A method for automatic gain control comprising the steps of measuring a signal using compressed sensing to produce a sequence of blocks of measurements, applying a gain to one of the blocks of measurements, adjusting the gain based upon a deviation of a saturation rate of the one of the blocks of measurements from a predetermined nonzero saturation rate and applying the adjusted gain to a second of the blocks of measurements. Alternatively, a method for automatic gain control comprising the steps of applying a gain to a signal, computing a saturation rate of the signal and adjusting the gain based upon a difference between the saturation rate of the signal and a predetermined nonzero saturation rate.
OTHER PUBLICATIONS


* cited by examiner
FIG. 1A

FIG. 1B

FIG. 2

PRIOR ART
FIG. 3

\[ x^{[w]} \rightarrow \Phi \rightarrow y^{[w]} \rightarrow \theta^{[w]} \rightarrow R\{\cdot\} \rightarrow R\{\theta^{[w]} y^{[w]}\} \]

\[ z^{-1} \theta^{[w-1]} \rightarrow S \rightarrow \nu \rightarrow + \]

\[ \text{AGC} \]

\[ \text{Compute } \widehat{S}^{[w-1]} \]

310

320

330

340

350
METHOD AND APPARATUS FOR AUTOMATIC GAIN CONTROL FOR NONZERO SATURATION RATES

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the benefit of the filing date of U.S. Provisional Patent Application Ser. No. 61/306,992 filed by the present inventors on Feb. 23, 2010.

The aforementioned provisional patent application is hereby incorporated by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under National Science Foundation Grant Nos. CCF-0431150, CCF-0728867, CNS-0435425 and CNS-0520260, DARPA Grant No. N66001-08-1-2065, Office of Naval Research Grant No. N00014-07-1-0956, N00014-08-1-067, N00014-08-1-1112, and N00014-08-1-1066, Air Force Office of Scientific Research Grant Nos. FA9550-07-1-0301, and Department of Defense—Army Research Laboratory Grant Nos W911NF-07-1-0185, and W911NF-09-1-0383. The government has certain rights in the invention.

1 BACKGROUND OF THE INVENTION

1.1 Field of the Invention

The present invention relates to methods and apparatus for controlling the gain of signals before sampling and quantization. The invention further relates to methods that use randomized measurement systems, democratic measurement systems, and compressive measurement systems. The invention is applicable to any type of signal or sampling and quantization system, however, its inherent properties will only be beneficial to some.

1.2 Brief Description of the Related Art

1.2.1 Analog-to-digital Conversion

Analog-to-digital conversion (ADC) consists of two discretization steps: sampling, which converts a continuous-time signal to a discrete-time set of measurements, followed by quantization, which converts the continuous value of each measurement to one of several discrete values through a non-invertible function \( f \). This minimizes the expected quantization distortion and implies that the quantization error per measurement, \( |g| \), is bounded by \( \Delta/2 \). Figure 1A depicts the mapping performed by a midrise quantizer.

In practice, quantizers have a finite dynamic range, dictated by hardware constraints such as the voltage limits of the devices and the finite number of bits per measurement of the quantized representation. Thus, a finite-range quantizer represents a symmetric range of values \( [-G, G] \), where \( G > 0 \) is known as the saturation level. Gray and Zeoli, “Quantization and saturation noise due to analog-to-digital conversion,” IEEE Trans. Aerospace and Elect. Systems, vol. 7, no. 1, pp. 222-223, 1971. Values of \( G \) between \( -G \) and \( G \) will not saturate, thus, the quantization interval is defined by these parameters as \( \Delta = 2^{B-1} \cdot G \). Without loss of generality we assume a midrise \( B \)-bit quantizer, i.e., the quantization levels are \( q_i = \Delta/2 \cdot k + \Delta \), where \( k = 0, 1, \ldots, 2^{B-1} -1 \). Any measurement with magnitude greater than \( G \) saturates the quantizer.
i.e., it quantizes to the quantization level $G - \Delta/2$, implying an unbounded error. FIG. 1B depicts the mapping performed by a finite range midrife quantizer with saturation level $G$ and Table 1 summarizes the parameters defined with respect to quantization.

1.2.3 Compressive Sensing (CS)

In the CS framework, we acquire a signal $x \in \mathbb{R}^N$ via the linear measurements

$$ y = \Phi x + e, $$

where $\Phi$ is an $M \times N$ measurement matrix modeling the sampling system, $y \in \mathbb{R}^M$ is the vector of samples acquired, and $e$ is an $M \times 1$ vector that represents measurement errors. If $x$ is $K$-sparse when represented in the sparsity basis $\Psi$, i.e., $x = \Psi a$ with $|\Psi| \leq \sup(a) \leq K$, then one can acquire just $M = \mathcal{O}(K \log(N/K))$ measurements and still recover the signal $x$. A similar guarantee can be obtained for approximately sparse, or compressible, signals. Observe that if $K$ is small, then the number of measurements required can be significantly smaller than the Shannon-Nyquist rate.


**Definition 1.** A matrix $\Phi$ satisfies the RIP of order $K$ with constant $\delta(0, 1)$ if

$$(1-\delta(0, 1))|\Psi| \leq |\Phi \Psi| \leq (1+\delta(0, 1))|\Psi|$$

holds for all $x$ such that $|\Phi x| \leq K$.

In words, $\Phi$ acts as an approximate isometry on the set of vectors that are $K$-sparse in the basis $\Psi$. An important result is that for any unitary matrix $\Psi$, if we draw a random matrix $\Phi$ whose entries $\phi_{ij}$ are independent realizations from a sub-Gaussian distribution, then $\Phi \Psi$ will satisfy the RIP of order $K$ with high probability provided that $M = \mathcal{O}(K \log(N/K))$. R. Baraniuk, M. Davenport, R. DeVore, and M. Wakin, “A simple proof of the restricted isometry property for random matrices,” Const. Approx., vol. 28, no. 3, pp. 253-263, 2008. Without loss of generality, we fix $\Psi = I$, the identity matrix, implying that $x = a$.

The RIP is a necessary condition if we wish to be able to recover all sparse signals $x$ from the measurements $y$. Specifically, if $|\Phi x| \leq K$, then $\Phi$ must satisfy the lower bound of the RIP of order $2K$ with $\delta = 1$ in order to ensure that any algorithm can recover $x$ from the measurements $y$. Furthermore, the RIP also suffices to ensure that a variety of practical algorithms can successfully recover any sparse or compressible signal from noisy measurements. In particular, for bounded errors of the form $|\Phi y| \leq \epsilon$, the convex program

$$ x = \text{argmin}_{z \in \mathbb{R}^N} \|z\|_1 \text{ s.t. } \|y - \Phi z\|_2 \leq \epsilon $$

(3)

can recover a sparse or compressible signal $x$. The following theorem, a slight modification of Theorem 1.2 from E. Candès, “The restricted isometry property and its implications for compressed sensing,” Comptes rendus de l’Académie des Sciences, Série I, vol. 346, no. 9-10, pp. 589-592, 2008, makes this precise by bounding the recovery error of $x$ with respect to the measurement noise norm, denoted by $\epsilon$, and with respect the best approximation of $x$ by its largest $K$ terms, denoted using $x_K$.

**Theorem 1.** Suppose that $\Phi \Psi$ satisfies the RIP of order $2K$ with $\delta = \sqrt{2} - 1$. Given measurements of the form $y = \Phi \Psi x + e$, where $|\Phi x| \leq \epsilon$, then the solution to (3) obeys

$$ \|x - x_K\|_2 \leq C_1 \frac{\|y - \Phi x\|_2}{\sqrt{K}}, $$

where

$$ C_0 = \frac{4(1+\delta)}{1-(\sqrt{2}+1)^2}, \quad C_1 = \frac{4(1+\delta)}{1-(\sqrt{2}+1)^2}.$$
integrated. The output of the integrator is sampled, and the integrator is reset after each sample. The output measurements from the ADC are then quantized.

Systems such as these represent a linear operator mapping the analog input signal to a discrete output vector, followed by a quantizer. It is possible, but beyond the scope of this description, to relate this operator to a discrete measurement matrix $\Phi$ which maps, for example, the Nyquist-rate samples of the input signal to the discrete output vector $J$. Tropp, J. Laska, M. Duarte, J. Romberg, and R. Baraniuk, “Beyond Nyquist: Efficient sampling of sparse, bandlimited signals,” to appear in IEEE Trans. Inform. Theory, 2009, M. Mishali and Y. Eldar, “From theory to practice: Sub-Nyquist sampling of sparse wideband analog signals,” Preprint, 2009, J. Treichler, M. Davenport, and R. Baraniuk, “Application of compressive sensing to the design of wideband signal acquisition receivers,” in U.S./Australia Joint Work Defense Apps. of Signal Processing (DASP), Lihue, Hi., September 2009. In this application the description is focused on settings in which the measurement operator $\Phi$ can be represented as an $M \times N$ matrix.  

1.2.5 Saturation and Compressive Sensing
It has been shown that CS systems can be made robust to saturated measurements. One approach simply discards saturated measurements and performs signal reconstruction without them. Another approach is based on an alternative CS recovery algorithm that treats saturated measurements differently from unsaturated ones. This is achieved by employing a magnitude constraint on the indices of the saturated measurements while maintaining the conventional regularization constraint on the indices of the other measurements.

These methods exploit the democratic nature of CS measurements. Because each measurement contributes equally to the compressed representation, some of them can be removed while still maintaining a sufficient amount of information about the signal to enable recovery.

When employing these methods, in order to maximize the acquisition SNR, the optimal strategy is to allow the quantizer to saturate at some nonzero rate. This is due to the inverse relationship between quantization error and saturation rate: as the saturation rate increases, the distortion of remaining measurements decreases. Furthermore, experimental results show that on average, the optimal SNR is achieved at nonzero saturation rates.

2 SUMMARY OF THE INVENTION
To adapt to changes in signal power and to avoid saturation events, modern sampling systems employ automatic gain control (AGC). These AGC's typically target saturation rates that are close to zero. In this case, saturation events can be used to detect high signal strength; however, detecting low signal strength is more difficult. Thus, in conventional systems, saturation rate alone does not provide sufficient feedback to perform automatic gain control. Other measures, such as measured signal power are used in addition to saturation rate to ensure that the signal gain is sufficiently low but not too low.

However, when a positive saturation rate is desirable, the saturation rate can be used to provide sufficient feedback to the AGC circuit. Since the desired rate is significantly greater than zero, deviation from the desired rate can be used to both increase and decrease the gain in an AGC circuit to maintain a target saturation rate. Saturation events can be detected more easily and at earlier stages of the signal acquisition system compared to measures such as signal variance. Thus, the effectiveness of AGC increases and the cost decreases.

In a preferred embodiment, the present invention is a method for automatic gain control. The method comprises splitting a signal into consecutive blocks, applying a measurement matrix to each block separately to produce a plurality of measurements for each consecutive block, indexing each successive block of measurements, applying a window to each successive block of measurements, applying a gain to a block of measurements, quantizing the block of measurements to produce a set of output measurements, calculating a saturation rate of the block of measurements and calculating a new gain to apply to a next block of measurements by adding an error between a desired non-zero saturation rate and the computed saturation rate of the block to the gain. The window applied to each block may comprise a boxcar window or any other window. The quantizing step may comprise uniform or non-uniform quantizing.

In another embodiment, the present invention is a method for automatic gain control. The method comprises the steps of measuring a signal using compressed sensing to produce a sequence of blocks of measurements, applying a gain to one of the blocks of measurements, adjusting the gain based upon a deviation of a saturation rate of one of the blocks of measurements from a predetermined nonzero saturation rate and applying the adjusted gain to a second of the blocks of measurements.

In still another embodiment, the present invention is a method for automatic gain control. The method comprises the steps of applying a gain to a signal, computing a saturation rate of the signal and adjusting the gain based upon a difference between the saturation rate of the signal and a predetermined nonzero saturation rate.

Still other aspects, features, and advantages of the present invention are readily apparent from the following detailed description, simply by illustrating a preferable embodiments and implementations. The present invention is also capable of other and different embodiments and its several details can be modified in various obvious respects, all without departing from the spirit and scope of the present invention. Accordingly, the drawings and descriptions are to be regarded as illustrative in nature, and not as restrictive. Additional objects and advantages of the invention will be set forth in part in the description which follows and in part will be obvious from the description, or may be learned by practice of the invention.

3 BRIEF DESCRIPTION OF THE DRAWINGS
For a more complete understanding of the present invention and the advantages thereof, reference is now made to the following description and the accompanying drawings, in which:

FIG. 1 is a drawing of the scalar quantization function. FIG. 1A shows a midrise scalar quantizer. FIG. 1B shows a finite-range midrise scalar quantizer with saturation level $G$. FIG. 2 is a drawing of the random demodulator compressive ADC.

FIG. 3 is a diagram of an automatic gain control (AGC) system for tuning to nonzero saturation rates in CS systems in accordance with a preferred embodiment of the present invention.

FIG. 4 is a drawing of the performance of a preferred embodiment of the CS-AGC of the present invention in practice. FIG. 4A illustrates CS measurements with no saturation. Signal strength drops by 90% at measurement 900. FIG. 4B illustrates output gain from AGC. FIG. 4C illustrates output gain from AGC.
scaled by gain from AGC. FIG. 4D Saturation rate of scaled measurements. This figure demonstrates that the CS AGC is sensitive to decreases in signal strength.

4 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The notation for the description of the present invention is as follows. The signal $x$ is split into consecutive blocks of length $N$, and $\Phi_{310}$ is applied to each block separately such that there are $M$ measurements per block. Each successive block of measurements is indexed by $w$ and is denoted with the superscript $[w]$. In this example a boxcar window is applied to each block of $x$, but in general any window can be applied. For each block, a gain $\theta_{320}$ is applied to the measurements and then quantized $330$, resulting in a set of $M$ output measurements $R_{[w]}{8}_{[w]}$. Note that in different hardware implementations, the gain $320$ might be applied before, after, or within the measurement matrix $\Phi_{310}$; this change does not fundamentally affect the design. A goal is to tune the gain so that it produces a desired measurement saturation rate $s$. It also is assumed that the signal energy does not deviate significantly between consecutive blocks.

A drawing of a preferred embodiment of the present invention is depicted in FIG. 3 and the description is as follows. The saturation rate of the previous block of measurements, $S_{[w-1]}$, is computed $340$ after quantization. The new gain is then computed by adding $350$ the error between $s$ and $S_{[w-1]}$ to the previous gain, i.e.,

$$\theta_{[w]} = \theta_{[w-1]} + \alpha (s - S_{[w-1]}),$$

where $\alpha > 0$ is constant. This negative feedback system is BIBO (Bounded Input Bounded Output) stable for any finite positive $\alpha$ with $0 < \alpha < 1$. A. Oppenheim and A. Willsky, Signals and systems. Prentice-Hall, 1996.

A drawing of a preferred embodiment of the present invention is depicted in FIG. 3 and the description is as follows. The saturation rate of the previous block of measurements, $S_{[w-1]}$, is computed $340$ after quantization. The new gain is then computed by adding $350$ the error between $s$ and $S_{[w-1]}$ to the previous gain, i.e.,

$$\theta_{[w]} = \theta_{[w-1]} + \alpha (s - S_{[w-1]}),$$

where $\alpha > 0$ is constant. This negative feedback system is BIBO (Bounded Input Bounded Output) stable for any finite positive $\alpha$ with $0 < \alpha < 1$. A. Oppenheim and A. Willsky, Signals and systems. Prentice-Hall, 1996.

Typical AGC designs target saturation rates close to zero. For instance, according to one rule of thumb, a conventional AGC should set the gain such that there is an average of 63 clips per million samples J. Triechler, Personal Communication, October 2009. Thus, because the desired saturation rate is close to zero, saturation rate alone cannot be used to design a stable AGC. However, the present invention is novel in that we consider nonzero saturation rates and thus an AGC in accordance with the present invention need only the saturation rate to determine the gain.

To demonstrate that this AGC is sensitive to both increases in signal strength as well as decreases, an experiment was performed where the signal strength drops suddenly and significantly. The experiment is depicted in FIG. 4 and was performed as follows. A signal was generated such that the parameters per block were $N=512, K=5$, and $M=32$. We generated 63 blocks resulting in approximately 2000 measurements in total. The example measurements before the AGC is applied are depicted in FIG. 4A. The dashed lines represent the quantizer range $[-1, 1]$. We generated the measurements so that the saturation rate is zero, and starting at measurement $900$, the signal strength drops by 90%. These measurements are input into the AGC previously described with $v=12$ and we set a desired saturation rate of $s=0.2$. FIG. 4B shows the gain that the AGC applies as it receives each measurement. FIG. 4C shows the resulting output signal with quantizer range, and FIG. 4D shows the estimated output saturation rate. Initially, we achieve the desired saturation rate of $0.2$ within approximately 10 iterations. The system adapts to the sudden change in signal strength after measurement

What is claimed is:

1. A method for automatic gain control comprising:
   - splitting a signal into consecutive blocks;
   - applying a measurement matrix to each said block separately to produce a plurality of measurements for each consecutive block;
   - indexing each successive block of measurements;
   - applying a gain to one of said blocks of measurements;
   - quantizing said block of measurements to produce a set of output measurements;
   - calculating a saturation rate of said block of measurements;
   - calculating a new gain to apply to a next block of measurements by adding an error between a desired non-zero saturation rate and said computed saturation rate of said block to said gain.

2. A method according to claim 1, wherein said window comprises a boxcar window.

3. A method according to claim 1 wherein quantizing step comprises uniform quantizing.

4. A method according to claim 1 wherein said quantizing step comprises non-uniform quantizing.

5. A method for automatic gain control comprising the steps of:
   - measuring a signal using compressed sensing to produce a sequence of blocks of measurements;
   - applying a gain to one of said blocks of measurements;
   - adjusting said gain based upon a deviation of a saturation rate of said one of said blocks of measurements from a predetermined nonzero saturation rate; and
   - applying said adjusted gain to a second of said blocks of measurements.

6. A method for automatic gain control comprising the steps of:
   - applying a gain to a signal;
   - computing a saturation rate of a group of measurements of said signal; and
   - adjusting said gain based upon a difference between said computed saturation rate of said group of measurements of said signal and a predetermined nonzero saturation rate.
7. A method for automatic gain control according to claim 6, wherein said predetermined nonzero saturation rate is approximately 0.2.