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Kim et al.

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(54) **SHARED SPEECH PROCESSING NETWORK FOR MULTIPLE SPEECH APPLICATIONS**

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(Continued)

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Related U.S. Application Data

(63) Continuation of application No. 16/844,836, filed on Apr. 9, 2020, now Pat. No. 11,276,415.

(57) **ABSTRACT**

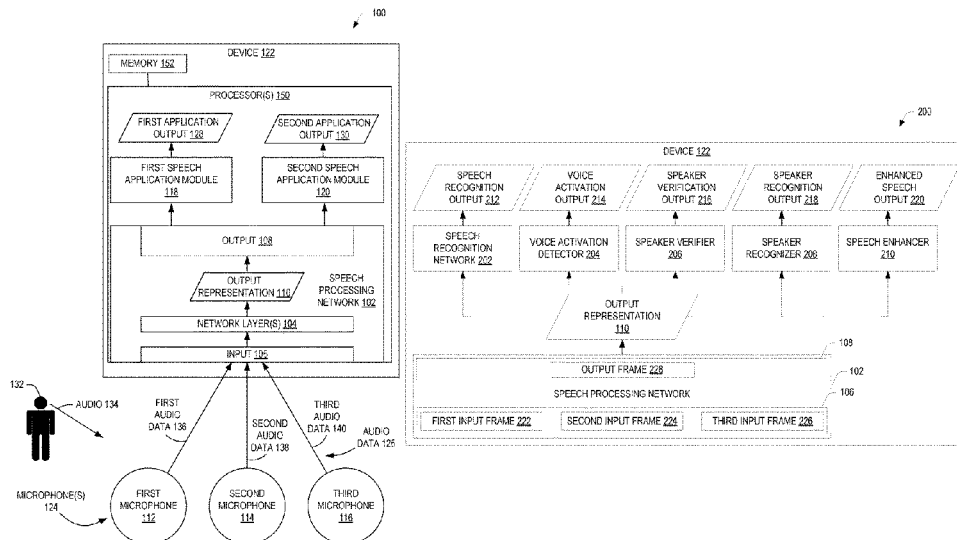
(51) **Int. Cl.**
H04R 3/00 (2006.01)
G10L 21/02 (2013.01)
(Continued)

A device to process speech includes a speech processing network that includes an input configured to receive audio data corresponding to audio captured by one or more microphones. The speech processing network also includes one or more network layers configured to process the audio data to generate a network output. The speech processing network includes an output configured to be coupled to multiple speech application modules to enable the network output to be provided as a common input to each of the multiple speech application modules. A first speech application module corresponds to a speaker verifier, and a second speech application module corresponds to a speech recognition network.

(52) **U.S. Cl.**
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CPC H04R 3/005; H04R 5/04; H04R 2499/13; H04R 2420/07; G06F 18/217; G06F

30 Claims, 11 Drawing Sheets



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H04L 65/80 (2022.01)
G06F 18/21 (2023.01)
G06V 10/82 (2022.01)
G06V 20/20 (2022.01)

- (52) **U.S. Cl.**
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 (2013.01); *H04L 65/60* (2013.01); *H04L 65/80*
 (2013.01); *H04R 5/04* (2013.01); *H04R*
2420/07 (2013.01); *H04R 2499/13* (2013.01)

- (58) **Field of Classification Search**
 CPC .. H04L 65/80; H04L 65/1016; H04L 65/1069
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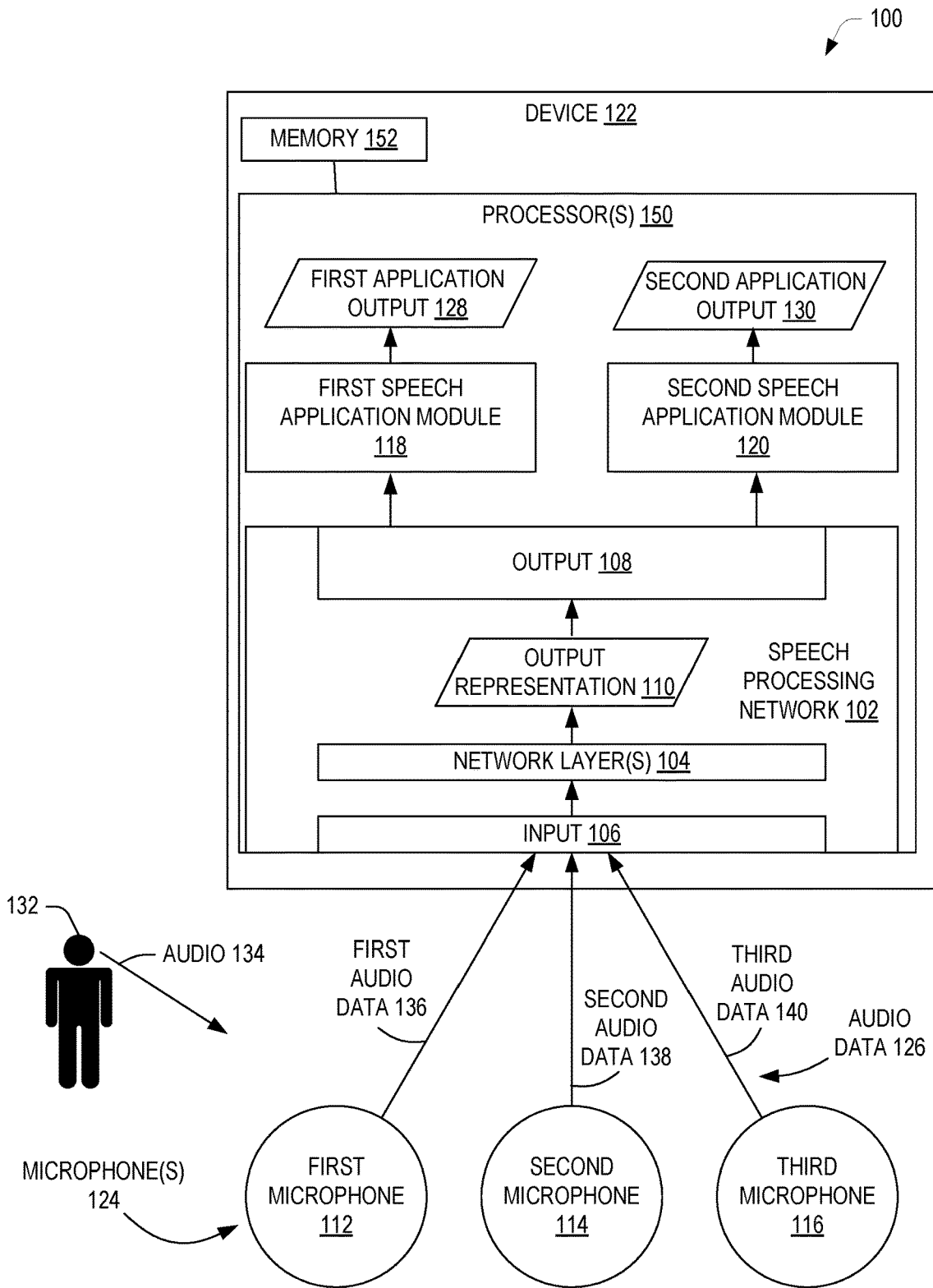


FIG. 1

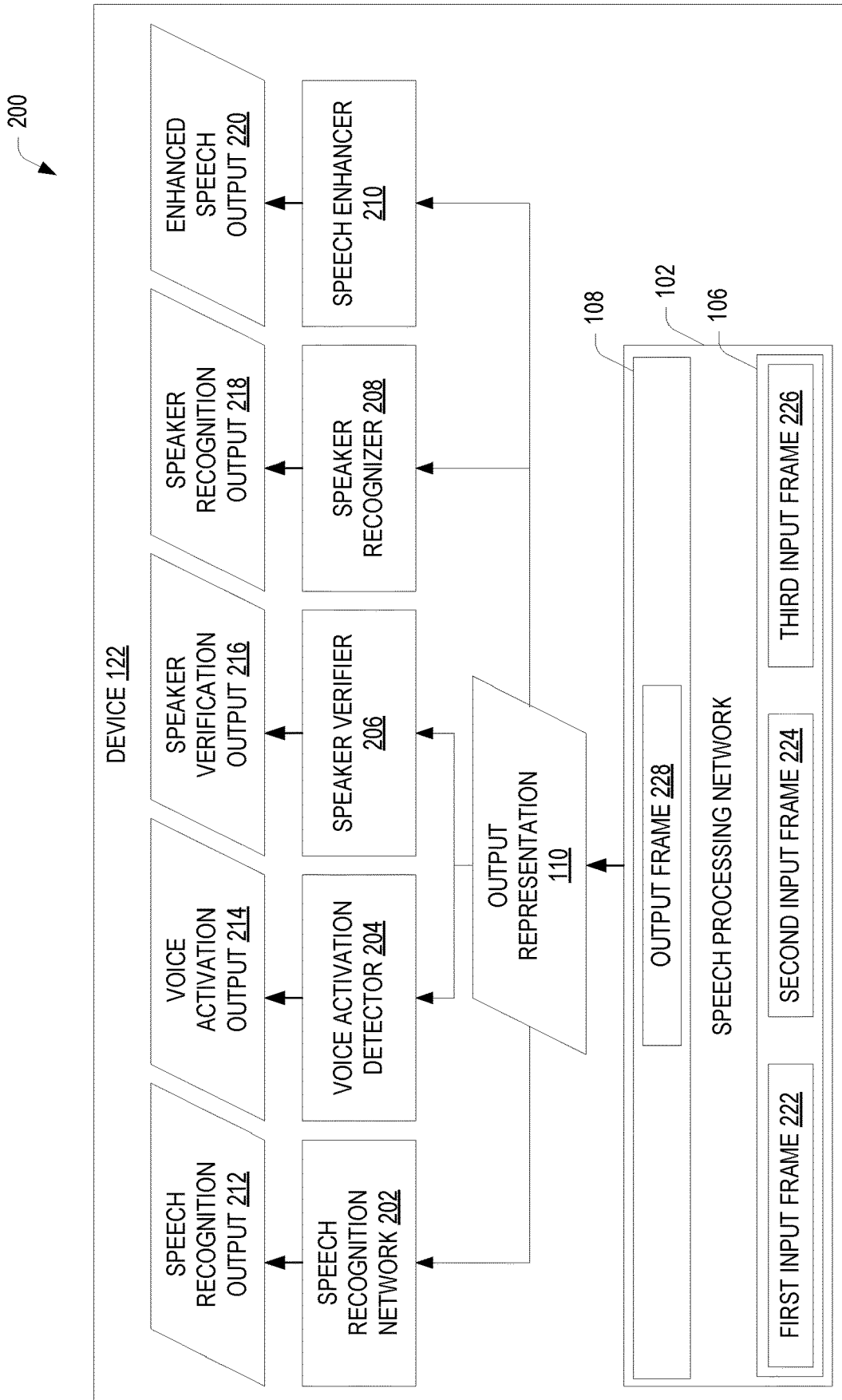


FIG. 2

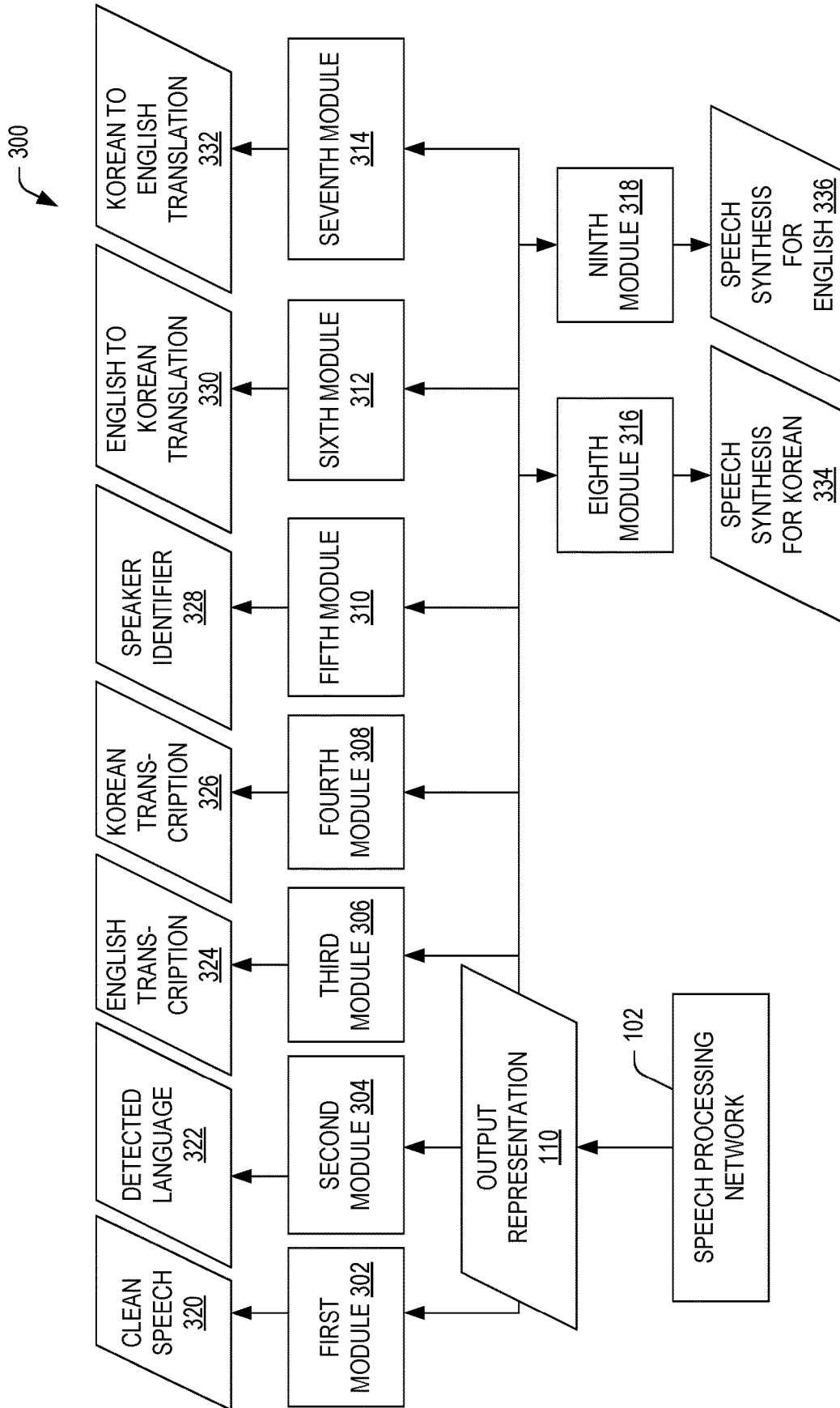


FIG. 3

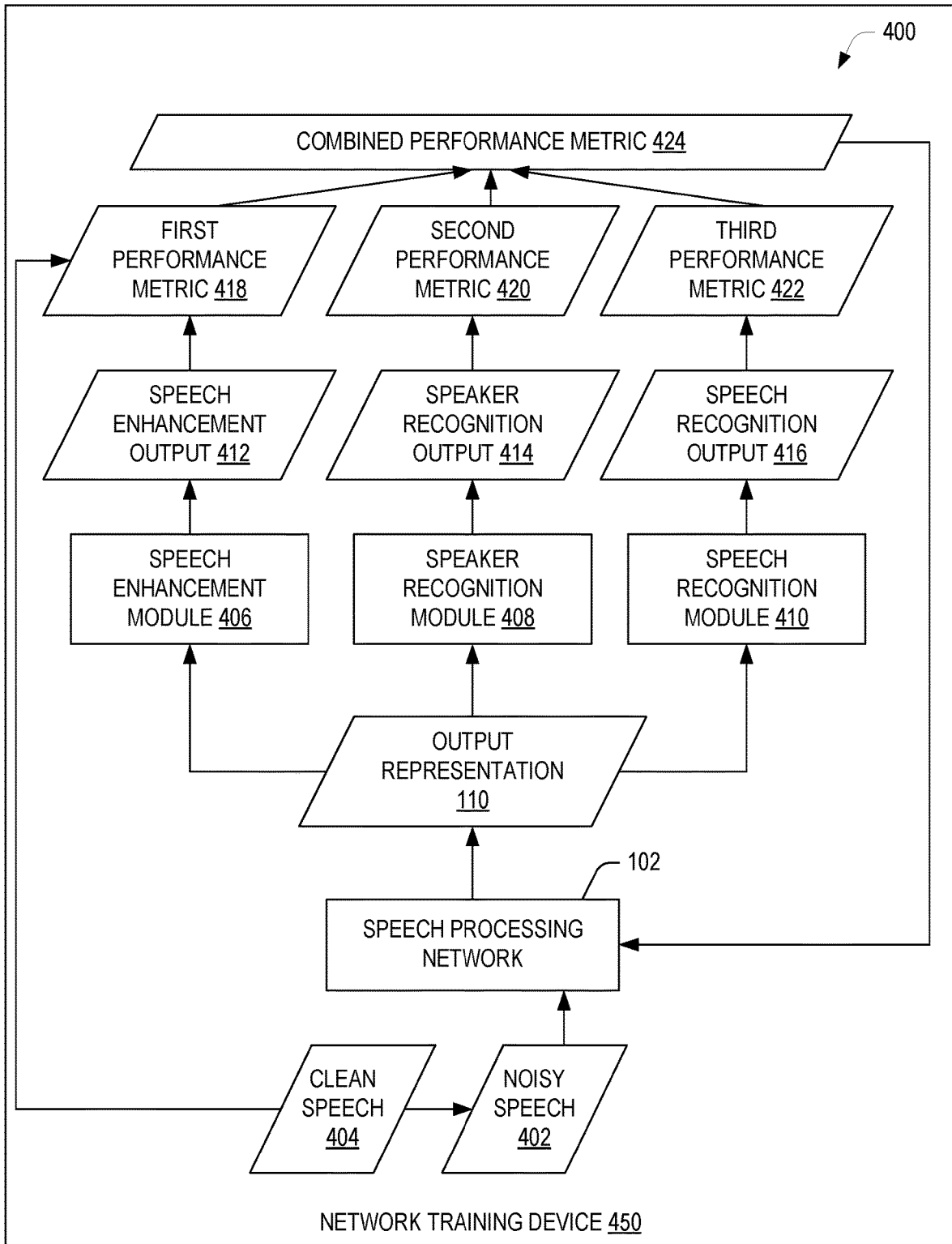


FIG. 4

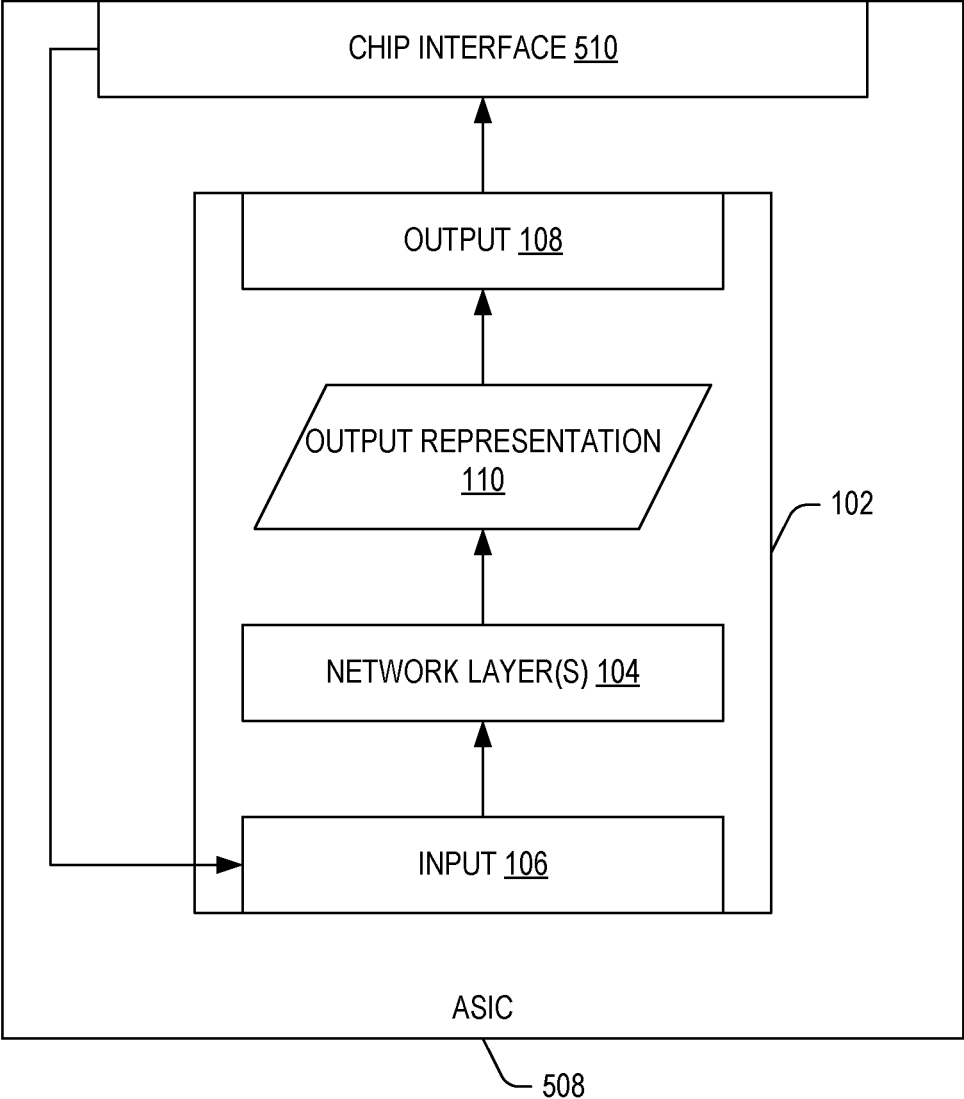


FIG. 5

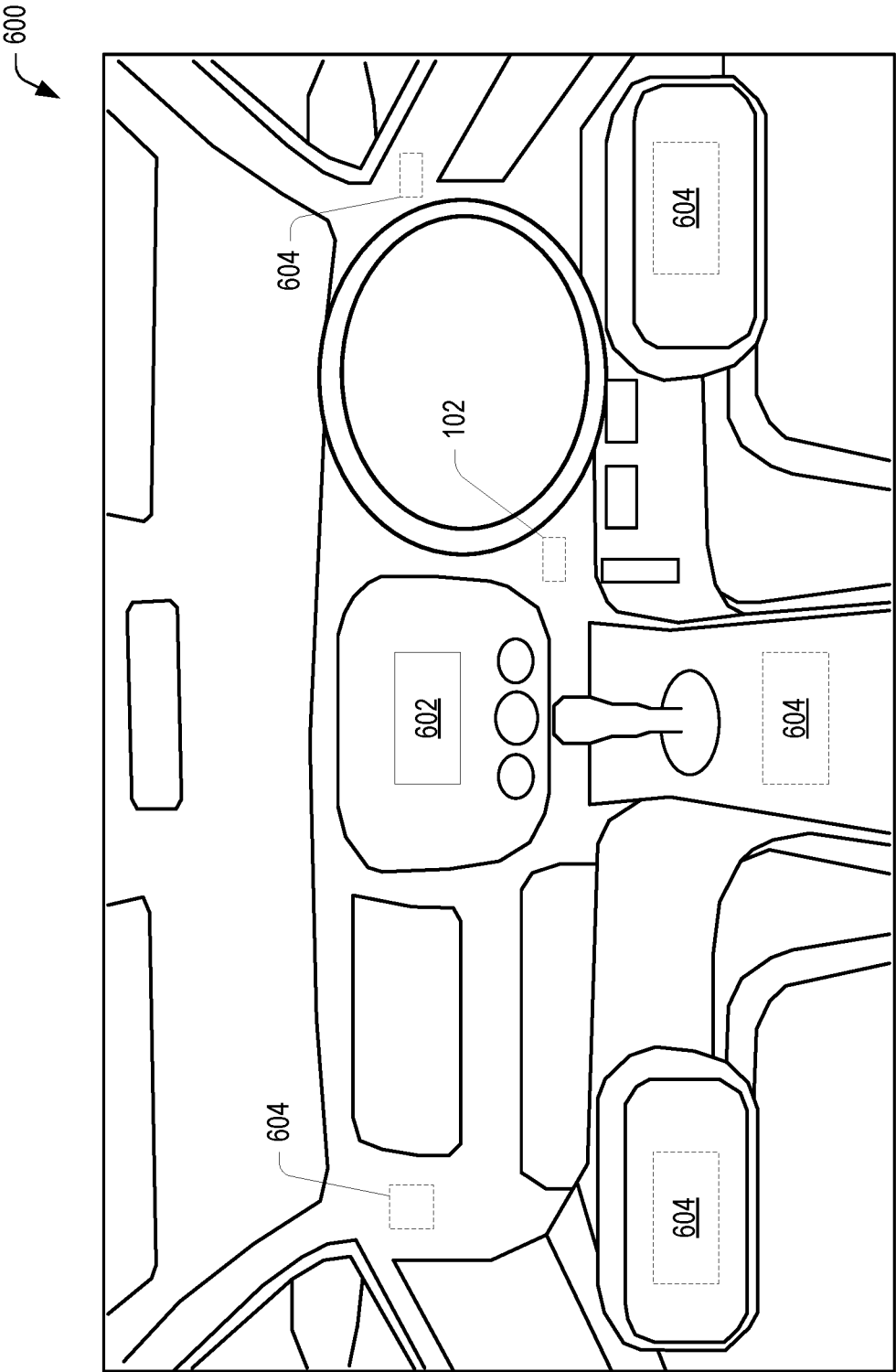


FIG. 6

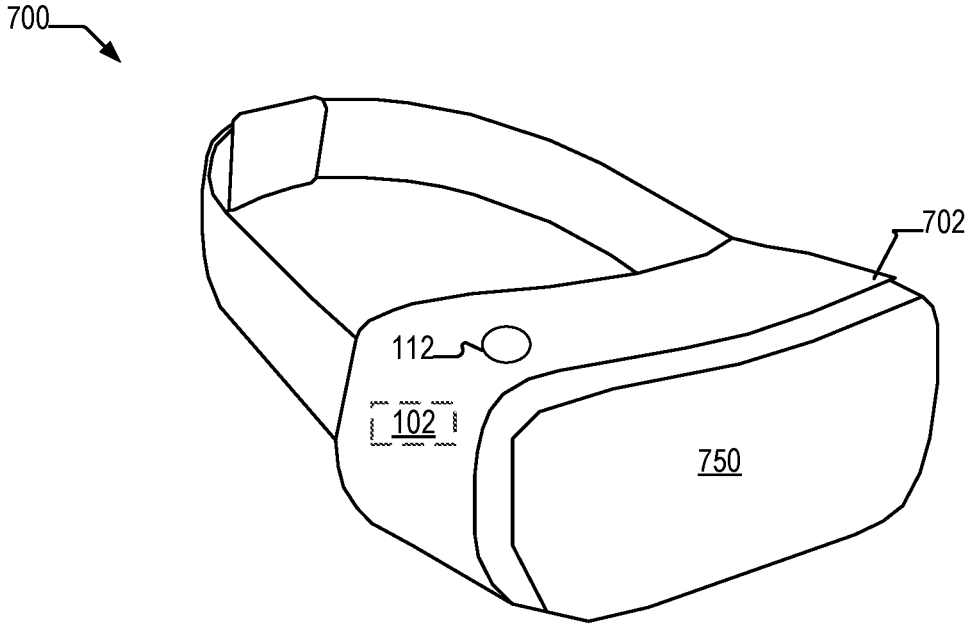


FIG. 7

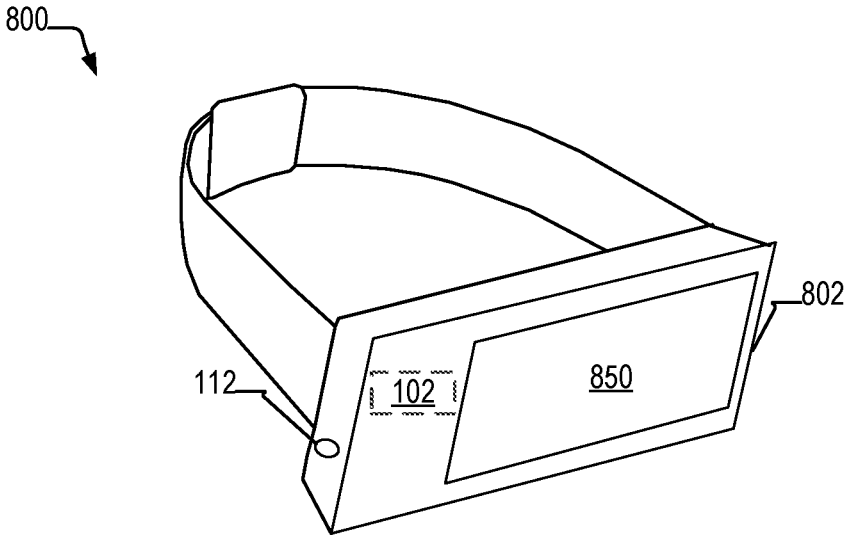


FIG. 8

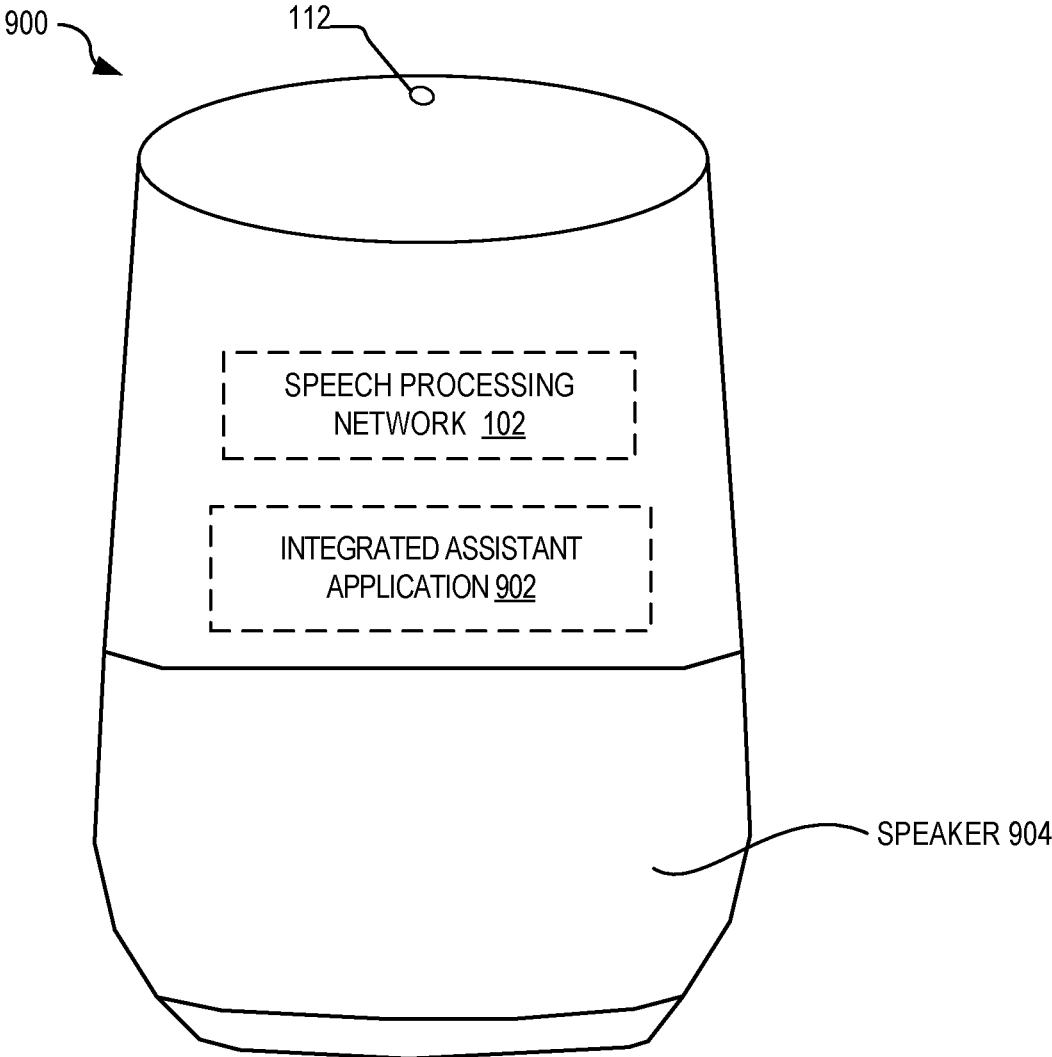
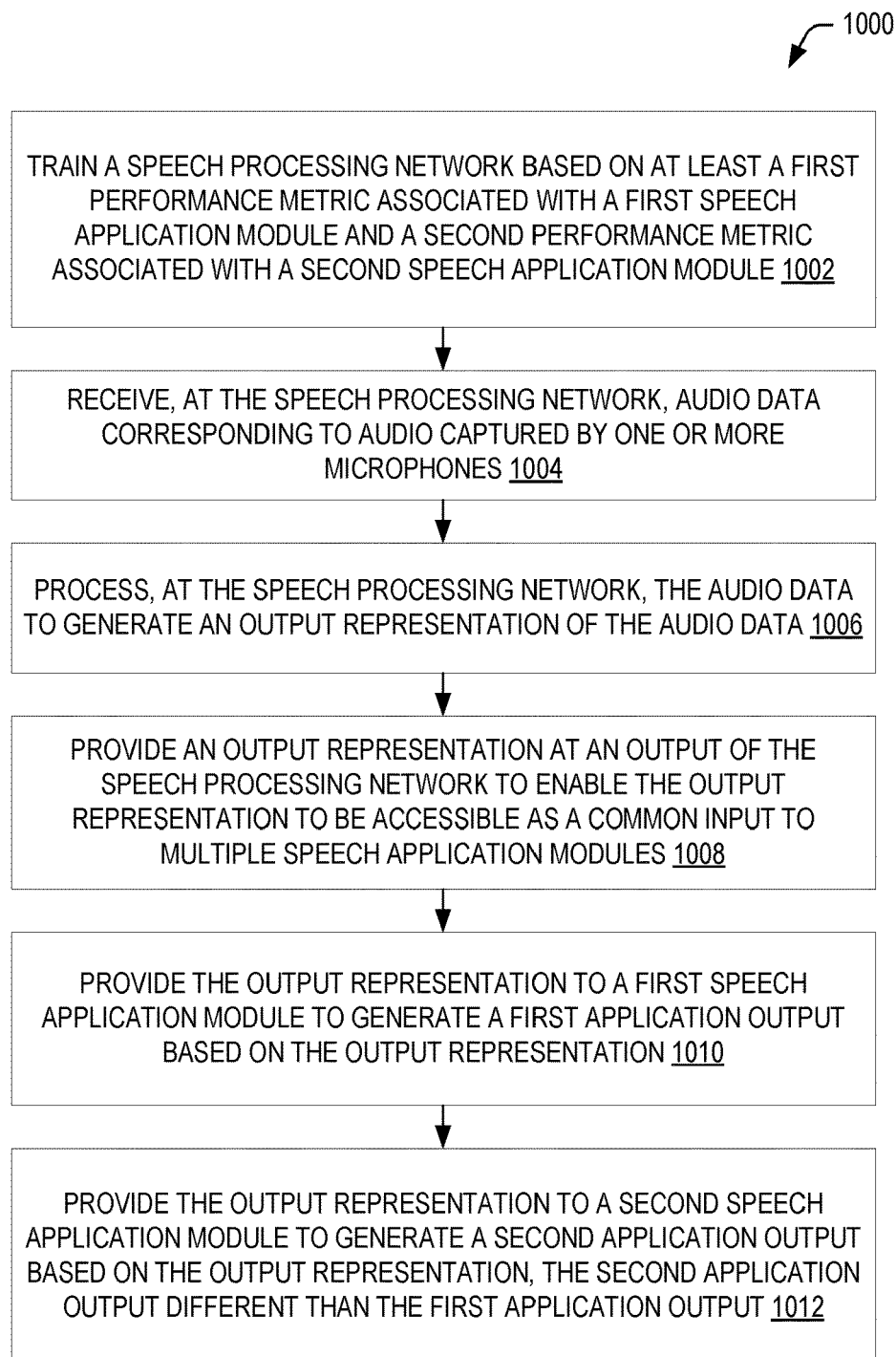


FIG. 9

**FIG. 10**

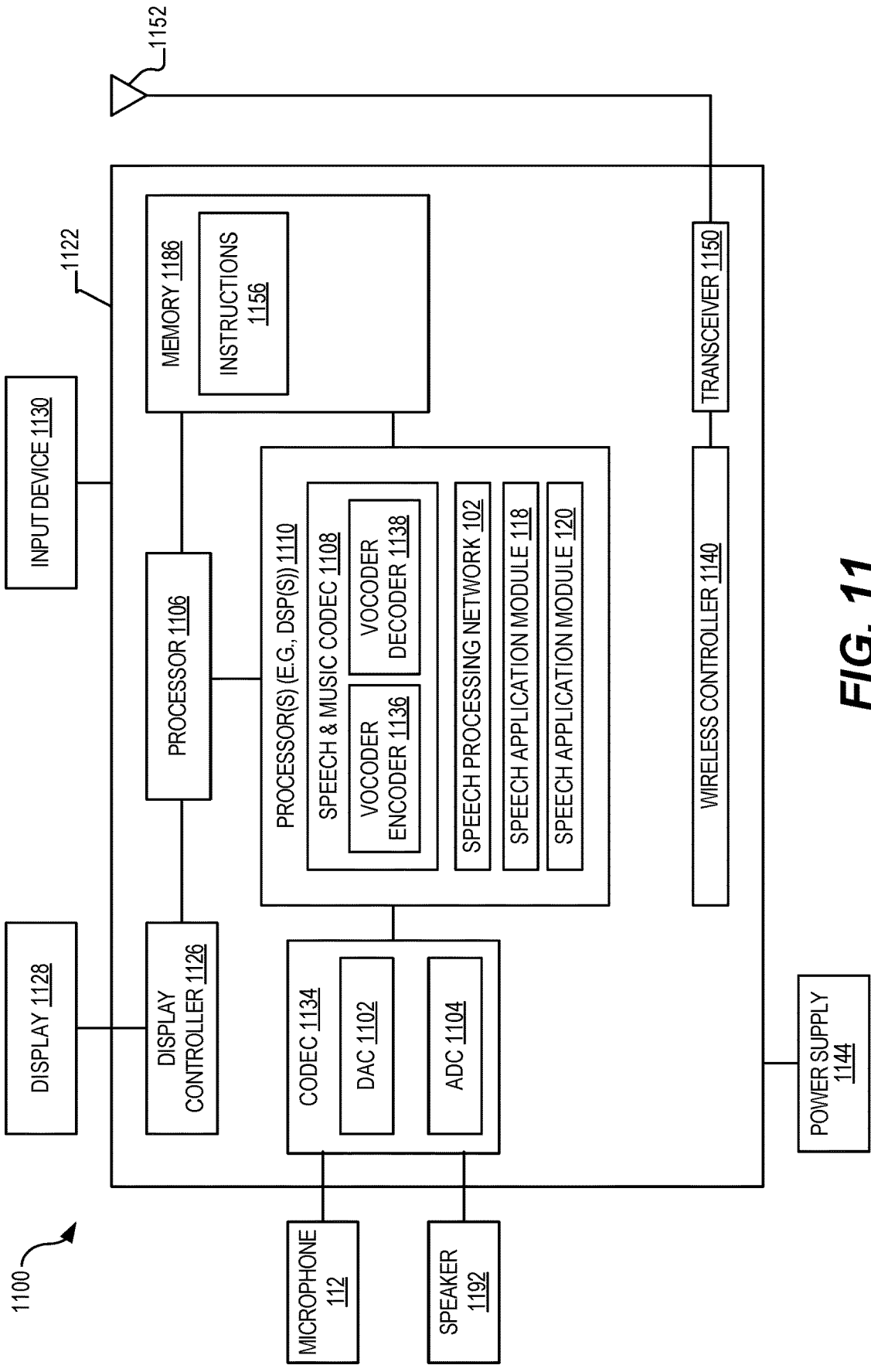


FIG. 11

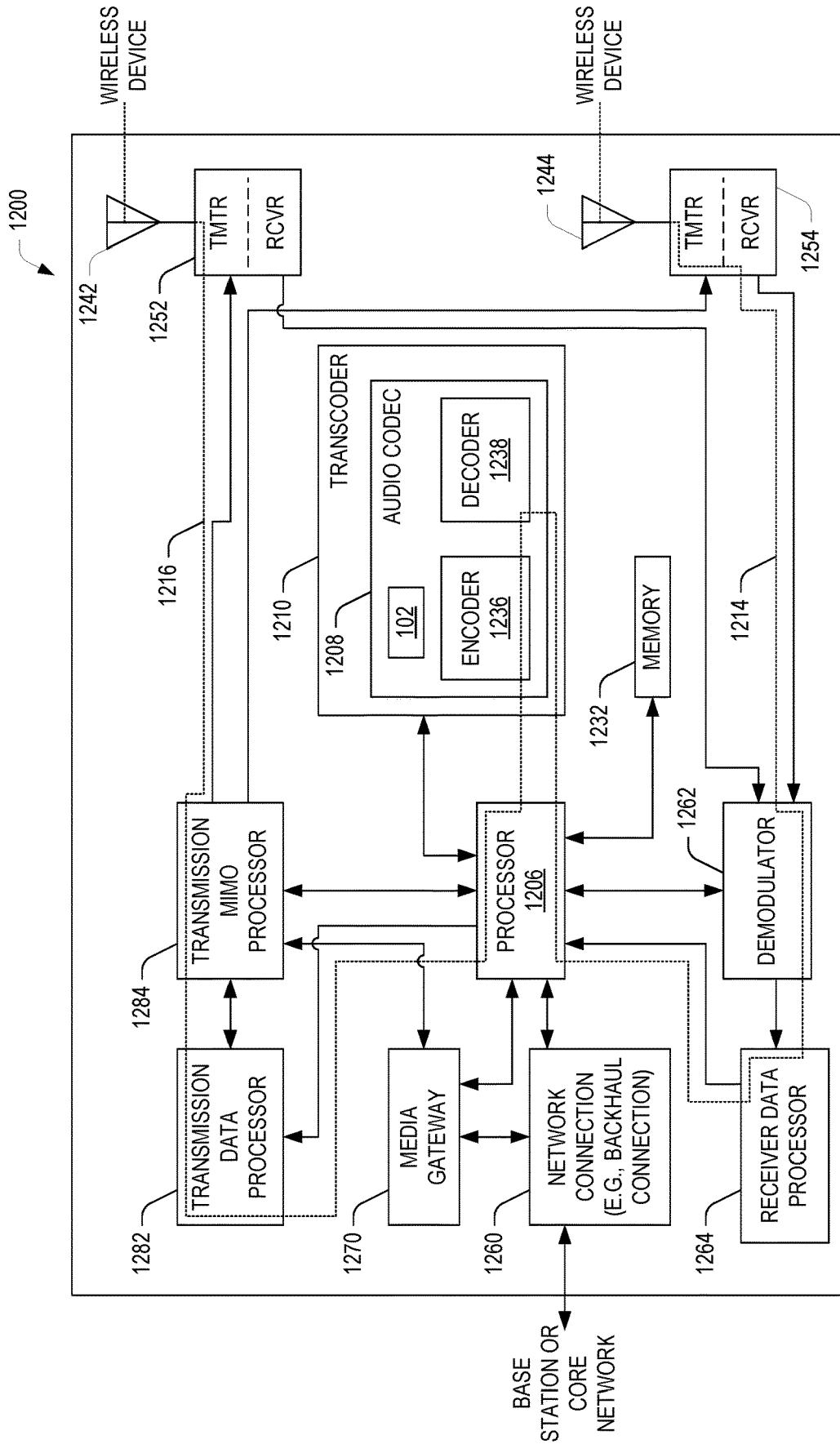


FIG. 12

SHARED SPEECH PROCESSING NETWORK FOR MULTIPLE SPEECH APPLICATIONS

I. CROSS-REFERENCE TO RELATED APPLICATIONS(S)

The present application claims priority from and is a continuation application of U.S. patent application Ser. No. 16/844,836, filed Apr. 9, 2020, and entitled "SHARED SPEECH PROCESSING NETWORK FOR MULTIPLE SPEECH APPLICATIONS," the content of which is incorporated herein by reference in its entirety.

II. FIELD

The present disclosure is generally related to speech processing.

III. DESCRIPTION OF RELATED ART

Advances in technology have resulted in smaller and more powerful computing devices. For example, a variety of portable personal computing devices, including wireless telephones such as mobile and smart phones, tablets, and laptop computers are small, lightweight, and easily carried by users. These devices can communicate voice and data packets over wireless networks. Further, many such devices incorporate additional functionality such as a digital still camera, a digital video camera, a digital recorder, and an audio file player. Also, such devices can process executable instructions, including software applications, such as a web browser application, that can be used to access the Internet. As such, these devices can include significant computing capabilities.

Many such devices perform processing of speech for various purposes. For example, speech recognition devices, such as virtual assistants, can translate spoken commands into actions that are to be performed. As another example, speaker identification can identify a user based on voice or speech characteristics, such as to determine whether a speaker is an authorized user of the device. Neural networks have become popular to enable speech processing due to the high performance attainable using neural networks as compared to alternative techniques. However, neural network applications for speech processing can be computation-intensive with a relatively large memory footprint and, in general, improvements in speech processing performance are usually associated with increases in the complexity and model size of the neural network applications.

As a result, high-performance neural network speech processing can be difficult to deploy in memory- or computation-constrained environments, such as a smart phone, a "smart watch," or another battery-powered personal electronic device. Additionally, because different aspects of speech processing implement different models, memory and computation constraints further impact the number of speech processing applications that can be concurrently run at such devices. For example, concurrently processing audio data to concurrently perform both speech recognition (e.g., recognizing speech in a speaker-agnostic manner) and speaker identification (e.g., recognizing a speaker in a speech-agnostic manner) can double the computation and memory usage as compared to performing speech recognition or speaker identification individually.

Various techniques have been introduced to improve the efficiency of applying neural network-based solutions in other contexts, such as text-based tasks. As an example,

Bidirectional Encoder Representations from Transformers (BERT) is a technique for language understanding that reduces an amount of training time required to generate models for specific tasks related to language understanding. In BERT, a model is pre-trained using unlabeled textual input, and the pre-trained model can subsequently be fine-tuned for use with different text-based tasks, such as question answering and language inference, without substantial task-based architecture modifications.

Although techniques such as BERT can reduce the development time associated with creating text-based applications, the techniques do not alleviate the underlying issue of providing multiple speech processing models concurrently in a constrained environment. Solutions that enable concurrent, high-performance speech processing applications to be implemented in a resource-constrained environment can improve a user experience, such as by enabling concurrently keyword detection and speaker authentication from a single phrase uttered by the user instead of requiring the user to speak one phrase for speaker authentication and a second phrase for keyword detection, as an illustrative, non-limiting example.

IV. SUMMARY

According to one implementation of the techniques disclosed herein, a device includes a speech processing network that includes an input configured to receive audio data corresponding to audio captured by one or more microphones. The speech processing network also includes one or more network layers configured to process the audio data to generate an output representation of the audio data. The speech processing network includes an output configured to be coupled to multiple speech application modules to enable the output representation to be provided as a common input to each of the multiple speech application modules.

According to another implementation of the techniques disclosed herein, a method of speech processing includes receiving, at a speech processing network, audio data corresponding to audio captured by one or more microphones. The method includes processing, at the speech processing network, the audio data to generate an output representation of the audio data. The method also includes providing the output representation at an output of the speech processing network to enable the output representation to be accessible as a common input to multiple speech application modules.

According to another implementation of the techniques disclosed herein, a non-transitory computer-readable medium includes instructions that, when executed by one or more processors, cause the one or more processors to receive, at a speech processing network, audio data corresponding to audio captured by one or more microphones. The instructions, when executed by the one or more processors, cause the one or more processors to process, at the speech processing network, the audio data to generate an output representation of the audio data. The instructions, when executed by the one or more processors, cause the one or more processors to provide the output representation at an output of the speech processing network to enable the output representation to be accessible as a common input to multiple speech application modules.

According to another implementation of the techniques disclosed herein, an apparatus includes means for receiving audio data corresponding to audio captured by one or more microphones. The apparatus also includes means for processing the audio data to generate an output representation of the audio data. The apparatus further includes means for

providing the output representation to be accessible as a common input to multiple means for performing speech applications.

Other implementations, advantages, and features of the present disclosure will become apparent after review of the entire application, including the following sections: Brief Description of the Drawings, Detailed Description, and the Claims.

V. BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram of a particular illustrative implementation of a system including a device that includes a shared speech processing network for multiple speech applications, in accordance with some examples of the present disclosure.

FIG. 2 is a diagram of a particular implementation of the device of FIG. 1, in accordance with some examples of the present disclosure.

FIG. 3 is a diagram of a particular illustrative implementation of a system that includes a shared speech processing network for multiple speech applications, in accordance with some examples of the present disclosure.

FIG. 4 is a diagram of a particular example of training a shared speech processing network for multiple speech applications, in accordance with some examples of the present disclosure.

FIG. 5 illustrates an example of an integrated circuit that includes a speech processing network for multiple speech applications, in accordance with some examples of the present disclosure.

FIG. 6 is a diagram of a first example of a vehicle that includes a shared speech processing network for multiple speech applications, in accordance with some examples of the present disclosure.

FIG. 7 is a diagram of a headset, such as a virtual reality or augmented reality headset, that includes a shared speech processing network for multiple speech applications, in accordance with some examples of the present disclosure.

FIG. 8 is a diagram of a wearable electronic device that includes a shared speech processing network for multiple speech applications, in accordance with some examples of the present disclosure.

FIG. 9 is a diagram of a voice-controlled speaker system that includes a shared speech processing network for multiple speech applications, in accordance with some examples of the present disclosure.

FIG. 10 is diagram of a particular implementation of a method of speech processing that may be performed by the device of FIG. 1, in accordance with some examples of the present disclosure.

FIG. 11 is a block diagram of a particular illustrative example of a device that includes a shared speech processing network for multiple speech applications, in accordance with some examples of the present disclosure.

FIG. 12 is a block diagram of a particular illustrative example of a base station that includes a shared speech processing network for multiple speech applications, in accordance with some examples of the present disclosure.

VI. DETAILED DESCRIPTION

A shared speech processing network for multiple speech applications is described. Because high-performance neural network-based speech processing can be computation-intensive with a relatively large memory footprint, conventional neural network speech processing can be difficult to deploy in memory- or computation-constrained devices. Addition-

ally, because different models are used for different aspects of speech processing conventionally, memory and computation constraints further impact the number of speech processing applications that can be concurrently run at such devices.

The shared speech processing network for multiple speech applications of the present disclosure is configured to generate, for an audio input, an output that is appropriate for use by multiple different speech processing applications. In some implementations, the shared speech processing network processes a microphone input to generate an embedding (e.g., a feature vector) representative of the microphone input. The embedding is provided as a common output to multiple neural networks that are each configured to perform different speech applications. As used herein, the term “common” is used in accordance with its dictionary definition of “shared by, coming from, or done by more than one.” It should be noted that the term “common” is not used herein as a synonym for “usual,” “ordinary,” or “customary.” Instead, the term “conventional” is used to indicate that which is usual, ordinary, or customary.

In some implementations, the shared speech processing network is trained to reduce losses associated with multiple speech processing applications, such as speech enhancement, speech recognition, and speaker recognition (as non-limiting examples), to generate an output that provides high-quality information for use by each of the speech processing applications. Because each of the speech processing applications uses the common output, at least a portion of the processing that conventionally would be performed independently, and thus duplicated, by each of the speech processing applications is instead performed by the shared speech processing network. As a result, each of the speech processing applications can have a smaller model with reduced computation and memory requirement as compared to conventional applications, and the smaller models can be more efficiently trained as compared to conventional models. Further, overall computation and memory usage are reduced by reducing or removing duplication of processing among concurrently executing speech processing models.

In addition to reducing or removing duplication of processing between multiple concurrent speech processing applications, in some implementations processing resource (e.g., digital signal processor (DSP) or other processor cores) usage is further reduced using a hardware implementation of the shared speech processing network. Because the network topology and coefficients associated with the shared speech processing network are set independently of any later-added speech processing applications, the network topology, the coefficients, or both, can be implemented using dedicated circuitry for faster performance, reduced power consumption, and reduced use of processor resources and memory.

Particular aspects of the present disclosure are described below with reference to the drawings. In the description, common features are designated by common reference numbers. As used herein, various terminology is used for the purpose of describing particular implementations only and is not intended to be limiting of implementations. For example, the singular forms “a,” “an,” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It may be further understood that the terms “comprise,” “comprises,” and “comprising” may be used interchangeably with “include,” “includes,” or “including.” Additionally, it will be understood that the term “wherein” may be used interchangeably with “where.” As used herein, “exemplary” may indicate an example, an

implementation, and/or an aspect, and should not be construed as limiting or as indicating a preference or a preferred implementation. As used herein, an ordinal term (e.g., “first,” “second,” “third,” etc.) used to modify an element, such as a structure, a component, an operation, etc., does not by itself indicate any priority or order of the element with respect to another element, but rather merely distinguishes the element from another element having a same name (but for use of the ordinal term). As used herein, the term “set” refers to one or more of a particular element, and the term “plurality” refers to multiple (e.g., two or more) of a particular element.

In the present disclosure, terms such as “determining,” “calculating,” “estimating,” “shifting,” “adjusting,” etc. may be used to describe how one or more operations are performed. It should be noted that such terms are not to be construed as limiting and other techniques may be utilized to perform similar operations. Additionally, as referred to herein, “generating,” “calculating,” “estimating,” “using,” “selecting,” “accessing,” and “determining” may be used interchangeably. For example, “generating,” “calculating,” “estimating,” or “determining” content (or a signal) may refer to actively generating, estimating, calculating, or determining the content (or the signal) or may refer to using, selecting, or accessing the content (or signal) that is already generated, such as by another component or device.

As used herein, “coupled” may include “communicatively coupled,” “electrically coupled,” or “physically coupled,” and combinations thereof. Two devices (or components) may be coupled (e.g., communicatively coupled, electrically coupled, or physically coupled) directly or indirectly via one or more other devices, components, wires, buses, networks (e.g., a wired network, a wireless network, or a combination thereof), etc. Two devices (or components) that are electrically coupled may be included in the same device or in different devices and may be connected via electronics, one or more connectors, or inductive coupling, as illustrative, non-limiting examples. In some implementations, two devices (or components) that are communicatively coupled, such as in electrical communication, may send and receive electrical signals (digital signals or analog signal) directly or indirectly, such as via one or more wires, buses, networks, etc.

Referring to FIG. 1, an illustrative example of a system 100 is shown. The system 100 includes a device 122 that is configured to process speech and includes a speech processing network 102. The speech processing network 102 is configured to receive audio data 126 from one or more microphones 124 and to process the audio data 126 to generate an output representation 110 as a common output that is used by multiple speech application modules. In some implementations, the device 122 corresponds to or is included in a vehicle, such as depicted in FIG. 6, a headset, such as depicted in FIG. 7, a wearable electronic device, such as depicted in FIG. 8, a smart speaker system, such as depicted in FIG. 9, or a communication device such as a portable electronic device, as depicted in FIG. 11, or a base station, as depicted in FIG. 12.

The one or more microphones 124 are configured to capture audio, such as audio 134 (e.g., speech) from a user 132. The one or more microphones 124 include a first microphone 112 configured to generate first audio data 136, a second microphone 114 configured to generate second audio data 138, and a third microphone 116 configured to generate third audio data 140. The first audio data 136, the second audio data 138, and the third audio data 140 are received at the device 122 as the audio data 126. According

to one implementation, one or more of the first audio data 136, the second audio data 138, or the third audio data 140 is an analog signal. According to another implementation, one or more of the first audio data 136, the second audio data 138, or the third audio data 140 is a digital signal. For example, in response to capturing the audio 134, each of the first microphone 112, second microphone 114, and third microphone 116 can perform a respective analog-to-digital conversion (ADC) operation to convert the audio 134 to a respective digital signal. Although three microphones are illustrated, other implementations can include any other number of microphones, such as one microphone, two microphones, or four or more microphones.

The device 122 includes one or more processors 150 coupled to a memory 152. The one or more processors 150 include a speech processing network 102, a first speech application module 118, and a second speech application module 120. Although two speech application modules 118 and 120 are illustrated, in other implementations three or more speech application modules can be used, such as described further with reference to FIG. 2 and FIG. 3.

In some implementations, one or more of the speech processing network 102, the first speech application module 118, or the second speech application module 120 are implemented via execution, by the one or more processors 150, of instructions stored at the memory 152. According to one implementation, one or more components of the one or more processors 150 (e.g., the input 106, the one or more network layers 104, the output 108, the first speech application module 118, and the second speech application module 120) can be implemented using dedicated circuitry, such as an application-specific integrated circuit (ASIC) or a field-programmable gate array (FPGA).

The speech processing network 102 includes an input 106, one or more network layers 104, and an output 108. The input 106 is configured to receive audio data 126 corresponding to audio captured by the one or more microphones 124. In an example, the input 106 includes one or more bus interfaces, such as a multi-channel audio bus interface, to enable the audio data 126 to be received from the one or more microphones 124.

The one or more network layers 104 are configured to process the audio data 126 to generate an output representation 110 of the audio data 126. In a particular implementation, the one or more network layers 104 include stacked long short-term memory (LSTM), gated recurrence unit (GRU) layers, or a combination thereof. The output 108 is configured to be coupled to multiple speech application modules to enable the output representation 110 to be provided as a common input to each of the multiple speech application modules 118 and 120. For example, the output 108 can include one or more bus interfaces, one or more registers or buffers, or a dedicated region of a memory that is accessible to the first speech application module 118 and the second speech application module 120.

The first speech application module 118 is coupled to the output 108 and is configured to generate a first application output 128 based on the output representation 110. In an illustrative example, the first speech application module 118 corresponds to at least one of a speech recognition network, a voice activation detector, a speaker verifier, a speaker recognizer, or a speech enhancer. In some implementations, a speech recognition network is configured to output text corresponding to input data, a voice activation detector is configured to generate an output representative of whether a wake-up phrase (e.g., “Hey, Snapdragon”) has been detected in the input data, a speaker verifier is configured to generate

an output indicative of whether the input data exhibits voice characteristics matching a particular speaker, a speaker recognizer is configured to generate an output indicating which of several stored speaker profiles match the voice characteristics exhibited in the input data, and a speech enhancer is configured to enhance the audio associated with the input data (e.g., denoising, echo cancellation, etc.) such as to generate an enhanced speech signal for telephone, playback, etc.

The second speech application module **120** is coupled to the output **108** and is configured to generate a second application output **130** based on the output representation **110**. The second application output **130** is different than the first application output **128**. For example, in one implementation the first speech application module **118** is a speech enhancer and the second speech application module **120** is a speaker recognizer, while in another implementation the first speech application module **118** is a speech recognizer and the second speech application module **120** is a speaker verifier.

During operation, the one or more microphones **124** capture the audio data **126** responsive to receiving the audio **134**. The audio data **126** is received at the input **106** and processed at the one or more network layers **104** to generate the output representation **110**. The output representation **110** is provided as an input to the first speech application module **118** and to the second speech application module **120**.

The first speech application module **118** and the second speech application module **120** operate in parallel with each other, with the first speech application module **118** processing the output representation **110** concurrently with the second speech application module **120** processing the output representation **110**. The first application output **128** (e.g., text generated during speech recognition) and the second application output **130** (e.g., a verification of whether the source of the audio **134** matches stored speech characteristics associated with the user **132**) are provided to one or more other applications (not shown), such as a digital voice assistant.

The combination of the speech processing network **102** and the first speech application module **118** operates in a similar manner as a multi-stage speech application module, with the speech processing network **102** functioning as a first stage and the first speech application module **118** functioning as a second stage. The combination of the speech processing network **102** and the second speech application module **120** also operate in a similar manner as a multi-stage speech application module, with the speech processing network **102** functioning as a first stage and the second speech application module **120** functioning as a second stage. By "sharing" the first stage among multiple speech processing applications, overall power consumption and memory usage is reduced as compared to concurrently running multiple conventional speech processing applications.

In some implementations, prior to the speech processing network **102** being incorporated into the device **122**, the one or more network layers **104** are trained to reduce or minimize losses associated with using the output representation **110** in a variety of different applications so that the output representation **110** is broadly applicable for use in a wide range of speech processing applications. For example, the one or more network layers **104** may be trained based on at least a first performance metric associated with a first speech application module and a second performance metric associated with a second speech application module, which may be the same as, or different from, the first speech application

module **118** and the second speech application module **120**, respectively. In an example, the one or more network layers **104** are trained responsive to a combined performance metric that corresponds to a combination of at least the first performance metric and the second performance metric. To illustrate, the first speech application module may include at least one of a speech enhancement module, a speech recognition module, or a speaker recognition module. The second speech application module may include a different one of the speech enhancement module, the speech recognition module, or the speaker recognition module, or may include a different type of module. An example of training of the one or more network layers **104** is provided with reference to FIG. 4.

Because each of the speech application modules **118** and **120** uses the common output representation **110**, at least a portion of the processing that conventionally would be performed independently, and thus duplicated, by each of the speech application modules **118** and **120** is instead performed by the shared speech processing network **102**. As a result, overall computation and memory usage are reduced by reducing or removing duplication of processing by sharing the speech processing network **102**. Further, each of the speech application modules **118** and **120** can have a smaller model with reduced computation and memory requirement as compared to conventional applications, and the smaller models can be more efficiently trained as compared to conventional models. Additional speech processing applications that use the output representation **110** as the input to be processed may be developed and later added, such as via an end-user initiated download to the device **122**.

FIG. 2 depicts an example **200** of components that can be implemented in the device **122** according to a particular implementation. In the example **200**, the device **122** includes five speech applications that are coupled to the output **108** of the speech processing network **102** and that receive the output representation **110** as input: a speech recognition network **202**, a voice activation detector **204**, a speaker verifier **206**, a speaker recognizer **208**, and a speech enhancer **210**.

The input **106** of the speech processing network **102** is configured to synchronously receive multiple frames of the audio data **126**. In an illustrative example, each of the multiple frames is received from a respective microphone of the one or more microphones **124** of FIG. 1. To illustrate, a first input frame **222** is received from the first microphone **112**, a second input frame **224** is received from the second microphone **114**, and a third input frame **226** is received from the third microphone **116**. The frames **222**, **224**, and **226** are received substantially concurrently at the input **106** and represent the same, or substantially the same, sampling window of captured audio (e.g., a 20 millisecond window) from the one or more microphones **124**.

The speech processing network **102** is configured to process the multiple frames **222**, **224**, and **226** to generate a single frame **228** of the output representation **110**. The output frame **228** corresponds to a common framewise embedding of the multiple frames **222**, **224**, and **226** received as input audio data. The output frame **228** is provided as the output representation **110** to be available for processing by the speech recognition network **202**, the voice activation detector **204**, the speaker verifier **206**, the speaker recognizer **208**, and the speech enhancer **210**.

The speech recognition network **202** is configured to process the output frame **228** and to generate a speech recognition output **212** that includes decoded text (e.g., words or characters) corresponding to the captured audio.

The voice activation detector **204** is configured to generate a voice activation output **214** that is representative of whether that captured audio includes a wake-up phrase (e.g., “Hey, Snapdragon”). The speaker verifier **206** is configured to generate a speaker verification output **216** indicative of whether the captured audio exhibits voice characteristics matching a particular speaker. The speaker recognizer **208** is configured to generate a speaker recognition output **218** indicating which of several stored speaker profiles available to the device **122** matches the voice characteristics of the captured audio (or indicating when none of the speaker profiles match the captured audio). The speech enhancer **210** is configured to enhance the captured audio associated with the input frames **222**, **224**, and **226** (e.g., denoising, echo cancellation, etc.) to generate an enhanced speech output **220**, such as for use in telephony or video conferencing, recording, or playback, as illustrative, non-limiting examples.

Although three input frames are depicted, in other implementations the speech processing network **102** is configured to receive one, two, or more than three frames concurrently at the input **106**. In some implementations, the input **106** is sized to receive a fixed number of frames, corresponding to an upper limit of the number of simultaneously operating microphones that can be used for speech processing. The fixed number of frames may be independent of the actual number of microphones included in, or coupled to, the device **122**. In implementations in which the device **122** has (or uses) fewer microphones than the input frame capacity of the input **106**, one or more portions of the input **106** may be unused (e.g., set to “0” values). In implementations in which the device **122** has (or uses) more microphones than the input frame capacity of the input **106**, the audio data from one or more of the microphones may be discarded, such as by discarding the microphone input that has the lowest signal energy in a frequency range associated with speech (e.g., 20-20,000 Hertz).

Referring to FIG. 3, an illustrative example of a system **300** is shown in which the speech processing network **102** is deployed for operation of a conference call between Korean-speaking participants and English-speaking participants. The speech processing network **102** is coupled to provide the output representation **110** to each of multiple modules **302-318**.

A first module **302**, such as a speech enhancer, is configured to process the output representation **110** to generate clean speech **320**. A second module **304**, such as a language detector, is configured to process the output representation **110** to indicate a detected language **322**. A third module **306**, such as an English speech recognizer, is configured to process the output representation **110** to generate an English transcription **324**. A fourth module **308**, such as a Korean speech recognizer, is configured to process the output representation **110** to generate a Korean transcription **326**. A fifth module **310**, such as a speaker recognizer, is configured to process the output representation **110** to generate a speaker identifier **328**.

A sixth module **312**, such as a first translation model, is configured to process the output representation **110** to generate an English-to-Korean translation **330**. A seventh module **314**, such as a second translation model, is configured to process the output representation **110** to generate a Korean-to-English translation **332**. An eighth module **316**, such as a first speech synthesizer, is configured to process the output representation **110** to generate a speech synthesis for Korean **334**. A ninth module **318**, such as a second speech synthe-

sizer, is configured to process the output representation **110** to generate a speech synthesis for English **336**.

In some implementations, information is exchanged between one or more of the modules **302-318**. In an illustrative, non-limiting example, language identification (e.g., the detected language **322**) can be used for speech recognition engines for English (e.g., the third module **306**) or Korean (e.g., the fourth module **308**).

During operation, the speech processing network **102** can be implemented in a conference call system. Korean-speaking people at one or more first locations, each wearing a headset, and English-speaking people at one or more second locations, each wearing a headset, may connect (e.g., dial-in or otherwise establish communication) with the conference call system. Each speaker may speak during the conference call using that speaker’s preferred language (e.g., Korean or English).

The system can perform several speech processing functions simultaneously. For example, speech enhancement is performed to provide a high-quality speech stream to call participants, from what may be a noisy or distorted speech input from a speaker. Each speaker’s identity is detected for informing listeners of which participant is speaking. The language being spoken (e.g., Korean) is detected to transcribe and translate to the other language (e.g., English). The translated speech can be synthesized, based on which speaker uttered the speech, and played out to emulate the voice characteristics of that speaker.

Thus, the system **300** illustrates an example of a relatively large number of specific application modules performing a large variety of speech processing tasks that can be used concurrently in conjunction with the single speech processing network **102**.

FIG. 4 is an illustrative example of a training operation **400** in which the one or more network layers **104** of the speech processing network **102** are trained by a network training device **450** based on one or more performance metrics. In some implementations, the network training device **450** corresponds to a computing device that includes one or more processors and a memory. In an example, the network training device **450** corresponds to one or more servers or high-performance computing platforms to perform computationally intensive workloads associated with the training operation **400**, and after the training operation **400** is complete, the trained speech processing network **102** is provided to the device **122** of FIG. 1. In another example, the training device **450** corresponds to the device **122** of FIG. 1 and the training operation **400** is performed by the one or more processors **150** of FIG. 1.

During the training operation **400**, the output **108** of the speech processing network **102** is coupled to inputs of a speech enhancement module **406**, a speaker recognition module **408**, and a speech recognition module **410**. Clean speech **404** is provided as training data and used to generate noisy speech **402**, such as via addition of a Gaussian noise signal to the clean speech **404**, as an illustrative, non-limiting example. The noisy speech **402** is input to the speech processing network **102** and processed to generate an output representation **110** corresponding to the noisy speech **402**.

The speech enhancement module **406** processes the output representation **110** to generate a speech enhancement output **412**. The speech enhancement output **412** is compared to the clean speech **404** to generate a first performance metric **418**. For example, the first performance metric **418** can correspond to a L1 metric (e.g., an absolute value of a difference between the speech enhancement output **412** and

the clean speech **404**), a mean-squared error (MSE) metric, one or more other metrics based on the similarity or difference between the speech enhancement output **412** and the clean speech **404**, or any combination thereof.

The speaker recognition module **408** processes the output representation **110** to generate a speaker recognition output **414**. The speaker recognition output **414** is compared to speaker identification data associated with the clean speech **404** to generate a second performance metric **420** based on an accuracy of the speaker recognition output **414**.

The speech recognition module **410** processes the output representation **110** to generate a speech recognition output **416**. The speech recognition output **416** is compared to speech data (e.g., a transcription) associated with the clean speech **404** to generate a third performance metric **422** based on accuracy of the speech recognition output **416**.

The first performance metric **418**, the second performance metric **420**, and the third performance metric **422** are used to generate a combined performance metric **424**. For example, the combined performance metric **424** may represent a sum or average of the first performance metric **418**, the second performance metric **420**, and the third performance metric **422**. In some implementations, weightings may be used based on relative importance or effect of each of the first performance metric **418**, the second performance metric **420**, or the third performance metric **422** in the training operation **400**.

The first performance metric **418**, the second performance metric **420**, the third performance metric **422**, the combined performance metric **424**, or any combination thereof, is used to update coefficients of the speech processing network **102**, such as via backpropagation. In some aspects, the first performance metric **418**, the second performance metric **420**, the third performance metric **422**, the combined performance metric **424**, or any combination thereof, is also used to update coefficients of one or more of the speech enhancement module **406**, the speaker recognition module **408**, and the speech recognition module **410**. Training may continue until each of the first performance metric **418**, the second performance metric **420**, the third performance metric **422**, and the combined performance metric **424** satisfies the respective threshold value for that particular performance metric.

In an illustrative example, the first performance metric **418** corresponds to a speech enhancement loss, the second performance metric **420** corresponds to a speaker recognition loss, and the third performance metric **422** corresponds to a speech recognition loss. Speech enhancement is known to be beneficial for a wide range (or all) speech inference problems. Speech recognition focuses on utterances regardless of the speaker's identity, and speaker recognition focuses on the speaker's identity regardless of the utterances. The speech recognition loss and the speaker recognition loss are largely disjoint from each other, while the speech enhancement loss is common for both of the speech recognition loss and the speaker recognition loss. In other words, an output representation **110** that results in poor speech enhancement at the speech enhancement module **406** will also negatively affect the accuracy of speaker recognition and speech recognition. However, an output representation **110** that results in poor speaker recognition is unlikely to negatively affect the accuracy of speech recognition, and an output representation **110** that results in poor speech recognition is unlikely to negatively affect the accuracy of speaker recognition.

By training the speech processing network **102** to generate an output representation **110** that enables accurate speech

enhancement, speaker recognition, and speech recognition, the speech processing network **102** provides broad applicability for use with a wide range of speech processing applications. Although only three processing modules **406**, **408**, and **410** are illustrated, in other implementations one or more fewer, additional, or different speech processing modules may be used during training of the speech processing network **102**.

Although the speech enhancement module **406**, the speaker recognition module **408**, and the speech recognition module **410** are used in the training operation **400**, such modules are not necessarily the same modules depicted in FIGS. 1-3. For example, in some implementations the speech processing network **102** is provided for incorporation into a device without also providing one or more of the speech enhancement module **406**, the speaker recognition module **408**, and the speech recognition module **410**. Other suppliers may separately provide modules to perform the various speech applications using the output of the speech processing network **102**, and the separately provided modules may have different network topologies and different (e.g., improved) accuracy as compared to the corresponding modules that were used during training of the speech processing network **102**.

FIG. 5 depicts an example of the speech processing network **102** implemented in an application-specific integrated circuit (ASIC) **508**. The input **106** of the speech processing network **102** is coupled to a chip interface **510** to enable processing of audio data received via the chip interface **510**. The output **108** of the speech processing network **102** is also coupled to the chip interface **510** to enable the output representation **110** to be provided to speech application modules that are external to the ASIC **508**.

In some implementations, the speech processing network **102** is implemented via a processor (e.g., the one or more processors **150** of FIG. 1). In other implementations, the speech processing network **102** is implemented in hardware, such as using dedicated circuitry corresponding to the specific network topology of the one or more network layers **104**, the coefficients associated with cells of the one or more network layers **104**, or both.

The ASIC **508** enables implementation of the speech processing network **102** into a variety of systems that include one or more microphones, such as a vehicle as depicted in FIG. 6, a virtual reality or augmented reality headset as depicted in FIG. 7, a wearable electronic device as depicted in FIG. 8, a voice-controlled speaker system as depicted in FIG. 9, or a wireless communication device as depicted in FIG. 11.

FIG. 6 depicts an example of a vehicle **600** that includes the speech processing network **102**. According to one implementation, the vehicle **600** is a self-driving car. According to other implementations, the vehicle **600** can be a car, a truck, a motorcycle, an aircraft, a water vehicle, etc. The vehicle **600** includes multiple microphones **604** (illustrated using dashed lines to indicate internal components that are not necessarily visible to occupants of the vehicle **600**) that are arranged within a cabin to enable capture of utterances by the operator and passengers of the vehicle **600**. In a particular aspect, the microphones **604** correspond to the one or more microphones **124** of FIG. 1.

Audio data received from one or more of the microphones **604** can be processed by the speech processing network **102** to generate an output representation **110** for further speech application processing. For example, the vehicle **600** may include a hands-free speech interface that enables users to say a destination for a navigation application. The speech

13

processing network **102** generates an output representation **110** based on audio data corresponding to speech of a user and provides the output representation **110** to a speech recognition module, which in turn processes the output representation **110** and provides a textual representation of the speech as an input to the navigation application. In other implementations, the navigation application processes the output representation **110** to perform speech recognition (e.g., without using an intervening speech processing module). The navigation application generates navigation directions and/or a map that may be displayed on a screen **602**. Other examples include entertainment system controls, personal assistant inquiries or instructions, driver (or other occupant) authentication for security, one or more other voice-based applications, or any combination thereof.

FIG. 7 depicts an implementation **700** in which the speech processing network **102** and one or more microphones, such as the first microphone **112**, are integrated in a portable electronic device that corresponds to a virtual reality, augmented reality, or mixed reality headset **702**. Speech processing can be performed based on an audio signal received from the microphone **112** of the headset **702**. A visual interface device, such as a screen **750**, is positioned in front of the user's eyes to enable display of augmented reality or virtual reality images or scenes to the user while the headset **702** is worn. In a particular example, the screen **750** is configured to display a notification indicating results (e.g., via launching an application or navigating a graphical user interface) of processing speech received via the microphone **112**. To illustrate, the speech processing network **102** generates an output representation **110** based on audio data received from the microphone **112** and provides the output representation **110** to an application. The application processes the output representation **110** and generates a notification that may be displayed on the screen **750**.

FIG. 8 depicts an implementation **800** in which the device **122** is a portable electronic device that corresponds to a wearable electronic device **802**, illustrated as a "smart watch." The speech processing network **102** and one or more microphones, such as the first microphone **112**, are integrated into the wearable electronic device **802**. Speech processing can be performed based on an audio signal received from the microphone **112** of the wearable electronic device **802**. The wearable electronic device **802** includes a display screen **850** that is configured to display a notification indicating results (e.g., via launching an application or navigating a graphical user interface) of processing speech received via the microphone **112**.

FIG. 9 is an illustrative example of a voice-controlled speaker system **900** in which the speech processing network **102** is implemented in an audio device that includes a wireless speaker and a voice activated device with an integrated assistant application **902**. The wireless speaker and voice activated device can have wireless network connectivity and is configured to execute an assistant operation. The speech processing network **102**, one or more microphones, such as the first microphone **112**, and a speaker **904** are included in the wireless speaker and voice activated device. During operation, in response to receiving a verbal command via the first microphone **112**, the verbal command can be processed by the speech processing network **102** and one or more other speech processing modules, such as a speech recognition module and a speaker recognition module, and results of the speech processing can be provided to the integrated assistant application **902**. The integrated assis-

14

tant application **902** can initiate operations responsive to the verbal command, such as adjusting a temperature, playing music, turning on lights, etc.

Referring to FIG. 10, a flowchart of a method **1000** of speech processing is shown. The method **1000** can be performed by any of the devices or systems of FIGS. 1-9, or any combination thereof.

In some implementations, the method **1000** includes, at **1002**, training a speech processing network based on at least a first performance metric associated with a first speech application module and a second performance metric associated with a second speech application module. For example, the network training device **450** of FIG. 4 performs the training operation **400** to train the speech processing network **102** based on the first performance metric **418** associated with the speech enhancement module **406**, the second performance metric **420** associated with the speaker recognition module **408**, and the third performance metric **422** associated with the speech recognition module **410**. In some examples, the speech processing network **102** is trained responsive to a combined performance metric, such as the combined performance metric **424**, that corresponds to a combination of at least the first performance metric and the second performance metric. In some examples, the first speech application module includes at least one of a speech enhancement module, a speech recognition module, or a speaker recognition module.

The method **1000** includes, at **1004**, receiving, at the speech processing network, audio data corresponding to audio captured by one or more microphones. For example, the speech processing network **102** of FIG. 1 receives the audio data **126** corresponding to the audio **134** captured by the one or more microphones **124**.

The method **1000** includes, at **1006**, processing, at the speech processing network, the audio data to generate an output representation of the audio data. For example, the speech processing network **102** of FIG. 1 processes the audio data **126** at the one or more network layers **104** to generate the output representation **110**.

The method **1000** includes, at **1008**, providing the output representation at an output of the speech processing network to enable the output representation to be accessible as a common input to multiple speech application modules. As an example, the output representation **110** of FIG. 1 is provided at the output **108** to enable the output representation **110** to be accessible as a common input to the first speech application module **118** and the second speech application module **120**. In some examples, the audio data is received as multiple frames that are synchronously received from respective microphones of the one or more microphones, and the speech processing network **102** processes the multiple frames to generate a single frame of the output representation, such as described with reference to the input frames **222**, **224**, and **226** and the output frame **228** of FIG. 2. In some implementations, the output representation is provided to a chip interface of an application-specific integrated circuit (ASIC), such as the ASIC **508** of FIG. 5, to enable the output representation to be provided to speech application modules that are external to the ASIC.

In some implementations, the method **1000** includes, at **1010**, providing the output representation to a first speech application module to generate a first application output based on the output representation. In such implementations, the method **1000** also includes, at **1012**, providing the output representation to a second speech application module to generate a second application output based on the output representation, the second application output different than

the first application output. To illustrate, the output representation 110 is provided concurrently to the first speech application module 118 and the second application output 130 of FIG. 1, to generate the first application output 128 and the second application output 130, respectively. The second application output 130 is different than the first application output 128.

In some examples, the first application output and the second application output correspond to different ones of at least: a speech recognition output, a voice activation output, a speaker verification output, a speaker recognition output, or an enhanced speech output. For example, the first speech application module 118 and the second speech application module 120 can correspond to different ones of the speech recognition network 202, the voice activation detector 204, the speaker verifier 206, the speaker recognizer 208, or the speech enhancer 210 of FIG. 2, and the first application output 128 and the second application output 130 can correspond to different ones of the speech recognition output 212, the voice activation output 214, the speaker verification output 216, the speaker recognition output 218, or the enhanced speech output 220, respectively.

In some implementations, the device 122 corresponds to a communication device that further includes an antenna and a transceiver coupled to the antenna and configured to receive the audio data via wireless transmission from the one or more microphones. For example, FIG. 11 depicts an implementation in which the speech processing network 102, the antenna, and the transceiver are integrated into a mobile device, and FIG. 12 depicts an implementation in which the speech processing network 102, the antenna, and the transceiver are integrated into a base station.

Referring to FIG. 11, a block diagram of a particular illustrative implementation of a device is depicted and generally designated 1100. In various implementations, the device 1100 may have more or fewer components than illustrated in FIG. 11. In an illustrative implementation, the device 1100 may correspond to the device 122. In an illustrative implementation, the device 1100 may perform one or more operations described with reference to FIGS. 1-10.

In a particular implementation, the device 1100 includes a processor 1106 (e.g., a central processing unit (CPU)). The device 1100 may include one or more additional processors 1110 (e.g., one or more DSPs). In an illustrative, non-limiting example, the processors 1110 may include a speech and music coder-decoder (CODEC) 1108, the speech processing network 102, the first speech application module 118, the second speech application module 120, or a combination thereof. The speech and music codec 1108 may include a voice coder ("vocoder") encoder 1136, a vocoder decoder 1138, or both.

The device 1100 may include a memory 1186 and a CODEC 1134. In a particular aspect, the memory 1186 corresponds to the memory 152 of FIG. 1. The memory 1186 may include instructions 1156, that are executable by the one or more additional processors 1110 (or the processor 1106) to implement the functionality described with reference to the speech processing network 102, the first speech application module 118, the second speech application module 120, one or more other speech processing applications, the network training device 450, or any combination thereof. In a particular implementation, the memory 1186 includes a computer-readable storage medium and the instructions 1156, when executed by one or more processors (e.g., the processor 1106 or the one or more additional processors

1110), cause the one or more processors to receive, at the speech processing network 102, audio data (e.g., the audio data 126) corresponding to audio captured by one or more microphones. The instructions 1156, when executed by the one or more processors, cause the one or more processors to process, at the speech processing network 102, the audio data to generate an output representation 110 of the audio data. The instructions, when executed by the one or more processors, cause the one or more processors to provide the output representation 110 at an output 108 of the speech processing network 102 to enable the output representation 110 to be accessible as a common input to multiple speech application modules, such the first speech application module 118 and the second speech application module 120. The memory 1186 may also include speech processing model data, such as coefficients for the one or more network layers 104 of the speech processing network 102. The device 1100 may include a wireless controller 1140 coupled, via a transceiver 1150, to an antenna 1152.

The device 1100 may include a display 1128 coupled to a display controller 1126. A speaker 1192 and one or more microphones, such as the microphone 112, may be coupled to the CODEC 1134. The CODEC 1134 may include a digital-to-analog converter 1102 and an analog-to-digital converter 1104. In a particular implementation, the CODEC 1134 may receive analog signals from the microphone 112, convert the analog signals to digital signals using the analog-to-digital converter 1104, and provide the digital signals to the speech and music codec 1108. The speech and music codec 1108 may process the digital signals, and the digital signals may further be processed by the speech processing network 102. In a particular implementation, the speech and music codec 1108 may provide digital signals to the CODEC 1134. The CODEC 1134 may convert the digital signals to analog signals using the digital-to-analog converter 1102 and may provide the analog signals to the speaker 1192.

In a particular implementation, the device 1100 may be included in a system-in-package or system-on-chip device 1122. In a particular implementation, the memory 1186, the processor 1106, the processors 1110, the display controller 1126, the CODEC 1134, and the wireless controller 1140 are included in a system-in-package or system-on-chip device 1122. In a particular implementation, an input device 1130 and a power supply 1144 are coupled to the system-on-chip device 1122. Moreover, in a particular implementation, as illustrated in FIG. 11, the display 1128, the input device 1130, the speaker 1192, the microphone 112, the antenna 1152, and the power supply 1144 are external to the system-on-chip device 1122. In a particular implementation, each of the display 1128, the input device 1130, the speaker 1192, the microphone 112, the antenna 1152, and the power supply 1144 may be coupled to a component of the system-on-chip device 1122, such as an interface or a controller.

The device 1100 may include a smart speaker, a speaker bar, a mobile communication device, a smart phone, a cellular phone, a laptop computer, a computer, a tablet, a personal digital assistant, a display device, a television, a gaming console, a music player, a radio, a digital video player, a digital video disc (DVD) player, a tuner, a camera, a navigation device, a vehicle, a headset, an augmented reality headset, a virtual reality headset, an aerial vehicle, or any combination thereof.

Referring to FIG. 12, a block diagram of a particular illustrative example of a base station 1200 is depicted. In various implementations, the base station 1200 may have more components or fewer components than illustrated in FIG. 12. In an illustrative example, the base station 1200

may include one or more components of the device **122** of FIG. **1**. In an illustrative example, the base station **1200** may operate according to one or more of the methods or systems described with reference to FIGS. **1-11**.

The base station **1200** may be part of a wireless communication system. The wireless communication system may include multiple base stations and multiple wireless devices. The wireless communication system may be a Long Term Evolution (LTE) system, a Code Division Multiple Access (CDMA) system, a Global System for Mobile Communications (GSM) system, a wireless local area network (WLAN) system, or some other wireless system. A CDMA system may implement Wideband CDMA (WCDMA), CDMA 1X, Evolution-Data Optimized (EVDO), Time Division Synchronous CDMA (TD-SCDMA), or some other version of CDMA.

The wireless devices may also be referred to as user equipment (UE), a mobile station, a terminal, an access terminal, a subscriber unit, a station, etc. The wireless devices may include a cellular phone, a smartphone, a tablet, a wireless modem, a personal digital assistant (PDA), a handheld device, a laptop computer, a smartbook, a netbook, a tablet, a cordless phone, a wireless local loop (WLL) station, a Bluetooth device, etc. The wireless devices may include or correspond to the device **1100** of FIG. **11**.

Various functions may be performed by one or more components of the base station **1200** (and/or in other components not shown), such as sending and receiving messages and data (e.g., audio data). In a particular example, the base station **1200** includes a processor **1206** (e.g., a CPU). The base station **1200** may include a transcoder **1210**. The transcoder **1210** may include an audio CODEC **1208** that includes the speech processing network **102**. For example, the transcoder **1210** may include one or more components (e.g., circuitry) configured to perform operations of the audio CODEC **1208**. As another example, the transcoder **1210** may be configured to execute one or more computer-readable instructions to perform the operations of the audio CODEC **1208**. Although the audio CODEC **1208** is illustrated as a component of the transcoder **1210**, in other examples one or more components of the audio CODEC **1208** may be included in the processor **1206**, another processing component, or a combination thereof. For example, a decoder **1238** (e.g., a vocoder decoder) may be included in a receiver data processor **1264**. As another example, an encoder **1236** (e.g., a vocoder encoder) may be included in a transmission data processor **1282**.

The transcoder **1210** may function to transcode messages and data between two or more networks. The transcoder **1210** may be configured to convert message and audio data from a first format (e.g., a digital format) to a second format. To illustrate, the decoder **1238** may decode encoded signals having a first format and the encoder **1236** may encode the decoded signals into encoded signals having a second format. The transcoder **1210** may also be configured to perform, with use of the speech processing network **102**, speech enhancement, speech recognition, translations from one language to another, or one or more other speech processing applications as described with reference to FIGS. **1-11**. Additionally or alternatively, the transcoder **1210** may be configured to perform data rate adaptation. For example, the transcoder **1210** may down-convert a data rate or up-convert the data rate without changing a format the audio data. To illustrate, the transcoder **1210** may down-convert 124 kbit/s signals into 16 kbit/s signals.

The base station **1200** may include a memory **1232**. The memory **1232**, such as a computer-readable storage device,

may include instructions. The instructions may include one or more instructions that are executable by the processor **1206**, the transcoder **1210**, or a combination thereof, to perform one or more operations described with reference to the methods and systems of FIGS. **1-11**. The base station **1200** may include multiple transmitters and receivers (e.g., transceivers), such as a first transceiver **1252** and a second transceiver **1254**, coupled to an array of antennas. The array of antennas may include a first antenna **1242** and a second antenna **1244**. The array of antennas may be configured to wirelessly communicate with one or more wireless devices, such as the device **1100** of FIG. **11**. For example, the second antenna **1244** may receive a data stream **1214** (e.g., a bitstream) from a wireless device. The data stream **1214** may include messages, data (e.g., encoded speech data), or a combination thereof.

The base station **1200** may include a network connection **1260**, such as backhaul connection. The network connection **1260** may be configured to communicate with a core network or one or more base stations of the wireless communication network. For example, the base station **1200** may receive a second data stream (e.g., messages or audio data) from a core network via the network connection **1260**. The base station **1200** may process the second data stream to generate messages or audio data and provide the messages or the audio data to one or more wireless device via one or more antennas of the array of antennas or to another base station via the network connection **1260**. In a particular implementation, the network connection **1260** may be a wide area network (WAN) connection, as an illustrative, non-limiting example. In some implementations, the core network may include or correspond to a Public Switched Telephone Network (PSTN), a packet backbone network, or both.

The base station **1200** may include a media gateway **1270** that is coupled to the network connection **1260** and the processor **1206**. The media gateway **1270** may be configured to convert between media streams of different telecommunications technologies. For example, the media gateway **1270** may convert between different transmission protocols, different coding schemes, or both. To illustrate, the media gateway **1270** may convert from PCM signals to Real-Time Transport Protocol (RTP) signals, as an illustrative, non-limiting example. The media gateway **1270** may convert data between packet switched networks (e.g., a Voice Over Internet Protocol (VoIP) network, an IP Multimedia Subsystem (IMS), a fourth generation (4G) wireless network, such as LTE, WiMax, and UMB, etc.), circuit switched networks (e.g., a PSTN), and hybrid networks (e.g., a second generation (2G) wireless network, such as GSM, GPRS, and EDGE, a third generation (3G) wireless network, such as WCDMA, EV-DO, and HSPA, etc.).

Additionally, the media gateway **1270** may include a transcoder and may be configured to transcode data when codecs are incompatible. For example, the media gateway **1270** may transcode between an Adaptive Multi-Rate (AMR) codec and a G.711 codec, as an illustrative, non-limiting example. The media gateway **1270** may include a router and a plurality of physical interfaces. In some implementations, the media gateway **1270** may also include a controller (not shown). In a particular implementation, the media gateway controller may be external to the media gateway **1270**, external to the base station **1200**, or both. The media gateway controller may control and coordinate operations of multiple media gateways. The media gateway **1270** may receive control signals from the media gateway con-

troller and may function to bridge between different transmission technologies and may add service to end-user capabilities and connections.

The base station **1200** may include a demodulator **1262** that is coupled to the transceivers **1252**, **1254**, the receiver data processor **1264**, and the processor **1206**, and the receiver data processor **1264** may be coupled to the processor **1206**. The demodulator **1262** may be configured to demodulate modulated signals received from the transceivers **1252**, **1254** and to provide demodulated data to the receiver data processor **1264**. The receiver data processor **1264** may be configured to extract a message or audio data from the demodulated data and send the message or the audio data to the processor **1206**.

The base station **1200** may include a transmission data processor **1282** and a transmission multiple input-multiple output (MIMO) processor **1284**. The transmission data processor **1282** may be coupled to the processor **1206** and the transmission MIMO processor **1284**. The transmission MIMO processor **1284** may be coupled to the transceivers **1252**, **1254** and the processor **1206**. In some implementations, the transmission MIMO processor **1284** may be coupled to the media gateway **1270**. The transmission data processor **1282** may be configured to receive the messages or the audio data from the processor **1206** and to code the messages or the audio data based on a coding scheme, such as CDMA or orthogonal frequency-division multiplexing (OFDM), as an illustrative, non-limiting examples. The transmission data processor **1282** may provide the coded data to the transmission MIMO processor **1284**.

The coded data may be multiplexed with other data, such as pilot data, using CDMA or OFDM techniques to generate multiplexed data. The multiplexed data may then be modulated (i.e., symbol mapped) by the transmission data processor **1282** based on a particular modulation scheme (e.g., Binary phase-shift keying (“BPSK”), Quadrature phase-shift keying (“QSPK”), M-ary phase-shift keying (“M-PSK”), M-ary Quadrature amplitude modulation (“M-QAM”), etc.) to generate modulation symbols. In a particular implementation, the coded data and other data may be modulated using different modulation schemes. The data rate, coding, and modulation for each data stream may be determined by instructions executed by processor **1206**.

The transmission MIMO processor **1284** may be configured to receive the modulation symbols from the transmission data processor **1282** and may further process the modulation symbols and may perform beamforming on the data. For example, the transmission MIMO processor **1284** may apply beamforming weights to the modulation symbols. The beamforming weights may correspond to one or more antennas of the array of antennas from which the modulation symbols are transmitted.

During operation, the second antenna **1244** of the base station **1200** may receive a data stream **1214**. The second transceiver **1254** may receive the data stream **1214** from the second antenna **1244** and may provide the data stream **1214** to the demodulator **1262**. The demodulator **1262** may demodulate modulated signals of the data stream **1214** and provide demodulated data to the receiver data processor **1264**. The receiver data processor **1264** may extract audio data from the demodulated data and provide the extracted audio data to the processor **1206**.

The processor **1206** may provide the audio data to the transcoder **1210** for transcoding. The decoder **1238** of the transcoder **1210** may decode the audio data from a first format into decoded audio data and the encoder **1236** may encode the decoded audio data into a second format. In some

implementations, the encoder **1236** may encode the audio data using a higher data rate (e.g., up-convert) or a lower data rate (e.g., down-convert) than received from the wireless device. In other implementations, the audio data may not be transcoded. Although transcoding (e.g., decoding and encoding) is illustrated as being performed by a transcoder **1210**, the transcoding operations (e.g., decoding and encoding) may be performed by multiple components of the base station **1200**. For example, decoding may be performed by the receiver data processor **1264** and encoding may be performed by the transmission data processor **1282**. In other implementations, the processor **1206** may provide the audio data to the media gateway **1270** for conversion to another transmission protocol, coding scheme, or both. The media gateway **1270** may provide the converted data to another base station or core network via the network connection **1260**.

Encoded audio data generated at the encoder **1236**, such as transcoded data, may be provided to the transmission data processor **1282** or the network connection **1260** via the processor **1206**. The transcoded audio data from the transcoder **1210** may be provided to the transmission data processor **1282** for coding according to a modulation scheme, such as OFDM, to generate the modulation symbols. The transmission data processor **1282** may provide the modulation symbols to the transmission MIMO processor **1284** for further processing and beamforming. The transmission MIMO processor **1284** may apply beamforming weights and may provide the modulation symbols to one or more antennas of the array of antennas, such as the first antenna **1242** via the first transceiver **1252**. Thus, the base station **1200** may provide a transcoded data stream **1216**, that corresponds to the data stream **1214** received from the wireless device, to another wireless device. The transcoded data stream **1216** may have a different encoding format, data rate, or both, than the data stream **1214**. In other implementations, the transcoded data stream **1216** may be provided to the network connection **1260** for transmission to another base station or a core network.

In conjunction with the described techniques, an apparatus includes means for receiving audio data corresponding to audio captured by one or more microphones. For example, the means for receiving may include the input **106**, the chip interface **510**, the codec **1134**, one or more other devices, circuits, or modules configured to receive audio data, or any combination thereof.

The apparatus also includes means for processing the audio data to generate an output representation of the audio data. For example, the means for processing may include the speech processing network **102**, the one or more network layers **104**, the one or more processors **150**, the processor **1106**, the one or more processors **1110**, one or more other devices, circuits, or modules, configured to generate an output representation of the data, or any combination thereof.

The apparatus also includes means for providing the output representation to be accessible as a common input to multiple means for performing speech applications. The means for providing the output representation may include the output **108**, the chip interface **510**, the one or more processors **150**, the processor **1106**, the one or more processors **1110**, one or more other devices, circuits, or modules configured to provide the output representation to be accessible as a common input to multiple means for performing speech applications, or any combination thereof. The multiple means for performing speech applications can correspond to the first speech application module **118**, the second

speech application module 120, the speech recognition network 202, the voice activation detector 204, the speaker recognizer 208, the speech enhancer 210, any one or more of the modules 302-318 of FIG. 3, any one or more of the modules 406-410 of FIG. 4, or any combination thereof.

In some implementations, the means for processing the audio data is implemented in an application-specific integrated circuit (ASIC), and the means for providing the output representation is coupled to means for performing speech applications that are external to the ASIC. For example, FIG. 5 depicts the speech processing network 102 implemented in the ASIC 508, and the output 108 can be coupled, via the chip interface 510, to one or more of the modules 118, 120, 202-210, 302-314, 406-410 that are external to the ASIC 508 and that are coupled to the chip interface 510 to receive the output representation 110.

In some implementations, the apparatus also includes means for generating a first application output based on the output representation and includes means for generating a second application output based on the output representation. The means for generating the first application output is coupled to the means for providing the output representation, the means for generating the second application output is coupled to the means for providing the output representation, and the second application output is different than the first application output. The first application output may correspond to at least one of: a speech recognition output; a voice activation output; a speaker verification output; a speaker recognition output; or an enhanced speech output. For example, the means for generating the first application output may correspond to one or more of the modules 118, 120, 202-210, 302-314, 406-410, and the means for generating the second application output may correspond to a different one of the modules 118, 120, 202-210, 302-314, 406-410.

It should be noted that various functions performed by the one or more components of the systems and devices disclosed herein are described as being performed by certain components or modules. This division of components and modules is for illustration only. In an alternate implementation, a function performed by a particular component or module may be divided amongst multiple components or modules. Moreover, in an alternate implementation, two or more components or modules may be integrated into a single component or module. Each component or module may be implemented using hardware (e.g., a field-programmable gate array (FPGA) device, an application-specific integrated circuit (ASIC), a DSP, a controller, etc.), software (e.g., instructions executable by a processor), or any combination thereof.

Those of skill would further appreciate that the various illustrative logical blocks, configurations, modules, circuits, and algorithm steps described in connection with the implementations disclosed herein may be implemented as electronic hardware, computer software executed by a processing device such as a hardware processor, or combinations of both. Various illustrative components, blocks, configurations, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or executable software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present disclosure.

The steps of a method or algorithm described in connection with the implementations disclosed herein may be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two. A software module may reside in a memory device, such as random access memory (RAM), magnetoresistive random access memory (MRAM), spin-torque transfer MRAM (STT-MRAM), flash memory, read-only memory (ROM), programmable read-only memory (PROM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), registers, hard disk, a removable disk, or a compact disc read-only memory (CD-ROM). An exemplary memory device is coupled to the processor such that the processor can read information from, and write information to, the memory device. In the alternative, the memory device may be integral to the processor. The processor and the storage medium may reside in an application-specific integrated circuit (ASIC). The ASIC may reside in a computing device or a user terminal. In the alternative, the processor and the storage medium may reside as discrete components in a computing device or a user terminal.

The previous description of the disclosed implementations is provided to enable a person skilled in the art to make or use the disclosed implementations. Various modifications to these implementations will be readily apparent to those skilled in the art, and the principles defined herein may be applied to other implementations without departing from the scope of the disclosure. Thus, the present disclosure is not intended to be limited to the implementations shown herein but is to be accorded the widest scope possible consistent with the principles and novel features as defined by the following claims.

What is claimed is:

1. A device to process speech, comprising:

a speech processing network comprising:

- an input configured to receive audio data corresponding to audio captured by one or more microphones;
- one or more network layers configured to process the audio data to generate a network output; and
- an output configured to be coupled to multiple speech application modules to enable the network output to be provided as a common input to each of the multiple speech application modules, wherein a first speech application module corresponds to a speaker verifier and a second speech application module corresponds to a speech recognition network.

2. The device of claim 1, wherein the first speech application module is coupled to the output and configured to generate a speaker verification output based on the network output, and wherein the speaker verification output is indicative of whether the captured audio exhibits voice characteristics matching a particular speaker.

3. The device of claim 1, wherein the second speech application module is coupled to the output and configured to generate a speech recognition output based on the network output, and wherein the speech recognition output includes text corresponding to the captured audio.

4. The device of claim 1, further comprising a third speech application module coupled to the output, wherein the third speech application module corresponds to at least one of: a voice activation detector; a speaker recognizer; or a speech enhancer.

5. The device of claim 1, wherein the one or more network layers are trained based on at least a first performance metric

23

associated with the first speech application module and a second performance metric associated with the second speech application module.

6. The device of claim 5, wherein the one or more network layers are trained responsive to a combined performance metric that corresponds to a combination of at least the first performance metric and the second performance metric.

7. The device of claim 1, wherein the speech processing network is implemented in an application-specific integrated circuit (ASIC), wherein at least one speech application module of the multiple speech application modules is external to the ASIC, and wherein the output of the speech processing network is coupled to a chip interface to enable the network output to be provided to the at least one speech application module that is external to the ASIC.

8. The device of claim 1, wherein the input is configured to synchronously receive multiple frames of the audio data, each of the multiple frames received from a respective microphone of the one or more microphones, and wherein the speech processing network is configured to process the multiple frames to generate a single frame of the network output.

9. The device of claim 1, wherein the speech processing network is included in a vehicle.

10. The device of claim 1, wherein the speech processing network is implemented in an audio device, and wherein the audio device includes a wireless speaker and voice activated device with an integrated assistant application.

11. The device of claim 1, further comprising:
an antenna; and

a transceiver coupled to the antenna and configured to receive the audio data via wireless transmission from the one or more microphones.

12. The device of claim 11, wherein the speech processing network, the antenna, and the transceiver are integrated into a mobile device.

13. The device of claim 11, wherein the speech processing network, the antenna, and the transceiver are integrated into a base station.

14. A method of speech processing, comprising:
receiving, at a speech processing network, audio data corresponding to audio captured by one or more microphones;

processing, at the speech processing network, the audio data using one or more network layers to generate a network output; and

providing the network output at an output of the speech processing network to enable the network output to be accessible as a common input to multiple speech application modules, wherein a first speech application module corresponds to a speaker verifier and a second speech application module corresponds to a speech recognition network.

15. The method of claim 14, further comprising generating, at the first speech application module, a speaker verification output based on the network output and indicative of whether the captured audio exhibits voice characteristics matching a particular speaker.

16. The method of claim 14, further comprising generating, at the second speech application module, a speech recognition output based on the network output and including text corresponding to the captured audio.

17. The method of claim 14, further comprising providing the network output to a third speech application module to generate at least one of:

a voice activation output;
a speaker recognition output; or
an enhanced speech output.

24

18. The method of claim 14, further comprising training the speech processing network based on at least a first performance metric associated with the first speech application module and a second performance metric associated with the second speech application module.

19. The method of claim 18, wherein the speech processing network is trained responsive to a combined performance metric that corresponds to a combination of at least the first performance metric and the second performance metric.

20. The method of claim 14, wherein the network output is provided to a chip interface of an application-specific integrated circuit (ASIC) to enable the network output to be provided to at least one speech application module of the multiple speech application modules that is external to the ASIC.

21. The method of claim 14, wherein the audio data is received as multiple frames that are synchronously received from respective microphones of the one or more microphones, and wherein the speech processing network processes the multiple frames to generate a single frame of the network output.

22. A non-transitory computer-readable medium storing instructions that, when executed by one or more processors, cause the one or more processors to:

receive, at a speech processing network, audio data corresponding to audio captured by one or more microphones;

process, at the speech processing network, the audio data using one or more network layers to generate a network output; and

provide the network output at an output of the speech processing network to enable the network output to be accessible as a common input to multiple speech application modules, wherein a first speech application module corresponds to a speaker verifier and a second speech application module corresponds to a speech recognition network.

23. The non-transitory computer-readable medium of claim 22, wherein execution of the instructions further causes the one or more processors to:

provide the network output to the first speech application module to generate a speaker verification output based on the network output; and

provide the network output to the second speech application module to generate a speech recognition output based on the network output.

24. The non-transitory computer-readable medium of claim 23, wherein execution of the instructions further causes the one or more processors to provide the network output to a third speech application module to generate at least one of:

a voice activation output;
a speaker recognition output; or
an enhanced speech output.

25. The non-transitory computer-readable medium of claim 22, wherein execution of the instructions further causes the one or more processors to train the speech processing network based on at least a first performance metric associated with the first speech application module and a second performance metric associated with the second speech application module.

25

26. The non-transitory computer-readable medium of claim 25, wherein the speech processing network is trained responsive to a combined performance metric that corresponds to a combination of at least the first performance metric and the second performance metric.

27. An apparatus comprising:

means for receiving audio data corresponding to audio captured by one or more microphones;

means for processing the audio data using one or more network layers to generate a network output; and

means for providing the network output to be accessible as a common input to multiple means for performing speech applications, the multiple means for performing speech applications including:

means for generating a speaker verification output based on the network output; and

means for generating a speech recognition output based on the network output.

26

28. The apparatus of claim 27, further comprising: means for generating, based on the network output, at least one of:

a voice activation output;

a speaker recognition output; or

an enhanced speech output.

29. The apparatus of claim 27, wherein the speaker verification output is indicative of whether the captured audio exhibits voice characteristics matching a particular speaker, and wherein the speech recognition output includes text corresponding to the captured audio.

30. The apparatus of claim 27, wherein the means for processing the audio data is implemented in an application-specific integrated circuit (ASIC), wherein at least one of the multiple means for performing speech applications is external to the ASIC, and wherein the means for providing the network output is coupled to the at least one of the means for performing speech applications that is external to the ASIC.

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