $S_2(t)$. The phase errors can be caused by intrinsic properties of the components, intrinsic properties of the system, component variations, time delays, etc. In the presence of the phase errors:

$$\begin{aligned} D_1(t)S(t) &= 2A_1S_1(t)\sin(\omega t+\phi_1)\sin\omega t + \\ &\quad 2A_2S_2(t)\cos(\omega t+\phi_2)\sin\omega t \\ &= 2A_1S_1(t)\sin\omega t[\sin\omega t\cos\phi_1 + \cos\omega t\sin\phi_1] + \\ &\quad 2A_2S_2(t)\sin\omega t[\cos\omega t\cos\phi_2 + \sin\omega t\sin\phi_2] \\ &= A_1S_1(t)\cos\phi_1 - A_1S_1(t)\cos\phi_1 2\omega t + \\ &\quad A_1S_1(t)\sin\phi_1\sin 2\omega t + A_2S_2(t)\cos\phi_2\sin\omega t - \\ &\quad A_2S_2(t)\sin\phi_2 + A_2S_2(t)\sin\phi_2\cos 2\omega t \end{aligned} \tag{16}$$

Thus, after lowpass filtering

$$\hat{S}_1(t)=A_1S_1(t)\cos\phi_1-A_2S_2(t)\sin\phi_2 \tag{17}$$

The above equation shows crosstalk because $\hat{S}_1(t)$ depends in part on components of $S_2(t)$ when $A_2\neq 0$ and $\phi_2\neq n\pi$ where $n=0, \pm 1, \pm 2 \ldots$.

Similarly,

$$\hat{S}_1(t)=A_1S_1(t)\sin\phi_1-A_2S_2(t)\cos\phi_2 \tag{17}$$

The above equations can be expressed in matrix form as:

$$\begin{bmatrix}\hat{S}_1(t)\\ \hat{S}_2(t)\end{bmatrix} = \begin{bmatrix}A_1\cos\phi_1 & -A_2\sin\phi_2\\ A_1\sin\phi_1 & A_2\cos\phi_2\end{bmatrix}\begin{bmatrix}S_1(t)\\ S_2(t)\end{bmatrix} \tag{19}$$

After inversion

$$\begin{bmatrix}S_1(t)\\ S_2(t)\end{bmatrix} = \frac{1}{\cos(\phi_1-\phi_2)}\begin{bmatrix}\frac{\cos\phi_2}{A_1} & \frac{\sin\phi_1}{A_1}\\ -\frac{\sin\phi_2}{A_2} & \frac{\cos\phi_1}{A_2}\end{bmatrix}\begin{bmatrix}\hat{S}_1(t)\\ \hat{S}_2(t)\end{bmatrix} \tag{20}$$

$$\begin{bmatrix}S_1(t)\\ S_2(t)\end{bmatrix} = \frac{1}{\cos(\phi_1-\phi_2)}\begin{bmatrix}\frac{\cos\phi_2}{A_1} & \frac{\sin\phi_1}{A_1}\\ -\frac{\sin\phi_2}{A_2} & \frac{\cos\phi_1}{A_2}\end{bmatrix}\begin{bmatrix}D_1(t)\\ D_2(t)\end{bmatrix}S(t) \tag{21}$$

Then

$$\begin{bmatrix}S_1(t)\\ S_2(t)\end{bmatrix} = \begin{bmatrix}\overline{D}_1(t)\\ \overline{D}_2(t)\end{bmatrix}S(t) \tag{22}$$

Where $\overline{D}_i(t)$ are modified demodulation functions, given by:

$$\begin{bmatrix}\overline{D}_1(t)\\ \overline{D}_2(t)\end{bmatrix} = \frac{1}{\cos(\phi_1-\phi_2)}\begin{bmatrix}\frac{\cos\phi_2\sin\omega t+\sin\phi_1\cos\omega t}{A_1}\\ \frac{-\sin\phi_2\sin\omega t+\cos\phi_1\cos\omega t}{A_2}\end{bmatrix} \tag{23}$$

The modified demodulation functions have the form

$$\overline{D}_i(t) = \sum_{j=1}^{N}\alpha_j\Phi_j(t) \tag{24}$$

Choosing the coefficients α_j to eliminate crosstalk configures the modulator.

In one embodiment, the coefficients α_j can be fixed coefficients computed using known properties of the system. However, as system properties change over time, such fixed coefficients may lead to unacceptably high levels of crosstalk. Moreover, variations from device to device may cause the fixed coefficients to give unacceptably high levels of crosstalk.

Higher performance (that is, lower crosstalk) can be obtained by computing the coefficients as part of a system calibration or initialization procedure. Such calibration can be performed during system startup (e.g., when the system is turned on, or when the system begins processing data, etc.) and/or at regular intervals. In one embodiment, the adjuster algorithm **450** computes the coefficients α_j from the calibration data. In one embodiment, the coefficients α_j are chosen by making four calibration-type measurements to measure four parameters ξ_{11}, ξ_{12}, ξ_{21}, and ξ_{22}, where:

$$\xi_{11}=\hat{S}_1|_{S_1=A,\,S_2=0}=A\alpha_1\cos\phi_1 \tag{25}$$

$$\xi_{12}=\hat{S}_1|_{S_1=0,\,S_2=B}=-B\alpha_2\sin\phi_2 \tag{26}$$

$$\xi_{21}=\hat{S}_2|_{S_1=A,\,S_2=0}=A\alpha_1\sin\phi_1 \tag{27}$$

$$\xi_{22}=\hat{S}_2|_{S_1=0,\,S_2=B}=B\alpha_2\cos\phi_1 \tag{28}$$

where A and B are amplitudes. Then

$$a_1 = \frac{\sqrt{\xi_{11}^2+\xi_{21}^2}}{A} \tag{29}$$

$$a_2 = \frac{\sqrt{\xi_{12}^2+\xi_{22}^2}}{B} \tag{30}$$

$$\tan\phi_1 = \frac{\xi_{21}}{\xi_{11}} \tag{31}$$

$$\tan\phi_2 = -\frac{\xi_{12}}{\xi_{22}} \tag{32}$$

From the above equations, it is evident that crosstalk depends only ϕ_1 and ϕ_2. Moreover, ϕ_1 and ϕ_2 can be chosen to eliminate crosstalk without knowing A or B. This is useful for systems such as pulse oximetry systems where absolute measurements of a channel are difficult or impractical, but where relative measurements (e.g., channel-to-channel measurements) are practical.

The demodulation signals $D_i(t)$ can be generated using the values of ϕ_1 and ϕ_2 from the above equations. Alternatively, the demodulation signals $D_i(t)$ can be generated from quadrature components as:

$$D_1(t)=b_{11}\sin\omega t+b_{12}\cos\omega t \tag{33}$$

$$D_2(t)=b_{21}\sin\omega t+b_{22}\cos\omega t \tag{34}$$

where the coefficients b_{ij} are computed from ϕ_1 and ϕ_2.

In one embodiment, the demodulation functions are adapted from baseline coefficients, which are then improved through a calibration or initialization procedure to produce actual coefficients. The baseline coefficients are typically obtained from known properties of the system. The actual coefficients are usually relatively close in value to the baseline coefficients. This provides one way to assess the operational status of the system and to evaluate the calibration procedure. In one embodiment, if the actual coefficients are too different from the baseline parameters then it is assumed that the calibration procedure failed in some manner or that the equipment has failed in some manner, and appropriate measures can be taken (e.g., alert the operator, sound a warning, etc.)

To find the actual coefficients, the demodulation functions are initially given by:

$$D_1(t)=\alpha_{11}\sin\omega t+\alpha_{12}\cos\omega t \tag{35}$$

$$D_2(t)=\alpha_{21}\sin\omega t+\alpha_{22}\cos\omega t \tag{36}$$

Where the coefficients α_{ij} are the baseline coefficients determined from known or assumed properties of the signal S(t). For example, in one embodiment $\alpha_{ij}=\delta_{ij}$. In one embodiment, where initial estimates are available for ϕ_1 and ϕ_2, then the values of α_{ij} can be computed as discussed above.

The crosstalk reduction obtained using demodulation functions based on the coefficients α_{ij} can often be improved by computing new coefficients $\overline{\alpha}_{ij}$ and corresponding new demodulation functions $\overline{D}_i$ (t) where:

$$\overline{D}_1(t)=\overline{\alpha}_{11}\sin\omega t+\overline{\alpha}_{12}\cos\omega t \tag{37}$$

$$\overline{D}_2(t)=\overline{\alpha}_{21}\sin\omega t+\overline{\alpha}_{22}\cos\omega t \tag{38}$$

The process of finding the coefficients $\overline{\alpha}_{ij}$ begins by measuring two data sets, x_1(t) and x_2(t), as follows:

$$x_1(t)=S(t)|_{S_1=A,\ S_2 32\ 0} \tag{39}$$

$$x_2(t)=S(t)|_{S_1=0,\ S_2 32\ B} \tag{40}$$

The data sets x_1(t) and x_2(t) are used to enforce the following constraint:

$$\int_0^{nT} x_i(T)\overline{D}_i(t)d = 0 \tag{41}$$

where i=1, 2, n=1, 2, 3 . . . , and T is a time period corresponding to one complete modulation cycle. From the above constraint and the definitions of the demodulation functions, it follows that:

$$\overline{\alpha}_{11}\int_0^{nT} x_1(t)\sin\omega t\,dt+\overline{\alpha}_{12}\int_0^{nT} x_1(t)\cos\omega t\,dt=0 \tag{42}$$

$$\overline{\alpha}_{21}\int_0^{nT} x_2(t)\sin\omega t\,dt+\overline{\alpha}_{22}\int_0^{nT} x_2(t)\cos\omega t\,dt=0 \tag{43}$$

It is convenient to define

$$\gamma_{11}=\int_0^{nT} x_1(t)\sin\omega t\,dt \tag{44}$$

$$\gamma_{12}=\int_0^{nT} x_1(t)\cos\omega t\,dt \tag{45}$$

$$\gamma_{21}=\int_0^{nT} x_2(t)\sin\omega t\,dt \tag{46}$$

$$\gamma_{22}=\int_0^{nT} x_2(t)\cos\omega t\,dt \tag{47}$$

and to define

$$\beta_{ij}=\frac{\gamma_{ij}}{\left[\sum_k \gamma_{ik}^2\right]^{1/2}} \tag{48}$$

where

$$\sum_k \beta_{ik}^2=1 \tag{49}$$

Then

$$\overline{\alpha}_{11}\beta_{11}+\overline{\alpha}_{12}\beta_{12}=0 \tag{50}$$

$$\overline{\alpha}_{21}\beta_{21}+\overline{\alpha}_{22}\beta_{22}=0 \tag{51}$$

In one embodiment, to reduce crosstalk, it is desired to find the coefficients $\overline{\alpha}_{ij}$ closest (in the sense of minimizing some specified error, such as, for example, a least squared error) to the coefficients α_{ij} such that the above constraints are satisfied. One solution, obtained by minimizing the least squared error is:

$$\overline{\alpha}_{ij}=a_{ij}-\left(\sum_k \alpha_{ik}\beta_{ik}\right)\beta_{ij} \tag{52}$$

The term in parentheses can be described as the baseline crosstalk.

One of ordinary skill in the art will recognize that optimization methods other than least squares can be used. The solution methods for configuration are, for simplicity, described above in terms of a two-channel system. Using the above teachings, the extension to multi-channel systems is straightforward.

Although described above in connection with a particular embodiment of the present disclosure, it should be understood the description of the embodiment is illustrative of the disclosure and are not intended to be limiting. Although described above in connection with a pulse oximetry system wherein a parameter to be measured is the attenuation of red and infrared light passing through a portion of a subject's body, it should be understood that the method and apparatus described herein can also be used for other measurements where two or more signals are passed through a system to be analyzed. In particular, the present disclosure can be used to demodulate two combined parametric signals responsive to the system to be analyzed where the two parametric signals have a predetermined timing relationship between them, as described herein. The disclosure can be used in connection with various physiological parameter measurement systems, such as, for example, systems that measure blood constituents, blood oxygen carboxyhemoglobin, methemoglobin, glucose, etc. Various modifications and applications may occur to those skilled in the art without departing from the true spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. A system which measures one or more physiological characteristics of a living subject non-invasively by measuring pulsing light of two or more wavelengths after attenuation by body tissue, the system comprising:

at least one emitter configured to emit light of at least two or more different wavelengths using a modulation scheme that cycles the at least two or more different wavelengths, the at least one emitter positioned to emit light in the direction of a living subject;

at least one detector configured to detect the light of the at least two or more different wavelengths emitted from the at least one detector after the light has been attenuated by tissue of the living subject, the detector further configured to generate a detector signal representative of the emitted light;

a demodulation system configured to demodulate the detector signal, the demodulation system configured to adjust the demodulation of the detector signal to reduce crosstalk based, at least in part, on detector configuration data.

2. The system of claim **1**, the demodulation system is further configured to adjust the demodulation based on previously demodulated signal values.

3. The system of claim **1**, wherein the demodulation is adjusted during an initial calibration period.

4. The system of claim **3**, wherein the demodulation is adjusted during periodic calibration periods during measurement.

5. The system of claim **2**, wherein the previously demodulated signal values comprises a plurality of demodulated signal values corresponding respectively to the at least two or more different wavelengths.

6. The system of claim **5**, wherein each of the plurality of demodulated signal values is determined using a demodulation coefficient.

7. The system of claim **1**, wherein the demodulation system comprises a plurality of demodulation coefficients used to demodulate the detector signal.

8. The system of claim **7**, wherein at least one demodulation coefficient is used for each of the at least two or more different wavelengths.

9. The system of claim **1**, wherein the demodulation has been diagonalized.

10. A method of demodulating a composite signal generated by applying at least first and second periodic pulses of electromagnetic energy to a system having a physiological parameter to be measured and by non-invasively receiving signals responsive to said electromagnetic energy after attenuation by body tissue of a living subject, said signals received as a composite signal having at least first and second components responsive to said at least first and second pulses respectively, said method comprising:

receiving, at one or more signal processors, a composite signal responsive to electromagnetic energy of at least first and second periodic pulses of electromagnetic energy after attenuation by body tissue;

applying, using the one or more signal processors, a first demodulation scheme to said composite signal to generate at least a first demodulated signal; and

automatically adjusting, using the one or more signal processors, the first demodulation scheme based at least in part on detector configuration data.

11. The method of claim **10**, wherein the adjustment reduces crosstalk.

12. The method of claim **10**, further comprising applying a second demodulation scheme to said composite signal to generate a second demodulated signal and adjusting the second demodulation scheme based at least in part on the second demodulated signal.

13. The method of claim **12**, wherein said signal processor is further configured to adjust at least one of the first and second demodulation schemes in the absence of at least one of the first and second periodic pulses of electromagnetic energy.

14. The method of claim **12**, wherein said signal processor is further configured to adjust at least one of the first and second demodulation schemes based on the demodulated signals in order to further reduce crosstalk interspersed with measurements.

15. The method of claim **10**, wherein said adjusting occurs continuously.

16. The method of claim **10**, wherein said adjusting occurs interspersed with measurements.

17. A system for demodulating a composite signal generated by applying at least first and second periodic pulses of electromagnetic energy to a system having a physiological parameter to be measured and by non-invasively receiving signals responsive to said electromagnetic energy after attenuation by body tissue of a living subject, said signals received as a composite signal having at least first and second components responsive to said at least first and second pulses respectively, said system comprising:

means for receiving, at one or more signal processors, a composite signal responsive to electromagnetic energy of at least first and second periodic pulses of electromagnetic energy after attenuation by body tissue;

means for applying, using the one or more signal processors, a first demodulation scheme to said composite signal to generate at least a first demodulated signal; and

means for automatically adjusting, using the one or more signal processors, the first demodulation scheme based at least in part on detector configuration data.

18. The system of claim **17**, wherein the adjustment reduces crosstalk.

19. The system of claim **17**, further comprising applying a second demodulation scheme to said composite signal to generate a second demodulated signal and adjusting the second demodulation scheme based at least in part on the second demodulated signal.

20. The system of claim **19**, wherein said system further comprises means for adjusting, using the one or more processors, at least one of the first and second demodulation schemes in the absence of at least one of the first and second periodic pulses of electromagnetic energy.

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