US009270354B1

(12) **United States Patent**
Kukshya et al.

(10) **Patent No.: US 9,270,354 B1**
(45) **Date of Patent: Feb. 23, 2016**

(54) **BLIND BEAMFORMING USING KNOWLEDGE EMBEDDED IN TRANSMITTED SIGNALS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 7 days.

(21) Appl. No.: **14/326,121**

(22) Filed: **Jul. 8, 2014**

(51) **Int. Cl.**
H04B 17/02 (2006.01)
H04B 7/08 (2006.01)
H04B 1/06 (2006.01)
H04B 7/06 (2006.01)

(52) **U.S. Cl.**
CPC ***H04B 7/0617*** (2013.01); ***H04B 7/061*** (2013.01)

(58) **Field of Classification Search**
CPC H01Q 3/2605; H01Q 3/00; H01Q 3/26; H04B 7/0417; H04B 7/088; H04B 7/086; H04B 7/0854; H04B 1/712; H04B 1/7113; H04B 7/0857; H04B 7/10; H04B 17/00; H04B 17/02; H04B 1/06; Y02B 60/50
USPC 455/133, 135, 137, 273, 132, 226.1, 455/226.3, 226.4, 227, 272, 275, 277.1; 342/378, 375, 368, 383, 382; 375/299, 375/260, 267, 285, 295, 296
See application file for complete search history.

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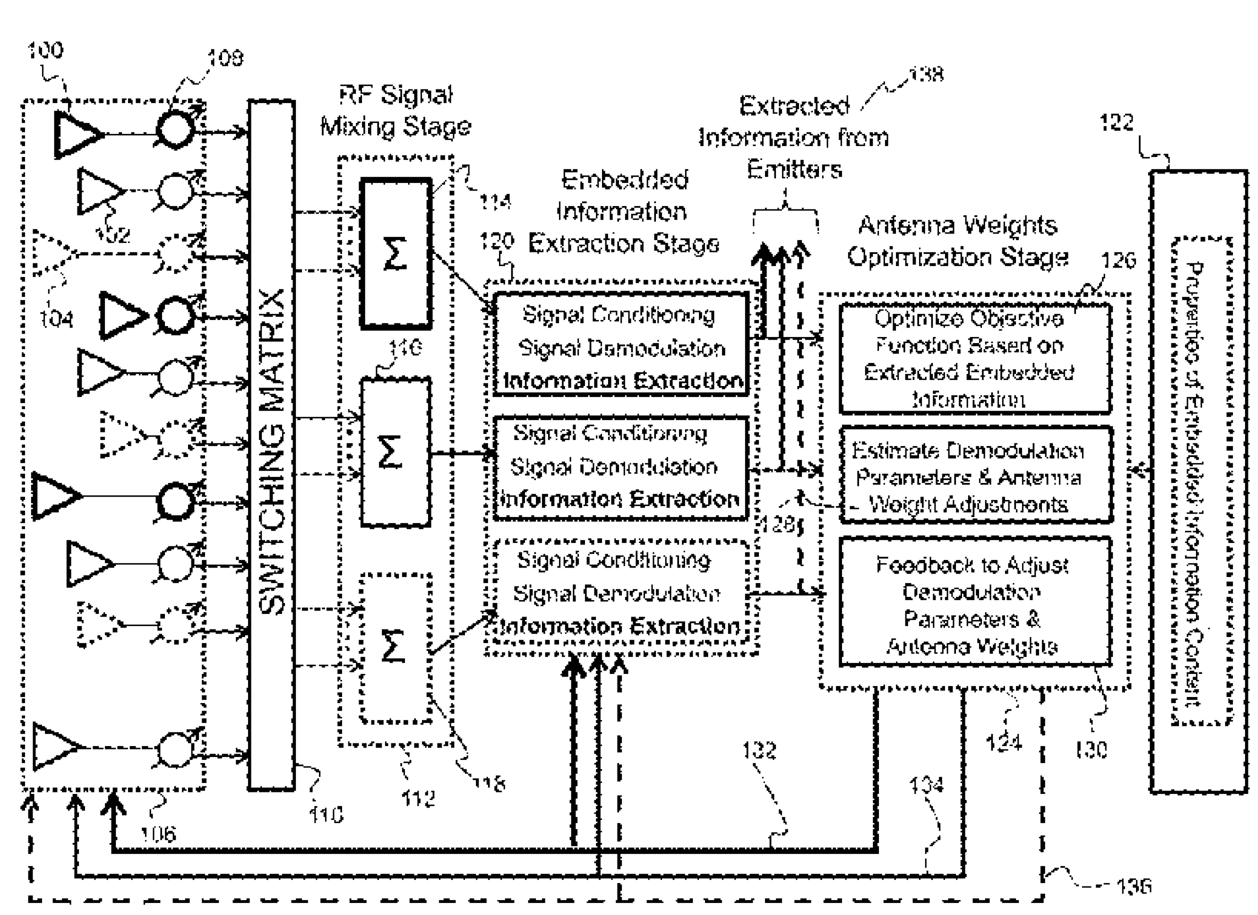
(74) *Attorney, Agent, or Firm* — Tope-McKay & Associates

(57) **ABSTRACT**

Described is system and method for blind beamforming using knowledge embedded in transmitted signals. Initial antenna weights are assigned for antenna elements of emitters of a beamforming system to generate a set of weighted radio-frequency (RF) signals at an output of each antenna element. The set of weighted RF signals are combined to form RF signal mixtures. Then, each RF signal mixture is processed to extract embedded information within signals of the emitters. The extracted embedded information is sent to an optimization module, where the extracted embedded information is used to perform simultaneous signal extractions for emitters in the beamforming system. Furthermore, feedback from the optimization module is used to modify antenna weights toward optimal beamforming.

18 Claims, 9 Drawing Sheets
(6 of 9 Drawing Sheet(s) Filed in Color)



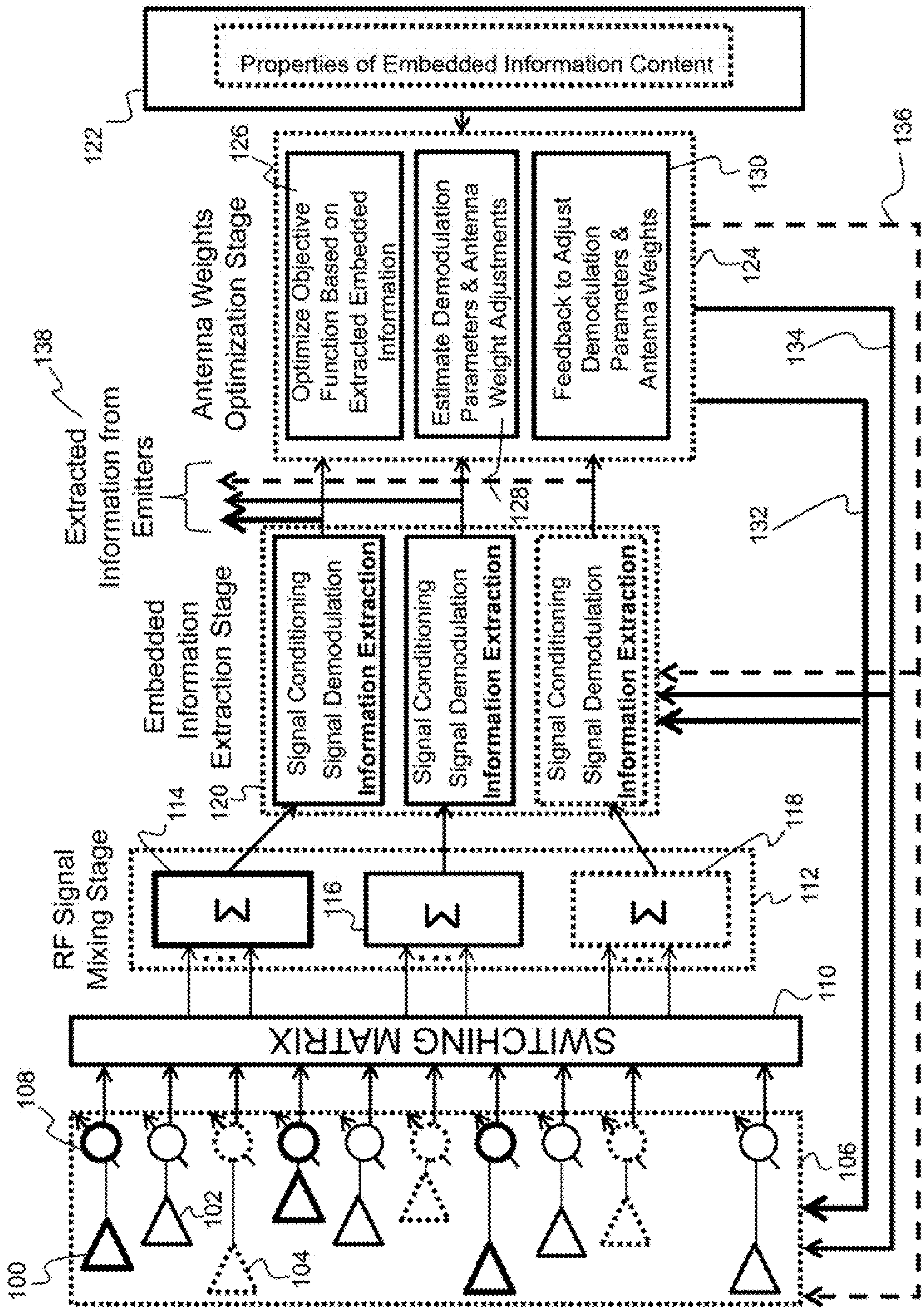

Properties of Embedded Information Content
Antenna Weights Optimization Stage
Optimize Objective Function Based on Extracted Embedded Information
Estimate Demodulation Parameters & Antenna Weight Adjustments
Feedback to Adjust Demodulation Parameters & Antenna Weights
Extracted Information from Emitters
Embedded Information Extraction Stage
Signal Conditioning
Signal Demodulation
Information Extraction
Signal Conditioning
Signal Demodulation
Information Extraction
Signal Conditioning
Signal Demodulation
Information Extraction
RF Signal Mixing Stage
M
M
M
SWITCHING MATRIX
100
102
104
106
108
110
112
114
116
118
120
122
124
126
128
130
132
134
136
138

FIG. 1

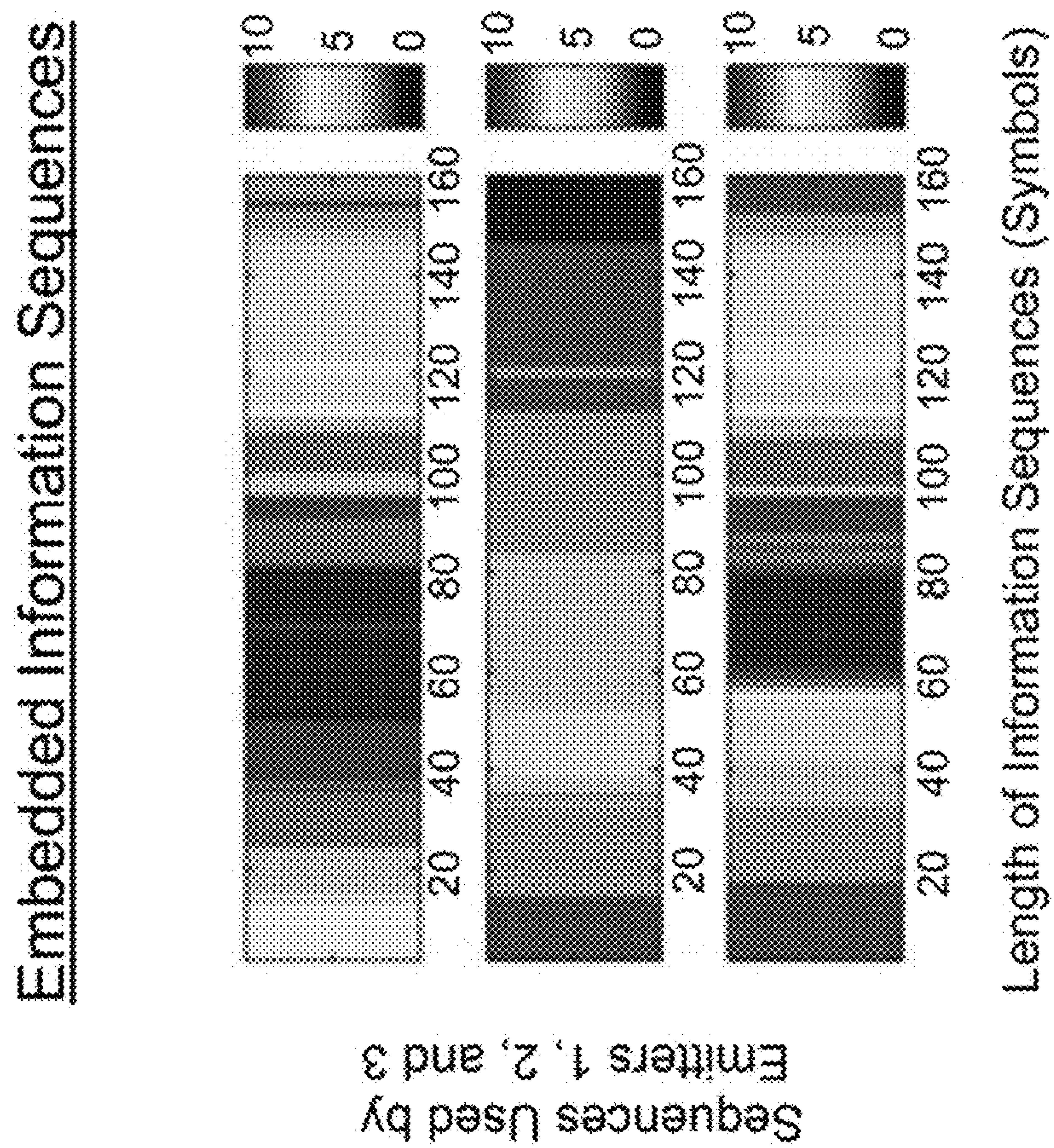

Embedded Information Sequences
Sequences Used by Emitters 1, 2, and 3
20 40 60 80 100 120 140 160
10 5 0
Length of Information Sequences (Symbols)

FIG. 2A

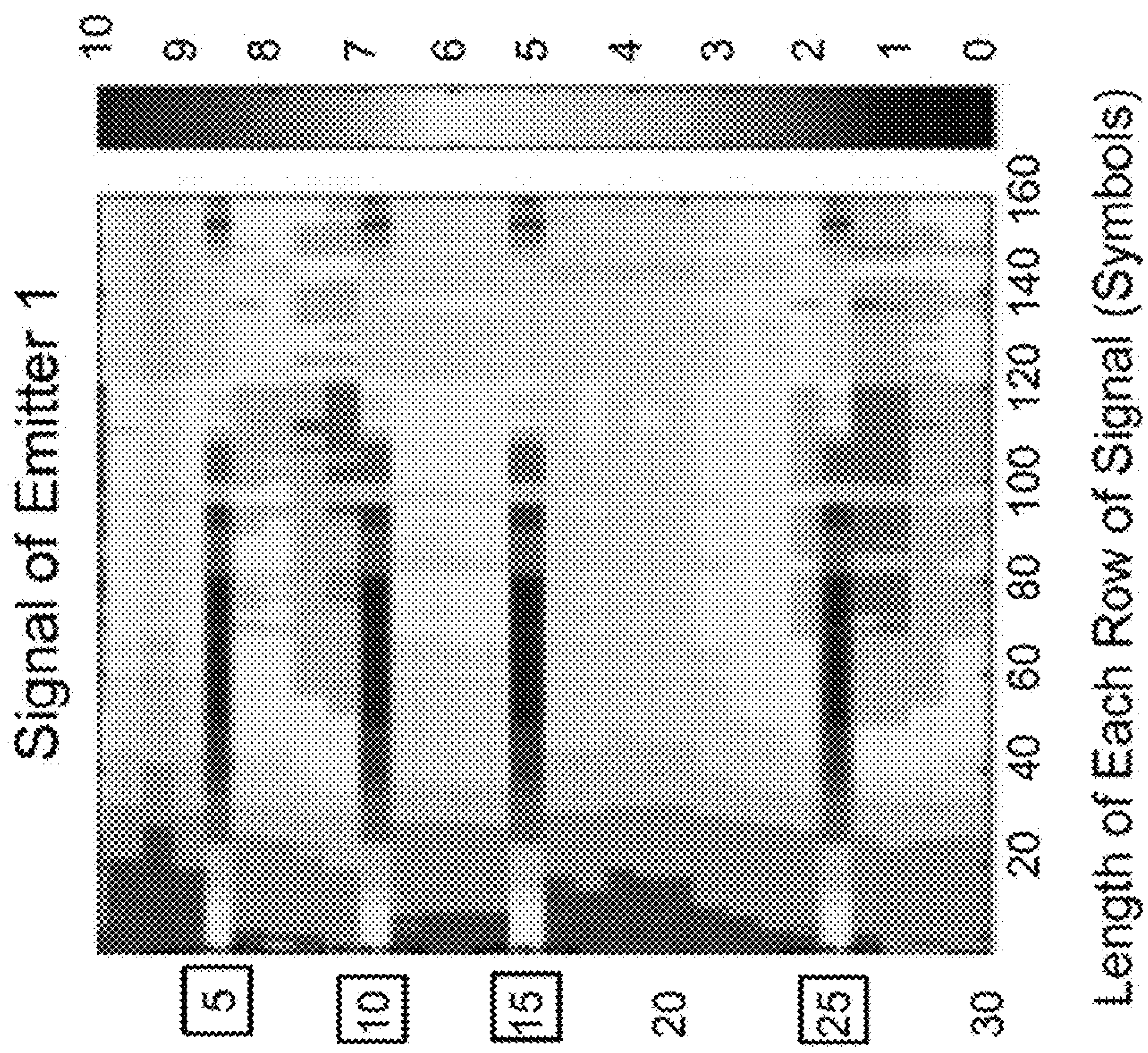

Signal of Emitter 1
Length of Each Row of Signal (Symbols)
20 40 60 80 100 120 140 160
5 10 15 20 25 30
0 1 2 3 4 5 6 7 8 9 10

FIG. 2B

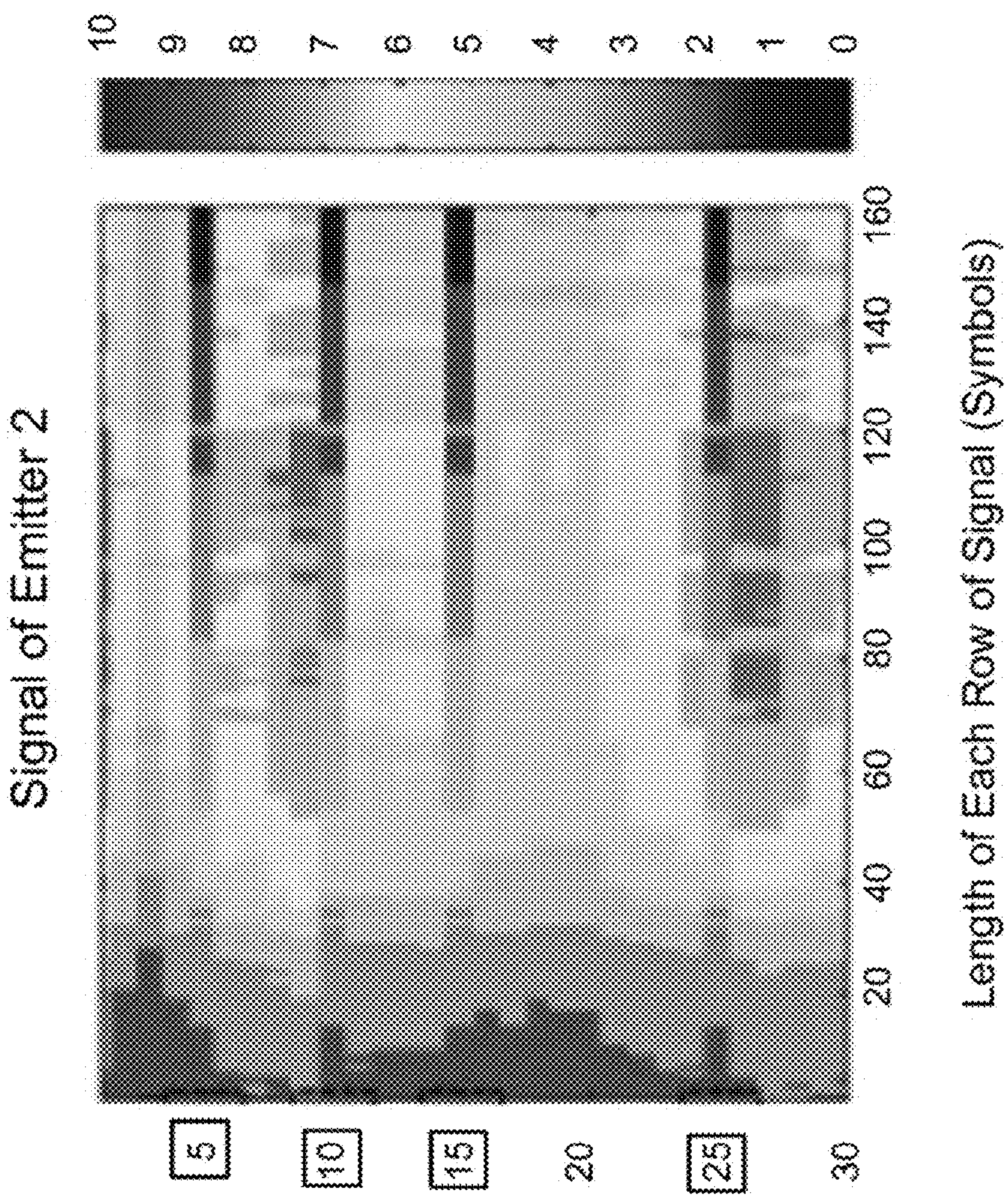

Signal of Emitter 2
Length of Each Row of Signal (Symbols)
20
40
60
80
100
120
140
160
5
10
15
20
25
30
0
1
2
3
4
5
6
7
8
9
10

FIG. 2C

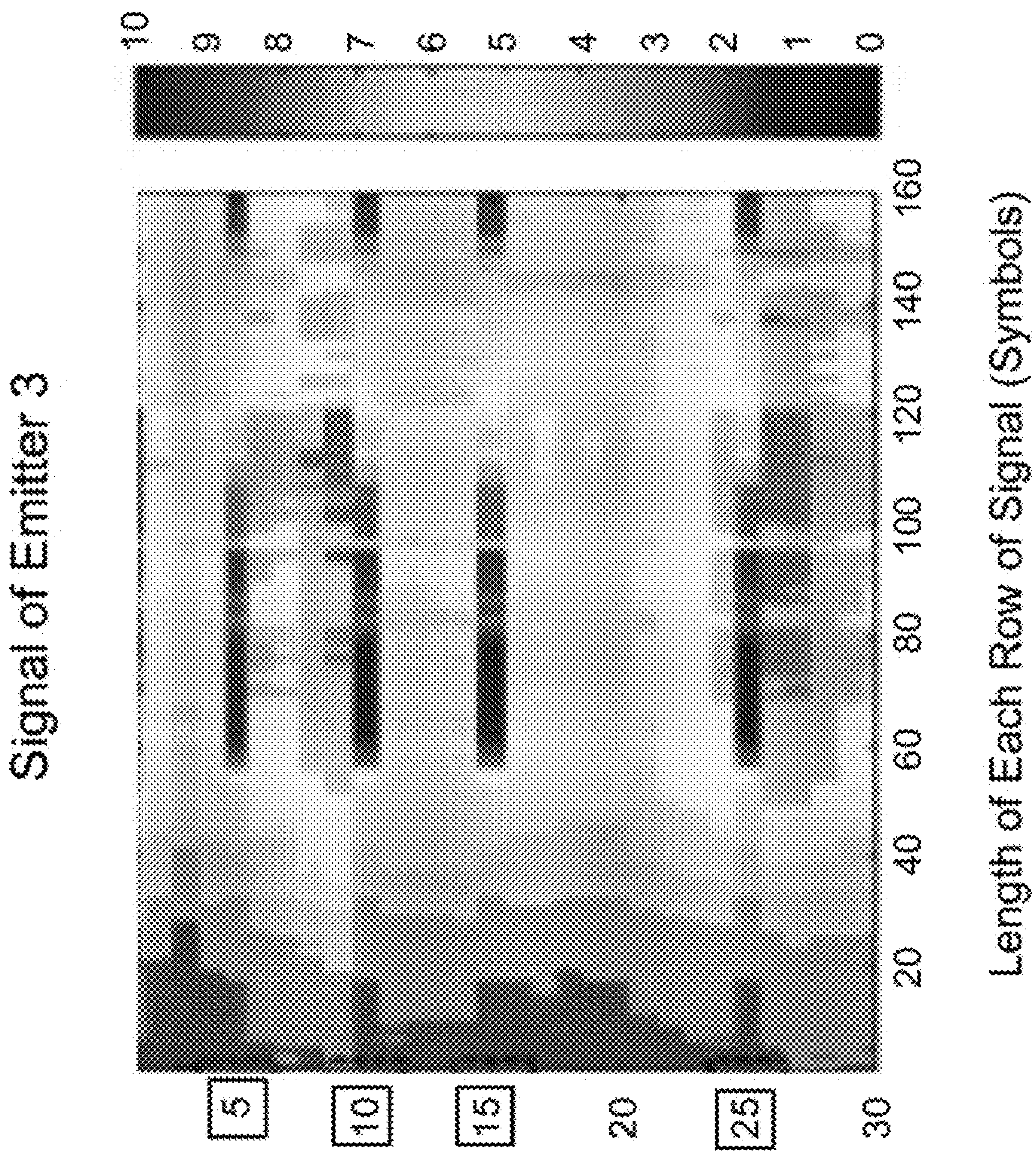

Signal of Emitter 3
Length of Each Row of Signal (Symbols)
20
40
60
80
100
120
140
160
5
10
15
20
25
30
0
1
2
3
4
5
6
7
8
9
10

FIG. 2D

300

302 304 306

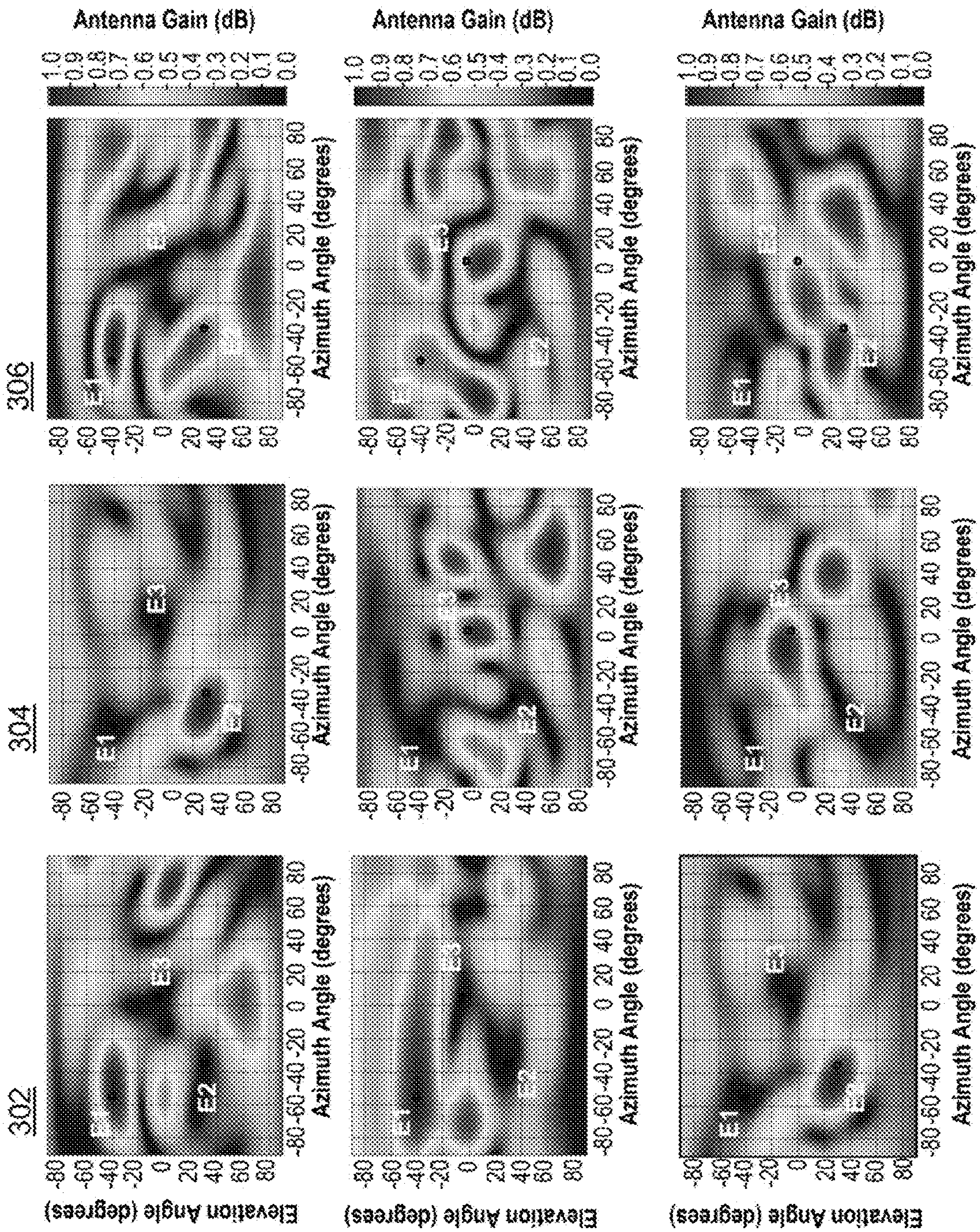


FIG. 3

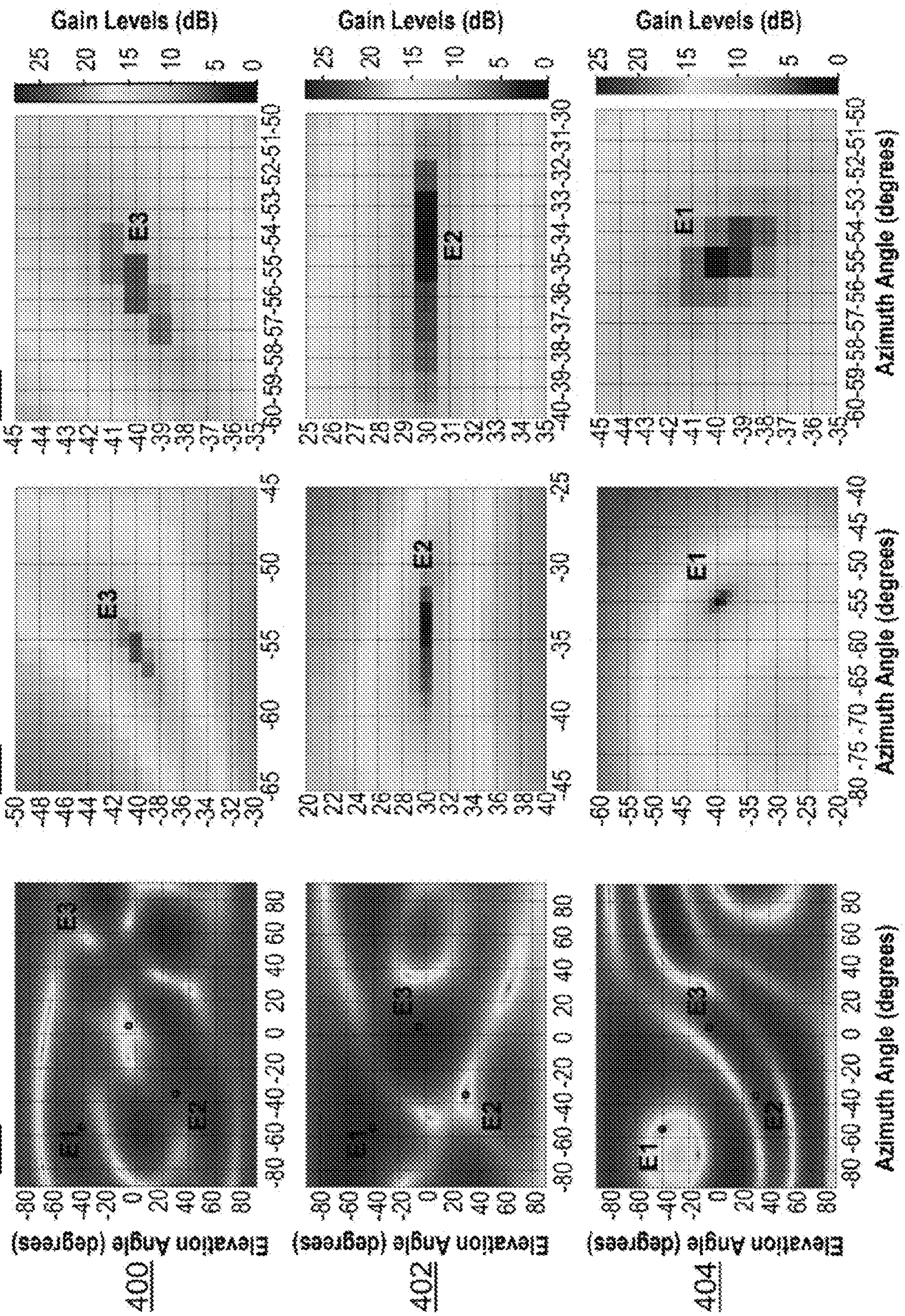

400
402
404
406
408
410
Elevation Angle (degrees)
Azimuth Angle (degrees)
Gain Levels (dB)
E1
E2
E3

FIG. 4

500

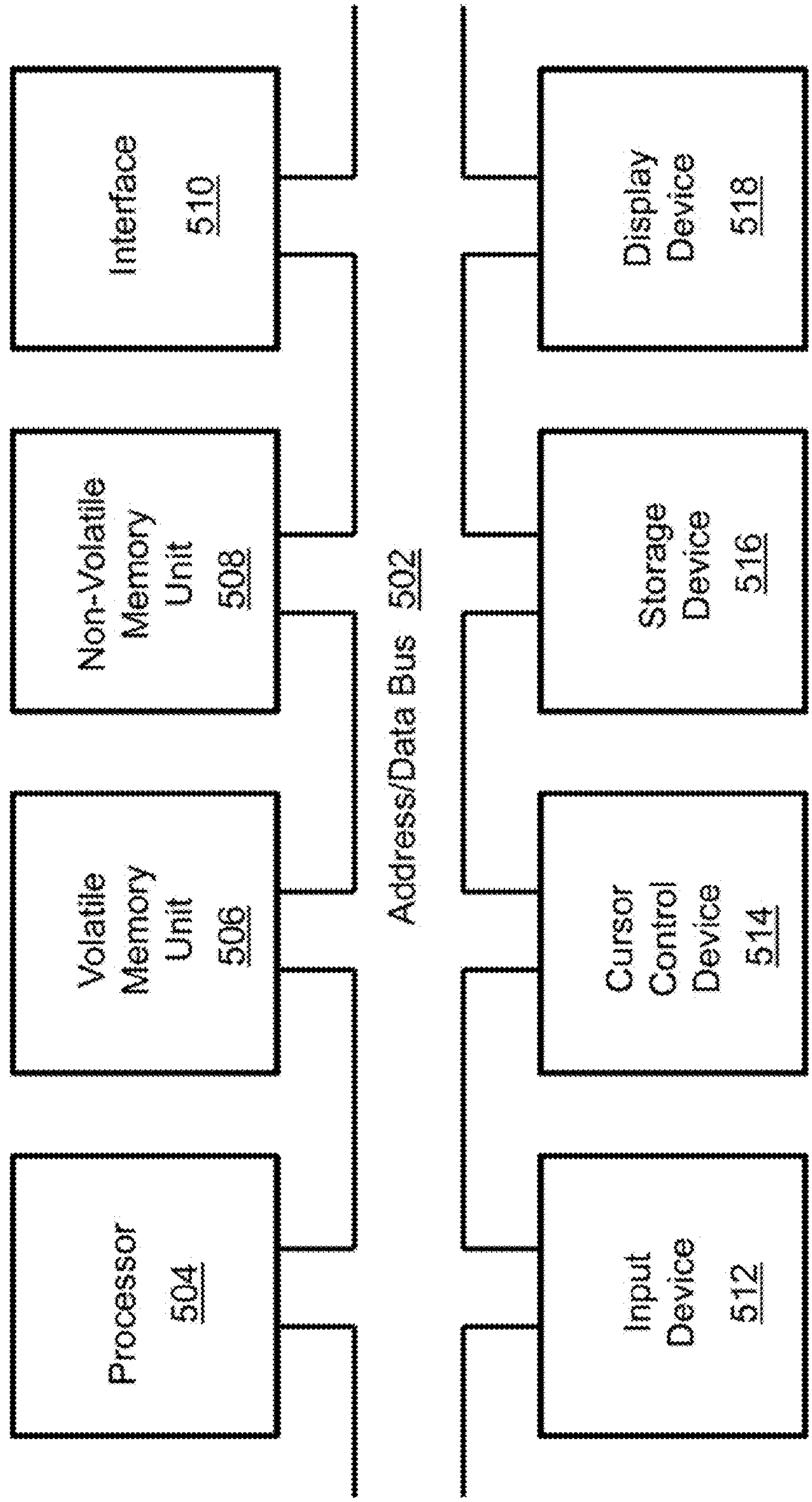

Processor 504
Volatile Memory Unit 506
Non-Volatile Memory Unit 508
Interface 510
Address/Data Bus 502
Input Device 512
Cursor Control Device 514
Storage Device 516
Display Device 518

FIG. 5

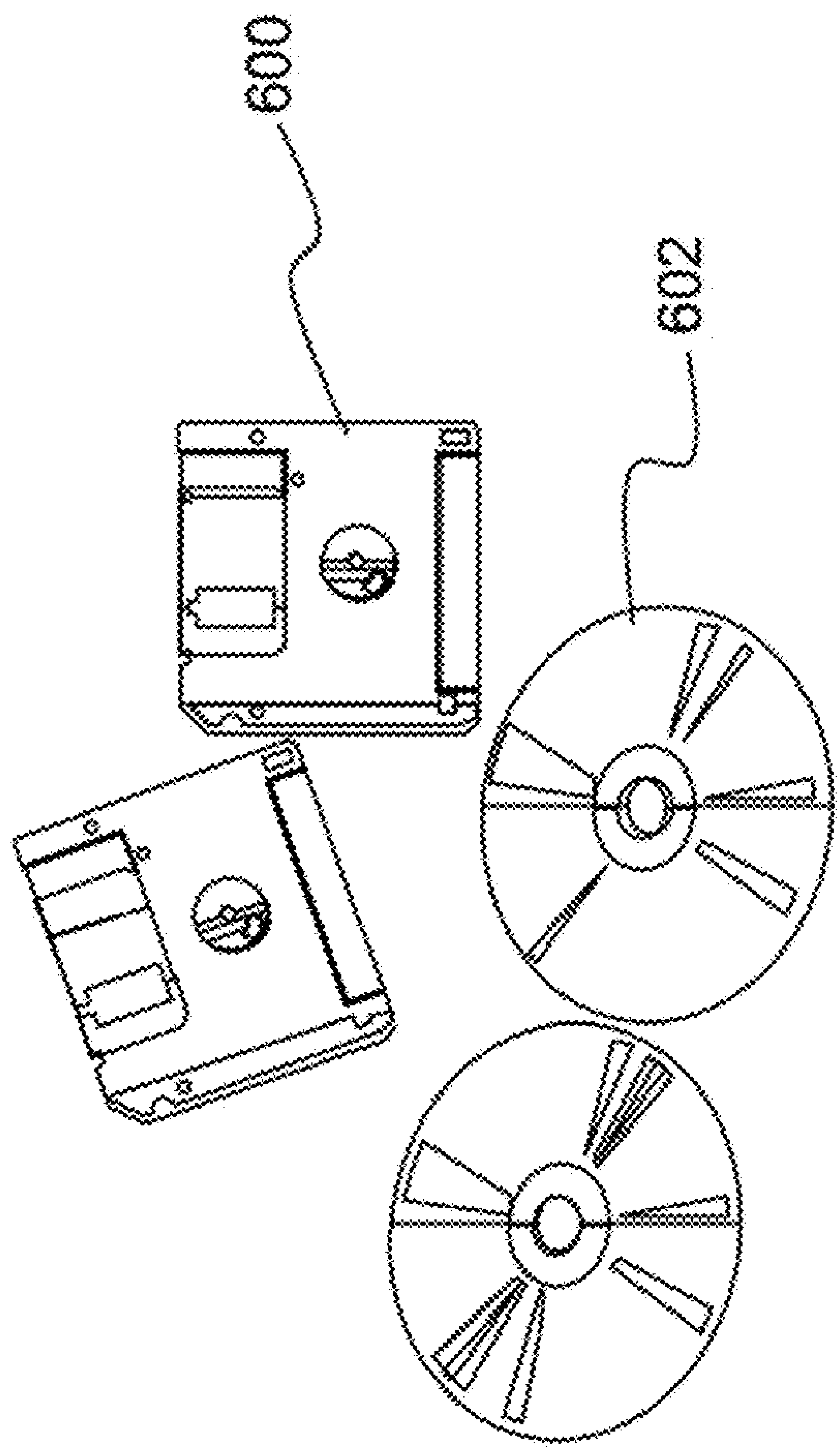


FIG. 6

BLIND BEAMFORMING USING KNOWLEDGE EMBEDDED IN TRANSMITTED SIGNALS

BACKGROUND OF THE INVENTION

(1) Field of Invention

The present invention relates to a system for blind beamforming and, more particularly, to a system for blind beamforming using knowledge embedded in transmitted signals to perform signal separation and extraction.

(2) Description of Related Art

Beamforming is a signal processing technique used in sensor arrays for directional signal transmission or reception. Elements in a phased array are combined such that signals at particular angles experience constructive interference, while others experience destructive interference. Blind signal separation, also known as blind source separation, is the separation of a set of source signals from a set of mixed signals, without the aid of information (or with very little information) about the source signals or the mixing process.

Traditional blind source signal separation beamforming algorithms rely on low-level statistical properties of signals to perform signal extraction, as described by A. J. van der Veen in "Algebraic methods for deterministic blind beam-forming," Proc. IEEE, vol. 86, pp. 1987-2008, Oct. 1998, which is hereby incorporated by reference as though fully set forth herein. Additionally, traditional blind source signal separation beamforming algorithms often fail when co-located interfering or jamming signals have similar statistical properties. Thus, a continuing need exists for a blind source signal separation beamforming system and method that uses high-level information embedded within the signal to perform signal separation and extraction.

SUMMARY OF THE INVENTION

The present invention relates to a system for blind beamforming and, more particularly, to a system for blind beamforming using knowledge embedded in transmitted signals to perform signal separation and extraction. The system comprises one or more processors and a memory having instructions such that when the instructions are executed, the one or more processors perform multiple operations. Initial antenna weights are assigned for a plurality of antenna elements of emitters of a beamforming system to generate a set of weighted radio-frequency (RF) signals at an output of each antenna element. The set of weighted RF signals are then combined to form a plurality of RF signal mixtures. Each RF signal mixture is processed to extract embedded information within signals of the emitters. The extracted embedded information is sent to an optimization module, wherein the extracted embedded information is used to perform simultaneous signal extractions for the emitters in the beamforming system.

In another aspect, an objective function is calculated based on the extracted embedded information with the optimization module.

In another aspect, feedback from the optimization module is used to modify antenna weights of the plurality of antenna elements toward optimal beamforming and to modify a set of demodulation parameters toward optimal information extraction.

In another aspect, the optimization module estimates at least one signal extraction error value, wherein if the at least one signal extraction error value is greater than a predefined threshold value, then the antenna weights of the plurality of antenna elements are modified.

In another aspect, the at least one signal extraction error value is defined as an absolute difference between one and the calculated objective function. The optimization module is configured to continue optimizing the antenna weights until the at least one signal extraction error value falls below the predefined threshold value.

In another aspect, the plurality of antenna elements are grouped into a plurality of sub-arrays, wherein each sub-array can use a different number of antenna elements to increase or relax a resolution of antenna beam patterns produced by the beamforming system.

In another aspect, the present invention also comprises a method for causing a processor to perform the operations described herein.

Finally, in yet another aspect, the present invention also comprises a computer program product comprising computer-readable instructions stored on a non-transitory computer-readable medium that are executable by a computer having a processor for causing the processor to perform the operations described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

The file of this patent or patent application publication contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

The objects, features and advantages of the present invention will be apparent from the following detailed descriptions of the various aspects of the invention in conjunction with reference to the following drawings, where:

FIG. **1** is a block diagram representation of a beamforming system that has been configured to use information embedded within signals of three emitters to extract and track all three emitter signals simultaneously according to the principles of the present invention;

FIG. **2**A is an illustration of sample embedded information sequences according to the principles of the present invention;

FIG. **2**B is an illustration of signals from an emitter **1** with specific information sequences embedded in rows **5**, **10**, **15**, and **25** according to the principles of the present invention;

FIG. **2**C is an illustration of signals from an emitter **2** with specific information sequences embedded in rows **5**, **10**, **15**, and **25** according to the principles of the present invention;

FIG. **2**D is an illustration of signals from an emitter **3** with specific information sequences embedded in rows **5**, **10**, **15**, and **25** according to the principles of the present invention;

FIG. **3** illustrates individual antenna beam patterns of two sub-arrays and the combined antenna beam patterns for three operational scenarios according to the principles of the present invention;

FIG. **4** illustrates optimized antenna beam patterns for three operational scenarios according to the principles of the present invention;

FIG. **5** is an illustration of a data processing system according to the principles of the present invention; and

FIG. **6** is an illustration of a computer program product according to the principles of the present invention.

DETAILED DESCRIPTION

The present invention relates to a system for blind beamforming and, more particularly, to a system for blind beamforming using knowledge embedded in transmitted signals to perform signal separation and extraction. The following description is presented to enable one of ordinary skill in the art to make and use the invention and to incorporate it in the context of particular applications. Various modifications, as well as a variety of uses, in different applications will be readily apparent to those skilled in the art, and the general principles defined herein may be applied to a wide range of embodiments. Thus, the present invention is not intended to be limited to the embodiments presented, but is to be accorded with the widest scope consistent with the principles and novel features disclosed herein.

In the following detailed description, numerous specific details are set forth in order to provide a more thorough understanding of the present invention. However, it will be apparent to one skilled in the art that the present invention may be practiced without necessarily being limited to these specific details. In other instances, well-known structures and devices are shown in block diagram form, rather than in detail, in order to avoid obscuring the present invention.

The reader's attention is directed to all papers and documents which are filed concurrently with this specification and which are open to public inspection with this specification, and the contents of all such papers and documents are incorporated herein by reference. All the features disclosed in this specification, (including any accompanying claims, abstract, and drawings) may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic series of equivalent or similar features.

Furthermore, any element in a claim that does not explicitly state "means for" performing a specified function, or "step for" performing a specific function, is not to be interpreted as a "means" or "step" clause as specified in 35 U.S.C. Section 112, Paragraph 6. In particular, the use of"step of" or "act of" in the claims herein is not intended to invoke the provisions of 35 U.S.C. 112, Paragraph 6.

Please note, if used, the labels left, right, front, back, top, bottom, forward, reverse, clockwise and counter-clockwise have been used for convenience purposes only and are not intended to imply any particular fixed direction. Instead, they are used to reflect relative locations and/or directions between various portions of an object. As such, as the present invention is changed, the above labels may change their orientation.

(1) Principal Aspects

The present invention has three "principal" aspects. The first is a system for blind beamforming. The system is typically in the form of a computer system, computer component, or computer network operating software or in the form of a "hard-coded" instruction set. This system may take a variety of forms with a variety of hardware devices and may include computer networks, handheld computing devices, cellular networks, satellite networks, and other communication devices. As can be appreciated by one skilled in the art, this system may be incorporated into a wide variety of devices that provide different functionalities. The second principal aspect is a method for blind beamforming. The third principal aspect is a computer program product. The computer program product generally represents computer-readable instruction means (instructions) stored on a non-transitory computer-readable medium such as an optical storage device, e.g., a compact disc (CD) or digital versatile disc (DVD), or a magnetic storage device such as a floppy disk or magnetic tape. Other, non-limiting examples of computer-readable media include hard disks, read-only memory (ROM), and flash-type memories.

The term "instructions" as used with respect to this invention generally indicates a set of operations to be performed on a computer, and may represent pieces of a whole program or individual, separable, software modules. Non-limiting examples of "instructions" include computer program code (source or object code) and "hard-coded" electronics (i.e., computer operations coded into a computer chip). The "instructions" may be stored on any non-transitory computer-readable medium such as a floppy disk, a CD-ROM, a flash drive, and in the memory of a computer.

(2) Specific Details

Traditional blind beamforming approaches rely on measuring and adjusting low-level, statistical properties of the received signals to perform extraction of the emitter signal. Not only do these approaches require long training sequences that result in high computational complexity and limited practical use in fast changing mixing channels, but they also often fail when the mixing signals (i.e., emitter and interfering) have similar low-level statistical properties. The present invention uses information embedded within various emitter signals to detect, extract, and track individual emitter signals simultaneously without measuring the statistical properties of the received signal and without using a calibrated antenna array. Existing systems use signal properties for separation that are not affected by the encoded information. Unlike existing systems, the present invention can separate signals even if they have the same properties, because the information embedded in the signals is utilized.

Significantly, the beamforming system, according to the principles of the present invention, can be used to track multiple emitters simultaneously (it is assumed that the emitters are uncooperative) by formulating an objective function for an optimization module that maximizes the measured degree of extraction of higher information embedded in the emitter signals. Non-limiting examples of the embedded information include known or unknown patterns, such as words, recognized speech, images (e.g., objects or textures in video), or data (e.g., specific symbol sequences). The objective function measures specific properties, such as the degree of match of the extracted information with known information, or it can measure more general properties of the extracted information, such as whether a recognition system can recognize any words, images, or data in it.

The present invention enables successful detection, extraction, and tracking of all desired signals simultaneously, even in the presence of various interfering or jamming signals. FIG. **1** is a block diagram of a non-limiting representation of an aspect of the beamforming system, according to the principles of the present invention, that has been configured to use information embedded within signals of three emitters to extract and track all three emitter signals simultaneously.

First, the system groups some or all antenna elements (represented by bold solid line triangles **100**, unbolded solid line triangles **102**, and dashed line triangles **104**) of a given antenna array **106** into several smaller arrays (i.e., sub-arrays). The number of sub-arrays is equal to or greater than the number of signals to be extracted in a given scene, and the number of antenna elements (**100**, **102**, and **104**) in each sub-array is determined by the desired resolution of the respective antenna beam patterns. Not only is antenna array calibration not needed for the embedded information-based beamforming of the present invention, but the sub-arrays can also use a different number of antenna elements to increase or relax the resolution of antenna beam patterns while tracking their respective emitters from one time instant to another. Furthermore, the beamforming method allows individual antenna elements (**100**, **102**, **104**) of the sub-arrays to have different antenna patterns that may have non-uniform or random shapes, and that may even vary with time. In other words, the system can work just as well with calibrated or uncalibrated antenna arrays **106** that may have time-varying number of antenna elements (**100**, **102**, **104**), randomly placed antenna elements (**100**, **102**, **104**), or antenna elements (**100**, **102**, **104**) with non-uniform, random, or time-varying antenna patterns.

An initial set of antenna weights **108** for various antenna elements of different sub-arrays can be chosen randomly. The amplitude and phase weights (i.e., antenna weights **108**) for individual antenna elements (e.g., **100**, **102**, **104**) are represented by circles in FIG. **1**. Then, using a switching matrix **110**, the system combines weighted, received radio frequency (RF) signals at the output of each antenna element **100**, **102**, and **104** of individual antenna sub-arrays in a RF signal mixing module **112** to form respective RF signal mixtures **114**, **116**, and **118** for post-processing. Next, the RF signal mixtures **114**, **116**, and **118** are down converted and demodulated in an information extraction module **120**, which involves processes of signal conditioning, signal demodulation, and information extraction for each RF signal mixture **114**, **116**, and **118**. Prior knowledge **122** of the properties of embedded information within an extracted baseband signal (i.e., actual embedded reference information or measurements of extracted information properties) is sent to an optimization module **124** of the system. Prior knowledge **122** of the properties of the embedded information is used by the optimization module **124** to perform simultaneous signal extractions, as described below.

With regards to the information extraction module **120**, any practical information extraction process can be used which enables the antenna weights and demodulation parameters to be adapted fast enough to track the emitters. After demodulation, the data embedded in the signal is available. The information extraction module **120** then extracts the higher level information or properties of the information that is represented by the data. The system will adjust the demodulation and antenna parameters to optimize an objective function that is based on the extracted information. Non-limiting examples of extracted information include the sequence of symbols being transmitted by the emitters. Other properties could also be used, such as the presence of particular words or languages that can be automatically recognized, or the statistical properties of the embedded data. An analogy is a person tuning a radio until he hears something of interest. His objective function could be how clearly he hears a particular language. If he turns the knob and he starts to hear something he understands, he keeps turning it until it starts to degrade. The system described herein does the same, but it can adjust many parameters at once (i.e., demodulation parameters, antenna weights) to optimize the objective function.

The optimization module **124** comprises several stages which together (1) calculate an objective function based on the extracted embedded information, (2) estimate information extraction error (i.e., the degree to which the extracted embedded information does not match pre-determined properties of the desired information), and (3) send feedback to adjust antenna weights and demodulation parameters **130**. The optimization module **124** can be any system that can adjust the parameters to optimize the objective function and do it fast enough to keep up with changes in the emitter, including its location. In the present application, and as a non-limiting example, particle swarm optimization (PSO) was used. However, as can be appreciated by one skilled in the art, genetic algorithms or other optimization algorithms could be used.

An objective function, designed using prior knowledge **122** of the properties of information embedded within signals of the n emitters, is used to evaluate the degree of mismatch between properties of the information extracted from the RF signal mixtures **114**, **116**, and **118** and the properties of the desired information. If the objective function value is greater than a predefined threshold limit (i.e., larger mismatch), a suitable heuristic optimization algorithm, non-limiting examples of which include genetic algorithms and particle swarm optimization, is used to modify both the weights of various antenna elements **100**, **102**, **104** of the sub-arrays and the demodulation parameter (i.e., send feedback to adjust antenna weights and the demodulation parameters **130**) to reduce the objective function. In other words, active feedback **132**, **134**, and **136** from the optimization module **124** guides antenna weights **108** towards optimal beamforming and the demodulation parameters towards extraction of the embedded information. Different weights are used to achieve different sensitivities. The process is repeated until the antenna pattern lobes (i.e., maxima) and nulls (i.e., signal goes to zero) are so aligned that the system is able to accurately extract signals from all n emitters simultaneously, generating extracted information from emitters **138**.

FIG. **2**A is an illustration of sample embedded information sequences according to the principles of the present invention. In this example, the desired property of the embedded information is the data or symbols represented by it. Other properties can also be used such as the presence of particular words or languages that can be automatically recognized or the statistical properties of the embedded information. FIGS. **2**B-**2**D depict a non-limiting example wherein each emitter signal consists of a collection of 4800 symbols arranged in 30 rows of 160 symbols each. A unique sequence of 640-symbols-long information (depicted as element **122** in FIG. **1**) is embedded within each of three signals (emitter **1**, emitter **2**, and emitter **3**) by dividing it into four equal 160 symbol subsequences and inserting them in rows **5**, **10**, **15**, and **25**. FIGS. **2**A-**2**D illustrate three sample information sequences and baseband emitter signals with specific information subsequences embedded in rows **5**, **10**, **15** and **25**.

FIGS. **2**B, **2**C, and **2**D illustrate the signals of emitters **1**, **2**, and **3**, respectively. Specifically, FIGS. **2**B, **2**C, and **2**D are plots of signals from the three emitters, referred to as stacked signal plots. The time series of symbols representing the signal have been divided into segments, and the segments are stacked vertically to form a two-dimensional representation of the long, one-dimensional signal. The marked rows, as indicated by a square surrounding the row number, contain the information sequence being transmitted; the rest of the signal is noise.

If one assumes that each symbol can be represented by four binary bits, then each unique, emitter-specific 160-symbols-long information sequence can be mapped into a corresponding 640-bits-long information subsequence. The antenna elements of the antenna array are divided into three sub-arrays, and each sub-array is tasked to track and extract an information signal from one of the three emitter signals. The objective function for each sub-array is designed such that each sub-array steers an antenna pattern lobe on the particular emitter of interest while forming deep antenna pattern nulls on the other two emitters.

The objective function (FIG. **1**, optimize objective function based on extracted embedded information **126**) in this example can be calculated as the weighted dot product (i.e., normalized cross-correlation) of the prior knowledge (depicted in FIG. **1** as element **122**) of the predefined embedded reference information sequence and one of the extracted 640-

bits-long information sequences. Alternatively, the objective function can be augmented to first calculate weighted dot products of all four embedded reference information subsequences and extracted information-bit-sequence pairs (corresponding to rows **5**, **10**, **15**, and **25** in FIGS. **2B-2D**) followed by averaging of all four dot products. If each sub-array were to successfully extract the respective emitter signal, then this objective function will calculate a value of one for each emitter. One can define the parameter signal extraction error (FIG. **1**, estimate demodulation parameters and antenna weight adjustments **128**) for each sub-array as the absolute difference between one and the calculated objective function value (FIG. **1**, optimize objective function based on extracted embedded information **126**), and then configure the optimization module (depicted as element **124** in FIG. **1**) of the beamforming system to continue optimizing antenna weights of sub-arrays and the demodulation parameters until the signal extraction error values for all sub-arrays fall below a predefined threshold value.

FIG. **3** shows antenna beam pattern simulation results demonstrating how the blind beamforming system and method according to the principles of the present invention can be used to simultaneously track multiple emitters. In this test case, the beamforming system was configured to simultaneously track two emitters and an interferer. The antenna array of the system was divided into two sub-arrays, with each sub-array tracking one of the two emitters. The plots in different rows of FIG. **3** show results corresponding to different simulation test cases. The plots in the first and second columns of each row show antenna beam patterns of individual sub-arrays, and the plots in the third column show the combined antenna beam pattern for both sub-arrays for the particular simulation test case in a given row. In the first test case in the first row, the system described herein was used to extract signals from emitter pairs **1** and **2** (E**1** and E**2**, respectively) simultaneously while also completely blocking any signal from emitter **3** (E**3**). In the second and third test cases in rows **2** and **3**, antenna pattern lobes were steered to extract signals from emitter pairs **1** and **3** (E**1** and E**3**, respectively), and **2** and **3** (E**2** and E**3**, respectively). To enable comparison of individual performances, all antenna patterns in FIG. **3** were normalized so that the antenna gain ranged between 1 and 0.

The plot in the first row **300** of the first column **302** of FIG. **3** shows the final antenna beam pattern of the first sub-array of the beamforming system. As a non-limiting example, the sub-array uses particle swarm optimization to optimize weights of its antenna elements to steer an antenna pattern lobe on emitter **1** (E**1**) and antenna pattern nulls on emitters **2** and **3** (E**2** and E**3**, respectively). The plot in the first row **300** of the second column **304** shows the final antenna beam pattern of the second sub-array of the beamforming system. This sub-array steers an antenna beam lobe on E**2** and antenna pattern nulls on E**1** and E**3**. The effective combined antenna beam pattern can be calculated using optimized weights of all antenna elements of both sub-arrays. This resulting pattern, for the first simulation test case, is shown in the plot in the first row **300** of the third column **306**. The deep null on E**3** (indicated by the E**3** point being in a dark blue area of the plot representing no signal) and prominent antenna pattern lobes on E**1** and E**2** (indicated by the E**1** and E**2** points being in red areas of the plot representing maxima) enable the blind beamforming system to successfully extract signals from E**1** and E**2** simultaneously.

In an alternative embodiment of the beamforming system of the present invention, rather than dividing antenna elements of a given antenna array into multiple sub-arrays, the optimization function is designed such that all elements of the antenna array are used to simultaneously steer multiple antenna pattern lobes on various emitters in the scene while forming deep antenna pattern nulls on the interferers. For the specific example and simulation test case discussed above, a number of different objective functions can be formed using the unique 640-bits-long information sequences of the two emitters. For example, in one implementation, the individual embedded information bit sequences (i.e., FIG. **1**, prior knowledge **122**) can be concatenated to form a new 1280-bits-long reference information bit sequence. The objective function can be as simple as the weighted dot product of the new reference and one of the extracted 1280-bits-long information sequences, or it can be augmented to first calculate the weighted dot product of all four reference and extracted information bit sequence pairs (corresponding to rows **5**, **10**, **15**, and **25**) followed by averaging of all four dot products. The optimization module (depicted in FIG. **1** as element **124**) of the beamforming system continues optimizing antenna weights until the signal extraction error value falls below a predefined threshold value (FIG. **1**, estimate demodulation parameters and antenna weight adjustments **128**).

FIG. **4** shows optimized antenna beam patterns for three operational scenarios: (1) signals of interest transmitted by an emitter **1-2** pair (first row **400**), (2) emitter **1-3** pair (second row **402**), and (3) emitter **2-3** pair (third row **404**). The simulation results in FIG. **4** demonstrate how the second embodiment of the blind beamforming system and method can be used to simultaneously track multiple emitters. In this test case, the beamforming system was configured to use all elements of the antenna array (i.e., no formation of sub-arrays) to simultaneously track two emitters and an interferer. The plots in the first column **406** of FIG. **4** show optimized antenna patterns corresponding to different simulation test cases, represented by different rows (first row **400**, second row **402**, and third row **404**). The plots in the second column **408** and third column **410** of a row show the depth and finer details of the antenna pattern null formed on the interferer in that scene. In the first test case (i.e., first row **400**), the beamforming system is used to extract signals from emitter pairs **1** (E**1**) and **2** (E**2**) simultaneously, while also completely blocking any signal from emitter **3** (E**3**). In the second and third test cases (i.e., second row **402** and third row **404**), antenna pattern lobes are steered to extract signals from emitter pairs **1** and **3**, and **2** and **3**, respectively. To enable comparison of individual performances, all antenna patterns in the first column **406** of FIG. **4** are normalized to respective minimum gain levels. The color scale shows normalized gain levels in decibels (dB).

In the first test case (i.e., first row **400**), the system steers two different antenna pattern lobes on the two emitters, E**1** and E**2**, while simultaneously forming a deep antenna pattern null on the interferer E**3**. The antenna pattern gain values at the location of the two emitters (E**1** and E**2**), relative to the gain value at the location of the interferer, are 21.8 and 22.1 dB, respectively. In the third test case (i.e., third row **404**), the system steers a single antenna-pattern-lobe on the two emitters, E**2** and E**3**, while forming a deep antenna pattern null on the interferer E**1**. Here, the relative antenna pattern gain values at the location of the two emitters are 23.1 and 23.1 dB, respectively.

In summary, the present invention comprises dynamic interference rejection, high system performance, and the use of uncalibrated antenna arrays. The optimization module (depicted as element **124** in FIG. **1**) of the present invention dynamically steers high gain lobes and nulls to quickly arrive at an antenna pattern that allows the system to retrieve information embedded within the desired signal, completely and accurately. In doing so, the system automatically rejects all of the interfering signals irrespective of their locations relative to the emitter, even if their statistical properties are similar to those of the emitter signal.

Furthermore, unlike traditional beamforming systems, wherein the signal extraction process is tied to artificially selected low-level properties of the received signals, the present invention utilizes active feedback from the high-level system (that actually uses the extracted signal) to intelligently govern the signal separation and extraction process, thereby improving overall performance of the system.

Additionally, the present invention can work just as well with calibrated or uncalibrated antenna arrays that may have a time-varying number of antenna elements, randomly placed antenna elements, or antenna elements with non-uniform, random, or time-varying antenna patterns.

In summary, existing blind source separation systems, such as antenna beamformers, separate signals on the basis of properties of the signals, including angle of arrival, statistical independence, or type of modulation. However, the system according to the principles of the present invention separates signals based on higher level information encoded in the signals, non-limiting examples of which include recognized speech, objects or textures in video, and specific symbol sequences. Existing systems use signal properties for separation that are not affected by the encoded information. Unlike existing systems, the present invention can separate signals even if they have the same properties, because the information embedded in the signals is utilized. The invention described herein provides advantages in the areas of inter-vehicular communications, vehicle-to-infrastructure communications, collision warning, collision avoidance, and other active safety applications.

An example of a computer system **500** in accordance with one aspect is shown in FIG. **5**. The computer system **500** is configured to perform calculations, processes, operations, and/or functions associated with a program or algorithm. In one aspect, certain processes and steps discussed herein are realized as a series of instructions (e.g., software program) that reside within computer readable memory units and are executed by one or more processors of the computer system **500**. When executed, the instructions cause the computer system **500** to perform specific actions and exhibit specific behavior, such as described herein.

The computer system **500** may include an address/data bus **502** that is configured to communicate information. Additionally, one or more data processing units, such as a processor **504**, are coupled with the address/data bus **502**. The processor **504** is configured to process information and instructions. In one aspect, the processor **504** is a microprocessor. Alternatively, the processor **504** may be a different type of processor such as a parallel processor, or a field programmable gate array.

The computer system **500** is configured to utilize one or more data storage units. The computer system **500** may include a volatile memory unit **506** (e.g., random access memory ("RAM"), static RAM, dynamic RAM, etc.) coupled with the address/data bus **502**, wherein a volatile memory unit **506** is configured to store information and instructions for the processor **504**. The computer system **500** further may include a non-volatile memory unit **508** (e.g., read-only memory ("ROM"), programmable ROM ("PROM"), erasable programmable ROM ("EPROM"), electrically erasable programmable ROM "EEPROM"), flash memory, etc.) coupled with the address/data bus **502**, wherein the non-volatile memory unit **508** is configured to store static information and instructions for the processor **504**. Alternatively, the computer system **500** may execute instructions retrieved from an online data storage unit such as in "Cloud" computing. In an embodiment, the computer system **500** also may include one or more interfaces, such as an interface **510**, coupled with the address/data bus **502**. The one or more interfaces are configured to enable the computer system **500** to interface with other electronic devices and computer systems. The communication interfaces implemented by the one or more interfaces may include wireline (e.g., serial cables, modems, network adaptors, etc.) and/or wireless (e.g., wireless modems, wireless network adaptors, etc.) communication technology.

In one aspect, the computer system **500** may include an input device **512** coupled with the address/data bus **502**, wherein the input device **512** is configured to communicate information and command selections to the processor **500**. In accordance with one aspect, the input device **512** is an alphanumeric input device, such as a keyboard, that may include alphanumeric and/or function keys. Alternatively, the input device **512** may be an input device other than an alphanumeric input device. In one aspect, the computer system **500** may include a cursor control device **514** coupled with the address/data bus **502**, wherein the cursor control device **514** is configured to communicate user input information and/or command selections to the processor **500**. In one aspect, the cursor control device **514** is implemented using a device such as a mouse, a track-ball, a track-pad, an optical tracking device, or a touch screen. The foregoing notwithstanding, in one aspect, the cursor control device **514** is directed and/or activated via input from the input device **512**, such as in response to the use of special keys and key sequence commands associated with the input device **512**. In an alternative aspect, the cursor control device **514** is configured to be directed or guided by voice commands.

In one aspect, the computer system **500** further may include one or more optional computer usable data storage devices, such as a storage device **516**, coupled with the address/data bus **502**. The storage device **516** is configured to store information and/or computer executable instructions. In one aspect, the storage device **516** is a storage device such as a magnetic or optical disk drive (e.g., hard disk drive ("HDD"), floppy diskette, compact disk read only memory ("CD-ROM"), digital versatile disk ("DVD")). Pursuant to one aspect, a display device **518** is coupled with the address/data bus **502**, wherein the display device **518** is configured to display video and/or graphics. In one aspect, the display device **518** may include a cathode ray tube ("CRT"), liquid crystal display ("LCD"), field emission display ("FED"), plasma display, or any other display device suitable for displaying video and/or graphic images and alphanumeric characters recognizable to a user.

The computer system **500** presented herein is an example computing environment in accordance with one aspect. However, the non-limiting example of the computer system **500** is not strictly limited to being a computer system. For example, one aspect provides that the computer system **500** represents a type of data processing analysis that may be used in accordance with various aspects described herein. Moreover, other computing systems may also be implemented. Indeed, the spirit and scope of the present technology is not limited to any single data processing environment. Thus, in one aspect, one or more operations of various aspects of the present technology are controlled or implemented using computer-executable instructions, such as program modules, being executed by a computer. In one implementation, such program modules include routines, programs, objects, components and/or data structures that are configured to perform particular tasks or implement particular abstract data types. In addition, one aspect provides that one or more aspects of the present technology are implemented by utilizing one or more distributed computing environments, such as where tasks are performed by remote processing devices that are linked through a communications network, or such as where various program modules are located in both local and remote computer-storage media including memory-storage devices.

An illustrative diagram of a computer program product embodying the present invention is depicted in FIG. **6**. As a non-limiting example, the computer program product is depicted as either a floppy disk **600** or an optical disk **602**. However, as mentioned previously, the computer program product generally represents computer readable code (i.e., instruction means or instructions) stored on any compatible non-transitory computer readable medium.

What is claimed is:

1. A system for blind beamforming, the system comprising:

one or more processors and a non-transitory computer-readable medium having executable instructions encoded thereon such that when executed, the one or more processors perform operations of:

assigning initial antenna weights for a plurality of antenna elements of emitters of a beamforming system to generate a set of weighted radio-frequency (RF) signals at an output of each antenna element;

combining the set of weighted RF signals to form a plurality of RF signal mixtures;

processing each RF signal mixture to extract embedded information within signals of the emitters;

sending the extracted embedded information to an optimization module; and

performing simultaneous signal extractions for emitters of the beamforming system using the extracted embedded information.

2. The system as set forth in claim **1**, wherein the one or more processors further perform an operation of calculating an objective function based on the extracted embedded information with the optimization module.

3. The system as set forth in claim **2**, wherein the one or more processors further perform an operation of using feedback from the optimization module to modify antenna weights of the plurality of antenna elements toward optimal beamforming and to modify a set of demodulation parameters toward optimal information extraction.

4. The system as set forth in claim **3**, wherein the one or more processors further perform an operation of estimating, with the optimization module, at least one signal extraction error value, wherein if the at least one signal extraction error value is greater than a predefined threshold value, then the antenna weights of the plurality of antenna elements are modified.

5. The system as set forth in claim **4**, wherein the one or more processors further perform operations of:

defining the at least one signal extraction error value as an absolute difference between one and the calculated objective function; and

configuring the optimization module to continue optimizing the antenna weights until the at least one signal extraction error value falls below the predefined threshold value.

6. The system as set forth in claim **1**, wherein the one or more processors further perform an operation of grouping the plurality of antenna elements into a plurality of sub-arrays, wherein each sub-array can use a different number of antenna elements to increase or relax a resolution of antenna beam patterns produced by the beamforming system.

7. A computer-implemented method for blind beamforming, comprising:

an act of causing one or more processors to execute instructions stored on a non-transitory memory such that upon execution, the data processor performs operations of:

assigning initial antenna weights for a plurality of antenna elements of emitters of a beamforming system to generate a set of weighted radio-frequency (RF) signals at an output of each antenna element;

combining the set of weighted RF signals to form a plurality of RF signal mixtures;

processing each RF signal mixture to extract embedded information within signals of the emitters;

sending the extracted embedded information to an optimization module; and

performing simultaneous signal extractions for emitters of the beamforming system using the extracted embedded information.

8. The method as set forth in claim **7**, wherein the one or more processors further perform an operation of calculating an objective function based on the extracted embedded information with the optimization module.

9. The method as set forth in claim **8**, wherein the one or more processors further perform an operation of using feedback from the optimization module to modify antenna weights of the plurality of antenna elements toward optimal beamforming and to modify a set of demodulation parameters toward optimal information extraction.

10. The method as set forth in claim **9**, wherein the one or more processors further perform an operation of estimating, with the optimization module, at least one signal extraction error value, wherein if the at least one signal extraction error value is greater than a predefined threshold value, then the antenna weights of the plurality of antenna elements are modified.

11. The method as set forth in claim **10**, wherein the one or more processors further perform operations of:

defining the at least one signal extraction error value as an absolute difference between one and the calculated objective function; and

configuring the optimization module to continue optimizing the antenna weights until the at least one signal extraction error value falls below the predefined threshold value.

12. The method as set forth in claim **7**, wherein the one or more processors further perform operations of grouping the plurality of antenna elements into a plurality of sub-arrays, wherein each sub-array can use a different number of antenna elements to increase or relax a resolution of antenna beam patterns produced by the beamforming system.

13. A computer program product for blind beamforming, the computer program product comprising computer-readable instructions stored on a non-transitory computer-readable medium that are executable by a computer having a processor for causing the processor to perform operations of:

assigning initial antenna weights for a plurality of antenna elements of emitters of a beamforming system to generate a set of weighted radio-frequency (RF) signals at an output of each antenna element;

combining the set of weighted RF signals to form a plurality of RF signal mixtures;

processing each RF signal mixture to extract embedded information within signals of the emitters;

sending the extracted embedded information to an optimization module; and performing simultaneous signal extractions for emitters of the beamforming system using the extracted embedded information.

14. The computer program product as set forth in claim **13**, further comprising instructions for causing the processor to perform an operation of calculating an objective function based on the extracted embedded information with the optimization module.

15. The computer program product as set forth in claim **14**, further comprising instructions for causing the processor to perform an operation of using feedback from the optimization module to modify antenna weights of the plurality of antenna elements toward optimal beamforming and to modify a set of demodulation parameters toward optimal information extraction.

16. The computer program product as set forth in claim **15**, further comprising instructions for causing the processor to perform an operation of estimating, with the optimization module, at least one signal extraction error value, wherein if the at least one signal extraction error value is greater than a predefined threshold value, then the antenna weights of the plurality of antenna elements are modified.

17. The computer program product as set forth in claim **16**, further comprising instructions for causing the processor to perform operations of:

defining the at least one signal extraction error value as an absolute difference between one and the calculated objective function; and

configuring the optimization module to continue optimizing the antenna weights until the at least one signal extraction error value falls below the predefined threshold value.

18. The computer program product as set forth in claim **13**, further comprising instructions for causing the processor to perform operations of grouping the plurality of antenna elements into a plurality of sub-arrays, wherein each sub-array can use a different number of antenna elements to increase or relax a resolution of antenna beam patterns produced by the beamforming system.

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