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(54) **DATA AIDED METHOD FOR ROBUST DIRECTION OF ARRIVAL (DOA) ESTIMATION IN THE PRESENCE OF SPATIALLY-COHERENT NOISE INTERFERERS**

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(57) **ABSTRACT**

A method and apparatus to determine a direction of arrival (DOA) of a talker in the presence of a source of spatially-coherent noise. A time sequence of audio samples that include the spatially-coherent noise is received and buffered. Aided by previously known data, a trigger point is detected in the time sequence of audio samples when the talker begins to talk. The buffered time sequence of audio samples is separated into a noise segment and a signal-plus-noise segment based on the trigger point. For each direction of a plurality of distinct directions: an energy difference is computed for the direction between the noise segment and the signal-plus-noise segment, and the DOA of the talker is selected as the direction of the plurality of distinct directions having a largest of the computed energy differences.

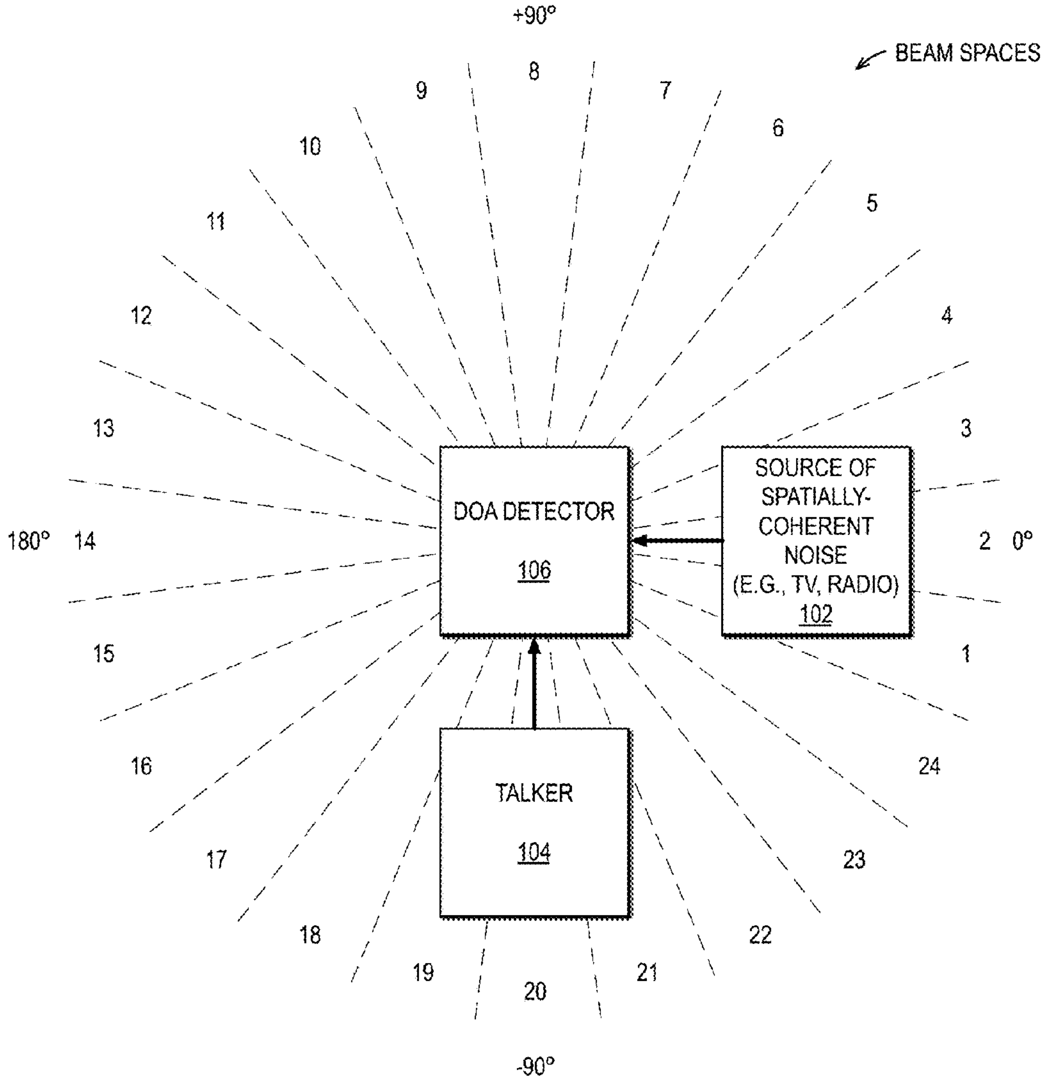


FIG. 1

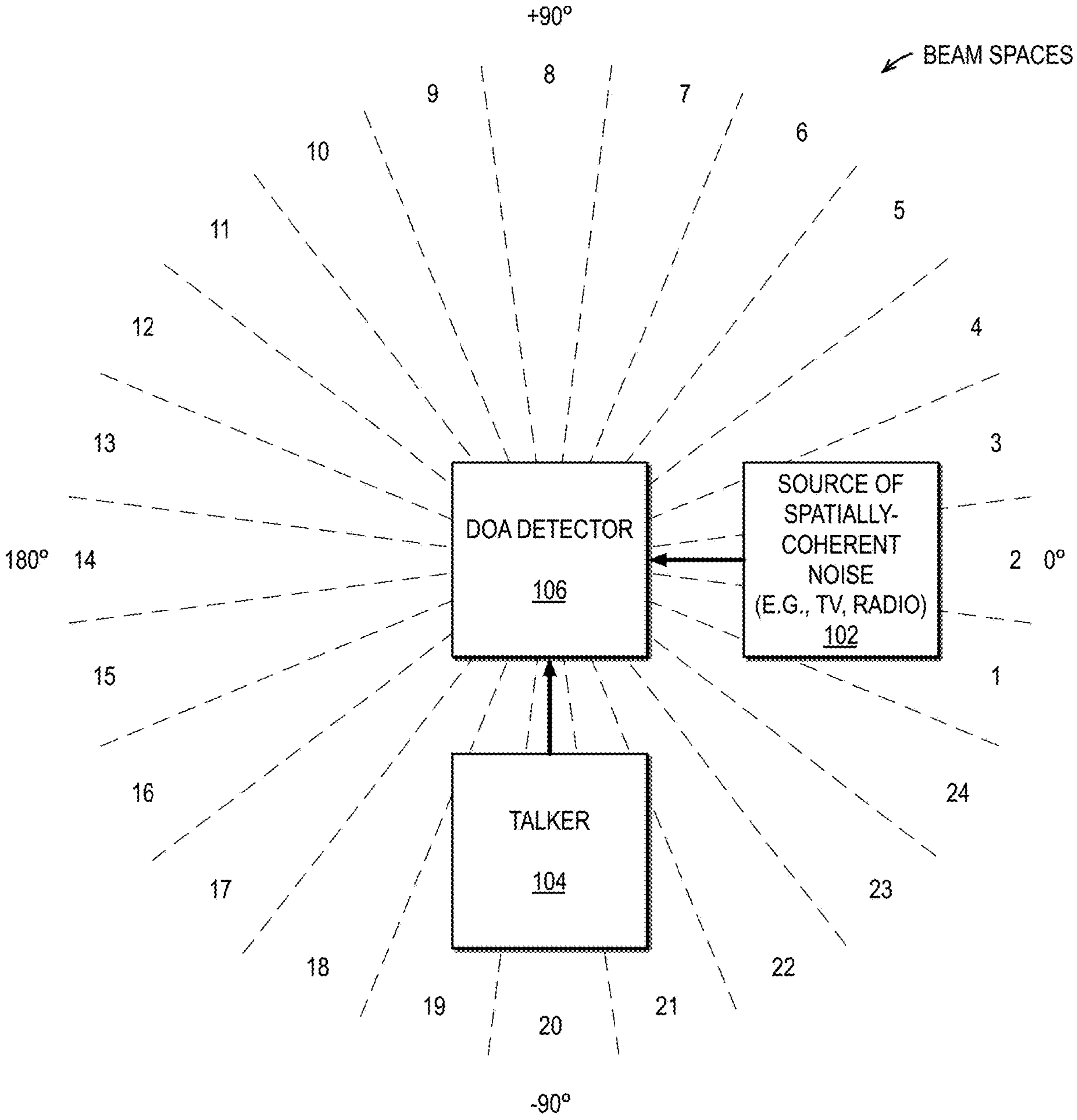

+90°
BEAM SPACES
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
180°
0°
-90°
DOA DETECTOR
106
SOURCE OF SPATIALLY-COHERENT NOISE (E.G., TV, RADIO)
102
TALKER
104

FIG. 2

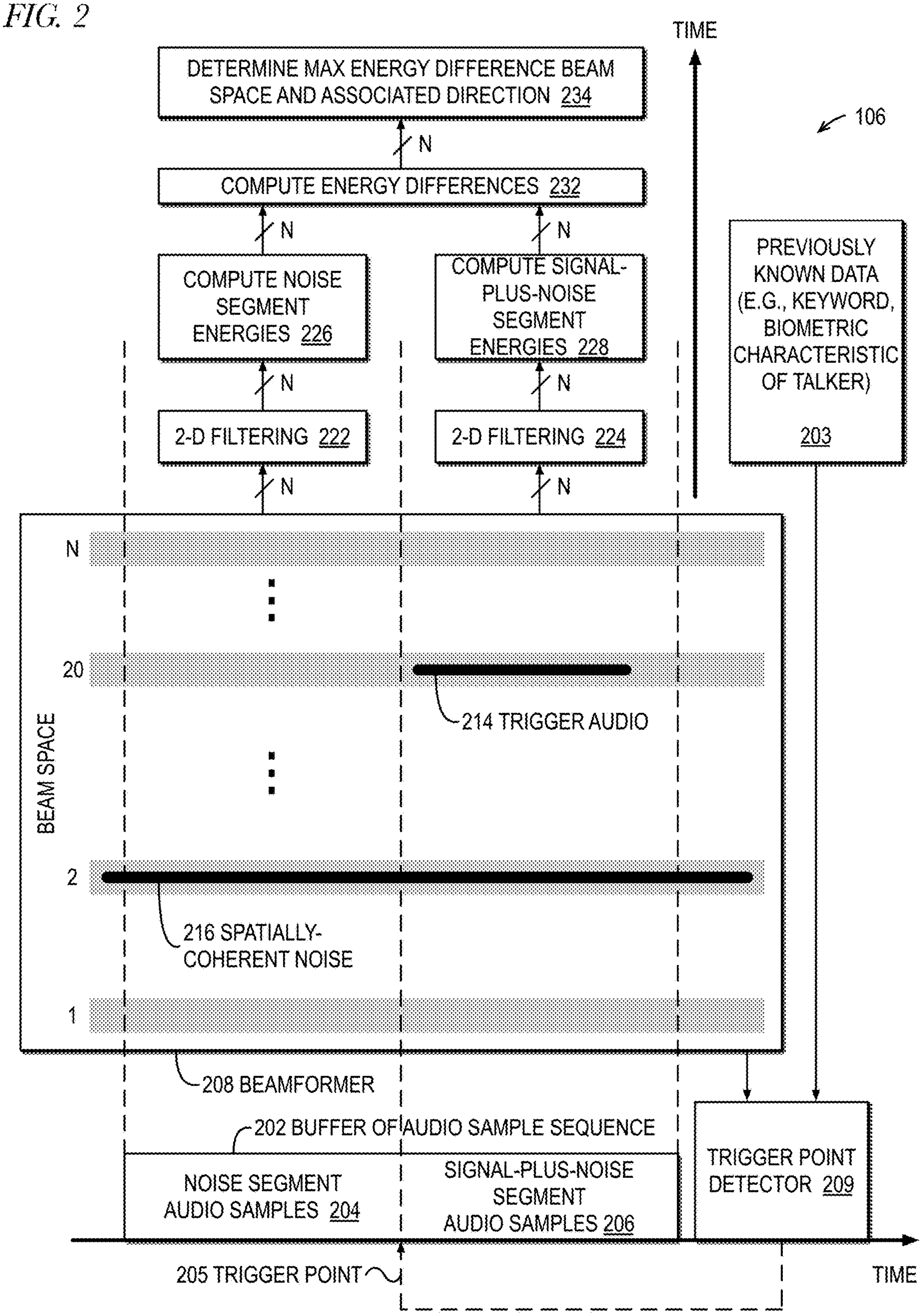

TIME
DETERMINE MAX ENERGY DIFFERENCE BEAM SPACE AND ASSOCIATED DIRECTION 234
N
106
COMPUTE ENERGY DIFFERENCES 232
N
N
COMPUTE NOISE SEGMENT ENERGIES 226
COMPUTE SIGNAL-PLUS-NOISE SEGMENT ENERGIES 228
PREVIOUSLY KNOWN DATA (E.G., KEYWORD, BIOMETRIC CHARACTERISTIC OF TALKER) 203
N
N
2-D FILTERING 222
2-D FILTERING 224
N
N
N
20
214 TRIGGER AUDIO
BEAM SPACE
2
216 SPATIALLY-COHERENT NOISE
1
208 BEAMFORMER
202 BUFFER OF AUDIO SAMPLE SEQUENCE
NOISE SEGMENT AUDIO SAMPLES 204
SIGNAL-PLUS-NOISE SEGMENT AUDIO SAMPLES 206
TRIGGER POINT DETECTOR 209
205 TRIGGER POINT
TIME

FIG. 3

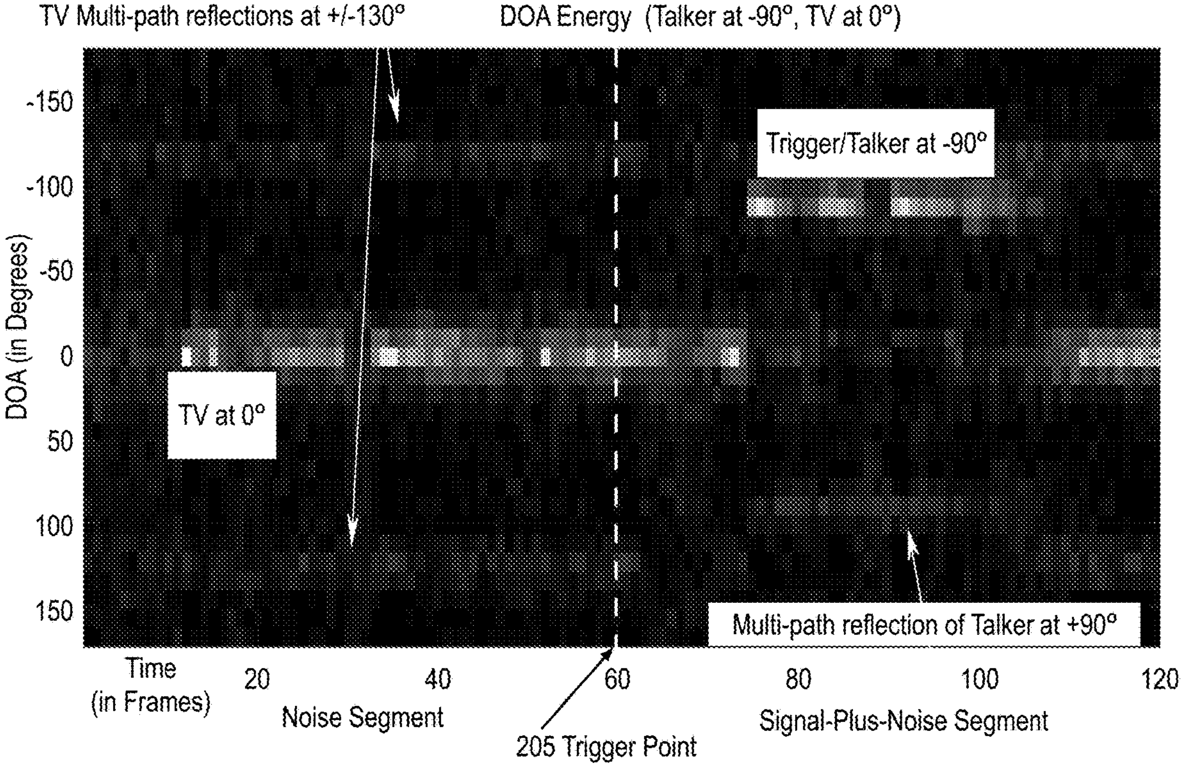

TV Multi-path reflections at +/-130°
DOA Energy (Talker at -90°, TV at 0°)
Trigger/Talker at -90°
TV at 0°
Multi-path reflection of Talker at +90°
DOA (in Degrees)
-150
-100
-50
0
50
100
150
Time
(in Frames)
20
40
60
80
100
120
Noise Segment
205 Trigger Point
Signal-Plus-Noise Segment

FIG. 4

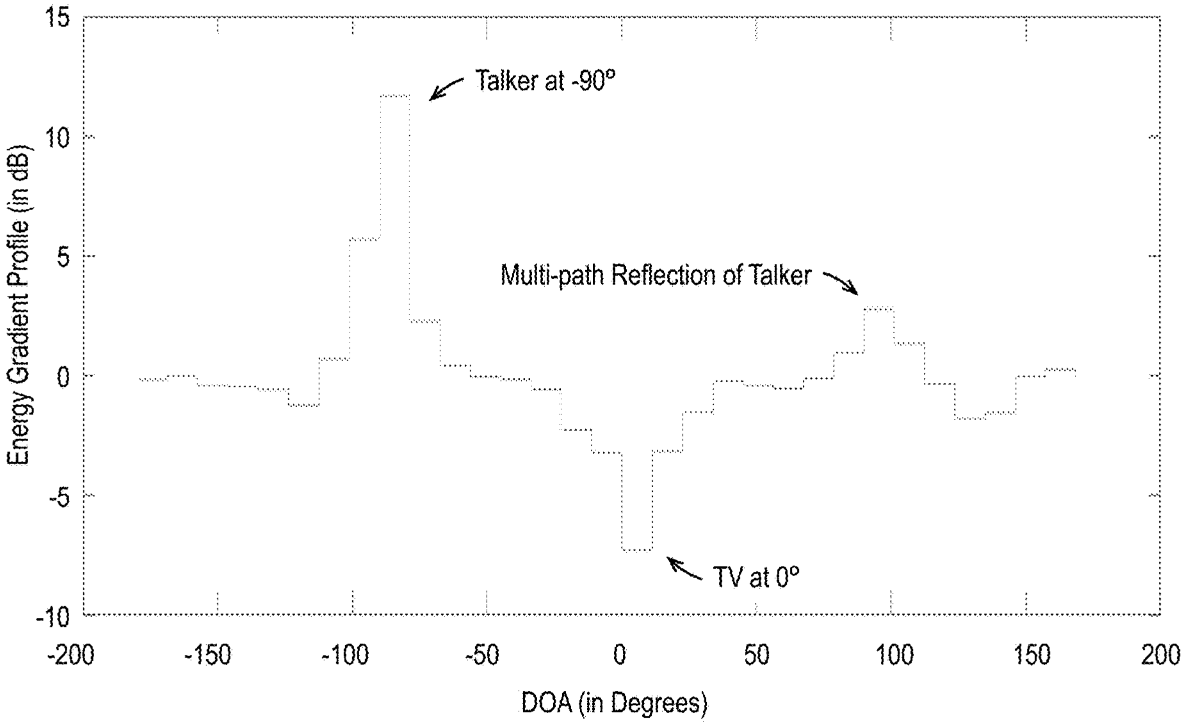
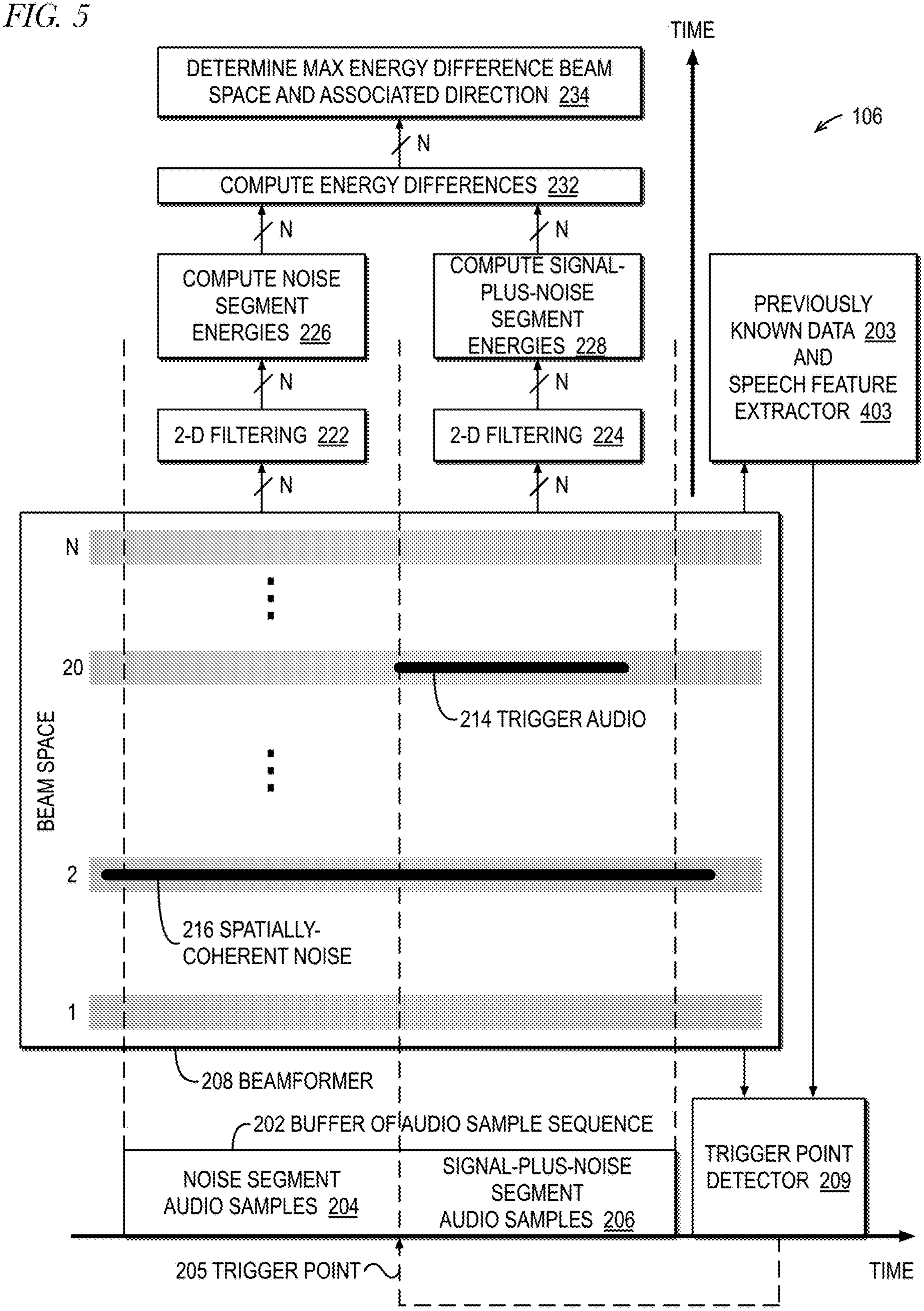

Talker at -90°
Multi-path Reflection of Talker
TV at 0°
Energy Gradient Profile (in dB)
15
10
5
0
-5
-10
-200
-150
-100
-50
0
50
100
150
200
DOA (in Degrees)

FIG. 5


TIME
DETERMINE MAX ENERGY DIFFERENCE BEAM SPACE AND ASSOCIATED DIRECTION 234
106
N
COMPUTE ENERGY DIFFERENCES 232
N
N
COMPUTE NOISE SEGMENT ENERGIES 226
COMPUTE SIGNAL-PLUS-NOISE SEGMENT ENERGIES 228
PREVIOUSLY KNOWN DATA 203 AND SPEECH FEATURE EXTRACTOR 403
N
N
2-D FILTERING 222
2-D FILTERING 224
N
N
N
20
214 TRIGGER AUDIO
BEAM SPACE
2
216 SPATIALLY-COHERENT NOISE
1
208 BEAMFORMER
202 BUFFER OF AUDIO SAMPLE SEQUENCE
NOISE SEGMENT AUDIO SAMPLES 204
SIGNAL-PLUS-NOISE SEGMENT AUDIO SAMPLES 206
TRIGGER POINT DETECTOR 209
205 TRIGGER POINT
TIME

DATA AIDED METHOD FOR ROBUST DIRECTION OF ARRIVAL (DOA) ESTIMATION IN THE PRESENCE OF SPATIALLY-COHERENT NOISE INTERFERERS

BACKGROUND

[0001] Intelligent voice interactive devices are required to work in highly reverberant environments in the presence of diffuse, as well as spatially-coherent, noise sources such as a television (TV), radio, smart speaker, stereo system, or surround sound system. Examples are home automation products that function as personal/virtual assistants. Home automation products have a requirement to estimate direction of arrival (DOA) in a noisy environment as described above. Several DOA estimators, with varied degrees of complexity, exist that can estimate DOA to some degree of accuracy when the noise is diffuse. When the interfering source is spatially-coherent (TV, radio, stereo), the estimator tends to capture the interference, rendering the DOA estimate useless. Therefore, there is a need for a DOA estimator that is computationally efficient and able to function in the presence of spatially-coherent interference.

[0002] One particular solution that is efficient but dysfunctional in the presence of spatially-coherent noise is a histogram-based beamformer described in the paper of Trinkle M. and Hashemi-Sakhtsari A., "Histogram Based DOA Estimation for Speaker Localisation in Reverberant Environments," 2015, 10'th Conference on Industrial & Applications, pp 166-170, 2015.

SUMMARY

[0003] In one embodiment, the present disclosure provides a method to determine a direction of arrival (DOA) of a talker in the presence of a source of spatially-coherent noise. The method includes receiving and buffering a time sequence of audio samples that include the spatially-coherent noise. The method also includes detecting, aided by previously known data, a trigger point in the time sequence of audio samples when the talker begins to talk. The method also includes separating the buffered time sequence of audio samples into a noise segment and a signal-plus-noise segment based on the trigger point. The method also includes, for each direction of a plurality of distinct directions: computing, for the direction, an energy difference between the noise segment and the signal-plus-noise segment and selecting as the DOA of the talker the direction of the plurality of distinct directions having a largest of the computed energy differences.

[0004] In another embodiment, the present disclosure provides an apparatus to determine a direction of arrival (DOA) of a talker in the presence of a source of spatially-coherent noise. The apparatus includes a buffer that stores a received time sequence of audio samples that include the spatially-coherent noise. The apparatus also includes a trigger point detector that detects, aided by previously known data, a trigger point in the time sequence of audio samples when the talker begins to talk. The apparatus also has circuitry configured to separate the buffered time sequence of audio samples into a noise segment and a signal-plus-noise segment based on the trigger point. The circuitry is also configured to, for each direction of a plurality of distinct directions, compute an energy difference between the noise segment and the signal-plus-noise segment. The circuitry is also configured to select as the DOA of the talker the direction of the plurality of distinct directions having a largest of the computed energy differences.

[0005] In yet another embodiment, the present disclosure provides a non-transitory computer-readable medium having instructions stored thereon that are capable of causing or configuring an apparatus to determine a direction of arrival (DOA) of a talker in the presence of a source of spatially-coherent noise by performing operations. The operations include receiving and buffering a time sequence of audio samples that include the spatially-coherent noise. The operations also include detecting, aided by previously known data, a trigger point in the time sequence of audio samples when the talker begins to talk. The operations also include separating the buffered time sequence of audio samples into a noise segment and a signal-plus-noise segment based on the trigger point. The operations also include, for each direction of a plurality of distinct directions: computing, for the direction, an energy difference between the noise segment and the signal-plus-noise segment and selecting as the DOA of the talker the direction of the plurality of distinct directions having a largest of the computed energy differences.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. **1** is a block diagram illustrating a space having a DOA detector that detects a DOA of a talker in the presence of a source of spatially-coherent noise.

[0007] FIG. **2** is a diagram illustrating in more detail an embodiment of the DOA detector **106** of FIG. **1** and its operation.

[0008] FIG. **3** is an energy density graph illustrating operation of the DOA detector of FIG. **1** in the presence of a spatially-coherent noise source.

[0009] FIG. **4** is an energy profile graph based on the energy density graph of FIG. **3** and illustrating operation of the DOA detector of FIG. **1** in the presence of a spatially-coherent noise source.

[0010] FIG. **5** is a diagram illustrating in more detail an alternate embodiment of the DOA detector of FIG. **1** and its operation.

DETAILED DESCRIPTION

[0011] Embodiments are described of a robust and computationally efficient method that can estimate DOA in the presence of spatially-coherent noise. In the context of the instant disclosure, direction of arrival (DOA) means the direction or bearing from the device to a talker of interest. Data-aided methods that exploit the detection of a trigger point are described. In one embodiment, the aiding data is a keyword (e.g., phrase or single word) the user (also referred to as a talker) utters to initiate communications with the device. In one embodiment, the aiding data is a biometric characteristic of the talker's voice. In one embodiment, the aiding data is knowledge of general characteristics of human speech (e.g., multi-tonal characteristic) as distinguished from non-human audio (e.g., single frequency audio of a dishwasher, washing machine or other appliance). For example, spectrum analysis may be performed or machine learning may be employed to compare received audio with known data of human speech characteristics to detect any talker speaking. Using the aiding data, a trigger point in time is detected that is used to separate a pre-trigger point segment (noise segment) from a post-trigger point segment (signal-plus-noise segment). For both of the segments, an energy difference is computed between the two segments for each of multiple beam spaces. The direction associated with the beam space having the largest energy difference is selected as the DOA. The approach makes use of an early gate/late gate concept. A sufficient number of samples is buffered to include both segments. Preferably, the energy is measured, filtered and normalized in each segment.

[0012] Referring now to FIG. **1**, a block diagram illustrating a space (e.g., a room or other reverberant location) having a DOA detector **106** that detects a DOA of a talker **104** (e.g., user of the detector **106**) in the presence of a source of spatially-coherent noise **102** (e.g., television, radio, stereo). In the context of the instant disclosure, spatially-coherent noise means noise which may be modeled by a finite number of point sources. As shown, the DOA detector **106** effectively divides the space into multiple beam spaces (also referred to as bins or sectors) each having an associated direction (e.g., angular direction relative to a reference angle). In the example embodiment of FIG. **1**, there are 24 beam spaces each of 15 degrees, numbered 1 through 24. As indicated in the example of FIG. **1**, the predominance of the audio energy generated by the talker **104** is received from the direction associated with beam space **20** at −90 degrees, and the predominance of the audio energy generated by the source of spatially-coherent noise **102** is received from the direction associated with beam space **2** at 0 degrees. Preferably, the DOA detector **106** effectively divides the space into multiple beam spaces by employing a beamformer (e.g., beamformer **208** of FIG. **2**). In one embodiment, the beamformer includes an array of microphones or antennas or channels (e.g., four) that receives audio that is mixed and sampled and stored in a buffer (e.g., buffer **202** of FIG. **2**). The number of beam spaces and associated directions into which the space is split may vary. For example, twelve different beam spaces of 30 degrees each may be employed to cover a 360-degree space; for another example, 36 different spaces of ten degrees each may be employed. Although FIG. **1** illustrates a single source of spatially-coherent noise **102**, embodiments may effectively estimate DOA in the presence of multiple sources of spatially-coherent noise.

[0013] Referring now to FIG. **2**, a diagram illustrating in more detail an embodiment of the DOA detector **106** of FIG. **1** and its operation is shown. The DOA detector **106** includes a buffer **202** that stores a time sequence of audio samples received by the DOA detector **106**, previously known data **203** (e.g., keyword or talker biometric characteristic), a beamformer **208** that effectively divides the space into N beam spaces (e.g., the beam spaces **1** through **24** of FIG. **1**) according to well-known beamforming techniques, a trigger point detector **209** that determines a trigger point **205** in the time sequence of audio samples stored in the buffer **202**, and blocks to perform various operations, including 2-dimensional filtering **222**/**224**, segment energy computation **226**/**228**, energy difference computation **232**, and determination of which beam space has the maximum energy difference between its noise segment and signal-plus-noise segment **234**. The DOA detector **106** may include a memory and a programmable processor that executes software to perform the various functions described, application-specific hardware, or a combination thereof.

[0014] As shown, time proceeds from left to right in FIG. **2** to the point of trigger detection and separation of the time sequence of audio samples into a noise segment **204** and a signal-plus-noise segment **206**, described in more detail below. The DOA detector **106** continually buffers audio samples received from the surrounding space into the buffer **202** over time. The audio samples may include diffuse noise (not shown) received on many of the beam spaces. The received audio may also include spatially-coherent noise **216** (e.g., generated by the source of spatially-coherent noise **102** of FIG. **1**), shown in FIG. **2** as primarily being received from beam space **2**. However, it should be understood that non-negligible portions of the energy of the spatially-coherent noise **216** may be received from beam spaces adjacent to beam space **2**. The trigger point detector **209** uses the previously known data **203** to continually analyze the received audio samples to detect the trigger point **205**, i.e., the point in time at which the talker **104** begins to speak.

[0015] At some point in time, the talker **104** begins to talk and the talker's audio is received, shown as trigger audio **214**, and captured in the buffer **202**. In the example, beam space **20** receives most of the energy of the trigger audio **214**, as shown. As the trigger point detector **209** analyzes the audio samples in the buffer **202** aided by the previously known data **203**, the trigger point detector **209** eventually detects a trigger point **205**. More specifically, the trigger point detector **209** detects the point in time approximately at which the talker **104** begins to speak with respect to the buffered audio samples. In the example of FIG. **2**, the detected trigger point **205** is slightly before the time the talker **104** begins to talk. The trigger point **205** is used to separate the buffered audio samples into the noise segment **204** and the signal-plus-noise segment **206**. Detection of the trigger point **205** is advantageous because it enables DOA determination based on computation of the energy difference in the different beam spaces before and after the trigger point **205**, which may significantly improve DOA estimation in the presence of a spatially-coherent noise source over conventional DOA detectors.

[0016] The trigger point detector **209** may detect the trigger point **205** as the presence of a keyword in the buffer **202** of audio samples that matches a keyword stored in the previously known data **203**. As described above, a keyword may include one or more words, e.g., a single word or a phrase (e.g., "My command is"). The trigger point detector **209** may detect the trigger point **205** as the presence of a biometric characteristic of the talker **104** in the buffer **202** of audio samples that matches a biometric characteristic stored in the previously known data **203**. Biometric data is a set of unique features that are extracted from a speech signal and is used to identify a talker in a speech identification system. The trigger point detector **209** may detect the trigger point **205** as simply the presence of human speech spoken by any talker **104** in the buffer **202** of audio samples based on extracted speech features stored in the previously known data **203** (e.g., according to the embodiment of FIG. **5**).

[0017] After detection of the trigger point **205**, the audio samples captured in the buffer **202** are separated into the noise segment **204** and the signal-plus-noise segment **206** based on the trigger point **205**. That is, the audio samples in the buffer **202** captured prior to the trigger point **205** are included in the noise segment **204**, and the audio samples in the buffer **202** captured after the trigger point **205** are included in the signal-plus-noise segment **206**. The audio samples in each of the segments **204/206** are then separated into the different N beam spaces. In an alternate embodiment, the audio samples in each of the segments **204/206** may be separated into the different N beam spaces prior to detection of the trigger point **205** and/or prior to separation of the audio samples into the noise segment **204** and the signal-plus-noise segment **206**.

[0018] After separation into the noise segment **204** and the signal-plus-noise segment **206**, time proceeds upward, as shown. 2-dimensional (2-D) filtering **222** is performed on the noise segment audio samples **204** for the N beam segments, and 2-dimensional (2-D) filtering **224** is performed on the signal-plus-noise segment audio samples **206** for the N beam segments. The filtering may be employed to clean up the sampled audio in both time and spatial dimensions to obtain a more consistent result and to enhance energy difference detection. For example, time filtering may include filling in blank samples or median filtering in which successive time samples are averaged (e.g., three successive time samples). For example, spatial filtering may include averaging the energy of a beam and its adjacent beams to combat a phenomenon commonly referred to as picket-fencing in which the energy may be divided between different beams. The filtering may include smoothing, linear filtering, non-linear filtering (e.g., median filtering), averaging, or other pre-processing. In one embodiment, the two-dimensional filtering is performed on each of the N beam spaces.

[0019] After filtering, a computation **226** of the energy of the noise segment **204** for the N beams is performed on the filtered samples, and a computation **228** of the energy of the signal-plus-noise segment **206** for the N beams is performed on the filtered samples. In one embodiment, the energy computations **226** and **228** comprise computation of a mean energy for each beam space/segment pair. Subsequently, a computation **232** is performed of the difference between the computed energies of the noise segment **204** and the signal-plus-noise segment **206** for the N beam spaces. In one embodiment, the energy difference computation **232** comprises computation for each of the N beam spaces of a gradient between the mean energy computations of the noise segment **204** and the signal-plus-noise segment **206**. Finally, a determination **234** is made of the beam space of the N beam spaces having the largest computed energy difference and its associated direction as the estimated DOA. In one embodiment, the largest computed energy difference determination comprises selecting the beam space having the largest computed energy gradient and its associated direction. The selection of the direction with the maximum energy difference may take various forms and may also include filtering. For example, assuming the DOA detector **106** returns a DOA answer once each second, the DOA detector **106** may determine ten different directions having the largest energy difference during ten successive 100 millisecond periods and then select the direction having the greatest number of largest energy differences of the ten as the DOA.

[0020] Although the audio samples are separated into the different beam spaces in order to determine the beam space with the maximum pre/post-trigger point energy difference, detection of the trigger point **205** may be performed by various means, and the audio samples need not be separated into the different beam spaces to perform trigger point detection.

[0021] Referring now to FIG. **3**, an energy density graph illustrating operation of the DOA detector **106** of FIG. **1** in the presence of a spatially-coherent noise source is shown. Time in frames is represented on the horizontal axis, and **120** frames are shown in the example. Direction is represented on the vertical axis with angles ranging from approximately −180 degrees to +180 degrees. The energy density of an audio sample at each time/direction pair is indicated by the brightness of the associated pixel in the graph. Brighter pixels correspond to higher energy audio samples, whereas darker pixels correspond to lower energy audio samples. As may be observed from the pixilation of FIG. **3**, the beamformer **208** effectively separated the space into beam spaces of approximately ten degrees each. As shown, a trigger point **205** was detected at approximately frame **60**, such that audio samples in frames **0** through **60** are included in the noise segment **204**, and audio samples in frames **61** through **120** are included in the signal-plus-noise segment **206**.

[0022] As may be observed in FIG. **3**, a television, functioning as a dominant spatially-coherent interferer **102**, is located at 0 degrees. The spatially-coherent noise of the television persists through most of the time frames, as indicated by the high concentration of bright pixels between approximately −20 degrees to +20 degrees and particularly at 0 degrees, although as shown the energy from the television drops out significantly between approximately frames **75** and **105** (e.g., brief relative silence and/or lack of speech, which may be typical of audio generated by a television). Two relatively strong multipath reflections are also clearly visible in FIG. **3** at approximately −120 degrees and +120 degrees. Later in time (at approximately frame **70**), a talker **104** located at −90 degrees utters (through approximately frame **110**) a trigger, e.g., keyword, talker biometric characteristic, and/or simply human speech, as indicated by the high concentration of bright pixels between approximately −100 degrees to −80 degrees and particularly at −90 degrees. A multi-path reflection of the talker **104** is also observed at approximately +90 degrees.

[0023] Referring now to FIG. **4**, an energy profile graph based on the energy density graph of FIG. **3** and illustrating operation of the DOA detector **106** of FIG. **1** in the presence of a spatially-coherent noise source is shown. Direction in degrees is represented on the horizontal axis and corresponds to the direction in degrees on the vertical axis of FIG. **3**. A comparison of the computed energy difference pre/post-trigger point **205** is represented on the vertical axis. In the embodiment of FIG. **4**, the vertical axis corresponds to a ratio in dB of the energy of audio samples in the signal-plus-noise segment **206** and the energy of audio samples in the noise segment **204** for the N different beam spaces. As may be observed from FIG. **4**, in the example, each beam space is approximately ten degrees.

[0024] For directions in which the received energy does not significantly change before and after the trigger point **205**, the energy difference is approximately 0 dB, which in the example are directions other than the direction of the talker (−90 degrees), the TV (0 degrees) and the multipath reflection of the talker **104** (+90 degrees). FIG. **4** demonstrates the ability of the DOA detector **106** to filter out the TV interferer **102** at 0 degrees and estimate the presence of the desired talker **104** at −90 degrees by selecting the beam space having the largest energy difference before and after the trigger point, which is readily observable from FIG. **4**. In particular, the computed energy difference of the multi-path reflection of the talker **104** is significant, but significantly smaller than the computed energy difference received from the direction of the desired talker **104**.

[0025] Referring now to FIG. **5**, a diagram illustrating in more detail an alternate embodiment of the DOA detector **106** of FIG. **1** and its operation is shown. The DOA detector **106** of FIG. **5** is similar in many respects to the DOA detector **106** of FIG. **2** and like-numbered elements are similar. However, in addition to the previously known data **203** of FIG. **2**, the DOA detector **106** of FIG. **5** includes a speech feature extractor **403**. The speech feature extractor **403** extracts features from the audio samples and provides the extracted features to the trigger point detector **209** in addition to the known data. The trigger point detector **209** detects a trigger point **205** if it detects the presence of any human speech from the known data and the extracted features. One class of extracted features is derived by well-known spectral analysis techniques, e.g., Mel Frequency Coefficients (MFCC), Line Spectral Frequencies (LSF) and Pitch frequency, among others. Another class of extracted features are generated by machine learning algorithms.

[0026] In the presence of a spatially-coherent noise source that includes human speech (e.g., a television, stereo, radio), embodiments in which the data-aided trigger point detection comprises detecting the talker speaking a keyword or detecting a biometric characteristic of the talker may be more effective than conventional DOA detectors at determining DOA. In the presence of a spatially-coherent noise source that does not include human speech (e.g., dishwasher, hair dryer, washing machine), embodiments in which the data-aided trigger point detection comprises using frequency analysis to detect the presence of any spoken human text (e.g., multi-tonal audio) may also be more effective than conventional DOA detectors at determining DOA.

[0027] It should be understood—especially by those having ordinary skill in the art with the benefit of this disclosure—that the various operations described herein, particularly in connection with the figures, may be implemented by other circuitry or other hardware components. The order in which each operation of a given method is performed may be changed, unless otherwise indicated, and various elements of the systems illustrated herein may be added, reordered, combined, omitted, modified, etc. It is intended that this disclosure embrace all such modifications and changes and, accordingly, the above description should be regarded in an illustrative rather than a restrictive sense.

[0028] Similarly, although this disclosure refers to specific embodiments, certain modifications and changes can be made to those embodiments without departing from the scope and coverage of this disclosure. Moreover, any benefits, advantages, or solutions to problems that are described herein with regard to specific embodiments are not intended to be construed as a critical, required, or essential feature or element.

[0029] Further embodiments likewise, with the benefit of this disclosure, will be apparent to those having ordinary skill in the art, and such embodiments should be deemed as being encompassed herein. All examples and conditional language recited herein are intended for pedagogical objects to aid the reader in understanding the disclosure and the concepts contributed by the inventor to furthering the art and are construed as being without limitation to such specifically recited examples and conditions.

[0030] This disclosure encompasses all changes, substitutions, variations, alterations, and modifications to the example embodiments herein that a person having ordinary skill in the art would comprehend. Similarly, where appropriate, the appended claims encompass all changes, substitutions, variations, alterations, and modifications to the example embodiments herein that a person having ordinary skill in the art would comprehend. Moreover, reference in the appended claims to an apparatus or system or a component of an apparatus or system being adapted to, arranged to, capable of, configured to, enabled to, operable to, or operative to perform a particular function encompasses that apparatus, system, or component, whether or not it or that particular function is activated, turned on, or unlocked, as long as that apparatus, system, or component is so adapted, arranged, capable, configured, enabled, operable, or operative.

1. A method to determine a direction of arrival (DOA) of a talker in the presence of a source of spatially-coherent noise, the method comprising:

receiving and buffering a time sequence of audio samples that include the spatially-coherent noise;

detecting, aided by previously known data, a trigger point in the time sequence of audio samples when the talker begins to talk;

separating the buffered time sequence of audio samples into a noise segment and a signal-plus-noise segment based on the trigger point;

for each direction of a plurality of distinct directions:

computing, for the direction, an energy difference between the noise segment and the signal-plus-noise segment; and

selecting as the DOA of the talker the direction of the plurality of distinct directions having a largest of the computed energy differences.

2. The method of claim **1**,

wherein the previously known data comprises a keyword spoken by the talker.

3. The method of claim **1**,

wherein the previously known data comprises a biometric characteristic of the talker.

4. The method of claim **1**,

wherein said detecting, aided by the previously known data, the trigger point in the time sequence of audio samples when the talker begins to talk comprises:

extracting speech features from the time sequence of audio samples; and

detecting when the time sequence of audio samples includes spoken human text using the extracted speech features.

5. The method of claim **1**, further comprising:

beamforming to separate the time sequence of audio samples into the plurality of distinct directions.

6. The method of claim **1**, further comprising:

filtering the time sequence of audio samples in a time dimension and a spatial dimension; and

wherein the energy differences are computed for each direction of the plurality of distinct directions using a result of said filtering.

7. The method of claim **1**, further comprising:

for each direction of the plurality of distinct directions:

calculating a mean energy during the noise segment for the direction;

calculating a mean energy during the signal-plus-noise segment for the direction; and

wherein said computing the energy difference for the direction comprises:

computing an energy gradient between the calculated mean energy during the noise segment for the direction and the calculated mean energy during the signal-plus-noise segment for the direction; and

wherein said selecting as the DOA of the talker the direction of the plurality of distinct directions having the largest of the computed energy differences comprises selecting as the DOA of the talker the direction of the plurality of distinct directions having a largest of the computed energy gradients.

8. An apparatus to determine a direction of arrival (DOA) of a talker in the presence of a source of spatially-coherent noise, comprising:

a buffer that stores a received time sequence of audio samples that include the spatially-coherent noise;

a trigger point detector that detects, aided by previously known data, a trigger point in the time sequence of audio samples when the talker begins to talk;

circuitry configured to:

separate the buffered time sequence of audio samples into a noise segment and a signal-plus-noise segment based on the trigger point;

for each direction of a plurality of distinct directions, compute an energy difference between the noise segment and the signal-plus-noise segment for the direction; and

select as the DOA of the talker the direction of the plurality of distinct directions having a largest of the computed energy differences.

9. The apparatus of claim **8**,

wherein the previously known data comprises a keyword spoken by the talker.

10. The apparatus of claim **8**,

wherein the previously known data comprises a biometric characteristic of the talker.

11. The apparatus of claim **8**,

wherein to detect, aided by the previously known data, the trigger point in the time sequence of audio samples when the talker begins to talk, the circuitry:

extracts speech features from the time sequence of audio samples; and

detects when the time sequence of audio samples includes spoken human text using the extracted speech features.

12. The apparatus of claim **8**, further comprising:

a beamformer configured to separate the time sequence of audio samples into the plurality of distinct directions.

13. The apparatus of claim **8**,

wherein the circuitry is further configured to filter the time sequence of audio samples in a time dimension and a spatial dimension; and

wherein the energy differences are computed for each direction of the plurality of distinct directions using a result of said filtering.

14. The apparatus of claim **8**,

wherein the circuitry is further configured to:

for each direction of the plurality of distinct directions:

calculate a mean energy during the noise segment for the direction;

calculate a mean energy during the signal-plus-noise segment for the direction; and

wherein to compute the energy difference for the direction, the circuitry computes an energy gradient between the calculated mean energy during the noise segment for the direction and the calculated mean energy during the signal-plus-noise segment for the direction; and

wherein to select as the DOA of the talker the direction of the plurality of distinct directions having the largest of the computed energy differences, the circuitry computes as the DOA of the talker the direction of the plurality of distinct directions having a largest of the computed energy gradients.

15. A non-transitory computer-readable medium having instructions stored thereon that are capable of causing or configuring an apparatus to determine a direction of arrival (DOA) of a talker in the presence of a source of spatially-coherent noise by performing operations comprising:

receiving and buffering a time sequence of audio samples that include the spatially-coherent noise;

detecting, aided by previously known data, a trigger point in the time sequence of audio samples when the talker begins to talk;

separating the buffered time sequence of audio samples into a noise segment and a signal-plus-noise segment based on the trigger point;

for each direction of a plurality of distinct directions:

computing, for the direction, an energy difference between the noise segment and the signal-plus-noise segment; and

selecting as the DOA of the talker the direction of the plurality of distinct directions having a largest of the computed energy differences.

16. The non-transitory computer-readable medium of claim **15**,

wherein the previously known data comprises a keyword spoken by the talker.

17. The non-transitory computer-readable medium of claim **15**,

wherein the previously known data comprises a biometric characteristic of the talker.

18. The non-transitory computer-readable medium of claim **15**,

wherein said detecting, aided by the previously known data, the trigger point in the time sequence of audio samples when the talker begins to talk comprises:

extracting speech features from the time sequence of audio samples; and

detecting when the time sequence of audio samples includes spoken human text using the extracted speech features.

19. The non-transitory computer-readable medium of claim **15**, wherein the operations further comprise:

beamforming to separate the time sequence of audio samples into the plurality of distinct directions.

20. The non-transitory computer-readable medium of claim **15**, wherein the operations further comprise:

filtering the time sequence of audio samples in a time dimension and a spatial dimension; and

wherein the energy differences are computed for each direction of the plurality of distinct directions using a result of said filtering.

21. The non-transitory computer-readable medium of claim **15**, wherein the operations further comprise:

for each direction of the plurality of distinct directions:

calculating a mean energy during the noise segment for the direction;

calculating a mean energy during the signal-plus-noise segment for the direction; and

wherein said computing the energy difference for the direction comprises:

computing an energy gradient between the calculated mean energy during the noise segment for the direction and the calculated mean energy during the signal-plus-noise segment for the direction; and

wherein said selecting as the DOA of the talker the direction of the plurality of distinct directions having the largest of the computed energy differences comprises selecting as the DOA of the talker the direction of the plurality of distinct directions having a largest of the computed energy gradients.

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