

## **System for and Method of Removing Unwanted Inband Signals from a Received Communication Signal**

This application is a continuation-in-part of U.S. Application No. 12/753,644, filed April 2, 2010, which claims the benefit of U.S. Provisional Application No. 61/266,312, filed December 3, 2009. The entire contents of both prior applications are hereby incorporated by reference.

### Field of the Invention

[0001] The invention relates to a novel system for and method of removing unwanted inband signals from a received communication signal, thereby improving the quality of the received communication.

### Background

[0002] Information can be transmitted across distances by encoding the information onto a carrier and transmitting the resulting communication signal across different types of wired or wireless media. At the receiving end, a composite signal is received that includes both the desired communication signal as well as other signals that become added either intentionally or unintentionally to and within the bandwidth of the desired communication signal. These other signals may include noise, interferences or any other undesirable signals, and are generally unwanted because they collectively and individually contribute to the degradation of the quality of the received communication signal. Because they are present within the frequency range (i.e. bandwidth) of the desired communication signal, these other signals are referred to as being "inband."

[0003] The quality of a received communication signal, such as that carried on a TV channel or a radio channel, can be expressed as a ratio of carrier power (C) to noise power (N), where C represents the power of the desired received communication signal and N represents the aggregate power of all the unwanted signals present in the bandwidth of the carrier. This invention is directed toward improving the quality of the received communication signal by removing these unwanted signals from the received communication signal.

### Summary

[0004] A system for and method of removing one or more unwanted inband signals from a received communications signal is described. The inband signal or signals may comprise noise, interference signals, or any other unwanted signals that impact

the quality of the underlying communications. A receiver receives a communication signal, the received communication signal including the desired communication signal and one or more inband signals. A signal separator processes the received signal to form an estimate of the desired communication signal and an estimate of the inband signals. A performance improver processes the received signal and the estimate of the one or more inband signals to form an improved estimate of the desired communication signal and an improved estimate of the inband signals.

#### Brief Description of the Drawings

[0005] Figure 1 illustrates a block diagram of an inband signal remover in accordance with an embodiment of the present invention;

[0006] Figure 2 illustrates a system for receiving and processing a communication signal in accordance with an embodiment of the present invention;

[0007] Figure 3 illustrates a constellation diagram of a received communication signal in accordance with an embodiment of the present invention;

[0008] Figure 4 illustrates a constellation diagram of the signal of Figure 2 after having been processed in accordance with an embodiment of the present invention;

[0009] Figure 5 illustrates a constellation diagram of a received communication signal along with an unwanted signal in accordance with an embodiment of the present invention;

[0010] Figure 6 illustrates a constellation diagram of the signal of Figure 5 after having been processed in accordance with an embodiment of the present invention;

[0011] Figure 7 illustrates an inband signal separator in accordance with an embodiment of the present invention;

[0012] Figure 8 illustrates a block diagram of an enhanced signal separator in accordance with an embodiment of the present invention;

[0013] Figure 9 illustrates a system employing the enhanced signal separator in conjunction with a signal demodulator in accordance with an embodiment of the present invention;

[0014] Figure 10 illustrates a system employing the enhanced signal separator in conjunction with two signal demodulators in accordance with an embodiment of the present invention; and

[0015] Figure 11 illustrates a block diagram of a performance improver in accordance with an embodiment of the present invention.

#### Description of an Embodiment of the Invention

[0016] We describe a new system and method for removing unwanted inband signals from a received communication signal thereby improving the quality of the communication signal. As used herein, the term "received communication signal" refers to a composite signal that includes both an information bearing communication signal (also referred to as a "desired" communication signal), and other signals that simultaneously occupy the same bandwidth that are either unanticipated or undesired (also referred to as "unwanted" signals). These unwanted signals include noise, interferences and any other inband signal that is not the desired communication signal. These signals are "unwanted" because they collectively and individually contribute to the degradation of the quality of the received communication signal. While undesired out-of-band signals can be readily filtered off by a frequency-selective filter, these inband unwanted signals cannot generally be filtered off. Therefore, the inband signals are more difficult to remove, especially if no prior knowledge of the characteristics of the inband signals are available.

[0017] The method does not require prior knowledge of characteristics of the unwanted inband signals, nor does it require a copy of any of the unwanted inband signals to be available from any source other than the composite signal itself. Thus, all processing is conducted solely from the composite received signal, which has both the desired communication signal and the unwanted signals in it. Because of this, random noise can be removed in addition to removing other inband signals, such as interferers.

[0018] To help illustrate this invention, consider the following received communication signal

$$S = C + I1 + I2 + \dots + In + NoB \quad (\text{equation 1})$$

Where,

S represents the composite received signal that includes both the desired communication signal and the unwanted inband signals

C represents the desired communication signal

I1 represents the first unwanted signal

In represents the nth unwanted signal and

NoB represents the received random noise

As such, we can describe the received carrier-to-noise performance of this signal as

$$\text{Carrier-to-noise} = C/(I1+I2+...+ In + NoB) \quad (\text{equation 2})$$

[0019] Using this invention, the unwanted signal components, I1, I2,..., In and NoB can be estimated from the received signal S. These estimates can be described as follows

I1\* - Estimate of first unwanted signal component

I2\* - Estimate of second unwanted signal component

In\* - Estimate of nth unwanted signal component

NoB\* - Estimate of received random noise

[0020] If we use these estimates to cancel the unwanted signal components, then we come up with the following

$$\varepsilon = I1-I1* + I2-I2* + ... + In - In* + NoB - NoB* \quad (\text{equation 3})$$

Where  $\varepsilon$  represents the residual error after the cancellation. Using this approach, the received carrier to noise performance of our communication signal can be expressed as  $C/\varepsilon$ , where  $\varepsilon \ll (I1 + I2 + ... + In + NoB)$  if the estimates of the undesirable components are sufficiently close to the actual components themselves.

[0021] This novel technique can be used in several different ways to improve the quality of a received communication signal as well as the capacity of a communications channel. In one formulation of this invention, it can be used to improve the effective received carrier-to-noise ratio when a communication signal is received with unwanted random noise, such as statics. By estimating and then removing the noise to within range of the error,  $\varepsilon$ , the received carrier-to-noise ratio can be improved. This aspect of the invention would save power—and therefore

energy consumption—by allowing communication signals to be transmitted at lower powers, and still be received with the same quality.

[0022] In another aspect of this invention, this technique can be used to remove one or more unwanted interfering signals that are received within the bandwidth of the desired communication signal. By estimating the interfering signals and then removing them to within range of the error,  $\epsilon$ , the quality of the received communication signal can be improved.

[0023] In a third aspect of this invention, it can be used to increase the communication capacity of a channel by allowing two or more communication signals to be transmitted simultaneously in the same bandwidth. In this formulation of the invention, both the desired carrier (C) and an inband interfering signal are communication signals. But, from the point-of-view of the desired carrier (C), the inband signal is an unwanted interferer. However, from the point-of-view of the inband signal (which is itself an desired communication signal), the carrier (C) is an unwanted interferer. The invention can be used to separate out these various communication signals from one another, effectively allowing multiple carriers to simultaneously share the same communications channel, and thereby resulting in a net gain in the capacity of the communications channel. The capacity increase that can be gained using this technique, for a given modulation scheme, can be described as shown in equation 4 below

$$C_i = (M-1)*100\% \quad (\text{equation 4})$$

Where  $C_i$  is the channel capacity improvement and  $M$  is the number of overlapped communication signals. For example, two communication signals ( $M=2$ ) transmitted this way would result in a 100% increase in capacity(i.e.,  $(2-1)*100\%$ ).

[0024] An advantage of this method is that it does not need a copy of a given unwanted signal in order to remove it and obtain the desired signal.

[0025] Figure 1 shows a system block diagram of a signal remover 100 in accordance with an embodiment of the present invention. As shown in Figure 1, the input signal  $S_1$  denotes the desired communication signal and  $S_2$  the unwanted signals which are received simultaneously in the same channel.  $S_1$  and  $S_2$  can be completely independent, meaning that  $S_2$  does not have to be related to  $S_1$  in any way such as, for example, when  $S_2$  is a modified version of  $S_1$ .

[0026] The signals S1 and S2 may be preprocessed prior to being processed by the signal remover 100. This may include, but not limited to, simultaneously receiving the combined signals S1+S2, and digitizing, filtering and resampling the signals.

[0027] In an embodiment of the present invention, S1 and S2 are presumed to be different in some way as, for example, the following:

$P_{s2} < P_{s1}$ , where

$P_{s1}$  = Received power of S1

$P_{s2}$  = Received power of S2

[0028] Using this framework, we now walk through the block diagram of Figure 1. Starting from the top left, S1 and S2 are received together and input to a first block (102). The processing steps are described in order below:

[0029] The signal S1 is demodulated using a processor, such as an adaptive equalizer or a matched filter. Figure 1 shows an adaptive equalizer 102, but a matched filter, or some other processing scheme, can be used as well. Thus, referring to Figure 1, the demodulation is performed by the adaptive equalizer 102, a phase lock loop (PLL) 104, a symbol decision block 106 and a symbols-to-bits converter block 108. With the condition that  $P_{s2} < P_{s1}$ , this demodulation stage will demodulate signal S1 (if the condition were such that  $P_{s2} > P_{s1}$ , then the demodulated signal would be S2). In some circumstances, the demodulation stage can also demodulate the signal S1 even in the presence of higher power S2 signals. An example of this would be if S2 was only partially overlapping in frequency with S1.

[0030] The adaptive equalizer 102 receives the combined signals S1+S2. The adaptive filter coefficients are updated using an adaptive algorithm such as the Least Mean Squared (LMS) error algorithm, which attempts to minimize the feedback signal E from summation block 110. The adaptive filter generates at its output an equalized estimate of S1 symbols. This equalized estimate is applied to a multiplier 112 along with a phase difference signal from the PLL 104 to generate a phase-compensated estimate of S1 symbols at the output of the multiplier 112 (this signal is labeled "Y" in Figure 1). This phase-compensated estimate of S1 symbols is provided to the symbol decision block 106 which outputs S1 symbols from a symbol map based on the phase-compensated estimate of S1 symbols (the output signal is labeled "D" in

Figure 1). In an embodiment of this invention, the symbol map for the signal S1 can be known in advance or derived from the received signal S1, such as is described in U.S. Patent No. 7,639,761, the entire contents of which are hereby incorporated by reference.

[0031] The output D of the symbol decision block 106 is applied to the symbols-to-bits block 108, to the summation block 110 and to the PLL 104. The summation block 110 determines a difference between each S1 symbol output from the symbol decision block 106 and the corresponding S1 symbol that was input to the symbol decision block 106 to form the feedback signal E which is used to adjust the equalizer parameters. The PLL 104 uses the phased-compensated S1 symbols from the multiplier 112 and the symbols output from the symbol decision block 106 to form the phase correction which is applied to the multiplier 112. Thus, the PLL 104 causes the demodulation stage to lock to the signal S1 by tracking and adjusting the phase offset from the equalizer output. The greater power of S1 results in locking to S1 rather than to S2.

[0032] The symbols-to-bits block 108 converts the phase compensated estimate of the symbols (the signal "D") to a S1 output bit stream. This bit stream represents the demodulated estimate of S1 bits.

[0033] Error correction can be performed on the demodulated S1 signal to correct some or all of the errors incurred during the demodulation process if forward error correction information is embedded in S1. Referring to Figure 1, error correction is performed by an error correction block 114. The output of the error correction block 114 is an-error corrected version of the S1 estimate and is different from the demodulated signal in that bit errors are reduced. It should be noted that in an embodiment of this invention, the error correction block 108 may be omitted. Error correction may be omitted where the signal S1 does not include forward error correction information.

[0034] The bits are converted into symbols using the symbol map for signal S1. This process is performed by a bits-to-symbols block 116 shown in Figure 1 and can use the known symbol map, or a symbol map that is derived from the received signal S1, as described above.

[0035] Pulse shaping and upsampling can also be performed. The upsampling is used to match the sampling rate of the signal S1 at the input. The input sampling rate

should be a multiple of the symbol rate of S1 such as 2 samples/symbol. Referring to Figure 1, this is performed by an upsample and pulse shape block 118. The pulse shaping applied should match the S1 transmit pulse shaping. The output of this step is an estimate of S1. This estimated signal is denoted as  $S1^*$ . If the pulse shaping of S1 is unknown, then the pulse shaping step can be omitted. This is because an adaptive filter configured as an adaptive noise canceller 120, discussed below, will also attempt to pulse shape the estimate,  $S1^*$ , to match that of the input signal S1. Therefore, where the pulse shaping of S1 is known, it can be applied to the estimated signal; otherwise, pulse shaping may be omitted.

[0036] The  $S1^*$  estimate is then input to the adaptive noise canceller block 120. The adaptive noise canceller 120 adaptively cancels the estimate of S1 from the combined received signal  $S1+S2$ . The adaptive noise canceller 120 can provide two outputs:

- a. The error signal from the adaptive canceller 120, which in this case is an estimate of S2, which is referred to as  $S2^{**}$ .
- b. A revised estimate of S1, which is referred to as  $S1^{**}$ . The adaptive noise canceller 120 generates this revised estimate  $S1^{**}$  by attempting to minimize the error  $\epsilon$  which is the difference between  $S1^{**}$  and S1.

[0037] The signal  $S1^{**}$  from the adaptive noise canceller 120 is applied to a summation block 122. The input signals  $S1+S2$  are applied to a delay block 124 and, then, to the summation block 122. The delay block 124 delays the combined input signal (that includes S1 and S2) with respect to the  $S1^{**}$  signal output from the noise canceller 120 by an amount of time equal to the time that the signal  $S1^{**}$  is delayed so that the signals applied to the summation block 122 are aligned in time.

[0038] The summation block 122 determines a difference between the delayed combined signal  $S1+S2$  and the estimated signal  $S1^{**}$ . This difference is the signal  $S2^{**}$ . The signal  $S2^{**}$  is used as an error signal by the adaptive noise canceller 120 in feedback loop that minimizes  $S2^{**}$ . Accordingly, the estimate of the unwanted signals, represented by  $S2^{**}$ , is removed from the combined received signal  $S1+S2$ . The parameters of the adaptive noise canceller can be updated using an adaptive algorithm such as the LMS or other suitable adaptive algorithms.

[0039] Since  $S1^{**}$  is an estimate of S1, then the relationship between S1 and  $S1^{**}$  can be expressed as follows

$$S1^{**} = S1 + \varepsilon \quad (\text{equation 5})$$

From the block diagram we can then derive that

$$S2^{**} = (S1 + S2) - S1^{**} \quad (\text{equation 6})$$

This can be simplified as follows by substituting equation 5

$$S2^{**} = S1 + S2 - S1 - \varepsilon = S2 - \varepsilon \quad (\text{equation 7})$$

[0040] From equations 5 and 7 we see that the received signal  $S1+S2$  has been separated into estimates  $S1^{**}$  and  $S2^{**}$  and that the fidelity of the separation is indicated by the error  $\varepsilon$ . Therefore, a composite received signal that includes both a desired communication signal and one or more unwanted inband signals is processed such that the unwanted inband signals are removed from the received signal leaving the desired signal available for further use. Additionally, the removed inband signals are separately available for further use.

[0041] Figure 2 illustrates system 200 for receiving and processing a communication signal in accordance with an embodiment of the present invention. An example of such a communication system 200 includes a satellite 202 that transmits a signal 204 that is then received by a satellite dish 206. The communication system 200 may include equipment other than the satellite 202 and the satellite dish 206; for example, the communication system may include, but is not limited to, a radio transmitter, a cable transmitter, a cell tower, a microwave transmitter, an optical transmitter; an antenna, a microwave dish, or an optical receiver. The present invention is applicable to any communication system that communicates a communication signal from a transmitter to a receiver, regardless of the medium or the communication signal frequency.

[0042] A signal 208 which includes a desired communication signal and unwanted signals is received by a receiver 210. From the receiver 210, a signal 212 is passed to a signal processor 214 which includes an unwanted signal remover 216 (which can be identical to the signal remover 100 in Figure 1). The signal processor 214 may perform signal processing on the signal in addition to the processing by the unwanted signal remover 216 though this is not necessary. For example, the signal processor 214 may perform preprocessing on the received signal prior to its being processed by the remover 216. A signal 218 output from the signal processor 214 is an estimate of

the desired communication signal S1 (which is referred to herein above as the signal S1\*\*). Another signal 220 may be output from the remover 216 and signal processor 214. This signal 220 corresponds to the error signal S2\*\* which as discussed above is an estimate of signal S2. The signal 220 may include noise, interference or other unwanted signals.

[0043] Either or both of the signals 218 and 220 may be provided to a computer system display so that they can be viewed or input to other equipment that makes use of the output signals 218 and/or 220, such as communications modems. For example, the signals 218 and/or 220 can be processed to determine, and to possibly also display, their properties, such as spectral properties (e.g. their frequency spectrum) or communication parameters (e.g. center frequency or encoding scheme). Therefore, as a further example, the system 200 can be used to detect and extract interference signals for the purpose of signal monitoring. Thus, the output signals 218 and 220 may be further processed to determine their spectral properties which may then be displayed as a spectrum display. The output signals 218 and 220 may also be stored in computer data storage for later use.

[0044] The receiver 210 and the signal processor 214 are each implemented with hardware circuits and may also include related software that controls at least a portion of the hardware. While the received signal is being processed by the signal remover 216, at least portions or components of the signal that are being actively processed are at least temporarily stored in the hardware circuitry that performs the signal processing steps. Additionally, the symbol map discussed herein may also be at least temporarily stored in the hardware.

#### Example 1 – S2 as Random Noise

[0045] In one formulation of the invention, consider S1 to be the desired communications carrier signal and S2 to be uncorrelated random noise received with the signal. If we follow this scenario through the block diagram we will end up with the following from equations 5 and 7

$$S1^{**} = S1 + \varepsilon$$

$$S2^{**} = S2 + \varepsilon$$

[0046] In this case, however, S2 is random noise. If we replace S2 with the notation N, we get the following

$$N^{**} = N + \varepsilon \text{ (equation 8)}$$

[0047] If  $\varepsilon$  is smaller than N, then we have effectively improved the received carrier-to-noise ratio of S1. From the block diagram, the input is  $S1 + N$ , which would have a carrier-to-noise ratio of  $S1/N$ . From equation 5, the system's output signal is  $S1 + \varepsilon$ , resulting in the following cause and effect:

$$\text{If } \varepsilon < N, \text{ then } S1/\varepsilon > S1/N \text{ (equation 9)}$$

[0048] From equation 9, we see that the received carrier-to-noise ratio has been improved. The following diagrams show a specific example of how this invention can be used to gain an improvement in the received carrier-to-noise ratio of a communication signal.

[0049] Figure 3 shows a constellation diagram of a received QPSK communications carrier signal with a received carrier-to-noise ratio of approximately 17 dB. Thus, Figure 3 shows a received signal which can be represented as  $S1 + N$ . Figure 4 shows a constellation display of the output signal,  $S1 + \varepsilon$ , after running this signal through the processing steps of this invention. The output signal can be represented as  $S1^{**}$  where  $S1^{**} = S1 + \varepsilon$ . Qualitatively, it is easy to see that the receive performance has been improved. In this particular case,  $\varepsilon$  is 7 dB smaller than N, and therefore the received carrier-to-noise ratio was improved to 24 dB. For this particular example, S1 does not include any forward error correction information and therefore the demonstrated cancellation gain is somewhat conservative.

#### Example 2 – S2 as an Unwanted Interfering Signal

[0050] In a second formulation of this invention, consider S1 to be our encoded communications carrier signal and S2 to be an unwanted interference signal. From the input, we know that the received carrier-to-noise ratio of S1 will be limited by the interfering signal S2 and will be no better than  $S1/S2$ . From equation 5, we know that after the cancellation process,

$$S1^{**} = S1 + \varepsilon$$

[0051] To illustrate the invention under this scenario, we have used the same communications carrier signal S1 which was used in Example 1(a QPSK carrier with a baseline performance of 17 dB – without S2 present). For S2, we have injected an interferer which is a communications carrier that is also QPSK. S2 has a bandwidth that is similar to S1 and is fully overlapping in frequency with S1. The total power of carrier S1 is greater than the total power of the interfering signal S2.

[0052] Figures 5 and 6 show the received performance of S1 before and after running through the system. More specifically, Figure 5 illustrates the receive performance of S1 with S2 present. Figure 5 illustrates the receive performance of S1 after S2 has been removed using this invention. The output signal can be represented as  $S1^{**}$  where  $S1^{**} = S1 + \epsilon$ . Intuitively, it is easy to see the performance improvement. Under this scenario, the received carrier-to-noise performance of our estimate,  $S1^{**}$ , is within  $\frac{1}{2}$  dB of the baseline case, meaning that the degradation of S1 due to S2 has almost been completely irradiated. For this example, S1 does not include any forward error correction information. With forward error correction, the demonstrated performance gain should be even better.

#### Example 3 – S2 as another Communications Carrier

[0053] In a third formulation of this invention, consider both S1 and S2 to be planned communications carriers. From equation 5 and 7 we know that S1 and S2 will be separated and output as follows.

$$S1^{**} = S1 + \epsilon$$

$$S2^{**} = S2 + \epsilon$$

[0054] Under this scenario, S1 and S2 are both communication signals that are overlapping in both frequency and time. Both are desired communication signals in their own right. However, each also appears to be an unwanted interferer to the other (as in Example 2). In practice, by transmitting S1 and S2 this way, an improvement in capacity can be gained. For example, consider the previous example where two QPSK carriers are transmitting in the same bandwidth. If S1 and S2 are separated to within an acceptable error,  $\epsilon$ , then twice the amount of information can be transmitted over the same channel. In essence, the capacity of the channel is doubled by this invention.

[0055] In the case where the invention is being used to improve channel capacity, the separation process described herein can be run recursively to separate more than two carriers. For example, assume that  $S_2$  represents two distinct communications signals. After the first pass of signal separation, the output would be as in equation 7. If this output is then fed back into the input of the block diagram shown in Figure 1 (which may be performed by the same hardware or by duplicate hardware), this process can be repeated to separate  $S_2$  into the two distinct signals. Thus, this invention can be used to recursively separate multiple desired communication signals that are overlapping in frequency and time. When applied this way, the invention can improve the channel capacity for a given modulation scheme as shown in equation 4.

[0056] Figure 7 illustrates an inband signal separator 300 in accordance with an embodiment of the present invention. The signal separator 300 shown in Figure 7 can be identical to the signal remover 100 shown in Figure 1. As shown in Figure 7, the signal separator 300 receives the combined signals  $S_1 + S_2$  and forms an estimate  $S_1^{**}$  of the communication signal  $S_1$  and an estimate  $S_2^{**}$  of any inband signals  $S_2$ .

[0057] Figure 8 illustrates a block diagram of an enhanced signal separator 304 in accordance with an embodiment of the present invention. As shown in Figure 8, the estimate  $S_2^{**}$  formed by the signal separator 300 is input to a performance improver 302. The combined signals  $S_1 + S_2$  are delayed by a delay block 306 and the delayed combined signals  $S_1 + S_2$  are also input to the performance improver 302. The performance improver 302 forms an improved estimate  $S_1'$  of the communication signal  $S_1$  and an improved estimate  $S_2'$  of the inband signal  $S_2$ .

[0058] Using the estimate of the inband signal  $S_2^{**}$ , the performance improver 302 performs a second stage of processing to cancel this estimate,  $S_2^{**}$ , from the received composite signal,  $S_1 + S_2$ . The improvement to the invention can provide a significant bit error rate (BER) improvement. For example, this improvement has shown to improve the bit error rate BER of the desired communication signal  $S_1$  by over 50 dB (by improving receive BER from  $10^{-3}$  to  $10^{-8}$ ).

[0059] Figure 9 illustrates a system employing the enhanced signal separator 304 in conjunction with a signal demodulator 306 (e.g. a modem) in accordance with an embodiment of the present invention. As shown in Figure 9, the enhanced signal separator 304 can be utilized to pre-process communication signals that are degraded by interference before being received by a demodulator 308.

[0060] As shown in Figure 9, communication signal S1 is degraded with inband interference S2. If this composite signal ( $S1 + S2$ ) is input directly to a receive modem, the bit error rate may be seriously degraded due to the loss of performance caused by the inband interference S2. The BER will be degraded because the modem will receive S1 with a performance of  $S1/(N+S2)$ . This is commonly referred to as the carrier power-to-noise + interference ratio. For example, if the power of S2 is equal to the power of the noise, N, then the receive performance of S1 will be degraded by 3 dB.

[0061] However, if the composite signal ( $S1 + S2$ ) is processed by the enhanced separator 304, as shown in Figure 9, then the receive performance of S1 will be  $S1/(N+S2-S2^{**})$ . If the estimate of  $S2^{**}$  is close to S2, then the receive performance of S1 can approach  $S1/N$ , which is the performance that would be observed without the presence of the inband signal S2.

[0062] If estimate  $S2^{**}$  produced by the signal separator 300 is defined as  $S2 + e$  where e is the difference between S2 and  $S2^{**}$ , then the performance of the received signal will be  $S1/(N+e)$ . As e approaches zero, the received performance will approach  $S1/N$ , which is the same performance that would be achieved without the inband signal S2.

[0063] The bit error rate (BER) of S1 will decrease as the carrier power-to-noise + interference ratio increases. If the interference power, represented by S2, can be significantly reduced, then the resulting BER of S1 can be dramatically lower.

[0064] Figure 10 shows a second application for the enhanced signal separator 304 in accordance with an embodiment of the present invention. Specifically, Figure 10 illustrates a system employing the enhanced signal separator 304 in conjunction with two signal demodulators 308, 310. This configuration can be utilized when the inband signal S2 is another desired communication signal. Thus, rather than cancel this signal, the system can output both the improved version of S1 as well as one of the estimates of S2 ( $S2^{**}$  or  $S2'$ ). An advantage of this configuration is that two signals or more can be transmitted in the same bandwidth, which increases the transmit capacity of a given amount of bandwidth.

[0065] Figure 11 illustrates a block diagram of a performance improver 302 in accordance with an embodiment of the present invention. As shown in Figure 11, the signal  $S2^{**}$  is input from the signal separator block 300 and is scaled in amplitude by amplitude scaling block 312 before being input to an adaptive filter 314 configured to

perform noise cancellation. The output,  $S2'$ , of the adaptive filter 314 is subtracted from the composite input signal,  $S1 + S2$ , by summation block 316. As before,  $S1$  is the desired communication signal and  $S2$  is an interfering signal. Filter taps of the adaptive filter 314 are adjusted to minimize the difference output of the summation block 316. In this case, the minimum difference will be the desired communication signal  $S1$  and will be achieved when the output of the adaptive filter 314,  $S2'$ , exactly matches  $S2$ . In general,  $S2'$  will be equal to  $S2 + e$  and the resulting output  $S1'$  of the performance improver block 302 will be equal to  $S1 - e$ . If  $e$  is much smaller than  $S2$ , then the resulting carrier power-to-noise + interference ratio will be greater than otherwise and the resulting BER will be lower. The parameters of the adaptive filter can be updated using an adaptive algorithm such as the LMS or other suitable adaptive algorithms.

[0066] The description above illustrates operation of embodiments of the invention and is not meant to limit the scope of the invention. It will be apparent to one skilled in the relevant art that variations will be encompassed by the spirit and scope of the invention and that the invention may be practiced in other embodiments. The system described herein may be implemented via a combination of hardware and software or entirely in hardware elements. Also, the particular division of functionality between the various system components described herein is merely exemplary. Thus, the methods and operations presented herein are not inherently related to any particular computer or other apparatus. Functions performed by a single system component may instead be performed by multiple components, and functions performed by multiple components may instead be performed by a single component. It will also be apparent that process steps described herein can be embodied in software, firmware or hardware. Thus, the present invention or portions thereof may be implemented by apparatus for performing the operations herein. This apparatus may be specially constructed or configured, such as application specific integrated circuits (ASICs) or Field Programmable Gate Arrays (FPGAs), as a part of an ASIC, as a part of FPGA, or it may comprise a general-purpose computer selectively activated or reconfigured by a computer program stored on a computer readable medium that can be accessed and executed by the computer. Such a computer program may be stored in a computer readable storage medium, such as, but is not limited to, any type of disk including floppy disks, optical disks, CD-ROMs, magnetic-optical disks, read-only memories (ROMs), random access memories (RAMs), EPROMs, EEPROMs, magnetic or optical cards, or any type of media suitable for storing electronic instructions, and or coupled to a computer system bus. Furthermore, the methods described in the specification may be implemented by a single processor or be

implemented in architectures employing multiple processor designs for increased computing capability. Accordingly, the disclosure of the present invention is intended to be illustrative, but not limiting, of the scope of the invention.

Claims

What is claimed is:

- 1           1. A system for removing one or more inband signals from a received  
2           communication signal comprising:  
3                 a receiver that receives a signal that includes a desired communication  
4           signal and one or more unwanted inband signals;  
5                 a signal separator that processes the received signal to form an estimate  
6           of the desired communication signal and an estimate of the inband signals,  
7           wherein the signal separator demodulates the received signal to form a  
8           demodulated signal and remodulates the demodulated signal to form the  
9           estimate of the desired communication signal and wherein the signal separator  
10          performs adaptive noise cancellation on the received signal using the estimate  
11          of the desired communication signal to form the estimate of the one or more  
12          inband signals; and  
13          a performance improver that processes the received signal and the  
14          estimate of the one or more inband signals to form an improved estimate of the  
15          desired communication signal and an improved estimate of the inband signals,  
16          wherein the performance improver comprises an adaptive filter that takes as  
17          input the received signal and the estimate of the one or more inband signals to  
18          form the improved estimate of the desired communication signal and the  
19          improved estimate of the inband signals.
- 1           2. The system according to claim 1, wherein the power of the desired received  
2           communication signal is greater than the aggregate received power of the  
3           inband signals and the signal separator uses the greater power of the desired  
4           communication signal to lock to the desired communication signal to form the  
5           demodulated signal.
- 1           3. The system according to claim 1, wherein the signal separator forms the  
2           estimate of the desired communication signal and the estimate of the inband  
3           signals without prior knowledge of characteristics of the inband signals and  
4           without obtaining a copy of any of the inband signals from any source other  
5           than the received signal.

- 1           4. The system according to claim 1, wherein the signal separator forms the  
2           estimate of the desired communication signal and the estimate of the inband  
3           signals using only the received signal as input.
- 1           5. The system according to claim 1, wherein the signal separator at least  
2           temporarily stores a portion of the received signal during said processing of  
3           the received signal.
- 1           6. The system according to claim 1, further comprising processing the  
2           improved estimate of the one or more inband signals to determine their  
3           properties.
- 1           7. The system according to claim 6, wherein the properties of the interfering  
2           signal comprise spectral properties.
- 1           8. The system according to claim 6, further comprising displaying the  
2           properties of the one or more inband signals.
- 1           9. The system according to claim 1, wherein the desired communication  
2           signal is a first desired communication signal and the one or more inband  
3           signals comprise a second desired communication signal that overlaps the first  
4           desired communication signal in both frequency and time and wherein the  
5           estimate of the in-band signals comprises an estimate of the second desired  
6           communication signal thereby the first and second desired communication  
7           signals are both recovered from the received signal.
- 1           10. The system according to claim 1, wherein the desired communication  
2           signal is a first desired communication signal and the one or more inband  
3           signals comprise two or more additional desired communication signals that  
4           overlap the first desired communication signal in both frequency and time and  
5           wherein the estimate of the one or more in-band signals is recursively  
6           processed to recover each of the two or more additional desired  
7           communication signals.
- 1           11. The system according to claim 1, wherein the signal separator comprises  
2           an adaptive equalizer that is used in the demodulation of the received signal to  
3           form the demodulated signal.

1 12. The system according to claim 1, wherein the signal separator comprises a  
2 matched filter that is used in the demodulation of the received signal to form  
3 the demodulated signal.

1 13. The system according to claim 1, wherein the desired communication  
2 signal includes forward error correction information and the signal separator  
3 performs forward error correction on the estimate of the desired  
4 communication signal.

1 14. The system according to claim 1, further comprising re-sampling the  
2 estimate of the desired communication signal to match a sampling rate of the  
3 desired communication signal.

1 15. The system according to claim 14, further comprising performing pulse  
2 shaping on the estimate of the desired communication signal.

1 16. The system according to claim 1, wherein the one or more inband signals  
2 comprise random noise.

1 17. The system according to claim 1, wherein the one or more inband signals  
2 comprises an interfering signal having a source that is independent from that  
3 of the desired communication signal.

1 18. A method of removing one or more inband signals from a received  
2 communication signal comprising:  
3 obtaining a received communication signal, the received  
4 communication signal including a desired communication signal and one or  
5 more inband signals;  
6 processing the received communication signal using a signal separator  
7 to form an estimate of the desired communication signal and an estimate of the  
8 inband signals signals, wherein the signal separator demodulates the received  
9 signal to form a demodulated signal and remodulates the demodulated signal  
10 to form the estimate of the desired communication signal and wherein the  
11 signal separator performs adaptive noise cancellation on the received signal  
12 using the estimate of the desired communication signal to form the estimate of  
13 the one or more inband signals; and  
14 processing the received signal and the estimate of the one or more  
15 inband signals using a performance improver to form an improved estimate of

16 the desired communication signal and an improved estimate of the inband  
17 signals, wherein the performance improver comprises an adaptive filter that  
18 takes as input the received signal and the estimate of the one or more inband  
19 signals to form the improved estimate of the desired communication signal  
20 and the improved estimate of the inband signals.

1 19. A non-transitory computer readable media having stored thereon  
2 computer code which when executed by a processor causes the processor to  
3 perform a method of removing inband signals from a received communication  
4 signal, the method comprising:  
5 obtaining a received communication signal, the received  
6 communication signal including a desired communication signal and one or  
7 more inband signals;  
8 processing the received communication signal using a signal separator  
9 to form an estimate of the desired communication signal and an estimate of the  
10 inband signals signals, wherein the signal separator demodulates the received  
11 signal to form a demodulated signal and remodulates the demodulated signal  
12 to form the estimate of the desired communication signal and wherein the  
13 signal separator performs adaptive noise cancellation on the received signal  
14 using the estimate of the desired communication signal to form the estimate of  
15 the one or more inband signals; and  
16 processing the received signal and the estimate of the one or more  
17 inband signals using a performance improver to form an improved estimate of  
18 the desired communication signal and an improved estimate of the inband  
19 signals, wherein the performance improver comprises an adaptive filter that  
20 takes as input the received signal and the estimate of the one or more inband  
21 signals to form the improved estimate of the desired communication signal  
22 and the improved estimate of the inband signals.