(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
27 December 2018 (27.12.2018)

WIPO | PCT

(10) International Publication Number
WO 2018/237392 A1

(51) International Patent Classification:
H02J 7/00 (2006.01) *H02J 50/80* (2016.01)
H02J 50/12 (2016.01) *H04B 5/00* (2006.01)
H02J 50/27 (2016.01)

(21) International Application Number:
PCT/US2018/039334

(22) International Filing Date:
25 June 2018 (25.06.2018)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
15/631,992 23 June 2017 (23.06.2017) US

(71) Applicant: ENERGOUS CORPORATION [US/US]; 3590 N. 1st Street, Suite 210, San Jose, CA 95134 (US).

(72) Inventors: LEABMAN, Michael, A.; 3590 N. 1st Street, Suite 210, San Jose, CA 95134 (US). HOSSEINI, Alister; 3590 N. 1st Street, Suite 210, San Jose, CA 95134 (US).

(74) Agent: STEIN, Alexander, B. et al.; Morgan Lewis & Bockius LLP, 1400 Page Mill Road, Palo Alto, CA 94304 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report (Art. 21(3))*

(54) Title: SYSTEMS, METHODS, AND DEVICES FOR UTILIZING A WIRE OF A SOUND-PRODUCING DEVICE AS AN ANTENNA FOR RECEIPT OF WIRELESSLY DELIVERED POWER

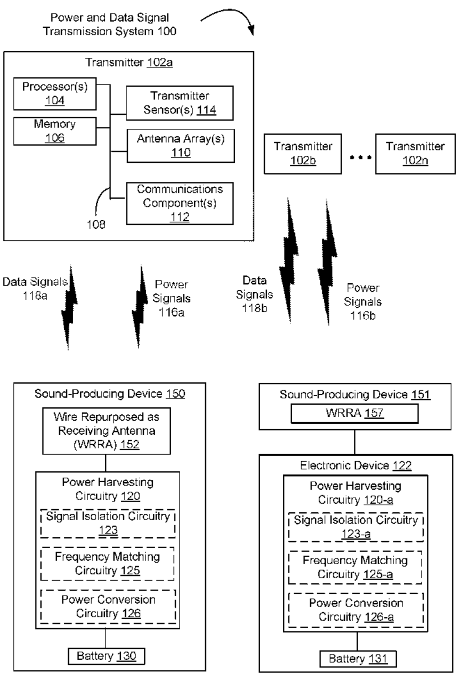

Figure 1

(57) Abstract: The wireless power receiver includes at least one wire of a sound-producing device. The at least one wire configured for both conveying sound signals or securing at least part of the sound-producing device to a user, and receiving power waves. The wireless power receiver also includes power harvesting circuitry coupled with the at least one wire and a power source of an electronic device, like a battery. The power harvesting circuitry is configured to isolate the received power waves from the conveyed sound signals, convert the received power waves to usable energy, and provide the usable energy to the power source of the electronic device.

WO 2018/237392 A1

Systems, Methods, and Devices for Utilizing a Wire of a Sound-Producing Device as an Antenna for Receipt of Wirelessly Delivered Power

TECHNICAL FIELD

[0001] The disclosed embodiments relate generally to antennas in wireless power transmission systems. In particular, the disclosed embodiments relate to repurposing wires found in sound-producing devices as antennas for receipt of wirelessly delivered power (so that these repurposed wires are then operated as antennas, while still performing their originally intended functions, such as conveying electrical signals and/or securing a sound-producing device to a user's ear).

BACKGROUND

[0002] Portable electronic devices, such as laptop computers, mobile phones, tablets, and other electronic devices, require frequent charging of a power-storing component (e.g., a battery) to operate. Many electronic devices require charging one or more times per day. Often, charging an electronic device requires manually connecting an electronic device to an outlet or other power source using a wired charging cable. In some cases, a power-storing component, e.g., a battery, is removed from an associated electronic device and inserted into charging equipment to charge. Such charging is inefficient because it often requires users to carry around multiple charging cables and/or other charging devices, and requires users to locate appropriate power sources, e.g., wall outlets, to charge their electronic devices. Additionally, conventional charging techniques potentially deprive a user of the ability to use the device while it is charging, and/or require the user to remain next to a wall outlet or other power source to which their electronic device or other charging equipment is connected.

[0003] Building a wireless charging system for consumer devices typically requires adding complicated, and often, expensive antenna components that receive wirelessly delivered power in the consumer devices. Many of these consumer devices are also small, compact, and/or do not contain enough space for added antenna components. As such, it would be desirable to provide a wireless charging system that addresses the above-mentioned drawbacks.

SUMMARY

[0004] Accordingly, there is a need for methods, apparatuses, and systems for wirelessly charging electronic devices, and for building such systems in a cost-effective fashion. As such, repurposing existing components of electronic devices and/or sound-producing devices (e.g., wires from headphones, hearing aids, or earpieces) in accordance with some of the embodiments described herein helps to lower costs while building more effective wireless charging systems. In some cases, utilizing existing components lowers costs for wireless power receivers, enables development of smaller and more compact wireless power receivers, and is more convenient to users. Many ear-interface devices (also referred to herein as sound-producing devices, sound-conveying devices, and sound-generating devices), examples of which include but are not limited to, headphones, hearing aids, and earpieces have conductive wires in their structure. These existing conductive wires may be used as receiving antennas for various wireless applications, such as wireless communications (e.g., Wi-Fi, Bluetooth, and GSM) and wireless charging (e.g., far-range, medium-range, and near-field charging systems). As one example, a method of wirelessly charging an electronic device (e.g., a mobile phone) may include repurposing one or more wires of a sound-producing device (e.g., one of the wires of a part of headphones) coupled to the electronic device to receive power waves, and energy from those power waves is then harvested and converted by power conversion circuitry into usable electricity for powering or charging the electronic device.

[0005] In some embodiments, the existing wires are connected to the power-conversion circuitry (or other circuity or integrated circuit suitable for the particular application, such as receiving Wi-Fi, Bluetooth, or GSM signals) through a matching network (e.g., an impedance matching network configured to minimize signal reflection) and optionally an isolating filter or circuitry. For example, if the existing wire is not purposed for conveying signals for the sound-producing device, then an isolating filter may not be needed. As another example, if the existing wire is purposed for conveying electrical signals to be converted to sound by a speaker, then an isolating filter may be utilized to isolate received power waves (or other types of signals, depending on the type of signal being received) from the electrical signals intended for the speaker.

[0006] Existing wires or conductors in sound-producing devices may have many different lengths. However, with an appropriate matching network based on the desired frequency, these wires can be tuned to receive signals and/or power at one or more desired frequencies, in accordance with some embodiments described in more detail below. For example, in headphones having two earpieces coupled to a volume/microphone control, a dipole antenna forms from the wire(s) connecting the two earpieces to a volume/microphone control component of the headphones. In some embodiments, a matching circuit and/or power conversion circuitry (that may also include the matching circuit) is located inside of the volume/microphone control component.

[0007] Some embodiments of the invention relate to a wireless power receiver. The wireless power receiver includes at least one wire of a sound-producing device (e.g., a headphone, hearing aid, earpiece, or cochlear or other implant) and power harvesting circuitry. The at least one wire is configured to convey sound signals or to secure at least part of the sound-producing device to a user. The at least one wire is also purposed to perform an additional function (in addition to its originally intended functions), such as performing the additional function of receiving power waves used for powering the sound-producing device. The power harvesting circuitry is coupled to the at least one wire and a power source of an electronic device, e.g., a rechargeable battery. The power harvesting circuitry is configured to convert the received power waves to usable energy, and provide the usable energy to the power source of the electronic device. This allows the same wire to be reused for power receipt (while still performing its originally intended functions), thereby reducing the need for additional antenna, reducing cost, while maintaining the size of the device.

[0008] In some embodiments, the at least one wire comprises an external wire of the sound-producing device. In some embodiments, the at least one wire includes a conductive shield adapted to receive power waves, and wherein the power harvesting circuitry is configured to receive the power waves via the conductive shield. In some embodiments, the sound-producing device further comprises a speaker coupled to the at least one wire, where the at least one wire is configured to transmit the electrical signals to the speaker for conversion to sound. In some embodiments, the sound-producing device is a headphone; an earbud; a pair of headphones; a pair of earbuds; one or more earpieces; or a hearing aid. In some embodiments, the electronic device is a mobile phone; a tablet computer; a laptop computer; a handheld electronic device; or a portable electronic device. In some embodiments, the sound-producing device is coupled to the electronic device via a headphone jack. In some embodiments, the power harvesting circuitry is configured to convert energy from two or more types of power waves. In some embodiments, the power harvesting circuitry includes a rectifier and a power converter. In some embodiments, the power harvesting circuitry is a component of an integrated wireless power receiving circuit. In some embodiments, the integrated wireless power receiving circuit includes a controller configured to manage power conversion by the integrated wireless power receiving circuit. In some embodiments, the integrated wireless power receiving circuit includes a matching circuit adapted to match a frequency for the at least one wire. In some embodiments, the integrated wireless power receiving circuit is configured to isolate the power waves from other electrical signals travelling along the at least one wire.

[0009] Some embodiments provide a method of utilizing at least one wire of a sound-producing device as an antenna for receipt of wirelessly delivered power. The at least one wire is coupled to power harvesting circuitry that is in turn coupled to a power source of an electronic device distinct from the sound-producing device. Initially, the at least one wire is used during operation the sound-producing device. The at least one wire also receives power waves. The power harvesting circuitry then converts the power waves (or energy extracted therefrom) to usable electricity, which is provided to the power source of the electronic device. For example, the at least one wire is coupled with a speaker of the sound-producing device, and using the at least one wire in operation comprises transmitting via the at least one wire electrical signals to the speaker for conversion to sound.

[0010] In some embodiments, the power waves are radio frequency signals that are transmitted so that they constructively interfere in proximity to the sound-producing device. In some embodiments the one or more power waves have a frequency of 915 MHz, 2.4 GHz, or 5.8 GHz. In some embodiments, the power waves are received from a far-field power transmitter. In some embodiments, the power waves are received from a near-field power transmitter. In some embodiments, receiving the power waves comprises utilizing the at least one wire as a monopole antenna. In some embodiments, the at least one wire comprises two wires, and receiving the one or more power waves comprises utilizing the two wires as a dipole antenna. In some embodiments, using the at least one wire in operation of the sound-producing device comprises utilizing the at least one wire to secure the sound-producing device to a user’s ear.

[0011] Some embodiments provide a sound-producing device configured to receive wirelessly delivered power. The sound producing device includes a speaker, power-harvesting circuitry, at least one wire coupled to the speaker and the power-harvesting circuitry. The at least one wire is configured to convey electrical signals to the speaker for conversion to audible sound, and operate as an antenna to receive power waves. The sound producing device also includes a power source coupled to the at least one power harvesting circuitry and configured to provide power to the sound-producing device sound. The power harvesting circuitry is configured to isolate the received power waves from the electrical signals, convert the isolated power waves to usable electricity, and provide the usable electricity to the power source.

[0012] In some embodiments, the at least one wire is further configured to secure the sound-producing device to a user's ear. In some embodiments, the power harvesting circuitry is configured to convert energy from two or more types of power waves. In some embodiments, the power harvesting circuitry includes a rectifier and a power converter.

[0013] In another aspect, some embodiments include a wireless power receiver with the means for performing the methods described herein. In another aspect, some embodiments include a wireless power transmission system with the means for performing the methods described herein.

[0014] Thus, devices, circuits, and systems are provided with methods for wirelessly conveying power (and/or data) to electronic devices by repurposing one or more wires of sound-producing devices to function as receiving antennas; thereby increasing the effectiveness, efficiency, and user satisfaction with such systems and devices. Such methods may complement or replace conventional methods for conveying power to electronic devices.

[0015] Note that the various embodiments described above can be combined with any other embodiments described herein. The features and advantages described in the specification are not all inclusive and, in particular, many additional features and advantages will be apparent to one of ordinary skill in the art in view of the drawings, specification, and claims. Moreover, it should be noted that the language used in the specification has been principally selected for readability and instructional purposes, and may not have been selected to delineate or circumscribe the inventive subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] So that the present disclosure can be understood in greater detail, a more particular description may be had by reference to the features of various embodiments, some of which are illustrated in the appended drawings. The appended drawings, however, merely illustrate pertinent features of the present disclosure and are therefore not to be considered limiting, for the description may admit to other effective features.

[0017] Figure 1 is a block diagram illustrating representative components of a wireless power transmission system in accordance with some embodiments.

[0018] Figures 2A-2B are block diagrams illustrating representative sound-producing devices that include wires that have been repurposed to function as receiving antennas in accordance with some embodiments.

[0019] Figures 3A-3B are block diagrams illustrating operation of the representative sound-producing device of Figure 2B in accordance with some embodiments.

[0020] In accordance with common practice, the various features illustrated in the drawings may not be drawn to scale. Accordingly, the dimensions of the various features may be arbitrarily expanded or reduced for clarity. In addition, some of the drawings may not depict all of the components of a given system, method or device. Finally, like reference numerals may be used to denote like features throughout the specification and figures.

DETAILED DESCRIPTION

[0021] Numerous details are described herein in order to provide a thorough understanding of the example embodiments illustrated in the accompanying drawings. However, some embodiments may be practiced without many of the specific details, and the scope of the claims is only limited by those features and aspects specifically recited in the claims. Furthermore, well-known processes, components, and materials have not been described in exhaustive detail so as not to unnecessarily obscure pertinent aspects of the embodiments described herein.

[0022] For the sake of brevity, the following detailed description describes embodiments directed at electronic devices that include a wire for transmitting a signal (e.g., an audio signal in a hearing-aid device), where the wire is repurposed to also harvest energy from power waves (also referred to interchangeably herein as power signals, power waves, or power transmission waves). Repurposing an existing wire to serve the additional power harvesting function eliminates the need for a separate antenna for receiving power waves. As used herein, "repurposing" of the wire means using the wire for an additional purpose, i.e., in addition to its intended purpose (e.g., its intended purpose of transmitting signals for the sound-producing device).

[0023] Figure 1 illustrates components of an example wireless power transmission system 100, in accordance with some embodiments. Wireless power transmission system 100 includes, e.g., transmitters 102 (e.g., transmitters 102a, 102b … 102n) and devices that are configured to receive wireless power. The devices that are configured to receive wireless power may include a sound-producing device 150 (e.g., a hearing-aid or a headset or headphone) with a wire 152 (with an existing function for the sound-producing device 150) that is repurposed to also operate as a receiving antenna and power harvesting circuitry 120 that is used to process signals (e.g., received RF power waves) received via the repurposed wire 152. The devices that are configured to receive wireless power also optionally include a sound-producing device 151 coupled to an electronic device 122, the sound-producing device 151 having a wire 157 that is repurposed to operate as a receiving antenna. In some embodiments, the sound-producing device 151 is coupled with an electronic device 122 that includes power harvesting circuitry 120-a used to process power waves received via the repurposed wire 157. In some embodiments, the power harvesting circuitry 120 (or components thereof) is included in the sound-producing device 151, while in other embodiments, components of the power harvesting circuitry 120 are split between the sound-producing device 151 and the electronic device 122. In some embodiments, the wireless power transmission system 100 includes a number of devices that include respective power harvesting circuitry 120. In some embodiments, a wireless power receiver includes a device that is able to receive wireless power, such as a sound-producing device 150 that includes power harvesting circuitry 120, or a sound-producing device 151 that is coupled with a separate electronic device 122 (each of which may include components of power harvesting circuitry in 120-a, 120-b).

[0024] An example transmitter 102 (e.g., transmitter 102a) includes, e.g., one or more processor(s) 104, a memory 106, one or more antenna arrays 110 (preferably multiple antennas), one or more communications components 112, and/or one or more transmitter sensors 114. In some embodiments, these components are, interconnected via a communications bus 108. References to these components of transmitters 102 cover embodiments in which one or more than one of each of these components (and combinations thereof) are included.

[0025] In some embodiments, memory 106 stores one or more programs (e.g., sets of instructions) and/or data structures, collectively referred to as "modules" herein. In some embodiments, memory 106, or the non-transitory computer readable storage medium of memory 106 stores the following programs, modules, and data structures, or a subset or superset thereof:

- information received from a device having power harvesting circuitry 120 (e.g., received via communication signals 118a);
- information received from transmitter sensor 114;
- an adaptive pocket-forming module that adjusts one or more power waves transmitted by one or more transmitters 102; and/or
- a beacon transmitting module that transmits a communication signal 118 for detecting and/or communicating with devices having power harvesting circuitry 120 (e.g., devices located within a transmission field of the one or more transmitters 102).

[0026] The above-identified modules (e.g., data structures and/or programs including sets of instructions) need not be implemented as separate software programs, procedures, or modules, and thus various subsets of these modules may be combined or otherwise re-arranged in various embodiments. In some embodiments, memory 106 stores a subset of the modules identified above. In some embodiments, an external mapping memory (not shown) that is communicatively connected to each of the transmitters 102 (or to a communications component thereof, such as communications component 112 of transmitter 102a) stores one or more modules identified above. Furthermore, the memory 106 and/or external mapping memory may store additional modules not described above. In some embodiments, the modules stored in memory 106, or a non-transitory computer readable storage medium of memory 106, provide instructions for implementing respective operations in the methods described below. In some embodiments, some or all of these modules may be implemented with specialized hardware circuits that subsume part or all of the module functionality. One or more of the above-identified elements may be executed by one or more of processor(s) 104. In some embodiments, one or more of the modules described with regard to memory 106 is implemented on memory of a server (not shown) that is communicatively coupled to one or more transmitters 102 and/or by a memory of electronic device 122 and/or memory associated with a power harvesting circuitry 120.

[0027] In some embodiments, a single processor 104 (e.g., processor 104 of transmitter 102a) executes software modules for controlling multiple transmitters 102 (e.g., transmitters 102b . . . 102n). In some embodiments, a single transmitter 102 (e.g., transmitter 102a) includes multiple processors 104, such as one or more transmitter processors (configured to, e.g., control transmission of waves 116 by antenna array 110), one or more communications component processors (configured to, e.g., control communications transmitted by communications component 112 and/or receive communications via communications component 112) and/or one or more sensor processors (configured to, e.g., control operation of transmitter sensor 114 and/or receive output from transmitter sensor 114).

[0028] Power harvesting circuitry 120 (e.g., power harvesting circuitry 120-a associated with an electronic device 122 or power harvesting circuitry 120 coupled with a sound-producing device 150) receives power waves 116 and/or communications 118 (e.g., 118a and 118b) transmitted by transmitters 102. In some embodiments, the power harvesting circuitry 120 includes one or more antennas including at least one antenna composed of a repurposed wire of a sound-producing device (e.g., the wire 157 repurposed as a receiving antenna of sound-producing device 151), and optionally one or more receiver sensors. In some embodiments, the power harvesting circuitry 120 includes one or more of: power conversion circuitry 126 (also referred to interchangeably herein as a power converter 126), signal isolation circuitry 123, and frequency matching circuitry 125. In some embodiments, various components of a power harvesting circuitry 120 are located within two or more distinct devices (e.g., some components are located with a sound-producing device 151 and other components are located within an electronic device 122). References to these components of power harvesting circuitry 120 cover embodiments in which one or more than one of each of these components (and combinations thereof) are included. Power harvesting circuitry 120 converts energy from received waves 116 (e.g., power waves) into electrical energy to power and/or charge an electronic device (e.g., electronic device 122 or sound-producing device 150). For example, power conversion circuitry 126 is used to convert captured energy from power waves 116 to alternating current (AC) electricity or direct current (DC) electricity usable to power and/or charge an electronic device. Non-limiting examples of power conversion circuitry 126 include rectifiers, rectifying circuits, voltage conditioners, among suitable circuitry and devices.

[0029] In some embodiments, the optional frequency matching circuitry 125 comprises a fixed wideband matching circuit that tunes the performance and/or matching of a particular repurposed wire (e.g., 152 or 157) antenna for limited orientation/applications (for example far-field and near-field applications). In some embodiments, the matching circuitry 125 comprises an adaptive matching chip and/or reconfigurable matching circuit (for example using a varactor) that tunes the matching for wider sets of applications and orientations (e.g., in real-time). In some embodiments, such circuits are connected to a feedback loop monitoring the received power (e.g., the feedback loop is formed between one or more transmitters 102 and the receiver over a wireless channel, e.g. BLUETOOTH or BLUETOOTH Low Energy (BLE), in order to control power transfer efficiency. In some embodiments, the one or more transmitters and the receiver exchange data over the feedback loop to tune transmitter (e.g., to tune characteristics used to transmit power waves to the receiver) and receiver (e.g., if power received by the receiver is less than a threshold level, the adaptive/reconfigurable circuitry changes until the received power reaches the threshold level).

[0030] In some embodiments, after the power waves 116 are received and/or energy is harvested from a concentration or pocket of energy, circuitry (e.g., integrated circuits, amplifiers, rectifiers, and/or voltage conditioner) of the power harvesting circuitry 120 converts the energy of the power waves (e.g., radio frequency electromagnetic radiation) to usable power (e.g., electricity), which directly powers electronic device 122 or sound-producing device 150 and/or is stored to battery 130 or battery 131. In some embodiments, a rectifying circuit of the power conversion circuitry 126 translates the electrical energy from AC to DC for use by electronic device 122. In some embodiments, a voltage conditioning circuit included with the power conversion circuitry 126 increases or decreases the voltage of the electrical energy as required by the battery 130 or 131. In some embodiments, an electrical relay of the power conversion circuitry 126 is used to convey electrical energy to the battery 130 or 131.

[0031] In some embodiments, power harvesting circuitry 120 is a component of a sound-producing device (that may or may not be coupled to an electronic device), the signal processing circuitry is a component of the electronic device (e.g., power harvesting circuitry 120-a is a component of electronic device 122), or the power harvesting circuitry 120 may be split between an electronic device and a sound-producing device. In some embodiments, electronic device 122 obtains power from multiple transmitters 102 (in other embodiments, each transmitter may be assigned to transmit wireless power to a particular electronic device or sound-producing device with repurposed wire antenna). In some embodiments, the wireless power transmission system 100 includes a plurality of electronic devices 122 and sound-producing devices 150 (and may also include electronic devices coupled with sound-producing devices 151), each having at least one respective power harvesting circuitry 120 that is used to harvest power waves from the transmitters 102 into usable power for charging the electronic devices 122.

[0032] In some embodiments, one or more transmitters generate power waves to form pockets of energy at target locations and adjust power wave generation based on sensed data to provide safe, reliable, and efficient wirelessly-delivered power to receivers (and devices associated therewith). In some embodiments, a controlled "pocket of energy" (e.g., a region in which available power is high or concentrated due to constructive interference of power waves) and/or null spaces (e.g., a region in which available power is low or nonexistent due to destructive interference of power waves) may be formed by convergence of the power waves transmitted into a transmission field of the one or more transmitters. In some embodiments, pockets of energy form at one or more locations in a two- or three-dimensional field due to patterns of constructive interference caused by convergences of transmitted power waves. Energy from the transmitted power waves may be harvested by receivers (i.e., received and converted into usable power) at the one or more locations.

[0033] In some instances, constructive interference of power waves occurs when two or more power waves 116 are in phase with each other and converge into a combined wave such that an amplitude of the combined wave is greater than amplitude of a single one of the power waves. For example, the positive and negative peaks of sinusoidal waveforms arriving at a location from multiple antennas "add together" to create larger positive and negative peaks. In some embodiments, a pocket of energy is formed at a location in a transmission field where constructive interference of power waves occurs.

[0034] In some instances, destructive interference of power waves occurs when two or more power waves are out of phase and converge into a combined wave such that the amplitude of the combined wave is less than the amplitude of a single one of the power waves. For example, the power waves "cancel each other out," thereby diminishing the amount of energy concentrated at a location in the transmission field. In some embodiments, destructive interference is used to generate a negligible amount of energy or "null" at a location within the transmission field where the power waves converge.

[0035] In some embodiments, adaptive pocket-forming is performed, e.g., by adjusting power wave transmission to achieve a target power level for at least some of the power waves transmitted by the one or more transmitters. For example, a system for adaptive pocket-forming includes a sensor. In some embodiments, when the sensor detects an object, such as a sensitive object (e.g., a person, an animal, equipment sensitive to the power waves, and the like) within a predetermined distance (e.g., a distance within a range of 1-5 feet) of a pocket of energy, of one or more of the power waves, or of a transmitter, then a respective transmitter of the one or more transmitters adjusts one or more characteristics of transmitted power waves. Non-limiting examples of the one or more characteristics include: frequency, amplitude, trajectory, phase, and other characteristics used by one or more antennas of the one or more transmitters to transmit the power waves. As one example, in response to receiving information indicating that transmission of power waves by a respective transmitter of the one or more transmitters should be adjusted (e.g., a sensor senses a sensitive object within a predetermined distance of a respective target location), the adaptive pocket-forming process adjusts the one or more characteristics accordingly.

[0036] In some embodiments, adjusting the one or more characteristics includes reducing a currently generated power level at a location by adjusting one or more transmitted power waves that converge at the target location. In some embodiments, reducing a currently generated power level includes transmitting a power wave that causes destructive interference with at least one other transmitted power wave. For example, a power wave is transmitted with a first phase that is shifted relative to a second phase of at least one other power wave to destructively interfere with the at least one other power wave in order to diminish or eliminate the currently generated power level at the target location.

[0037] In some embodiments, adjusting the one or more characteristics includes increasing a power level for some of the transmitted power waves to ensure that the receiver (e.g., with power harvesting circuitry 120) receives adequate energy sufficient to quickly charge a power-storing component of an electronic device that is associated with the receiver.

[0038] In some embodiments, an object is "tagged" (e.g., an identifier of the object is stored in memory in association with a flag) to indicate that the detected object is a sensitive object. In response to detection of a particular object within a predetermined distance of a target location, a determination is made as to whether the particular object is a sensitive object. In some embodiments, this determination includes performing a lookup in the memory to check whether the particular object has been previously tagged and is therefore known as a sensitive object. In response to determining that the particular object is a sensitive object, the one or more characteristics use to transmit the power waves are adjusted accordingly.

[0039] In some embodiments, sensing a sensitive object includes using a series of sensor readings from one or more sensors to determine motion of an object within a transmission field of the one or more transmitters. In some embodiments, sensor output from one or more sensors is used to detect motion of the object approaching within a predetermined distance of a pocket of energy or of power waves used to form the pocket of energy. In response to a determination that a sensitive object is approaching (e.g., moving toward and/or within a predefined distance of a pocket of energy), the currently generated power level at the location of the pocket of energy is reduced. In some embodiments, the one or more sensors include sensors that are internal to the one or more transmitters, the receiver, and/or sensors that are external to the one or more transmitters and the receiver and may include thermal imaging, optical, radar, and other types of sensors capable to detecting objects within a transmission field.

[0040] Although some embodiments herein include the use of RF-based wave transmission technologies as a primary example, it should be appreciated that the wireless charging techniques that might be employed are not be limited to RF-based technologies and transmission techniques. Rather, it should be appreciated that additional or alternative wireless charging techniques may be utilized, including any suitable technology and technique for wirelessly transmitting energy so that a receiver is capable of converting the transmitted energy to electrical power. Such technologies or techniques may transmit various forms of wirelessly transmitted energy including the following non-limiting examples: ultrasound, microwave, laser light, infrared, or other forms of electromagnetic energy.

[0041] In some embodiments, the one or more transmitters 102 adjust one or more characteristics (e.g., phase, gain, direction, and/or frequency) of power waves 116. For example, a transmitter 102 (e.g., transmitter 102a) selects a subset of one or more antenna elements of antenna array 110 to initiate transmission of power waves 116, cease transmission of power waves 116, and/or adjust one or more characteristics used to transmit power waves 116. In some embodiments, the one or more transmitters 102 adjust power waves 116 such that trajectories of power waves 116 converge at a predetermined location within a transmission field (e.g., a location or region in space), resulting in controlled constructive or destructive interference patterns.

[0042] In some embodiments, respective antenna arrays 110 of the one or more transmitters 102 may include a set of one or more antennas configured to transmit the power waves 116 into respective transmission fields of the one or more transmitters 102. Integrated circuits (not shown) of the respective transmitter 102, such as a controller circuit and/or waveform generator, may control the behavior of the antennas. For example, based on the information received from the receiver via the communications signal 118, a controller circuit may determine a set of one or more characteristics or waveform characteristics (e.g., amplitude, frequency, trajectory, phase, among other characteristics) used for transmitting the power waves 116 that would effectively provide power to the power harvesting circuitry 120 and electronic device 122. The controller circuit may also identify a subset of antennas from the antenna arrays 110 that would be effective in transmitting the power waves 116. As another example, a waveform generator circuit of the respective transmitter 102 coupled to the processor 104 may convert energy and generate the power waves 116 having the waveform characteristics identified by the controller, and then provide the power waves to the antenna arrays 110 for transmission.

[0043] In some embodiments, the one or more transmitters 102 transmit power waves 116 that create two or more discrete transmission fields (e.g., overlapping and/or non-overlapping discrete transmission fields). In some embodiments, a first transmission field is managed by a first processor 104 of a first transmitter (e.g. transmitter 102a) and a second transmission field is managed by a second processor 104 of a second transmitter (e.g., transmitter 102b). In some embodiments, the two or more discrete transmission fields (e.g., overlapping and/or non-overlapping) are managed by the transmitter processors 104 as a single transmission field.

[0044] In some embodiments, communications component 112 transmits communication signals 118 via a wired and/or wireless communication connection to power harvesting circuitry 120. In some embodiments, communications component 112 generates communications signals 118 used for triangulation of power harvesting circuitry 120. In some embodiments, communication signals 118 are used to convey information between transmitter 102 and power harvesting circuitry 120 (e.g., for adjusting one or more characteristics used to transmit the power waves 116). In some embodiments, communications signals 118 include information related to status, efficiency, user data, power consumption, billing, geo-location, and other types of information.

[0045] In some embodiments, communications component 112 (e.g., communications component 112 of transmitter 102a) includes a communications component antenna for communicating with power harvesting circuitry 120 and/or other transmitters 102 (e.g., transmitters 102b through 102n). In some embodiments, these communications signals 118 represent a distinct channel of signals transmitted by transmitter 102, independent from a channel of signals used for transmission of the power waves 116.

[0046] In some embodiments, the power harvesting circuitry 120 includes a receiver-side communications component (not shown) configured to communicate various types of data with one or more of the transmitters 102, through a respective communications signal 118 generated by the receiver-side communications component. The data may include location indicators for the power harvesting circuitry 120 or a device associated therewith (e.g., sound-producing device 150, sound-producing device 151, and/or electronic device 122); a power status of the power harvesting circuitry 120 or a device associated therewith (e.g., sound-producing device 150, sound-producing device 151, and/or electronic device 122); status information for the power harvesting circuitry 120 or a device associated therewith (e.g., sound-producing device 150, sound-producing device 151, and/or electronic device 122); status information for the power harvesting circuitry 120 or a device associated therewith (e.g., sound-producing device 150, sound-producing device 151, and/or electronic device 122); status information about transmission or reception of the power waves 116; and/or status information for pockets of energy. In other words, the power harvesting circuitry 120 may provide data to the transmitter 102, via the communications signal 118, regarding the current operation of the power transmission system 100, including: information identifying a present location of the power harvesting circuitry 120 or a device associated therewith (e.g., sound-producing device 150, sound-producing device 151, and/or electronic device 122), an amount of energy received by the power harvesting circuitry 120, and an amount of power received and/or used by a device associated with the power harvesting circuitry 120 (e.g., sound-producing device 150, sound-producing device 151, and/or electronic device 122), among other possible data points containing other types of information. In some embodiments, communications signals 118 sent by the power harvesting circuitry 120 or a device associated therewith may include data for, e.g., alerting transmitters 102 that the power harvesting circuitry 120 or a device associated therewith has entered or is about to enter a transmission field, indicate the effectiveness of received power waves 116, and/or provide updated characteristics or transmission parameters that the one or more transmitters 102 may use to adjust transmission of the power waves 116.

[0047] In some embodiments, the wire of a particular sound-producing device (e.g., 150 or 151) may also be repurposed (while continuing to perform its original function, such as conveying sound data or signals in a headphone or performing a securing function for a hearing aid) to function as a receiving or transmitting antenna for the communication and control signals 118 discussed above. For example, the wire 152 or 157 may be repurposed to send and/or receive data packets between power harvesting circuitry 120 and the transmitters 102.

[0048] In some embodiments, transmitter sensor 114 and/or receiver sensor (which may be a component of the power harvesting circuitry 120) detect and/or identify conditions of electronic device 122, sound-producing devices 150 or 151, power harvesting circuitry 120, transmitter 102, and/or a transmission field. In some embodiments, data generated by transmitter sensor 114 and/or receiver sensor is used by transmitter 102 to determine appropriate adjustments to the one or more characteristics used to transmit the power waves 116. Data from transmitter sensor 114 and/or receiver sensor received by transmitter 102 includes, e.g., raw sensor data and/or sensor data processed by a processor 104, such as a sensor processor. Processed sensor data includes, e.g., determinations based upon sensor data output. In some embodiments, sensor data received from sensors that are external to the power harvesting circuitry 120 and the transmitters 102 is also used (such as thermal imaging data, information from optical sensors, and others).

[0049] In some embodiments, the receiver sensors include a gyroscope that provides raw data such as orientation data (e.g., tri-axial orientation data), and processing this raw data may include determining a location of power harvesting circuitry 120 and/or a device associated therewith using the orientation data. The receiver sensors may also include one or more infrared sensors (e.g., that output thermal imaging information), and processing this infrared sensor data includes identifying a person (e.g., indicating presence of the person and/or indicating an identification of the person) or other sensitive object based upon the thermal imaging information. In some embodiments, the receiver sensors may further or alternatively include an accelerometer that provides orientation data for power harvesting circuitry 120 and/or a device associated therewith (the received orientation information may be used to determine whether electronic device 122 and/or sound-producing devices 150 or 151 are lying flat on a table, in motion, and/or in use).

[0050] Non-limiting examples of transmitter sensor 114 and/or receiver sensors include, e.g., infrared, pyroelectric, ultrasonic, laser, optical, Doppler, gyro, accelerometer, microwave, millimeter, RF standing-wave sensors, resonant LC sensors, capacitive sensors, and/or inductive sensors. In some embodiments, technologies for transmitter sensor 114 and/or receiver sensors include binary sensors that acquire stereoscopic sensor data, such as the location of a human or other sensitive object.

[0051] In some embodiments, transmitter sensor 114 and/or a receiver sensor is configured for human recognition (e.g., capable of distinguishing between a person and other objects, such as furniture). Examples of sensor data output by human recognition-enabled sensors include: body temperature data, infrared range-finder data, motion data, activity recognition data, silhouette detection and recognition data, gesture data, heart rate data, portable devices data, and wearable device data (e.g., biometric readings and output, accelerometer data).

[0052] In some embodiments, transmitters 102 adjust one or more characteristics used to transmit the power waves 116 to ensure compliance with electromagnetic field (EMF) exposure protection standards for human subjects. Maximum exposure limits are defined by

US and European standards in terms of power density limits and electric field limits (as well as magnetic field limits). These include, for example, limits established by the Federal Communications Commission (FCC) for maximum permissible exposure (MPE), and limits established by European regulators for radiation exposure. Limits established by the FCC for MPE are codified at 47 CFR § 1.1310. For electromagnetic field (EMF) frequencies in the microwave range, power density can be used to express an intensity of exposure. Power density is defined as power per unit area. For example, power density can be commonly expressed in terms of watts per square meter (W/m^2), milliwatts per square centimeter (mW/cm^2), or microwatts per square centimeter ($\mu W/cm^2$). In some embodiments, output from transmitter sensor 114 and/or a receiver sensor is used by transmitter 102 to detect whether a person or other sensitive object enters a power transmission region (e.g., a location within a predetermined distance of a transmitter 102, power waves generated by transmitter 102, and/or a pocket of energy). In some embodiments, in response to detecting that a person or other sensitive object has entered the power transmission region, the transmitter 102 adjusts one or more power waves 116 (e.g., by ceasing power wave transmission, reducing power wave transmission, and/or adjusting the one or more characteristics of the power waves). In some embodiments, in response to detecting that a person or other sensitive object has entered the power transmission region, the transmitter 102 activates an alarm (e.g., by transmitting a signal to a loudspeaker that is a component of transmitter 102 or to an alarm device that is remote from transmitter 102). In some embodiments, in response to detecting that a person or other sensitive object has entered a power transmission region, the transmitter 102 transmits a digital message to a system log or administrative computing device.

[0053] In some embodiments, antenna array 110 includes multiple antenna elements (e.g., configurable “tiles”) collectively forming an antenna array. Antenna array 110 generates, e.g., RF power waves, ultrasonic power waves, infrared power waves, and/or magnetic resonance power waves. In some embodiments, the antennas of an antenna array 110 (e.g., of a single transmitter, such as transmitter 102a, and/or of multiple transmitters, such as transmitters 102a, 102b, …, 102n) transmit two or more power waves that intersect at a defined location (e.g.,. a location corresponding to a detected location of a power harvesting circuitry 120), thereby forming a pocket of energy at the defined location.

[0054] In some embodiments, transmitter 102 assigns a first task to a first subset of antenna elements of antenna array 110, a second task to a second subset of antenna elements of antenna array 110, and so on, such that the constituent antennas of antenna array 110 perform different tasks (e.g., determining locations of previously undetected power harvesting circuitries 120 and/or transmitting power waves 116 to one or more power harvesting circuitries 120). As one example, in an antenna array 110 with ten antennas, nine antennas transmit power waves 116 that form a pocket of energy and the tenth antenna operates in conjunction with communications component 112 to identify new receivers in the transmission field. In another example, an antenna array 110 having ten antenna elements is split into two groups of five antenna elements, each of which transmits power waves 116 to two different power harvesting circuitries 120 in the transmission field.

[0055] Turning now to Figures 2A-2B, block diagrams illustrating example sound-producing devices are shown. These example sound-producing devices include wires that have been repurposed to function as receiving antennas in accordance with some embodiments. Figure 2A shows a representative sound-producing device 150 (e.g., a hearing aid) having sound-producing device control circuitry 204 (e.g., for controlling signals conveyed by sound-producing device 150), power harvesting circuitry 120, and a wire 152. In accordance with some embodiments, the power harvesting circuitry 120 optionally includes signal isolation circuitry 123 configured to isolate signals received via an antenna composed of repurposed wire 152 from signals conveyed by the sound-producing device 150, frequency matching circuitry 125 configured to match frequencies of signals received via repurposed wire 152, and/or power conversion circuitry 126 configured to convert power received via repurposed wire 152 to usable energy for directly powering sound-producing device 150 and/or for charging a battery associated with sound-producing device 150 (e.g., battery 130, Figure 1).

[0056] In some embodiments, the wire 152 is adapted to convey signals of the sound-producing device (e.g., to convey audio signals received and amplified by sound-producing device 150 to a speaker in the user's ear). In some embodiments, power conversion circuitry 126 includes a rectifier and/or a power converter, as discussed above in reference to Figure 1. In some embodiments, power conversion circuitry 126 harvests power received via wire 152 and converts the power to usable energy for sound-producing device 150.

[0057] In some embodiments, the wire 152 is a wire that is used to help secure the sound-producing device 150 to a user's ear, and is not used to convey audio signals. In this way, some embodiments are able to repurpose wires that are not currently used to convey electrical signals to then function as receiving antennas for, e.g., receipt of wireless power. In some embodiments, the power harvesting circuitry 120 is coupled to a conductive shielding of the wire 152 and configured to harvest energy from power waves received via the conductive shielding.

[0058] As is also shown in Figure 2A, the sound-producing control circuitry 204 is coupled to the power harvesting circuitry 120. This coupling allows the signal isolation circuitry 123 to provide isolated audio data and signals (i.e., isolated from power waves or signals derived therefrom that may be traveling along a same repurposed wire 152) to the sound-producing circuitry 204, as is described in more detail in reference to Figures 3A-3B.

[0059] Figure 2B shows a representative sound-producing device 151 (e.g., headphones) coupled to electronic device 122 via wire(s) 210 and having sound-producing device control circuitry 204, power harvesting circuitry 120-b, earpieces 212 and 214, and wires 206 and 206 coupling earpieces 212 and 214 to sound-producing device control circuitry 204. In some embodiments, the wires 206 and 208 physically and communicatively couple earpieces 212 and 214 to the sound-producing device control circuitry 204. In some embodiments, and as discussed above in reference to Figure 1, portions of power harvesting circuitry 120 may be included in either or both of the sound-producing device 151 and the electronic device 122. In this example, the sound-producing device 151 is shown as including power harvesting circuitry 120-b with optional components and electronic device 122 is shown as including power harvesting circuitry 120-a with optional components.

[0060] Figure 2B also shows that the power harvesting circuitries 120-a and 120-b each may optionally include signal isolation circuitry 123-a, 123-b configured to isolate signals received via an antenna composed of a repurposed wire(s) (e.g., wires 206, 208, and 210 may be used as the wire 157 shown in Figure 1) from signals conveyed by the sound-producing device 151, frequency matching circuitry 125-a, 125-b configured to match frequencies of signals received via repurposed wire 157, and/or power conversion circuitry 126-a, 126-b configured to convert power received via repurposed wire 157 to usable energy (e.g., for powering electronic device 122 or charging a battery 131 associated therewith). For example, the isolation circuitry 123-a, 123-b separates signals to be converted to sound by earpiece(s) 212 and 214 from power waves received at wire(s) 206 and 208. In some embodiments, the power harvesting circuitry 120-b is coupled to a conductive shielding of wire(s) 206, 208, and/or 210 and configured to harvest energy from power waves received via the conductive shielding. In some embodiments, the power harvesting circuitry 120-a and/or 120-b is coupled to a one or more of wire(s) 206, 208, and 210 and configured to harvest energy from power waves received via those wires.

[0061] Although in Figure 2B signal processing circuitry 204 is shown within sound-producing device control circuitry 204, in some embodiments power harvesting circuitry 120-b is located at a different location within sound-producing device 151 and/or the components of the signal processing circuitry are split between the sound-producing device 151 and the electronic device 122. For example, in accordance with some embodiments, power harvesting circuitry 120-a includes the power conversion circuitry 126-a and is coupled with an audio connector of electronic device 122 (e.g., a headphone jack) and with a battery 131 of the device 122, and the power harvesting circuitry 120-b includes the signal isolation circuitry 123-b and the frequency matching circuitry 125-b. In this way, the system is able to isolate and perform the matching functions within the sound-producing device 151, and to perform the power conversion functions closer to where the battery is located within the electronic device 122 (in some embodiments, this also helps to reduce extra power loss due to redirecting the power and also gives the designer more control to limit the power leakage).

[0062] In some embodiments, earpiece 212 and/or 214 includes a speaker and one or more of wire(s) 206 and 208 are adapted to transmit signals to the speaker(s). In some embodiments, earpiece 212 and/or 214 includes a microphone and one or more of the wire(s) 206 and 208 is adapted to transmit signals from the microphone. In some embodiments, sound-producing device control circuitry 204 includes an audio chipset, volume control circuitry, microphone control circuitry, and/or speaker control circuitry.

[0063] In some embodiments, sound-producing device 151 is coupled to electronic device 122 via an audio port or audio connector (e.g., a headphone jack). In some embodiments, the sound-producing device 151 is coupled to the electronic device 122 via an audio port composed of wire(s) 210.

[0064] In some embodiments, one or more of wires 206, 208, and 210 are shielded with a conductive shielding (e.g., a metal shielding). In some embodiments, one or more of wires 206, 208, and 210 are shielded with an insulating shielding (e.g., a rubber or plastic shielding). In various embodiments, one or more of wires 206, 208, and 210 (or conductive shielding of the wires) is utilized as an antenna (e.g., repurposed wire 157, Figure 1) for a wireless power receiver (e.g., with power harvesting circuitry 120, Figure 1). In some embodiments, multiple wires of sound-producing device 151 are used (e.g., concurrently used) as antennas. For example, wire 206 is used to receive power waves of a first frequency (e.g., 915 MHz) and one or more of wire(s) 210 are used to receive waves of a second frequency (e.g., 2.4 GHz). In some embodiments, a wire (e.g., wire 206) is used to receive waves of multiple frequencies (e.g., 915 MHz and 2.4 GHz).

[0065] In some embodiments, the wires 206 and 208 may be operated as a dipole antenna (i.e., the repurposed wire 157 antenna includes the wires 206 and 208 operating as a dipole antenna). In these embodiments, the control circuitry 204 (which may be a volume control unit on a pair of headphones) functions as a dipole excitation point, and the power harvesting circuitry 120-b is used to send usable power back to an associated electronic device (e.g., device 122). For example, at 900 MHz, a far-field gain of 2.82 dBi can be observed from a standard two-wire headphone when these two wires form a dipole antenna in accordance with one example implementation.

[0066] In some embodiments, the wire 210 may be operated as a monopole antenna in reference to the PCB ground (i.e., the repurposed wire 157 antenna includes the wire 210 operating as a monopole antenna). In these embodiments, the headphone jack on an associated device (e.g., headphone jack of the device 122) functions as a monopole excitation point, and the power harvesting circuitry 120-a is used to send usable power back to an associated electronic device (e.g., device 122). As an example, a far-field gain of 2.2 dBi at 900 MHz can be achieved when this wire is used to from a monopole antenna in accordance with one example implementation.

[0067] Figures 3A-3B are block diagrams illustrating prophetic operation of the representative sound-producing device of Figure 2B in accordance with embodiments. Figure 3A shows the sound-producing device 151 receiving audio data 302 (e.g., digital and/or analog audio data) from electronic device 122. Figure 3A also shows that the audio data may be isolated (using, e.g., signal isolation circuitry 123-b) from other signals traveling along a same wire (e.g., one of the repurposed wires discussed herein), and then the sound-producing device 151 generates audio signals 304 (e.g., via sound-producing device control circuitry 204) corresponding to audio data 302 and conveying the audio signals 304 through repurposed wire(s) 244 to earpiece 245. Figures 3A also shows the earpiece 245 generating sounds 306 corresponding to the audio signals 304. The wire 244 is shown for example purposes and may correspond to any of the wires 206, 208, and 210 shown in Figure 2B (and combinations thereof, depending on how the repurposed wire 157 antenna is designed to operate).

[0068] Figure 3B shows the sound-producing device 151 continuing to receive audio data 302 and generate corresponding sounds 306. Figure 3B also shows reception of power waves 308 (e.g., power waves 116, Figure 1) at repurposed wire(s) 244 and corresponding power signals 310 conveyed from wire(s) 244 to power harvesting circuitry 120-b. Figure 3B also shows transmission of electricity 312 corresponding to the power signals 310 transmitted from sound-producing device 151 to the electronic device 122. In some embodiments (not shown), sound-producing device 151 receives power waves 308 and transmits corresponding electricity 312 to electronic device 122 when sound-producing device 151 is not receiving audio data 302 and/or is not generating corresponding sounds 306. In some embodiments (not shown), sound-producing device 151 receives communication waves and transmits corresponding communication signals to electronic device 122.

[0069] In some embodiments, the wire 243 is used to convey electricity 312 to a power source (e.g., battery) of the device 122, so that the power source may be charged using the electricity 312. In some embodiments, the wire 243 conveys both electricity and audio data.

[0070] In light of the principles described above with reference to the figures, we now turn to certain example embodiments.

[0071] In one aspect, some embodiments include a method of re-purposing at least one wire of a sound-producing device (e.g., wire 152 of sound-producing device 150, Figure 2A) as an antenna for receipt of wirelessly delivered power. The method includes: (1) coupling the at least one wire of the sound-producing device (e.g., wire 152, Figure 2A, or wires 206 and 208 operated as a repurposed wire 157 antenna) with power conversion circuitry (e.g., power conversion circuitry 126, Figure 2A), where the power conversion circuitry is coupled to a power source of an electronic device (e.g., battery 131 of electronic device 122, Figure 1) distinct from the sound-producing device; (2) receiving, by the at least one wire, one or more power waves (e.g., power waves 308, Figure 3B); (3) converting, by the power conversion circuitry, energy from the one or more power waves to usable electricity; and (4) providing the usable electricity to the power source of the electronic device (e.g., via wire(s) 210, Figure 2B). For example, in accordance with some embodiments, wires 206 and 208 in Figure 2B (operating as wire 157, Figure 1) both receive one or more power waves, power harvesting circuitry (e.g., 120, 120-a, and/or 120-b) converts the power waves to usable electricity, and wire(s) 210 provide the usable electricity to electronic device 122. In some embodiments, the power source is of the sound-producing device and the usable electricity is provided to that power source (e.g., to battery 130 of the sound-producing device 150, Figure 1)

[0072] In some embodiments, the at least one wire is coupled with a speaker of the sound-producing device; and the method further includes: (1) transmitting electrical signals to the speaker via the at least one wire; and (2) converting, by the speaker, the electrical signals to sound. For example, the wires 206, 208 (operating as wire 157) in Figure 2B is coupled with earpiece 212 and, in accordance with some embodiments, these wires convey electrical signals to the earpiece 212, 214 and the earpieces convert the electrical signals to sound for a user. In some embodiments, the transmitting is concurrent with the receiving.

[0073] In some embodiments, the one or more power waves (e.g., power waves 308, Figure 3B) comprise radio frequency signals. In some embodiments, the one or more power waves have a frequency of 915 MHz, 2.4 GHz, and/or 5.8 GHz. In some embodiments, the power waves are received from a far-field power transmitter. In some embodiments, the power waves are received from a near-field power transmitter.

[0074] In some embodiments, receiving, by the at least one wire, the one or more power waves comprises utilizing the at least one wire as a monopole antenna. For example, in accordance with some embodiments, the wire 152 in Figure 2A (or the wire 210 is Figure 2B) is utilized as a monopole antenna to receive power waves (e.g., power waves 116, Figure 1). In some embodiments, the at least one wire includes two wires. In some embodiments, receiving the one or more power waves comprises utilizing the two wires as a dipole antenna. For example, in accordance with some embodiments, the wires 206 and 208 in Figure 2B are utilized as a dipole antenna to receive power waves (e.g., power waves 116, Figure 1).

[0075] In some embodiments, the at least one wire includes a wire adapted to secure the sound-producing device to a user. For example, in accordance with some embodiments, the wire 152 in Figure 2A is utilized to secure sound-producing device 150 to a user's ear. In these embodiments, the repurposed wire 152 was not previously used to convey electrical signals and is now being repurposed to also function as a receiving antenna for receiving wireless power and/or data signals.

[0076] In another aspect, a wireless power receiver (e.g., a sound-producing device 150 that includes power harvesting circuitry 120 or a sound-producing device 151 that is coupled with a device 122 (each of which may include components of power harvesting circuitry in 120-a, 120-b), Figure 1) includes: (1) at least one wire (e.g., wire 244, Figure 3A) of a sound-producing device (e.g., sound-producing device 151, Figure 3A), where the at least one wire is used by the wireless power receiver to receive power waves (e.g., power waves 308, Figure 3B); and (2) power harvesting circuitry (e.g., power harvesting circuitry 120), or power conversion circuitry (e.g., power conversion circuitry 126), coupled with (i) the at least one wire and (ii) a power source of an electronic device (e.g., electronic device 122, Figure 3A) distinct from the sound-producing device, the power conversion circuitry configured to: (a) convert energy from the received power waves to usable electricity; and (b) provide the usable electricity to the power source of the electronic device (e.g., via wire(s) 243, Figure 3A). In some embodiments, the at least one wire is an external wire of the sound-producing device. For example, the wire(s) 244 in Figure 3A are external wires coupling the control circuitry 204 to the earpiece 245.

[0077] In some embodiments, the sound-producing device further includes a speaker (e.g., earpiece 245, Figure 3A) coupled to the at least one wire. In some embodiments, the at least one wire is adapted to transmit electrical signals (e.g., audio signals 304, Figure 3A) to the speaker, the electrical signals to be converted to sound by the speaker.

[0078] In some embodiments, the wireless power receiver is adapted to receive and convert the power waves (e.g., power waves 308, Figure 3B) while the at least one wire is transmitting the electrical signals to the speaker. In some embodiments, the sound-producing device is a headphone, an earbud, a pair of headphones, a hearing aid, and/or a pair of earbuds. In some embodiments, the sound-producing device includes a wearable speaker.

[0079] In some embodiments, the electronic device is a mobile phone, a tablet computer, a laptop computer, a handheld electronic device, and/or a portable electronic device. In some embodiments, the sound-producing device is coupled to the electronic device via an audio port (e.g., a 3.5 mm headphone jack).

[0080] In some embodiments, the power waves comprise radio frequency signals (e.g., 915 MHz signals). In some embodiments, the power conversion circuitry is configured to convert energy from two or more types of power waves (e.g., power waves having different transmission characteristics, such as frequencies of 2.4 GHz and 5.8 GHz). In some embodiments, the two or more types include power waves having different intensities, such as a higher intensity for when the sound-producing device is not in use, or worn, by a user and a lower intensity for when the sound-producing device is in use or worn. Adaptive matching circuitry can be used to optimize the system for these operating modes; for example, the loading of these wire antennas will change significantly when is placed near a human body and, as such and in some embodiments, the adaptive matching circuitry may be used to tune operation for such operating modes (e.g., when the wires are placed near a human body). In some embodiments, the power conversion circuitry includes a rectifier and a power converter. In some embodiments, the power conversion circuitry is a component of an integrated wireless power receiving circuit or signal processing circuit (e.g., the power harvesting circuitry 120, 120-a, 120-b shown in the figures). In some embodiments, the integrated wireless power receiving circuit includes a controller configured to manage power conversion by the integrated wireless power receiving circuit. In some embodiments, the integrated wireless power receiving circuit includes a frequency matching circuit (e.g., matching circuitry 125, Figure 1) adapted to match a frequency of the sound-producing device. In some embodiments, the integrated wireless power receiving circuit includes an impedance matching circuit (e.g., matching circuitry 125, Figure 1) adapted to match an impedance of the sound-producing device.

[0081] In some embodiments, the power harvesting circuitry is configured to isolate or filter the power waves from other electrical signals travelling along the at least one wire. For example, power harvesting circuitry 120-b in Figure 3B includes isolation circuitry 123-b for isolating the power signals 310 from the audio signals 304.

[0082] In some embodiments, the at least one wire includes a conductive shield and the power conversion circuitry is configured to receive the power waves via the conductive shield. In some embodiments, the at least one wire includes a wire enclosed in a non-conductive shield. In some embodiments, the at least one wire includes a hanging wire of the sound-producing device (e.g., a wire not used to convey audio signals).

[0083] In another aspect, a system for wireless power delivery includes: (1) a wireless power transmitter (e.g., transmitter 102a, Figure 1) configured to transmit one or more power waves (e.g., waves 116, Figure 1); and (2) a wireless power receiver remote from the wireless power transmitter, the wireless power receiver configured to: (a) receive the one or more power waves via at least one wire of a sound-producing device (e.g., wire 208 of sound-producing device 200, Figure 2B); (b) convert energy from the received power waves to usable energy (e.g., via power harvesting circuitry 120, Figure 2B); and (c) provide the usable energy to a power source of an electronic device (e.g., electronic device 122, Figure 2B), the electronic device coupled to the sound-producing device.

[0084] In some embodiments, the wireless power transmitter is further configured to: (1) determine whether the sound-producing device is in use (e.g., based on an orientation or position of the sound-producing device, proximity to human body, or based on data signals received from the sound-producing device or a device, such as device 122, connected therewith); (2) transmit power waves having a first characteristic in accordance with a determination that the sound-producing device is in use; and (3) transmit power waves having a second characteristic in accordance with a determination that the sound-producing device is in use. For example, the power transmitter is configured to transmit power signals having lower relative intensity in accordance with a determination that the sound-producing device is in use and is configured to transmit power signals having a higher relative intensity in accordance with a determination that the sound-producing device is not in use. In some embodiments, the transmitter receives operating data from the sound-producing device (e.g., via signals 118, Figure 1). For example, the sound-producing device transmits a particular signal only when in operation and the transmitter uses the presence or absence of the signal to determine whether the sound-producing device is in use.

[0085] In some embodiments, the wireless power receiver is configured to receive and convert energy from power waves having either the first characteristic or the second characteristic. For example, in accordance with some embodiments, power harvesting circuitry 120 in Figure 2A is configured to receive and convert power signals having multiple intensities and/or multiple frequencies. In some embodiments, the wireless power transmitter is configured to adjust a characteristic of the power waves based on an orientation of the sound-producing device. For example, if the sound-producing device is in a horizontal orientation, the wireless transmitter determines that the sound-producing device is not in use by the user, whereas if the sound-producing device is in a vertical orientation, the transmitter determines that the sound-producing device is in use. In some embodiments, the transmitter receives orientation data from the sound-producing device (e.g., via signals 118, Figure 1). As a second example, the antenna will see variable loading (due to proximity to the human body) when is being used, and therefore in some embodiments, can determine if the system is being used or not.

[0086] In some alternative embodiments, a repurposed wire is additionally or alternatively used to receive communication/ data signals from remote devices. For example, the existing wire is used for the receipt of point-to-point communications (e.g., using BLUETOOTH protocols) and/or to receive broadband communications (e.g., using WI-FI protocols). In such embodiments, as will be appreciated by those skilled in the art, the power conversion circuitry 126 of Figure 1 is replaced with the appropriate signal processing circuitry for processing the desired type of communication signals. As an example, a wire that couples a headset to a smart phone is repurposed so that, in addition to conveying audio signals from the smart phone to speakers in the headset, the wire is also used as an antenna to receive point-to-point communications that are processed and conveyed to the smart phone (e.g., for presentation to the user).

[0087] Features of the present invention can be implemented in, using, or with the assistance of a computer program product, such as a storage medium (media) or computer readable storage medium (media) having instructions stored thereon/in which can be used to program a processing system to perform any of the features presented herein. The storage medium (e.g., memory 106) can include, but is not limited to, high-speed random access memory, such as DRAM, SRAM, DDR RAM or other random access solid state memory devices, and may include non-volatile memory, such as one or more magnetic disk storage devices, optical disk storage devices, flash memory devices, or other non-volatile solid state storage devices. Memory 106 optionally includes one or more storage devices remotely located from the CPU(s) or processor(s) 104. Memory 106, or alternatively the non-volatile memory device(s) within memory 106, comprises a non-transitory computer readable storage medium.

[0088] Stored on any one of the machine readable medium (media), features of the present invention can be incorporated in software and/or firmware for controlling the hardware of a processing system (such as the components associated with the transmitters 102 and/or power harvesting circuitries 120), and for enabling a processing system to interact with other mechanisms utilizing the results of the present invention. Such software or firmware may include, but is not limited to, application code, device drivers, operating systems, and execution environments/containers.

[0089] Communication systems as referred to herein (e.g., communications component 112, Figure 1) optionally communicate via wired and/or wireless communication connections. Communication systems optionally communicate with networks, such as the Internet, also referred to as the World Wide Web (WWW), an intranet and/or a wireless network, such as a cellular telephone network, a wireless local area network (LAN) and/or a metropolitan area network (MAN), and other devices by wireless communication. Wireless communication connections optionally use any of a plurality of communications standards, protocols and technologies, including but not limited to radio-frequency (RF), radio-frequency identification (RFID), infrared, radar, sound, Global System for Mobile Communications (GSM), Enhanced Data GSM Environment (EDGE), high-speed downlink packet access (HSDPA), high-speed uplink packet access (HSUPA), Evolution, Data-Only (EV-DO), HSPA, HSPA+, Dual-Cell HSPA (DC-HSPDA), long term evolution (LTE), near field communication (NFC), ZigBee, wideband code division multiple access (W-CDMA), code division multiple access (CDMA), time division multiple access (TDMA), Bluetooth, Wireless Fidelity (Wi-Fi) (e.g., IEEE 102.11a, IEEE 102.11ac, IEEE 102.11ax, IEEE 102.11b, IEEE 102.11g and/or IEEE 102.11n), voice over Internet Protocol (VoIP), Wi-MAX, a protocol for e-mail (e.g., Internet message access protocol (IMAP) and/or post office protocol (POP)), instant messaging (e.g., extensible messaging and presence protocol (XMPP), Session Initiation Protocol for Instant Messaging and Presence Leveraging Extensions (SIMPLE), Instant Messaging and Presence Service (IMPS)), and/or Short Message Service (SMS), or any other suitable communication protocol, including communication protocols not yet developed as of the filing date of this document.

[0090] It will be understood that, although the terms “first,” “second,” etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another.

[0091] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the claims. As used in the description of the embodiments and the appended claims, the singular forms “a,” “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will also be understood that the term “and/or” as used herein refers to and encompasses any and all possible combinations of one or more of the associated listed items. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0092] As used herein, the term “if” may be construed to mean “when” or “upon” or “in response to determining” or “in accordance with a determination” or “in response to detecting,” that a stated condition precedent is true, depending on the context. Similarly, the phrase “if it is determined [that a stated condition precedent is true]” or “if [a stated condition precedent is true]” or “when [a stated condition precedent is true]” may be construed to mean “upon determining” or “in response to determining” or “in accordance with a determination” or “upon detecting” or “in response to detecting” that the stated condition precedent is true, depending on the context.

[0093] The foregoing description, for purpose of explanation, has been described with reference to specific embodiments. However, the illustrative discussions above are not intended to be exhaustive or to limit the claims to the precise forms disclosed. Many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described in order to best explain principles of operation and practical applications, to thereby enable others skilled in the art.

What is claimed is:

1. A wireless power receiver, comprising:

at least one wire of a sound-producing device, the at least one wire configured for:

conveying sound signals or securing at least part of the sound-producing device to a user; and

receiving power waves; and

power harvesting circuitry coupled with (i) the at least one wire and (ii) a power source of an electronic device, the power harvesting circuitry configured to:

convert the received power waves to usable energy; and

provide the usable energy to the power source of the electronic device.

2. The wireless power receiver of claim 1, wherein the power harvesting circuitry is also configured to isolate the received power waves from the conveyed sound signals.

3. The wireless power receiver of claim 1, wherein the at least one wire comprises an external wire of the sound-producing device.

4. The wireless power receiver of claim 1, wherein the at least one wire includes a conductive shield adapted to receive power waves; and

wherein the power harvesting circuitry is configured to receive the power waves via the conductive shield.

5. The wireless power receiver of claim 1, wherein the sound-producing device further comprises a speaker coupled to the at least one wire, wherein the at least one wire is configured to transmit the electrical signals to the speaker for conversion to sound.

6. The wireless power receiver of claim 1, wherein the sound-producing device is selected from a group consisting of:

a headphone;

an earbud;

a pair of headphones;

a pair of earbuds; and

a hearing aid.

7. The wireless power receiver of claim 1, wherein the electronic device is selected from a group consisting of:

a mobile phone;

a tablet computer;

a laptop computer;

a handheld electronic device; and

a portable electronic device.

8. The wireless power receiver of claim 1, wherein the sound-producing device is coupled to the electronic device via a headphone jack.

9. The wireless power receiver of claim 1, wherein the power harvesting circuitry is configured to convert energy from two or more types of power waves.

10. The wireless power receiver of claim 1, wherein the power harvesting circuitry includes a rectifier and a power converter.

11. The wireless power receiver of claim 1, wherein the power harvesting circuitry is a component of an integrated wireless power receiving circuit.

12. The wireless power receiver of claim 11, wherein the integrated wireless power receiving circuit includes a controller configured to manage power conversion by the integrated wireless power receiving circuit.

13. The wireless power receiver of claim 11, wherein the integrated wireless power receiving circuit includes a matching circuit adapted to match a frequency for the at least one wire.

14. The wireless power receiver of claim 11, wherein the integrated wireless power receiving circuit is configured to isolate the power waves from other electrical signals travelling along the at least one wire.

15. A method of utilizing at least one wire of a sound-producing device as an antenna for receipt of wirelessly delivered power, where the at least one wire is coupled to power harvesting circuitry that is in turn coupled to a power source of an electronic device distinct from the sound-producing device, the method comprising:

using the at least one wire during operation of the sound-producing device;

receiving, by the at least one wire, power waves;

converting, by the power harvesting circuitry, the power waves to usable electricity; and

providing the usable electricity to the power source of the electronic device.

16. The method of claim 15, where the at least one wire is coupled with a speaker of the sound-producing device, and using the at least one wire in operation of the sound-producing device comprises transmitting via the at least one wire electrical signals to the speaker for conversion to sound.

17. The method of claim 15, wherein the power waves are radio frequency signals that are transmitted so that they constructively interfere in proximity to the sound-producing device.

18. The method of claim 15, wherein the one or more power waves have a frequency of 915 MHz, 2.4 GHz, or 5.8 GHz.

19. The method of claim 15, wherein the power waves are received from a far-field power transmitter.

20. The method of claim 15, wherein the power waves are received from a near-field power transmitter.

21. The method of claim 15, wherein receiving, by the at least one wire, the power waves comprises utilizing the at least one wire as a monopole antenna.

22. The method of claim 15, wherein the at least one wire comprises two wires and receiving the one or more power waves comprises utilizing the two wires as a dipole antenna.

23. The method of claim 15, wherein using the at least one wire in operation of the sound-producing device comprises utilizing the at least one wire to secure the sound-producing device to a user’s ear.

24. A sound-producing device configured to receive wirelessly delivered power, comprising:

a speaker;

power-harvesting circuitry;

at least one wire coupled to the speaker and the power-harvesting circuitry, the at least one wire configured to:

convey electrical signals to the speaker for conversion to audible sound; and

operate as an antenna to receive power waves; and

a power source coupled to the at least one power harvesting circuitry and configured to provide power to the sound-producing device sound,

wherein the power harvesting circuitry is configured to:

isolate the received power waves from the electrical signals;

convert the isolated power waves to usable electricity; and

provide the usable electricity to the power source.

25. The sound-producing device of claim 24, wherein the at least one wire is further configured to secure the sound-producing device to a user's ear.

26. The sound-producing device of claim 24, wherein the power harvesting circuitry is configured to convert energy from two or more types of power waves.

27. The sound-producing device of claim 24, wherein the power harvesting circuitry includes a rectifier and a power converter.

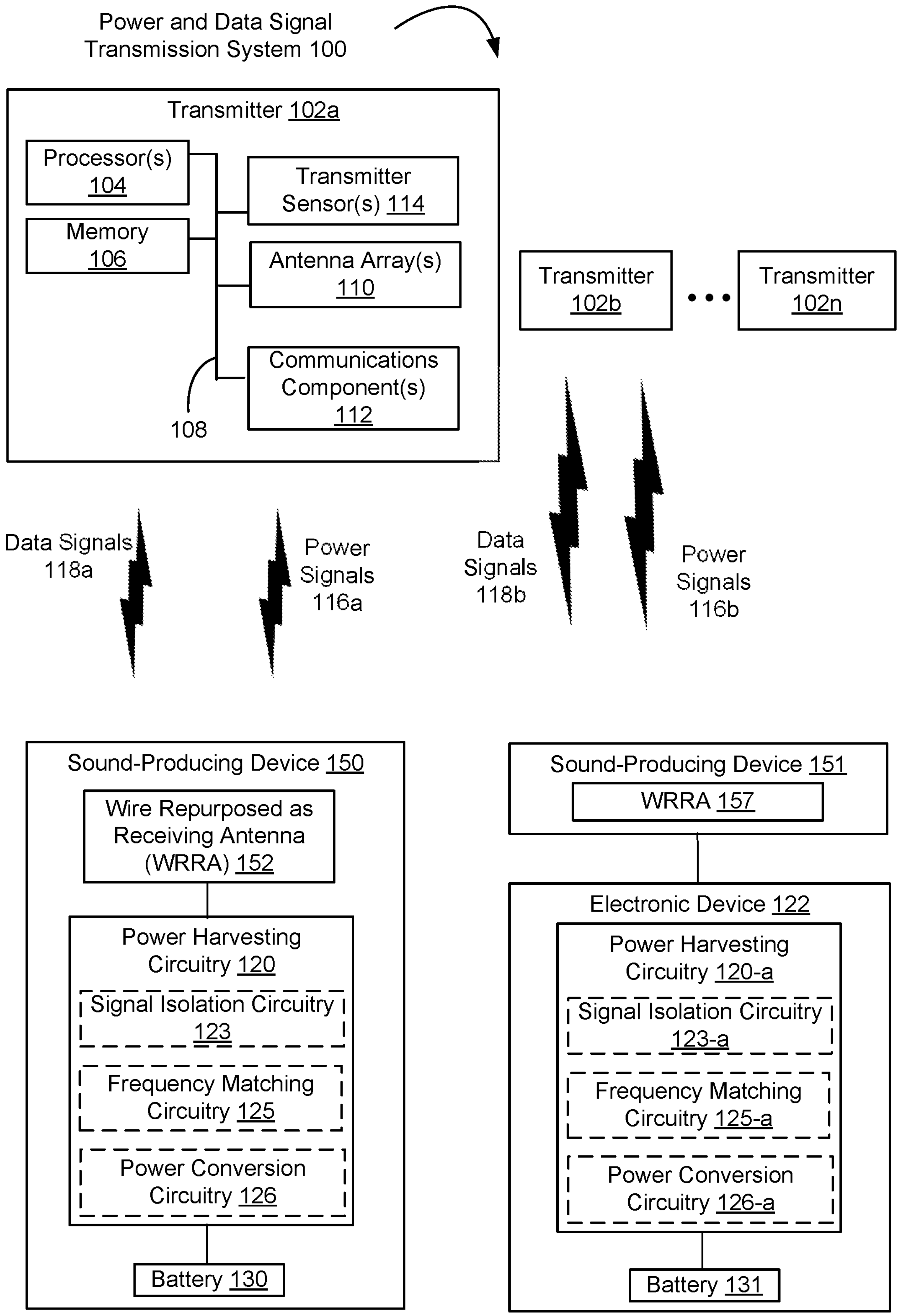
Power and Data Signal Transmission System 100
Transmitter 102a
Processor(s) 104
Memory 106
Transmitter Sensor(s) 114
Antenna Array(s) 110
Communications Component(s) 112
108
Transmitter 102b
Transmitter 102n
Data Signals 118a
Power Signals 116a
Data Signals 118b
Power Signals 116b
Sound-Producing Device 150
Wire Repurposed as Receiving Antenna (WRRA) 152
Power Harvesting Circuitry 120
Signal Isolation Circuitry 123
Frequency Matching Circuitry 125
Power Conversion Circuitry 126
Battery 130
Sound-Producing Device 151
WRRA 157
Electronic Device 122
Power Harvesting Circuitry 120-a
Signal Isolation Circuitry 123-a
Frequency Matching Circuitry 125-a
Power Conversion Circuitry 126-a
Battery 131

Figure 1

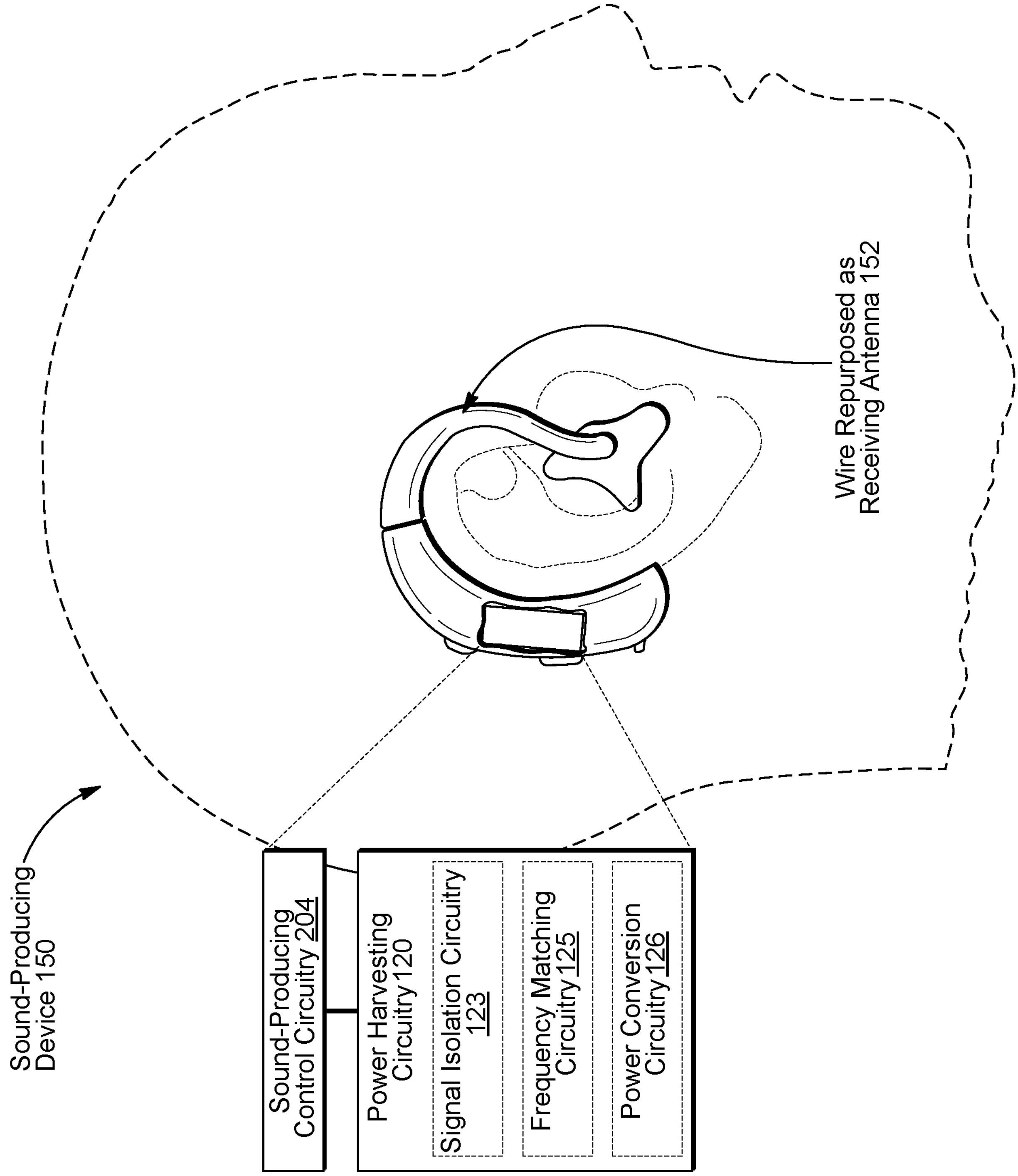
Sound-Producing
Device 150
Sound-Producing
Control Circuitry 204
Power Harvesting
Circuitry 120
Signal Isolation Circuitry
123
Frequency Matching
Circuitry 125
Power Conversion
Circuitry 126
Wire Repurposed as
Receiving Antenna 152

Figure 2A

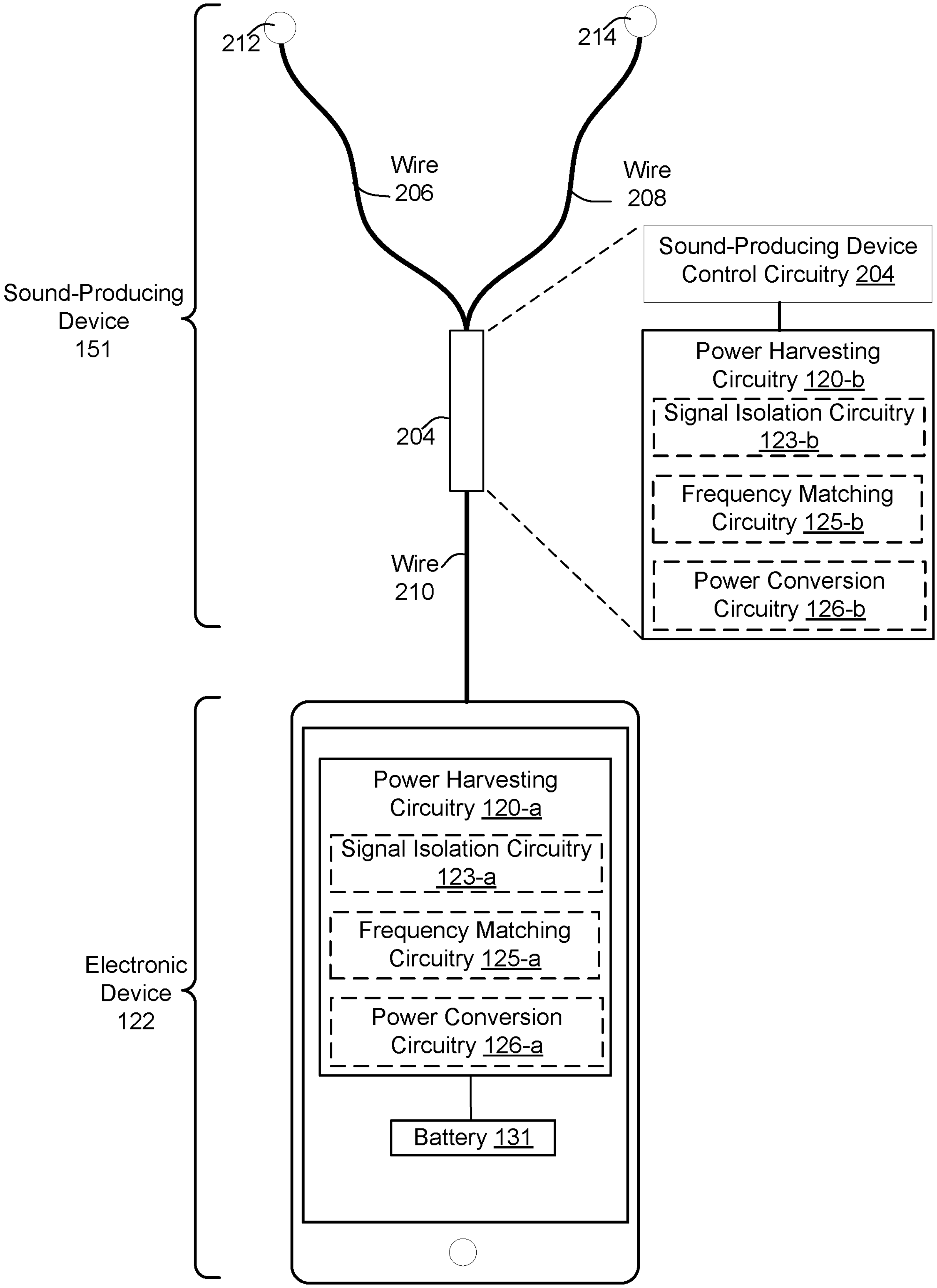
212
214
Wire
206
Wire
208
Sound-Producing Device
151
Sound-Producing Device Control Circuitry 204
Power Harvesting Circuitry 120-b
Signal Isolation Circuitry 123-b
Frequency Matching Circuitry 125-b
Power Conversion Circuitry 126-b
204
Wire
210
Electronic Device
122
Power Harvesting Circuitry 120-a
Signal Isolation Circuitry 123-a
Frequency Matching Circuitry 125-a
Power Conversion Circuitry 126-a
Battery 131

Figure 2B

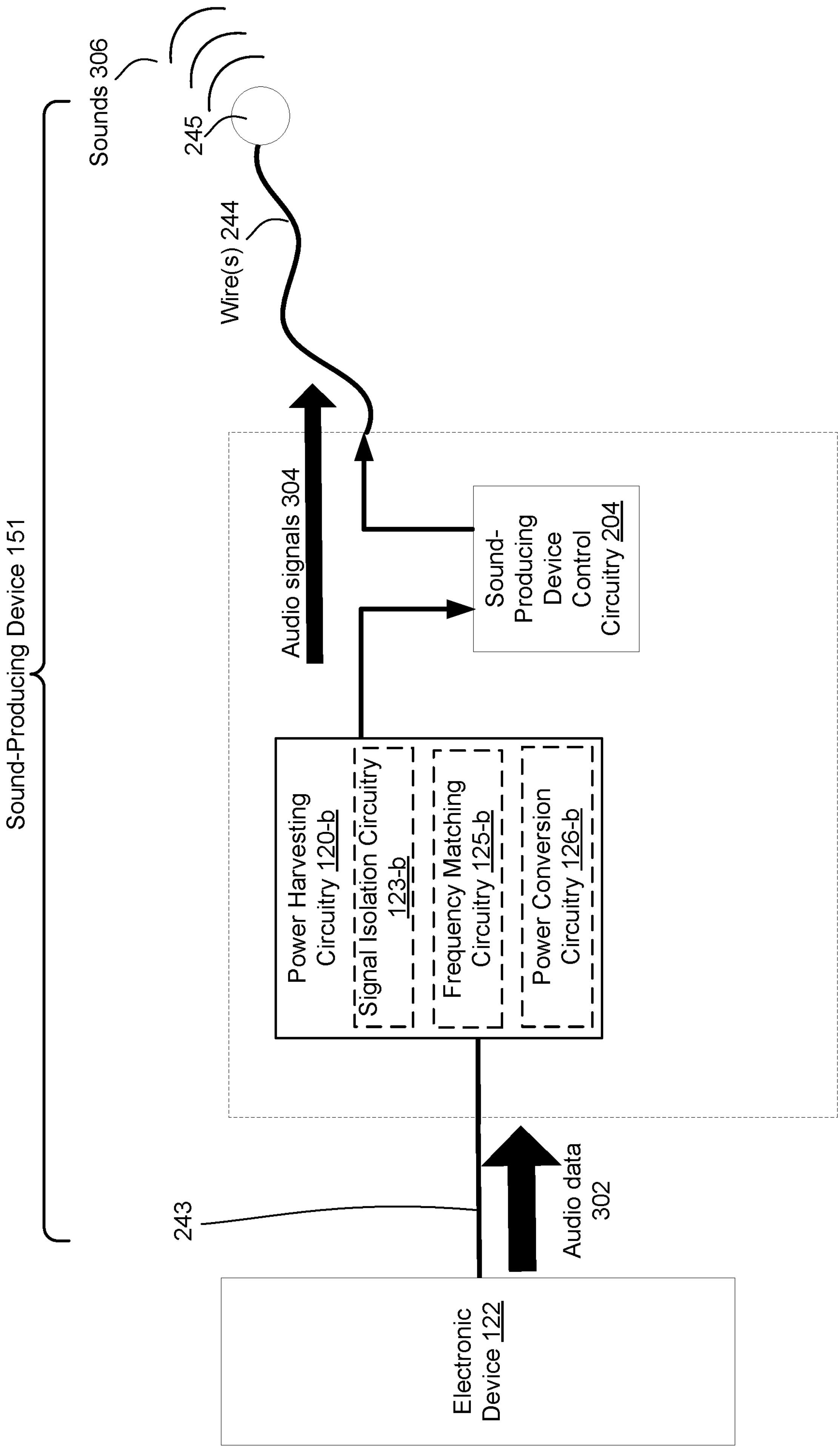
Sound-Producing Device 151
Sounds 306
245
Wire(s) 244
Audio signals 304
Sound-Producing Device Control Circuitry 204
Power Harvesting Circuitry 120-b
Signal Isolation Circuitry 123-b
Frequency Matching Circuitry 125-b
Power Conversion Circuitry 126-b
243
Audio data 302
Electronic Device 122

Figure 3A

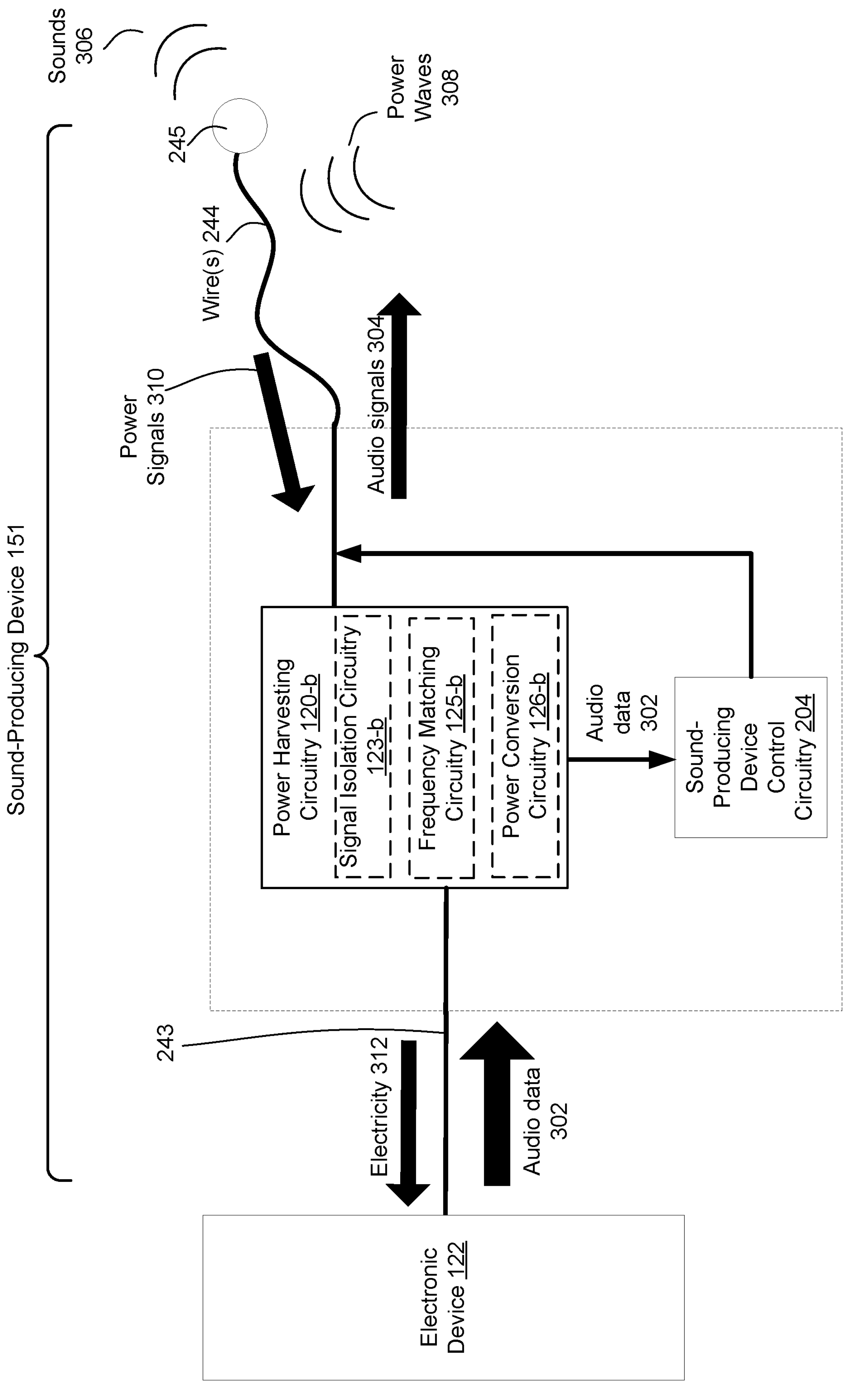
Sound-Producing Device 151
Sounds 306
245
Power Waves 308
Wire(s) 244
Power Signals 310
Audio signals 304
Power Harvesting Circuitry 120-b
Signal Isolation Circuitry 123-b
Frequency Matching Circuitry 125-b
Power Conversion Circuitry 126-b
Audio data 302
Sound-Producing Device Control Circuitry 204
243
Electricity 312
Audio data 302
Electronic Device 122

Figure 3B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US18/39334

A. CLASSIFICATION OF SUBJECT MATTER
IPC - H02J 7/00, 50/12, 50/27, 50/80; H04B 5/00 (2018.01)
CPC - H02J 5/005, 7/025, 50/12, 50/27, 50/80; H04B 5/0037

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
See Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2017/0127196 A1 (POGOTEC, INC.) May 4, 2017; FIG. 32, paragraphs [0098], [0131], & [0254]-[0262]	1, 2, 5-7, 10-12, 14, 24, & 27 --- 3, 4, 8, 9, 13, 15-23, 25, & 26
Y	US 2016/0112787 A1 (APPLE INC.) April 21, 2016; FIG. 1, paragraphs [0018], [0021], [0024], & [0025]	3, 8, & 15-23
Y	US 2013/0120052 A1 (SISKA, A) May 16, 2013; paragraph [0026]	4
Y	US 2012/0007441 A1 (JOHN, M) January 12, 2012; paragraphs [0095] & [0096]	9, 19, & 26
Y	US 2014/0191818 A1 (WAFFENSCHMIDT, E et al.) July 10, 2014; paragraphs [0041] & [0044]	13
Y	US 2014/0375253 A1 (DIVINE WAVE INC.) December 25, 2014; paragraph [0022], claim 10	17 & 18
Y	US 2002/0123776 A1 (VON ARX, J et al.) September 5, 2002; paragraphs [0007], [0016] & [0017]	21 & 22
Y	US 2009/0180653 A1 (SJURSEN, W et al.) July 16, 2009; paragraphs [0015] & [0016]	23 & 25

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 August 2018 (14.08.2018)	11 SEP 2018

Name and mailing address of the ISA/	Authorized officer
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774