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### Continuously variable dynamic element matching network

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#### Abstract

This disclosure relates to a system for mitigating distortion in a signal, including a plurality of bit-cells, a calculation circuit configured to determine a bit-cell population that is available to be activated for a given clock cycle, a dynamic element matching network configured to activate a subset of bit-cells of the bit-cell population, and a controller configured to control a pattern of activation of the subset of bit-cells of the bit-cell population.

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## **Background/Summary**

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application claims priority under 35 U.S.C. § 119 to U.S. Provisional Patent Application No. 63/379,510, titled CONTINUOUSLY VARIABLE DYNAMIC ELEMENT MATCHING NETWORK, filed on Oct. 14, 2022, which is incorporated by reference in its entirety for all purposes, and to U.S. Provisional Patent Application No. 63/379,511, titled NOISE SHAPED DRIVE AND POPULATION BALANCED NETWORK, filed on Oct. 14, 2022, which is incorporated by reference in its entirety for all purposes.

## BACKGROUND

(1) Signals, such as audio or electromagnetic signals, may be subject to distortion due to processes for converting said signals from analog to digital form, and vice versa. Distortion can cause undesirable effects, such as unwanted signal characteristics. In audio signal processing, for example, distortion can cause audible popping, clicking, and other sounds that may impact the listening experience.

## SUMMARY

(2) According to at least one aspect of the present disclosure there is disclosed a system for mitigating distortion in a signal. the system may comprise a plurality of bit-cells; a calculation circuit configured to determine a bit-cell population that is available to be activated for a given clock cycle; a dynamic element matching network configured to activate a subset of bit-cells of the bit-cell population; and a controller configured to control a pattern of activation of the subset of bit-cells of the bit-cell population.

(3) In some examples, the dynamic element matching network is further configured to activate each bit-cell of the subset of bit-cells on a first clock cycle, and deactivate each bit-cell of the subset of bit-cells on a second clock cycle. In various examples, the second clock cycle is a clock cycle immediately following the first clock cycle. In many examples, the dynamic element matching network is further configured to activate a second subset of bit-cells of the plurality of bit-cells on the second clock cycle, the second subset not including any bit-cells of the first subset. In some examples, the calculation circuit is further configured to periodically determine the bit-cell population based on a peak signal strength of the signal.

(4) In some examples, the calculation circuit determines the bit-cell population responsive to a signal strength of the signal being zero or near-zero. In many examples, the subset of bit-cells is a second subset of bit-cells, and the dynamic element matching network further comprises a first shuffle network, a variable array, and a second shuffle network, wherein the first shuffle network is configured to provide a first subset of bit-cells activated on a previous clock cycle to the variable array; the variable array is configured to provide the bit-cells of the bit-cell population not including each bit-cell of the first subset of bit-cells to the second shuffle network, and to provide a number of bit-cells to be activated to the second shuffle network; and the second shuffle network is configured to randomly select from among the bit-cell population not including the first subset of bit-cells a second subset of bit-cells to activate, the second subset of bit-cells including a number of bit-cells equal to the number of bit-cells to be activated.

(5) In some examples, the first shuffle network is further configured to receive the second subset of bit-cells and provide the second subset to the variable array on a clock cycle following a clock cycle wherein the second subset of bit-cells was activated. In various examples, the system further comprises a barrel shifter, the barrel shifter being configured to activate the subset of bit-cells in a low population mode and the dynamic element matching network being configured to activate the subset of bit-cells in a high population mode. In some examples, the system operates in the low population mode when the bit-cell population is below a threshold bit-cell population level.

(6) According to at least one aspect of the present disclosure, there is disclosed a method for mitigating distortion in a signal. The method may comprise determining a bit-cell population of the plurality of bit-cells to be available to be activated based on a signal strength of a signal; randomly selecting a first subset of bit-cells of the bit-cell population to activate based on the signal strength; activating the first subset of bit-cells on a first clock cycle; and deactivating the first subset of bit-cells on a second clock cycle.

(7) In some examples, the method further comprises activating a second subset of bit-cells on the second clock cycle, the second subset not including any bit-cells of the first subset. In various examples, the second clock cycle is the clock cycle immediately following the first clock cycle. In many examples, the bit-cell population is determined at periodic intervals. In some examples, the

bit-cell population is determined when the signal strength of the signal is at or near zero. In many examples, a bit-cell is activated for no more than one clock cycle in a row.

(8) According to at least one aspect of this disclosure, a non-transitory, computer-readable medium containing instructions configured to be executed by at least one processor, the instructions being configured to instruct the at least one processor to execute any of the methods described herein is provided.

(9) According to at least one aspect of the present disclosure, a continuously variable bit-cell population dynamic element matching network (CVBP DEM network) is presented, the CVBP DEM comprising: an input; a bit-cell population calculator coupled to the input; a fixed-variable split calculator coupled to the input; a variable dynamic element matching network (variable DEM) coupled to the bit-cell population calculator and to the fixed-variable split calculator; a fixed dynamic element matching network (fixed DEM) coupled to the bit-cell population calculator and to the fixed-variable split calculator; and an output coupled to the variable DEM and the fixed DEM.

(10) In some examples, the bit-cell population calculator is configured to determine a total number of bit-cells to be turned on during a clock cycle, the total number of bit-cells based on a signal strength of a signal. In some examples, the fixed-variable split calculator is configured to: determine a first number of bit-cells and a second number of bit-cells, wherein a multiple of the first number summed with a multiple of the second number equals the total number of bit-cells; provide the first number of bit-cells to the variable DEM; and provide the second number of bit-cells to the fixed DEM. In some examples, the variable DEM determines a number of bit-cells to activate based on the first number of bit-cells. In some examples, the fixed DEM determines a number of bit-cells to activate based on the second number of bit-cells.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

(1) Various aspects of at least one embodiment are discussed below with reference to the accompanying figures, which are not intended to be drawn to scale. The figures are included to provide an illustration and a further understanding of the various aspects and embodiments, and are incorporated in and constitute a part of this specification, but are not intended as a definition of the limits of any particular embodiment. The drawings, together with the remainder of the specification, serve to explain principles and operations of the described and claimed aspects and embodiments. In the figures, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every figure. In the figures:

(2) FIG. 1 illustrates a continuously variable dynamic element matching network according to a high-level functional block diagram;

(3) FIG. 2 illustrates a block diagram of a windowed peak detector and bit-cell population register according to a functional block diagram;

(4) FIG. 3 illustrates a fixed/variable split calculator according to a functional block diagram;

(5) FIG. 4A illustrates a selective bit-enabled barrel shifter according to an example;

(6) FIG. 4B illustrates an expanded barrel shifter according to an example;

(7) FIG. 4C illustrates a graph of the growth of the expanded barrel shifter of FIG. 4B according to an example;

(8) FIG. 5 illustrates a variable-width dynamic element matching network according to a functional block diagram;

(9) FIG. 6 illustrates a fixed width dynamic element matching network according to a functional block diagram;

(10) FIG. 7 illustrates a swapping algorithm according to an example; and  
(11) FIG. 8 illustrates a flowchart of a process for determining a large or small population mode of operation.

#### DETAILED DESCRIPTION

(12) Examples of the methods and systems discussed herein are not limited in application to the details of construction and the arrangement of components set forth in the following description or illustrated in the accompanying drawings. The methods and systems are capable of implementation in other embodiments and of being practiced or of being carried out in various ways. Examples of specific implementations are provided herein for illustrative purposes only and are not intended to be limiting. Acts, components, elements, and features discussed in connection with any one or more examples are not intended to be excluded from a similar role in any other examples.

(13) Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. Any references to examples, embodiments, components, elements or acts of the systems and methods herein referred to in the singular may also embrace embodiments including a plurality, and any references in plural to any embodiment, component, element or act herein may also embrace embodiments including only a singularity. References in the singular or plural form are not intended to limit the presently disclosed systems or methods, their components, acts, or elements. The use herein of “including,” “comprising,” “having,” “containing,” “involving,” and variations thereof is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

(14) References to “or” may be construed as inclusive so that any terms described using “or” may indicate any of a single, more than one, and all of the described terms. In addition, in the event of inconsistent usages of terms between this document and documents incorporated herein by reference, the term usage in the incorporated features is supplementary to that of this document; for irreconcilable differences, the term usage in this document controls.

(15) In some applications, Digital to Analog Converters (DACs) are used to convert digital signals to analog signals. For example, audio DACs are commonly used in audio applications to convert digital audio signals to analog audio signals, such as converting an MP3 file stored on a computer into an audible signal in a pair of headphones. DACs can use a bit-coded input that scales with the input signal, such as a “thermometer” input, to encode values associated with the digital audio signal in preparation for conversion of the digital audio signal to analog. The thermometer input may then control an array of bit-cells associated with or part of the DAC, causing certain cells to turn on and/or off, thus producing an output signal. However, traditional DAC processes can introduce an error into the output signal, producing off-tones and other undesirable artifacts based on the input signal. This type of error is commonly referred to as “distortion.” The distortion introduced into the output signal will be proportional to the number of bit-cells turned on or off. Additionally, because the distortion depends on the input signal, every time a particular input signal is input into the DAC, the distortion associated with that particular input signal will be the same. Accordingly, there is a need in the art for a low distortion alternative to traditional DAC systems and methods.

(16) Aspects and elements of the present disclosure include a DAC with reduced distortion. In some examples, the DAC takes a digital input signal and converts the digital input signal to an analog output signal using an array of bit-cells. A dynamic element matching network (DEM) selects which bit-cells of an array of bit-cells are used to drive the analog signal. To reduce signal error (e.g., distortion), the DEM implements a continuously variable bit population (CVBP) in the bit-cell array.

(17) As mentioned, by using a DEM to select bit-cells of the DAC to activate, distortion in the output signal can be reduced. Distortion in some DACs may be caused by mismatches arising during production among circuit elements, such as nominally identical bit-cells. The mismatches among nominally identical circuit components cause nonlinear distortion in the output signals

generated by the DAC. For example, nominally identical amplifier circuit components may have different levels of gain at a particular voltage level due to the fabrication process. One method by which DEMs correct the distortion created by component mismatches is by randomly selecting circuit components (bit-cells) to use, such that the distortion becomes pseudorandom noise, and thus can be treated as a form of white noise, and filtered out of the output signal. It may be appreciated that this process, in broad terms, converts one type of error (distortion) into another type of error (noise). It will be appreciated that distortion is a form of substantially non-random error, while noise is a form of random or pseudorandom error.

(18) One example of a DEM DAC disclosed herein uses a single DEM with a variable bit-width (a “variable DEM”) to randomly select bit-cells to activate. The total bit-width of the variable DEM equals the total number of bit-cells of the DAC. In this case, the variable DEM is the only DEM selecting which bit-cells to activate and the variable DEM controls each and every bit-cell. One example of such a variable DEM is discussed with respect to FIG. 5. Such a variable DEM may also be implemented using a pair of Benes shuffle networks (a forward Benes shuffle network and inverse (or reverse) Benes shuffle network, the inverse Benes shuffle network carrying out the inverse transformation of the transformation carried out by the forward Benes shuffle network), an input, and a barrel shifter. The single variable DEM can then activate any arbitrary number of bit-cells of the DAC. However, the variable DEM discussed in this paragraph requires a considerable amount of logic gates, which may be disadvantageous despite the DEM's advantageous ability to activate any arbitrary number of bit-cells.

(19) A second example of a DEM DAC disclosed herein uses a single variable DEM with a smaller overall bit-width. The variable DEM is combined with one or more fixed-width DEMs to create a “telescoping” DEM topology which allows arbitrary numbers of bit-cells to be turned on and off, while also using considerably fewer gates than the preceding example of a single variable DEM. While only a single variable DEM is required when combined with fixed-width DEMs, multiple variable DEMs could be used if desired.

(20) For clarity, the single variable DEM DAC topology will be referred to as the fully variable DEM herein, and the mixed variable/fixed-width DEM DAC topology will be referred to as the telescoping DEM herein. In other cases, the DEM may be referred to simply as the DEM, such as when describing the general functionality of the DEM, such as in those cases where the operation of the DEM (or DEMs) may apply to both topologies.

(21) The DEM may control the number of bit-cells which are available for use. For clarity, the number of bit-cells available for use shall be referred to as the “bit-cell population.” In some examples, the bit-cell population is determined based on the digital input signal level and timing. For example, the bit-cell population may range between a minimum and maximum limit, both limits being based on a multiple of the level of the input signal. In various examples, the bit-cell population may increase or decrease during a zero crossing, the zero crossing being, for example, when a peak detector detects a zero and/or near zero value. Increasing or decreasing the bit-cell population at zero crossings may be advantageous because the input signal will be at or near zero during such crossings. As a result, any distortion may be proportional to the near zero value of the input. Put another way, if the input has an amplitude of zero, any distortion multiplied by zero is still zero. In this way, distortion and other undesirable audio artifacts may be minimized. In some examples, the bit-cell population may increase or decrease slowly in the absence of a zero crossing, such as in the case of an application that needs to allow decreases even with a DC signal. By slowly increasing or decreasing the bit-cell population, distortion may be minimized because slow changes to the bit-cell population prevent large numbers of bit-cells from being activated or deactivated at once. Activating or deactivating large numbers of bit-cells at once might introduce substantial error since doing so can increase the total amplitude of the output signal (when activating a large number at once) or abruptly reduce the total amplitude of the output signal (when deactivating a large number at once), thus potentially introducing distortion into the output signal.

(22) The DEM may control which bit-cells are active from among the bit-cell population. An active bit-cell is a bit-cell that is on, for example, a bit-cell that is driving the analog output signal. In some examples, the DEM may enable the exact number of bit-cells requested by a DEM input. In various examples, enabling the bit-cells requested by the DEM input may enable valid delta-sigma modulation (DSM) behavior of the system. The DEM may be configured such that each enabled bit-cell is used evenly. In some examples, the DEM may use bit-cells evenly by enabling one or more bit-cells for a single clock cycle, and then deactivating the enabled bit-cells for one or more clock cycles. The DEM may enable each bit-cell of the bit-cell population an equal number of times during a given period of operation, thus ensuring that each bit-cell is activated the same amount as any other bit-cell. In some examples, the DEM may shuffle the order of use of bit-cells of the bit-cell population, for example by using a shuffler component or a shifting component such as a barrel shifter.

(23) For clarity, the distinction between the total number of bit-cells, the bit-cell population, active and inactive bit-cells, and enabled bit-cells should be fully understood. Each of these terms refers to something slightly different. The total number of bit-cells means every bit-cell in the DAC, regardless of its status. The bit-cell population means the bit-cells in the DAC that may (or are available) be activated. The active bit-cells means bit-cells that are turned on (or that will be turned on), and therefore produce or contribute to an output signal. The inactive bit-cells means bit-cells that are not active but that could be activated. Therefore, the sum of the total number of active and inactive bit-cells equals the bit-cell population. The bit-cell population may be equal to or less than the total number of bit-cells. Finally, at times, bit cells may be referred to as enabled bit-cells. Enabled bit-cells are bit-cells belonging to the bit-cell population, but not necessarily active. In general, enabled bit-cells are the share of the bit-cell population allocated to a given fixed or variable-width DEM. Thus, the sum of the enabled bit-cells across each DEM equals the bit-cell population, whereas the total number of active bit-cells may be less than or equal to the bit-cell population and/or the enabled bit-cells.

(24) In some examples, the DEM—for example the telescoping DEM—may include more than one “sub-DEM.” That is, a DEM may include multiple constituent DEMs, for example, one variable width DEM and multiple fixed width DEMs.

(25) Turning to the drawings, FIG. 1 illustrates a CVBP DEM **100** according to a high-level functional block diagram. The illustrated CVBP DEM **100** is an example of a CVBP DEM suitable for use as a telescoping DEM. The CVBP DEM **100** includes a DEM input **102**, a bit cell population calculator (BCPC) **104**, a fixed/variable split calculator (FVSC) **106**, a variable DEM **108** (sometimes referred to as a variable-width DEM), a fixed DEM **110** (sometimes referred to as a fixed-width DEM), a shuffle controller **112**, an output array **114**, and a DEM output **116**. In some examples, more than one fixed DEM **110** may be included.

(26) The BCPC **104** includes an incrementor **104a**, a peak detector **104b**, and a bit-cell population register **104c** (referred herein as a “population register”). The FVSC **106** includes a Newton-Raphson reciprocator **106a**, fixed and variable delta-sigma modulator (DSM) inputs **106b**, and a delta-sigma modulator (DSM) **106c**. The variable DEM **108** includes a decoder **108a**, a reverse shuffle network **108b**, a variable DEM array **108c**, and a forward shuffle network **108d**. The fixed DEM **110** includes a random extra control **110a**, a fixed barrel shifter **110b**, a barrel shift offset array **110c**, and a butterfly network **110d**.

(27) The DEM input **102** is coupled to the BCPC **104** and to the FVSC **106**. The BCPC **104** is coupled to variable DEM **108**, the fixed DEM **110**, and the FVSC **106**. More particularly, in some examples, the BCPC **104** is coupled to the decoder **108a** of the variable DEM **108**, and to the fixed barrel shifter **110b** and random extra control **110a** of the fixed DEM **110**, as well as to the FVSC **106**. Certain additional details and internal aspects of the BCPC **104** will be discussed below, with respect to FIG. 2. The FVSC **106** is coupled to the BCPC **104**, the variable DEM **108**, and the fixed DEM **110**. More particularly, in some examples, the fixed/variable DSM inputs are coupled to the

fixed barrel shifter **110b**, and the DSM **106c** is coupled to the variable DEM array **108c** and to the random extra control **110a**. With respect to the BCPC **104** and the FVSC **106**, in some examples the internal components of those devices are coupled to one-another. That is, for example, the internal components of the BCPC **104** (e.g., the incrementor **104a**, peak detector **104b**, and population register **104v**) may all be coupled to each other.

(28) The variable DEM **108** is coupled to the BCPC **104**, the FVSC **106**, the fixed DEM **110**, the shuffle controller **112**, and the output array **114**. More particularly, in some examples, the decoder **108a** is coupled to the BCPC **104**, the FVSC **106**, the fixed barrel shifter **110b**, and the random extra control **110a**. The variable DEM array **108c** may be coupled to the DSM **106c**. The forward shuffle network **108d** may be coupled to the shuffle controller **112** and to the output array **114**. The fixed DEM **110** is coupled to the BCPC **104**, the FVSC **106**, the variable DEM **108**, the shuffle controller **112**, and the output array **114**. More particularly, in some examples, the random extra control **110a** may be coupled to the BCPC **104**, the FVSC **106**, the fixed barrel shifter **110b**, and the decoder **108a**. The fixed barrel shifter **110b** may be coupled to the random extra control **110a**, the fixed/variable DSM inputs **106c**, the BCPC **104**, and the decoder **108a**. The butterfly network **110d** may be coupled to the shuffle controller **112** and the output array **114**. In some examples, the butterfly network **110d** may be coupled to the output array **114** in more than one place, such as the highest address element and the lowest address element of the output array **114**.

(29) The shuffle controller **112** is coupled to the variable DEM **108** and the fixed DEM **110**. More particularly, in some examples, the shuffle controller **112** may be coupled to the forward shuffle network **108d** and to the butterfly network **110d**. The output array **114** is coupled to the variable DEM **108** and the fixed DEM **110**. More particularly, in some examples, the output array **114** is coupled to the forward shuffle network **108d** and to the butterfly network **110d**.

(30) Within the variable DEM **108**, the decoder **108a** is coupled to the reverse shuffle network **108b**. The reverse shuffle network **108b** is coupled to the variable DEM array **108c**, and the variable DEM array **108c** is coupled to the forward shuffle network **108d**. In some examples, the reverse shuffle network **108b** and the forward shuffle network **108d** may be coupled to one another.

(31) Within the fixed DEM **110**, the random extra control **110a** may be coupled to the barrel shift offset array **110c**. In some examples, the random extra control **110a** may be coupled to the barrel shift offset array **110c** in more than one location, such as the highest address element of the array and the lowest address element of the barrel shift output array **110c**. The fixed barrel shifter **110b** may be coupled to the barrel shift offset array **110c**. In some examples, the fixed barrel shifter **110b** may be coupled to the barrel shift offset array **110c** in such a way as to allow the fixed barrel shifter **110b** to provide the barrel shift offset array **110c** with two inputs, for example a “long” input and a “short” input, the “long” input having a larger width than the “short” input. The barrel shift offset array **110c** may be coupled to the random extra control **110a**, the fixed barrel shifter **110b**, and the butterfly network **110d**. In some examples, the barrel shift offset array **110c** may be coupled to the butterfly network **110d** in more than one location, such as at the highest address element and lowest address element of the butterfly network **110d**.

(32) The CVBP DEM **100** may operate in many modes of operation including a large population mode and a small population mode. These two modes operate differently from one another. Specifically, in the small population mode certain circuit elements are disabled (or ignored). The small population mode will be discussed with respect to FIG. 8. The following discussion, with respect to FIG. 1, applies primarily to the large population mode.

(33) The DEM input **102** receives a digital input signal which may be, for instance, a thermometer encoded input corresponding to the digital representation of an audio signal. The signal may be provided by any external circuit, for example, a DSM circuit. However, any type of digital signal may be received, and the invention is not limited to audio signals or thermometer encoded signals. The input **102** may provide the digital input signal to the BCPC **104** and/or to the FVSC **106**.

(34) The BCPC **104** calculates the active bit-cell population. In some examples, the BCPC **104**



determines the maximum number of active bit-cells and stores the maximum number of active bit-cells in the population register **104c**. The maximum possible value for the population register **104c** may be any value, but in some examples the maximum possible value will be equal to one-half of the total number of bit-cells. In examples where the maximum bit-cell population is one-half the total number of bit-cells, limiting the maximum bit-cell population to half the total number of bit-cells allows the DEM to select between the active half of the bit-cells and the inactive half of the bit-cells every clock cycle, thus ensuring that all the bit-cells are used evenly over time.

(35) In some examples, the BCPC **104** may recalculate the bit-cell population and store the recalculated value in the bit-cell population register **104c**. For example, the BCPC **104** may be configured to detect zero crossings of the digital input signal and then may increase or decrease the value in the population register **104c** by a multiple of the peak value detected by the peak detector **104b** of the digital input signal over a windowed peak period of digital input signal samples. In some cases, the incrementation and decrementation of the bit-cell population may be carried out by the incrementor **104a**. In some examples, the incrementation and decrementation coefficients may be multiples of the peak value of the DSM **106c** inputs. In some examples, the population register **104c** value is incremented upwards during a zero crossing when the bit-cell population register **104c** value is smaller than the peak value detected by the peak detector **104b** times an incrementation coefficient of the incrementor **104a**. In some examples, the bit-cell population **104c** value is decremented downwards during a zero crossing when the bit-cell population register **104c** value is greater than the peak value detected by the peak detector **104b** multiplied by a decrementation coefficient of the incrementor **104a**. In some examples, the value stored in the bit-cell population register **104c** may also be incremented or decremented during a non-zero crossing if the value is less than the peak detected by the peak detector **104b**.

(36) The FVSC **106** calculates the number of active bit-cells for the variable DEM **108** and the fixed DEM **110**. In some examples, there may be more than one fixed DEM **110** (e.g., 2, 3, 5, 10, or more) and the FVSC **106** may calculate the number of active bit-cells for each fixed DEM **110**. The Newton-Raphson Reciprocator **106a** calculates a reciprocal value, for example the reciprocal of the bit-cell population, using Newton-Raphson Reciprocation. It will be appreciated that any method of calculating a reciprocal could be used, such as any circuit capable of performing division. However, the Newton-Raphson Reciprocator **106a** has mostly static logic and low power consumption because the value of the bit-cell population changes relatively slowly. Thus, the Newton-Raphson Reciprocator **106a** offers advantages of less power usage and less time intensive division. Once the reciprocal is calculated, it is multiplied by the value of the digital input signal, and the resulting product is used to determine the number of active bit-cells for the variable DEM **108**. Once the number of active bit-cells for the variable DEM **108** is determined, the FVSC **106** calculates the number of active bit-cells for each fixed DEM **110**. The FVSC **106** is further configured to ensure that the value of active bit-cells for the variable DEM **108** averages approximately  $\frac{1}{2}$  too low over long periods of time. The values of active bit-cells for the variable DEM **108** and fixed DEM **110** are used as inputs to the DSM **106c** from the DSM inputs **106b**. It will be appreciated that, in some cases and/or examples, the values of active bit-cells may not be integers. The DSM **106c** is configured to account for this by taking any fractional inputs and correcting them in such a way that the average value of active bit-cells for both variable and fixed DEMs **108**, **110** averages out to be ideal or close to ideal over time. The FVSC **106** then provides the number of active bit-cells to the variable DEM **108** and the fixed DEMs **110**. An example of an FVSC **106**, and additional details about FVSCs are discussed with respect to FIG. 3.

(37) The variable DEM **108** controls which bit-cells will be activated from among the bit-cell population allocated to the variable DEM **108**. The variable DEM **108** then provides a drive signal to the output array **114** indicating which bit-cells should be driven (that is, which bit-cells should be activated and therefore outputting a signal). The variable DEM **108** is configured to ensure that the bit-cells are activated evenly, for example by ensuring that each bit-cell is active for no more than a

single clock cycle before being deactivated. The variable DEM **108** will be discussed in greater detail with respect to FIG. 5.

(38) The fixed DEM **110** controls which bit-cells will be activated from among the bit-cell population allocated to the fixed DEM **110**. The fixed DEM **110** provides a drive signal to the output array **114** indicating which bit-cells should be driven (that is, which bit-cells should be activated and therefore outputting a signal). The fixed DEM **110** is configured to ensure that the bit-cells are activated evenly, for example by ensuring that each bit-cell is active for no more than a single clock cycle before being deactivated. The fixed barrel shifter **108b** receives at least two input signals. One of the at least two input signals is received from the FVSC **106** and indicates the number of bit-cells to be activated per fixed DEM **110**, as in those cases where more than one fixed DEM **110** is present in the circuit. Another of the at least two input signals is received from the BCPC **104**, and may be indicative of the bit-cell population. The fixed barrel shifter **110b** may then determine the number of fixed DEMs **110** to activate such that a sufficient number of fixed DEMs **110** are providing output to the output array **114** to activate the determined number of bit-cells of the bit-cell population. The random extra control **110a** assigns an additional bit-cell to be activated to some of the fixed DEMs **110** to ensure that, in the case where the number of activated bit-cells is not a multiple of the number of activated variable DEM **108** and fixed DEM **110** bit-cells, that the difference may be made up by one or more of the fixed DEMs **110**. The random extra control **110a** is further configured to guarantee that the extra bit-cells are evenly distributed across the available fixed DEMs **110**.

(39) It will be appreciated that the random extra control **110a** and the fixed barrel shifter **110b** need not be implemented in each fixed DEM **110**. For example, a single random extra control **110a** and/or a single fixed barrel shifter **110b** could be implemented separately from the fixed DEM **110**. In such example, the fixed DEM **110** would include the barrel shift offset array **110c** and the butterfly network **110d**. In examples where the random extra control **110a** and the fixed barrel shifter **110b** are not part of the fixed DEMs **110**, and there are multiple fixed DEMs **110**, then each fixed DEM **110** may still have its own respective barrel shift offset array **110c** and butterfly network **110d**. In such examples, the random extra control **110a** and fixed barrel shifter **110b** are common to each fixed DEM **110**.

(40) The barrel shift offset array **110c** shuffles the bit-cells to be activated by the fixed DEM **110**. In some examples, the barrel shift offset array **110c** is configured to receive the last state of activated bit-cells (that is, the bit-cells activated in a previous clock cycle), and then activate new bit-cells while ensuring the previously activated bit-cells are not activated for more than a single clock cycle. The butterfly network **110d** may be configured to periodically change such that any tones from periodic cycling of the barrel shift offset array **110c** are broken up and/or removed, or shifted to a frequency that allows the tones from periodic cycling to be filtered and removed from the output audio signal. Furthermore, in examples where there are multiple fixed DEMs **110**, each respective butterfly network **110d** may have a unique randomization.

(41) The fixed DEM **110** will be discussed in greater detail with respect to FIG. 6.

(42) The shuffle controller **112** is configured to control the shuffle patterns and/or randomization of the forward shuffle network **108d**, reverse shuffle network **108b**, and butterfly network **110d**. In some examples, the shuffle controller **112** may provide a signal to any of the forward shuffle network **108d**, reverse shuffle network **108b**, and butterfly network **110d** indicating how those networks are to shuffle inputs they receive. In some examples, the forward and reverse shuffle networks **108d**, **108b** receive the same signal from the shuffle controller **112**, so that the reverse shuffle network **108b** is able to perform the inverse transformation on the output signals of the forward shuffle network **108d**.

(43) In some examples, the shuffle controller **112** may be configured to follow certain rules such that the randomization patterns/instructions it provides do not change constantly, such that fairness among bit-cells is maintained, and/or such that tones resulting from bit-cell mismatches are

avoided.

(44) The output array **114** is configured to receive inputs from the fixed and variable DEMs **110**, **108** and to provide a signal to the DEM output **116** indicative of which bit-cells to activate (i.e., which bit-cells to produce outputs) so that an audio signal can be generated without distortion.

(45) Where elements of arrays or networks are discussed, it will be appreciated that these elements may be individual registers having predetermined or known addresses associated with them. In each of the foregoing couplings, the coupling may be made in any manner, for example, via busses, wireless transmission, and so forth.

(46) FIG. 2 illustrates a block diagram of a windowed peak detector and bit-cell population register (referred to herein as “windowed peak detector”) **200** according to an example. The windowed peak detector **200** is an example of a peak detector, zero detector, and population register suitable for use in the BCPC **104** of FIG. 1. For example, the windowed peak detector **200** serves as one possible implementation of the peak detector **104b** and the population register **104c**. The windowed peak detector may be configured, in some examples, to only provide outputs during a windowed peak detection period. A windowed peak detection period is a period of time during which the windowed peak detector **200** is configured to determine whether a zero crossing has occurred and/or whether the bit-cell population should change.

(47) The windowed peak detector **200** includes an input **202**, a zero detector **204**, a near zero output **205**, a peak register **206**, a population change timer **208**, a multi-stage shift register (MSSR) **210**, a multiplexer (MUX) **212** and a peak output **214**. The input **202** is coupled to the zero detector **204** and the peak register **206**. The zero detector **204** is coupled to the near zero output **205**. The peak register **206** is coupled to the population change timer **208**, the MSSR **210**, and the MUX **212**. The pop change timer **208** is coupled to the peak register **206** and the MSSR **210**. The MSSR **210** is coupled to the peak register **206**, the population change timer **208**, and the MUX **212**. The MUX **212** is coupled to the peak register **206**, the MSSR **210**, and the peak output **214**. The peak output **214** is coupled to the MUX **212**.

(48) The input **202** receives an input signal, for example a DSM signal such as the DEM input **102** or the output of DSM **106c** in FIG. 1. The input **202** provides the input signal to the zero detector **204**, which may provide an output to the zero output **205** when the input signal value is at or near zero. For example, the zero detector **204** may compare the input signal value against a low value such as 3 or 0, and may output a signal to the zero output **205** if the input signal value is less than and/or equal to the low value. The value the zero detector **204** compares against to determine if a value is sufficiently close to zero may be programmed and/or set by a user, for example, an end-user or another part of the circuit. The zero detector **204** may also output a signal to the zero output **205** if a polarity, for example, the sign, of the input signal changes. In some examples, the zero detector **204** indicates that a zero crossing has occurred by providing an output signal to the zero output **205**. In some examples, the zero detector **204** may only detect zero crossings during the windowed peak detection period.

(49) The input **202** also provides the input signal to the peak register **206**. The peak register **206** receives and stores the value of the input signal received at the input **202**, and can provide the stored input signal value to the MSSR **210** and to the MUX **212**. The population change timer **208** provides a clock signal to the MSSR **210** and a reset signal to the peak register **206**. The population change timer **208** acts as a timer corresponding to the windowed peak detection period during which the peak detector **200** determines the windowed peak value of the DSM. That is, the population changer timer **208** may be configured to determine when the windowed peak detection period occurs. To determine the windowed peak value of the input signal, during the windowed peak detection period, the peak register **206** receives and stores input signal values, and provides those values to the MSSR **210**. The MUX **212** receives the input signal values stored in the MSSR **210** and peak register **206**, and outputs the maximum input signal value from among the values received from the MSSR **210** and peak register **206** to the peak output **214**.

(50) In some examples, when the windowed peak detector's **200** zero detector **204** provides an output to the zero output **205**, the MUX **212** provides the maximum digital input signal value to the peak output **214**. In examples where the windowed peak detector **200** is part of the BCPC **104** of the CVBP DEM **100**, the CVBP DEM **100** may then use the maximum digital input signal value to adjust the bit-cell population. For example, the CVBP DEM **100** may be configured to operate in various modes. Such modes may include a zero-decrement mode and a zero-update mode. The zero-decrement mode may correspond to the CVBP DEM **100** decreasing the number of active bit-cells by the maximum digital input signal value multiplied by a decrementation coefficient during a detected zero crossing. In zero-decrement mode the bit-cell population can increase by an incrementation coefficient multiplied by the peak value of the digital input signal at any time. In the zero-update mode, the bit-cell population may be adjusted up or down at a zero crossing. For example, the bit-cell population may be adjusted down if larger than a decrementation coefficient multiplied by the windowed peak value, or adjusted up if the bit-cell population is less than an incrementation coefficient multiplied by the digital input signal value.

(51) The windowed peak detector **200** may also be configured to include a timer value that can cause the bit-cell population to change even without detecting a zero crossing. For example, for a given time period, the timer value may decrease. When the timer value reaches zero the bit-cell population is decremented by some amount which may be set (e.g., 1, 4, etc.) or variable. In some examples, when decreasing the bit-cell population in this way, the change in the bit-cell population may be relatively small, thus minimizing any distortion or other audio artifacts which may occur. It will be appreciated that, since the distortion is proportional to the change in the number of bit-cells, by keeping the change low the distortion may be minimized.

(52) The windowed peak detector **200** may also include circuitry designed to determine the operation mode of the CVBP DEM **100**. In some examples, the bit-cell population value is compared to a value stored in a large/small mode register. If the bit-cell population value is less than and/or less than or equal to the value stored in the large/small mode register, the windowed peak detector **200** may control the CVBP DEM **100** to operate in the small population mode of operation. If the bit-cell population value is greater than and/or greater than or equal to the value stored in the large/small mode register, the windowed peak detector **200** may control the CVBP DEM **100** to operate in the large population mode of operation. The large and small modes of operation will be discussed in greater detail with respect to FIG. 8.

(53) FIG. 3 illustrates a fixed/variable split calculator (FVSC) **300** according to an example. The FVSC **300** is an example of a fixed/variable split calculator suitable for use as the FVSC **106** of FIG. 1. The FVSC **300** is configured to calculate the number of active bit-cells,  $v$ , of the variable DEM (e.g., variable DEM **108**) and to calculate the number of active bit-cells,  $f$ , for each of the one or more fixed DEMs (e.g., fixed DEMs **110**). Hereafter, reference will be made to the variable DEM **108** and fixed DEMs **110** for clarity. The fixed DEMs **110** and variable DEM **108** use the values of  $f$  and  $v$ , respectively, to determine how many bit-cells to activate.

(54) The FVSC **300** includes a population input **302**, a Newton-Raphson reciprocator **304**, a DSM input **306**, a DSM **308**, and a DSM output **310**. The Newton-Raphson reciprocator **304** may include various Look-up Tables (LUTs) **305**. The DSM **308** may include a variable DSM (V-DSM) corrector **308a** and a variable DSM (V-DEM) accumulator **308b**. The population input **302** is coupled to the Newton-Raphson Reciprocator **304**. The DSM input **306** is coupled to the DSM **308**. In some examples, DSM input **306** may be coupled to the DSM **308** in more than one place, for example, with a coupling corresponding to an input for the value  $f$ , and another for the value  $v$ . The V-DSM corrector **308a** and the V-DEM accumulator **308b** may be coupled to each other. The DSM output **310** is coupled to the DSM **308**.

(55) The FVSC **300** calculates the values of  $f$  and  $v$  such that the number of active bit-cells may be evenly distributed across the various DEMs over time. To determine the values of  $f$  and  $v$ , the FVSC **300** may determine a reciprocal value,  $1/P$ , where  $P$  is the bit-cell population (such as the bit-

cell population determined by the CCBP **104**). The Newton-Raphson reciprocator **304** may determine the value of  $1/P$ . For example, the Newton-Raphson reciprocator **304** may receive the value of  $P$  via the population input **302**, where the value of  $P$  corresponds to the bit-cell population. Then, through logic and/or by using the LUTs **307**, the Newton-Raphson reciprocator **304** may determine a value or approximate value for  $1/P$ . The Newton-Raphson reciprocator **304** may then provide the value of  $1/P$  to the DSM inputs **306**. It will be appreciated that the Newton-Raphson reciprocator **304** could be replaced with any circuit capable of performing division or suitable approximations of division, however the Newton-Raphson reciprocator **304** offers various advantages. For instance, the Newton-Raphson reciprocator **304** calculates the reciprocal using mostly static logic because the value of  $P$  changes infrequently, and thus consumes relatively little power compared to many other methods and may require less computational time to determine  $1/P$ .

(56) The DSM input **306** may include circuitry capable of performing mathematical operations, such as multiplication. The DSM input **306** receives the reciprocal  $1/P$  from the Newton-Raphson reciprocator **304**. The DSM input **306** is configured to calculate the initial values of  $v$  and  $f$  to provide to the DSM **308**. The DSM input **306** may receive a value,  $V$ , corresponding to the total number of enabled bit-cells for the variable DEM **108**. The DSM input **306** may also receive a value,  $F$ , corresponding to the total number of enabled bit-cells for each of the fixed DEMs **110**. In some examples,  $F$  equals  $M$  times the number of active fixed DEMs **110**, where  $M$  is the bit-width of the fixed DEMs **110**. For example, if each fixed DEM **110** has a bit-width of 32, and there are 7 active fixed DEMs **110** out of 10 total fixed DEMs **110**, then  $F=32 \cdot 7=224$ . It will be appreciated that not all fixed DEMs **110** need be active at the same time. Accordingly, in some examples,  $F+V=P$ . The DSM input **306** may also receive a value corresponding to the digital input signal, for example, the digital input signal's amplitude and polarity. The DSM input **306** then determines the value of  $v$  based on the digital input signal, the enabled bit-cells for the variable DEM **108**, and the reciprocal  $1/P$ . For example,  $v$  may be the value of the reciprocal multiplied by the value of the digital input signal and the number of enabled bit-cells allocated to the variable DEM **108**. That is:

$$(57) v = \frac{\text{DigitalInputSignalValue}}{P} V$$

where  $v$  is the number of active bit-cells for the variable DEM **108**,  $P$  is the bit-cell population, and  $V$  is the number of enabled bit-cells allocated to the variable DEM **108**. The number of active bit-cells for the fixed DEMs **110** are determined similarly. It will be appreciated that  $f$  corresponds to the number of bit-cells to be activated by each fixed DEM **110**, and not the total number of bit-cells to be activated across all fixed DEMs **110**. The value of  $f$  may be determined by multiplying the value of the digital input signal, the reciprocal, and  $F$  together. That is:

$$(58) f = \frac{\text{DigitalInputSignalValue}}{P} F$$

(59) The DSM input **306** provides  $f$  and  $v$  to the DSM **308**. It will be appreciated that  $1/P$  and the digital input signal value are not necessarily integer values. Accordingly,  $f$  and/or  $v$  may be fractional. However, bit-cells are integers: that is, each bit-cell is a discrete component that is either on or off. As a result, fractions of bit-cells cannot be activated. If the values of  $f$  and  $v$  were truncated, rounded up, or otherwise adjusted without taking into account the error induced by the fractional remainders of each value, over time the CVBP DEM **100** would experience an error in its output, and the error may potentially grow large and/or audible. The V-DSM corrector **308a** corrects the value of  $v$  based on the fractional remainder of  $v$ . The V-DSM corrector **308a** is configured to maintain the integer average of  $v$  very close to the ideal value. The V-DSM corrector **308a** may do this by adjusting the value of  $v$  some of the time. In some examples, the V-DSM corrector **308a** may decrease the value of  $v$  by 1 if the fractional remainder of  $v$  is below a certain value (for example, 0.25) and may increase the value of  $v$  by 1 if the fractional remainder of  $v$  is above a certain value (for example 0.75). In some examples, the V-DSM corrector **308a** may only adjust the value of  $v$  half of the time, even if  $v$ 's fractional remainder meets the adjustment condition (for example, being less than 0.25 and/or greater than 0.75). As a result, in some

examples, the average value of  $v$  over time approaches approximately one-half less than the ideal value for  $v$  (i.e.  $V_{\text{sub.ideal}} - \frac{1}{2}$ ).

(60) The V-DEM accumulator **308b** records values of  $v$  and monitors them over time. If the V-DEM accumulator **308b** detects that  $v$  has been too low and/or is trending to low, the V-DEM accumulator **308b** may increase or decrease the value of  $v$  by an appropriate amount, for example 1. In the example given above, where  $v$  is incremented about half the time when it meets one of the two conditions concerning the fractional remainder, the V-DEM accumulator **308b** may adjust the value of  $v$  about half the time as well. Once the value of  $v$  is known, the value of  $(f \cdot \text{Math.V} - v \cdot \text{Math.F})$  is stored in the V-DSM accumulator **308b**. If  $v$  is averaging too high, the V-DEM accumulator **308b** may go negative (i.e.,  $vF > fV$ ) and the V-DEM accumulator **308b** may increase at least the next value of  $v$  so that  $v$  will average too low (for example,  $\frac{1}{2}$  too low). As mentioned above, this incrementation may occur about half the time due to the averaging process described in the V-DSM corrector **308a**.

(61) The effect of the combined operation of the V-DSM corrector **308a** and the V-DSM accumulator **308b** is to cause, over time, the average integer value of  $v$  to approach the ideal value of  $v$ . Once  $v$  and  $f$  are fully adjusted by the V-DSM corrector **308a** and V-DEM accumulator **308b**, the DSM **308** may round, truncate, or otherwise dispose of the fractional remainder.

(62) The DSM **308** may also be configured such that the value of active bit cells for the fixed DEMs **110** divided by the total number of enabled bit-cells for the fixed DEMs **110** divided by the bit-cell population is equal to the total number of active bit-cells for the variable DEM **108** divided by the enabled bit-cells allocated to the variable DEM **108** divided by the bit-cell population when averaged over a short time span. That is, the DSM **308** may be configured such that:

$$(63) \frac{f}{(F/P)} = \frac{v}{(V/P)}$$

when averaged over a short time span. If this condition is met, any inequality is forced to have a higher frequency than the audio bandwidth. In some examples, this makes potential noise and/or distortion inaudible or filterable without affecting the audio output signal, for instance, by forcing the frequency of the distortion into a frequency not audible to the human ear.

(64) The value of  $f$  may be further adjusted by a value, for example 0 or 1. This random extra value is applied to a subset of the fixed DEMs **110** to ensure each fixed DEM **110** drives the same number of active bits every clock cycle, which may force any distortion and/or noise above the audio frequency.

(65) It will be appreciated that the adjustment values described herein are arbitrary, and that values could be picked to cause  $v$  to average more or less than  $\frac{1}{2}$  less than the ideal value, and the accumulator could adjust by more or less than 1 to account for this.

(66) FIG. 4A illustrates a selective bit-enabled barrel shifter (SBBS) **402** that may be combined with other SBBSs **402** to hierarchically construct an SBBS of arbitrary size, as discussed with respect to FIG. 4B. The SBBS **402** may be used by the fixed and variable DEMs (e.g., fixed DEM **110**, variable DEM **108**) to control which bit-cells are activated and which are not. The SBBS **402** may also be used to ensure that bits and/or bit-cells are evenly used by, for example, ensuring that active bits are deactivated after one clock cycle, as described in greater detail below.

(67) The SBBS **402** includes three inputs, BIT ENABLE, SKIP, and DRIVE, and two outputs, ENABLED CNT and BIT DRIVE. The BIT ENABLE input sets how many bits or bit-cells are enabled (for example, how many bit-cells are part of the bit-cell population). The DRIVE input determines which bits of the enabled bits are activated (for example, which bit-cells from among the bit-cell population are activated). The SKIP input determines if a bit is skipped (that is, not shifted by the SBBS **402**). In some examples, no inactive bits are shuffled (that is, all inactive bits are skipped). In some examples, the BIT ENABLE and BIT DRIVE busses may be  $N$  bits wide, and the SKIP, DRIVE, and ENABLED CNT busses may be  $N-1$  bits wide. For example,  $N$  may equal 3, and  $N-1$  may equal 2.

(68) In operation, the SBBS **402** may be configured such that, starting at index 0 of BIT DRIVE

and moving to positions 1, 2, 3, and so forth, any number of non-enabled bits are skipped along with the bits indicated to be skipped by the SKIP input. Such bits have their value set to off (which will be referred to as “0” herein). Skipped bits may not be activated and may not be shuffled. A number of bits equal to the DRIVE input are then turned on (which will be referred to as “1” herein), again skipping any non-enabled bits. Finally, any bits that are enabled, per the BIT ENABLE input, but that would result in more than DRIVE bits being actually driven, are set to 0 as well. The bits set to 1 may be set to 0 on the next clock cycle, ensuring they are not activated for two clock cycles in a row. For example, the bits set to 1 may be selected to be skipped or not enabled on the next clock cycle, and would thus be set to 0.

(69) FIG. 4B illustrates how the SBBS 402 may be hierarchically combined with each other to create larger selective bit-enabled barrel shifters. For clarity, the expanded SBBS of FIG. 4B shall be referred to as the expanded barrel shifter 404. The hierarchical combination of the SBBSs 402 into larger expanded barrel shifter 404 components (which can then be combined with additional expanded barrel shifter 404 components, in a recursive manner to increase the size of expanded barrel shifter 404 to any arbitrary size), allows the expanded barrel shifter 404 to use considerably less logic than implementing a hardware loop to execute the relevant functions. As a result, the expanded barrel shifter 404 may use less power, less space, and fewer logic gates than a hardware loop circuit. In some examples, the depth of the expanded barrel shifter 404 grows at  $\log_{\text{sub.2}}(N)$ , where N is the bit width of the expanded barrel shifter 404. Furthermore, because the depth of the hierarchical logic of the expanded barrel shifter 404 increases logarithmically compared to the bit-width (that is, the depth, in some examples, is always less than the bit-width), the expanded barrel shifter 404 also offers lower propagation delay compared to hardware loop circuits and other circuits capable of implementing the necessary logic.

(70) FIG. 4C illustrates the growth of the expanded barrel shifter at a bit-width of 32-bits. As shown, two 3-bit wide SBBS 402 components are combined to make a 6-bit wide expanded barrel shifter 404. Two 6-bit wide expanded barrel shifters 404 are combined to make a 12-bit expanded barrel shifter 404, two 12-bit wide expanded barrel shifters 404 are combined to make a 24-bit wide expanded barrel shifter 404, and then the 24-bit wide expanded barrel shifter 404 is combined with a 12-bit wide expanded barrel shifter 404 to create a 36-bit wide expanded barrel shifter 404. This expansion logic has a depth of 5, and a bit-width of 32, with 4 extra bits that need not be used for any purpose, but may, in some examples, be put to other uses. It will be noted that the  $\log_{\text{sub.2}}(32)$  is 5. It will be appreciated that other combinations are possible (for example combining a 3-bit wide SBBS 402 with a 6-bit wide expanded barrel shifter 404 to create an 8-bit wide expanded barrel shifter 404 with 1 extra bit, and so forth).

(71) FIG. 5 illustrates a variable-width DEM (variable DEM) 500 according to an example. The variable DEM 500 may be suitable for use as the variable DEM 108 of FIG. 1. The variable DEM 500 includes a variable DEM (VDEM) input 502, a decoder 504, a reverse shuffle network 506, a variable DEM (VDEM) array 508, a forward shuffle network 510, and a variable DEM (VDEM) output 512. The decoder 504 may be a thermometer-coded decoder, or any other type of decoder. The VDEM array 508 may be implemented as a barrel shifter of any given width. For example, the SBBS 402 and/or expanded barrel shifter 404 of FIGS. 4A-4C may be used as the VDEM array 508. The variable DEM 500 is configured to determine which bit-cells to activate from among the bit-cell population provided to the variable DEM 500.

(72) The VDEM input 502 is coupled to the decoder 504. The decoder 504 is coupled to the inverse shuffle network 506. The inverse shuffle network 506 is coupled to the decoder 504, the VDEM array 508, and to the forward shuffle network 510. The VDEM array 508 is coupled to the inverse shuffle network 506 and the forward shuffle network 510. The forward shuffle network 510 is coupled to the inverse shuffle network 506, the VDEM array 508, and the VDEM output 512. The operations described with respect to the variable DEM 500 may be executed in a single clock cycle, less than a single clock cycle, or more than a single clock cycle.

(73) The variable DEM **500** receives an input signal at the decoder **504**. The input signal may correspond to the bit-cell population calculation of, for example, the BCPC **104**. The decoder **504** decodes the input signal and provides it to the reverse shuffle network **506**. The reverse shuffle network **506** may have a topology identical to the forward shuffle network **510**, but the reverse shuffle network **506** is configured to perform an inverse shuffle on the shuffled output provided by the forward shuffle network **510**. For example, if the forward shuffle network **510** receives an original input signal and shuffles the original input signal into a shuffled signal, then the reverse shuffle network **506** can take the shuffled signal and reverse it through an inverse transformation to retrieve the original input signal provided to the forward shuffle network **510**. In some examples, the reverse shuffle network **506** is configured to receive an output from the forward shuffle network **510** corresponding to the activated bit-cells. The reverse shuffle network can then inversely transform the output from the forward shuffle network **510** to determine the original input to the VDEM array **508**. In this manner, the forward and reverse shuffle networks **510**, **506** can ensure that only un-activated bit-cells are activated by the VDEM Array **508**—that is, the system can guarantee that no bit-cell is activated for more than a single clock cycle. In other words, the VDEM Array **508** determines which bit-cells to activate based on the state of activated bit-cells one or more clock cycles earlier. The VDEM Array **508** also receives input signals from another circuit component, for example the DSM **106c**. The VDEM Array **508** may use the input signals from the DSM **106c** to determine which bit-cells to activate. For example, if the VDEM Array **508** is implemented according to the selected bit-enabled barrel shifter of FIGS. **4A-4C**, then the input signal from the DSM **106c** may be used to provide the DRIVE and SKIP inputs discussed with respect to FIG. **4**.

(74) In some examples, the variable DEM's **500** topology may be implemented in the random extra control **110a** of the fixed DEM **110**, as well as in the variable DEM **108**. The random extra control **110a** is configured to determine which fixed DEMs **110** (when there are more than one fixed DEMs **110** in the circuit) to use to activate one or more additional bit-cells when the number of activated bit-cells is not an integer multiple of the bit-cells to be activated by the variable DEM **108** and the fixed DEMs **110**. The extra bit-cells make up the difference. However, it is preferable that the extra bit-cells be randomly and evenly selected, such that no fixed DEM **110** activates an extra bit-cell for more than one clock cycle and/or such that no extra bit-cell is activated for more than one clock cycle. The random extra control **110a** ensures that no extra bit-cell will be on for more than a single clock cycle. The variable DEM **500** is already configured, as described above, to control the number of clock cycles bit-cells are active during, and can guarantee that a given bit-cell remain active for only a single clock cycle. Accordingly, the variable DEM's **500** logic can be configured to control which fixed DEMs **110** may provide an extra bit-cell by selecting from among the fixed DEMs **110** at random, and ensuring that no single fixed DEM **110** is selected to provide an extra bit-cell for more than one clock cycle at a time.

(75) In some examples, no fixed DEM **110** is present in the CVBP DEM **100**. In such examples, a single variable-width DEM **500** may be used with a bit-width equal to the bit-width of the CVBP DEM **100**. In such cases, the variable-width DEM **500** may shuffle and drive each bit-cell of the CVBP DEM **100**. Such an example is one implementation of a fully variable DEM as described herein.

(76) FIG. **6** illustrates a block diagram of a fixed width DEM (fixed DEM) **600** according to an example. The fixed DEM **600** may be an example of a fixed DEM suitable for use as fixed DEM **110** in FIG. **1**. The fixed DEM **600** includes a random extra control **602**, a fixed barrel shifter **604**, a barrel shift offset array **606**, and a butterfly network **608**. Also shown are the shuffle controller **112** and the output array **114**.

(77) As shown, the barrel shift offset array **606** and the butterfly network **608** are arrays of elements. In some examples, each element is associated with a unique address. Each element of each array **606**, **608** may store relevant data which may be accessed using the unique address



associated with that element, or which may be written and/or set by using the unique address associated with that element. The random extra control **602** is coupled to the highest address element of the barrel shift offset array **606** and to the lowest address element of the barrel shift offset array **606**. The fixed barrel shifter **604** is coupled to the highest address element of the barrel shift offset array **606** in two places, the first place corresponding to the least significant bits of the element and the second place corresponding to the most significant bits of the element. The most significant bits and least significant bits may be distributed in any contiguous manner. For example, the most significant bits may be the 5 most significant contiguous bits, the 7 most significant contiguous bits, or any other number of most significant continuous bits. The least significant bits may then be the remaining contiguous bits.

(78) The barrel shift offset array **606** is coupled to the butterfly network **608** at the highest address element and the lowest address element. The butterfly network **608** is coupled to the shuffle controller **112**. The butterfly network **608** is also coupled to the highest address element and lowest address element of the output array **114**.

(79) The CVBP DEM **100** may have one or more fixed DEMs (for example fixed DEMs **110**, **600**). The number of active fixed DEMs **600** is determined by the bit-cell population. Each fixed DEM **600** has a common bit-width corresponding to the number of bits the fixed DEM **600** can shuffle. For example, a fixed DEM **600** with a bit-width of 32 can shuffle 32 bits each clock cycle. Each fixed DEM **600** drives a subset of bits equal or less than the total bit-width of the fixed DEM **600**. In some examples, each active fixed DEM **600** drives a set minimum number of bits. That is, each fixed DEM **600** may drive at least the minimum number of bits. Each fixed DEM **600** may also drive an additional bit, as determined by the random extra control **602**. In some examples, the random extra control **602** determines a subset of the fixed DEMs **600** that may drive an additional bit. The random extra control **602** may be implemented using the variable DEM **500** topology as discussed with respect to FIG. 5.

(80) The barrel shift offset array **606** and the butterfly network **608** are configured to randomize the order of selected bit-cells to reduce tone generated from possible bit-cell mismatch. In some examples, the butterfly network **608** implements an algorithm to swap bit-cells. An algorithm **700** is illustrated in FIG. 7 according to an example. The algorithm **700** may swap only bit-cells selected to be swapped (i.e., enabled bit-cells). The algorithm **700** may perform multiple swaps. For example, at a zeroth level, the algorithm **700** may swap each adjacent bit-cell based on the index (and/or address) of the bit-cell. At a first level, the algorithm **700** may swap two adjacent bit-cells with two other adjacent bit-cells. At a second level, the algorithm **700** may swap three adjacent bit-cell with three other adjacent bit-cells, and so forth. Other algorithms may also be used, provided the algorithms swap the bit-cells evenly and fairly.

(81) Bit-cells which are not swapped may be powered off, and any logic associated with them may be held constant. It will be appreciated that the random extra control **602** and the fixed barrel shifter **604** need not be implemented as part of the fixed DEM **600**. In some examples, only one random extra control **602** and one fixed barrel shifter **604** are required, in which case the one random extra control **602** and one fixed barrel shifter **604** are connected to each of the barrel shift offset arrays **606** of the one or more fixed DEMs **600**.

(82) FIG. 8 illustrates a process **800** of the operation modes of the CVBP DEM **100** according to a functional block diagram. In some examples, the CVBP DEM **100** has a small population mode for when the bit-cell population is below a population threshold, and a large population mode for when the bit-cell population is above a population threshold. It will be appreciated that the population threshold may be set by a user, pre-set or pre-programmed, or determined dynamically by an algorithm.

(83) At act **802**, the CVBP DEM **100** determines if the bit-cell population is above and/or below a population threshold. If the bit-cell population is below the threshold (**802** LESS) the process **800** continues to act **804** and the CVBP DEM **100** operates in the small population mode. If the bit-cell

population is above the threshold (**802** GREATER) the process **800** continues to act **806** and the CVBP DEM **100** operates in the large population mode.

(84) In the small population mode, the CVBP DEM **100** may disable the shuffle functionality of the fixed and variable DEMs **108**, **110**, for example by disabling the forward and reverse shuffle networks **108b**, **108d**, and disabling the butterfly network **110d**. The CVBP DEM **100** may also hold the FVSC **106** static while the bit-cell population is below the population threshold. The CVBP DEM **100** may then shuffle the bit-cells using only barrel shifters, for example the fixed barrel shifter **110b**, the variable DEM array **108c**, and so forth. It will be appreciated that, in the low population mode, the barrel shifters may ensure sufficient randomness and fairness such that no bit-cell may be active for more than one clock cycle.

(85) In the large population mode, the CVBP DEM **100** is fully active, and no subcomponents (e.g., the shuffle networks **108b**, **108d** or butterfly network **110d**) are disabled. Accordingly, in the large population mode, the CVBP DEM **100** operates with all the functionalities described herein with respect to the other figures.

(86) It will be appreciated that distortion is not limited to audio signals. The present disclosure applies equally to any other electrical signal where predictable error, such as distortion, may occur. Such systems may include power systems (for example power amplifiers), and other systems where signals are converted between digital and analog form.

(87) Various controllers, such as the controller **112**, may execute various operations discussed above. Using data stored in associated memory and/or storage, the controller **112** also executes one or more instructions stored on one or more non-transitory computer-readable media, which the controller **112** may include and/or be coupled to, that may result in manipulated data. In some examples, the controller **112** may include one or more processors or other types of controllers. In one example, the controller **112** is or includes at least one processor. In another example, the controller **112** performs at least a portion of the operations discussed above using an application-specific integrated circuit tailored to perform particular operations in addition to, or in lieu of, a general-purpose processor. As illustrated by these examples, examples in accordance with the present disclosure may perform the operations described herein using many specific combinations of hardware and software and the disclosure is not limited to any particular combination of hardware and software components. Examples of the disclosure may include a computer-program product configured to execute methods, processes, and/or operations discussed above. The computer-program product may be, or include, one or more controllers and/or processors configured to execute instructions to perform methods, processes, and/or operations discussed above.

(88) Having thus described several aspects of at least one embodiment, it is to be appreciated various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be part of, and within the spirit and scope of, this disclosure. Accordingly, the foregoing description and drawings are by way of example only.

## Claims

1. A system for mitigating distortion in a signal comprising: a plurality of bit-cells; a calculation circuit configured to determine a bit-cell population that is available to be activated for a given clock cycle; a dynamic element matching network configured to activate a subset of bit-cells of the bit-cell population; and a controller configured to control a pattern of activation of the subset of bit-cells of the bit-cell population.
2. The system of claim 1 wherein the dynamic element matching network is further configured to activate each bit-cell of the subset of bit-cells on a first clock cycle, and deactivate each bit-cell of the subset of bit-cells on a second clock cycle.

3. The system of claim 2 wherein the second clock cycle is a clock cycle immediately following the first clock cycle.
4. The system of claim 2 wherein the dynamic element matching network is further configured to activate a second subset of bit-cells of the plurality of bit-cells on the second clock cycle, the second subset not including any bit-cells of the first subset.
5. The system of claim 1, the calculation circuit being further configured to periodically determine the bit-cell population based on a peak signal strength of the signal.
6. The system of claim 5 wherein the calculation circuit determines the bit-cell population responsive to a signal strength of the signal being zero or near-zero.
7. The system of claim 1 wherein the subset of bit-cells is a second subset of bit-cells, and the dynamic element matching network further comprises a first shuffle network, a variable array, and a second shuffle network, wherein the first shuffle network is configured to provide a first subset of bit-cells activated on a previous clock cycle to the variable array; the variable array is configured to provide the bit-cells of the bit-cell population not including each bit-cell of the first subset of bit-cells to the second shuffle network, and to provide a number of bit-cells to be activated to the second shuffle network; and the second shuffle network is configured to randomly select from among the bit-cell population not including the first subset of bit-cells the second subset of bit-cells to activate, the second subset of bit-cells including a number of bit-cells equal to the number of bit-cells to be activated.
8. The system of claim 7 wherein the first shuffle network is further configured to receive the second subset of bit-cells and provide the second subset to the variable array on a clock cycle following a clock cycle wherein the second subset of bit-cells was activated.
9. The system of claim 1 further comprising a barrel shifter, the barrel shifter being configured to activate the subset of bit-cells in a low population mode and the dynamic element matching network being configured to activate the subset of bit-cells in a high population mode.
10. The system of claim 9 wherein the system operates in the low population mode when the bit-cell population is below a threshold bit-cell population level.
11. A method of activating bit-cells of a plurality of bit-cells to mitigate distortion in a signal comprising: determining a bit-cell population of the plurality of bit-cells to be available to be activated based on a signal strength of a signal; randomly selecting a first subset of bit-cells of the bit-cell population to activate based on the signal strength; activating the first subset of bit-cells on a first clock cycle; and deactivating the first subset of bit-cells on a second clock cycle.
12. The method of claim 11 further comprising activating a second subset of bit-cells on the second clock cycle, the second subset not including any bit-cells of the first subset.
13. The method of claim 11 wherein the second clock cycle is the clock cycle immediately following the first clock cycle.
14. The method of claim 11 wherein the bit-cell population is determined at periodic intervals.
15. The method of claim 14 wherein the bit-cell population is determined when the signal strength of the signal is at or near zero.
16. The method of claim 11 wherein a bit-cell is activated for no more than one clock cycle in a row.
17. A dynamic element matching network (DEM) comprising: an input; a bit-cell population calculator coupled to the input; a variable dynamic element matching network (variable DEM) coupled to the bit-cell population calculator and to a fixed-variable split calculator; and an output coupled to the variable DEM.
18. The DEM network of claim 17 wherein the bit-cell population calculator is configured to determine a total number of bit-cells to be turned on during a clock cycle, the total number of bit-cells based on a signal strength of an input signal received at the input.
19. The DEM network of claim 18 wherein: the variable DEM is configured to active a number of bit-cells equal to the total number of bit-cells.

20. The DEM network of claim 19 wherein: the variable DEM is configured to deactivate the number of bit-cells on a clock cycle following a clock cycle on which the variable DEM activated the number of bit-cells.

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