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Ozaki et al.

(54) **SYSTEMS AND METHODS RELATING TO MULTI-DIMENSIONAL WIRELESS CHARGING**

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(21) Appl. No.: **12/567,339**

(22) Filed: **Sep. 25, 2009**

Related U.S. Application Data

(60) Provisional application No. 61/151,290, filed on Feb. 10, 2009, provisional application No. 61/244,391, filed on Sep. 21, 2009.

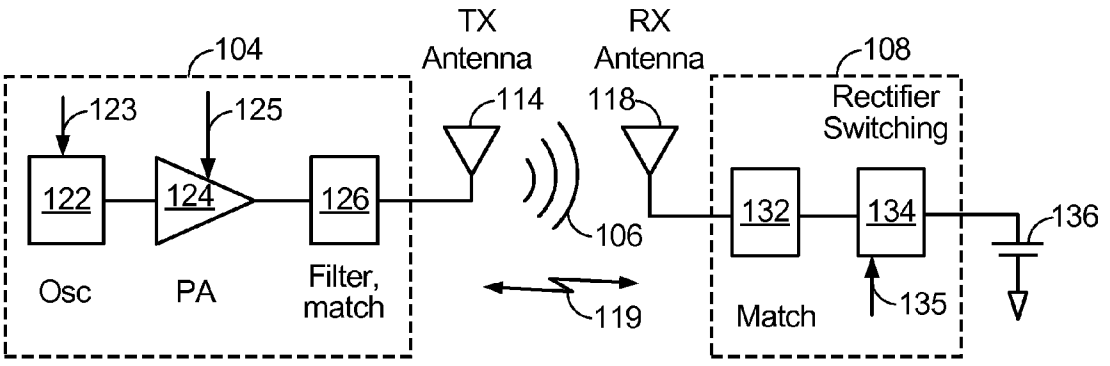
Publication Classification

(51) **Int. Cl.**
H02J 17/00 (2006.01)

(52) **U.S. Cl.** **307/104**

(57) **ABSTRACT**

Exemplary methods and systems related to wireless charging are disclosed. In an exemplary embodiment, a plurality of transmit antennas are used, wherein at least one transmit antenna of the plurality of transmit antennas is configured to be oriented in a different plane than at least one other transmit antenna of the plurality of transmit antennas. Furthermore, each transmit antenna of the plurality of transmit antennas is configured for transmitting power within an associated near-field.



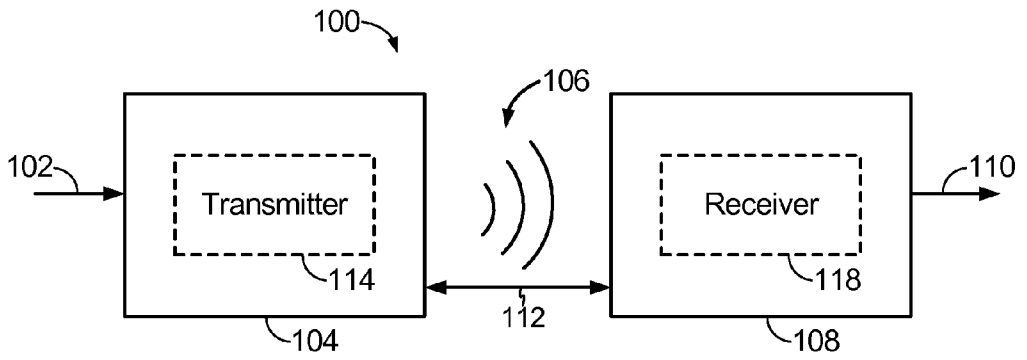

100
106
102
Transmitter
114
104
112
Receiver
118
108
110

FIG. 1

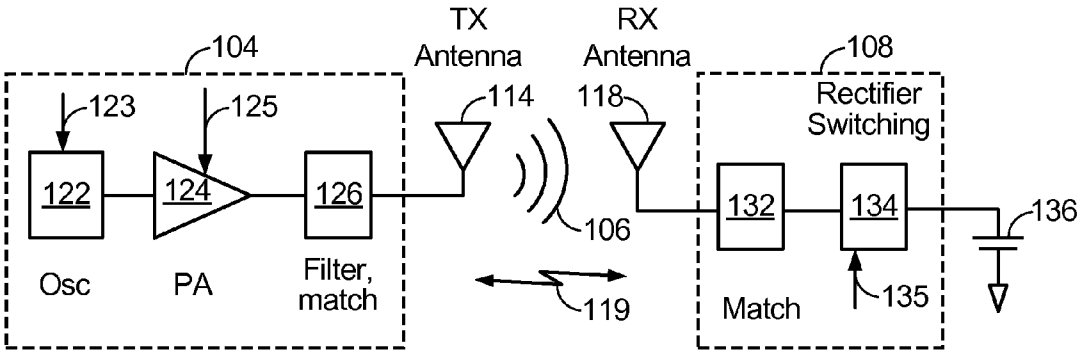

104
TX
Antenna
RX
Antenna
108
123
125
114
118
Rectifier
Switching
122
124
126
132
134
136
106
Osc
PA
Filter,
match
119
Match
135

FIG. 2

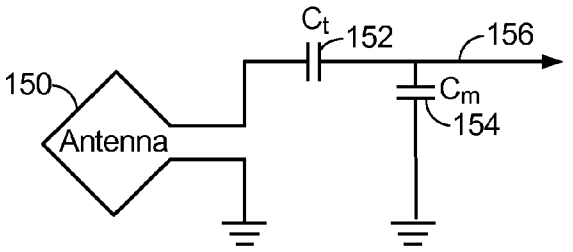

C_t
152
156
150
Antenna
C_m
154

FIG. 3

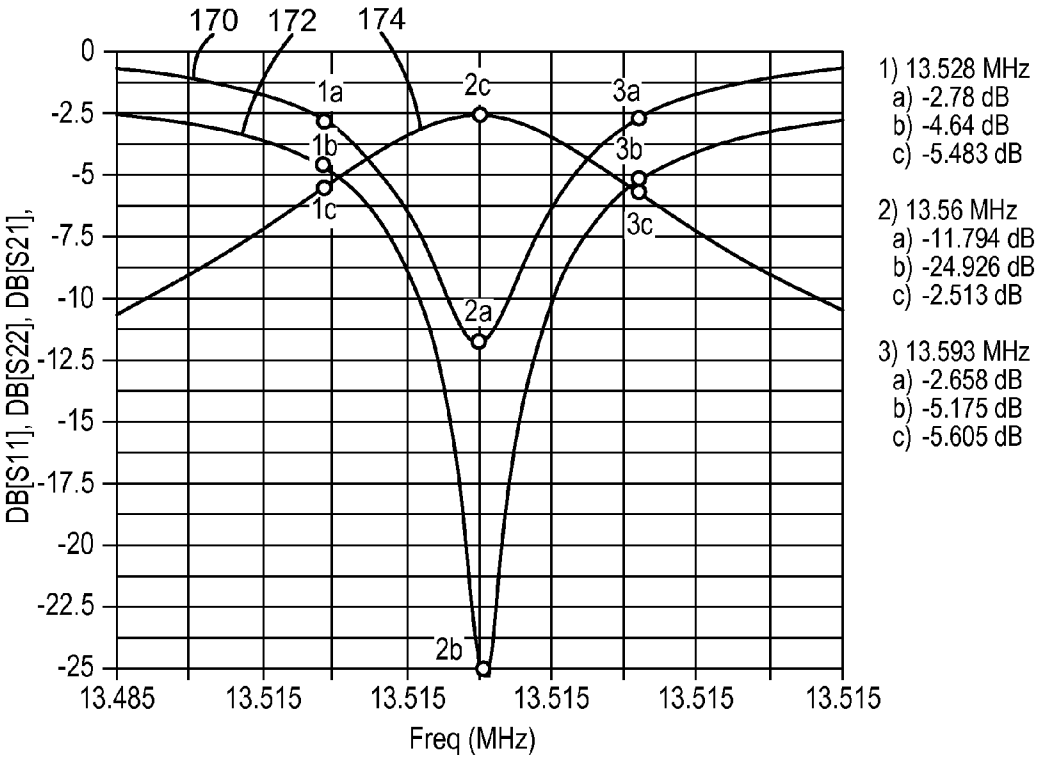

170
172
174
0
-2.5
-5
-7.5
-10
-12.5
-15
-17.5
-20
-22.5
-25
DB[S11], DB[S22], DB[S21],
1a
1b
1c
2a
2b
2c
3a
3b
3c
13.485
13.515
13.515
13.515
13.515
13.515
Freq (MHz)
1) 13.528 MHz
a) -2.78 dB
b) -4.64 dB
c) -5.483 dB
2) 13.56 MHz
a) -11.794 dB
b) -24.926 dB
c) -2.513 dB
3) 13.593 MHz
a) -2.658 dB
b) -5.175 dB
c) -5.605 dB

FIG. 4

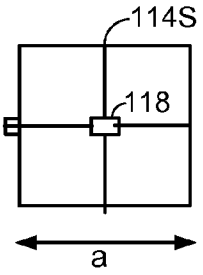


FIG. 5A

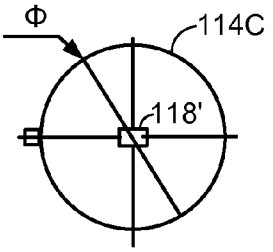


FIG. 5B

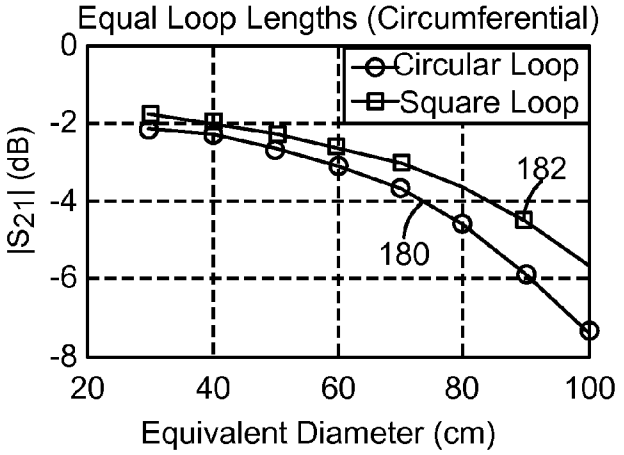


FIG. 6

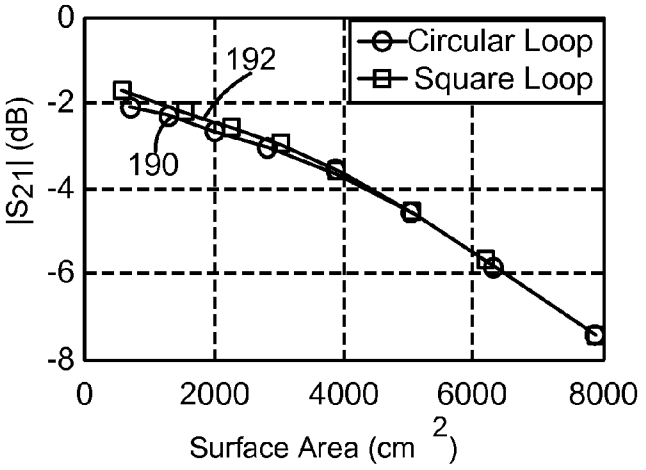


FIG. 7

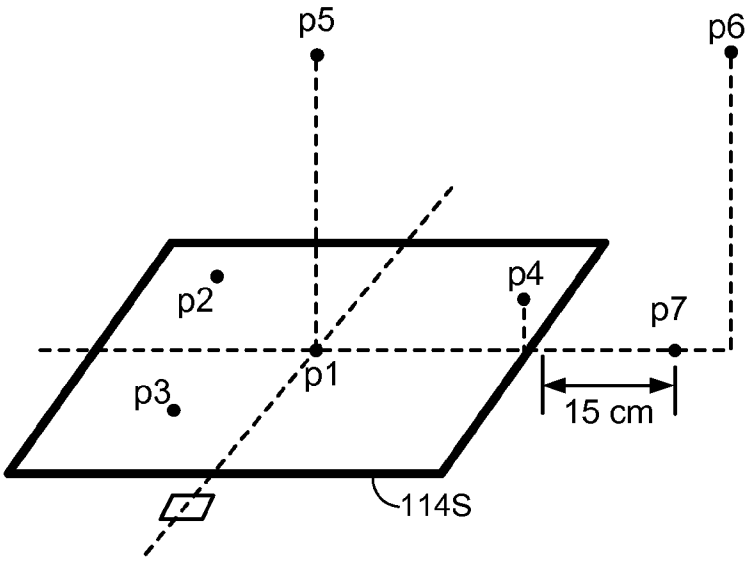

p5
p6
p2
p4
p7
p1
p3
15 cm
114S

FIG. 8

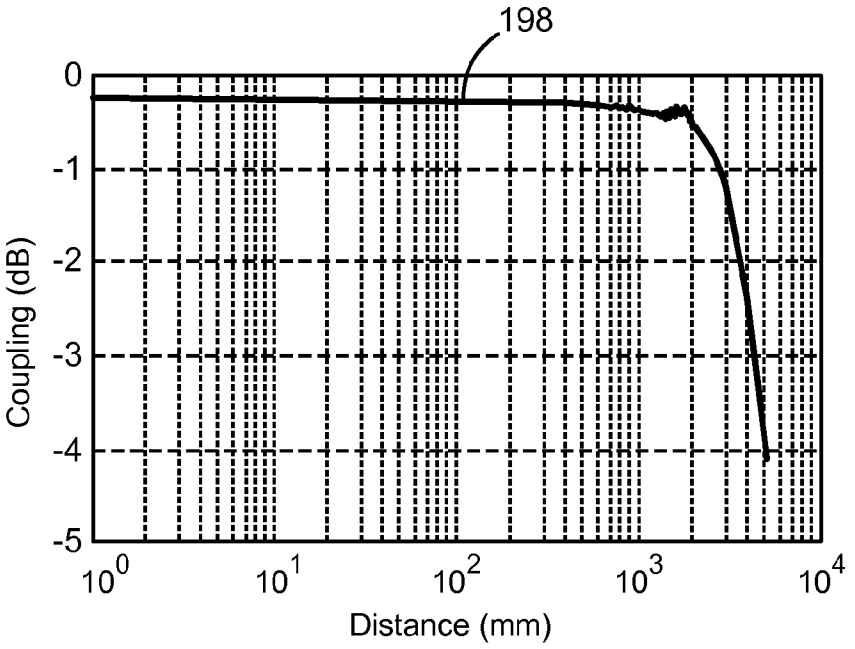

198
0
-1
-2
-3
-4
-5
Coupling (dB)
10^0
10^1
10^2
10^3
10^4
Distance (mm)

FIG. 9

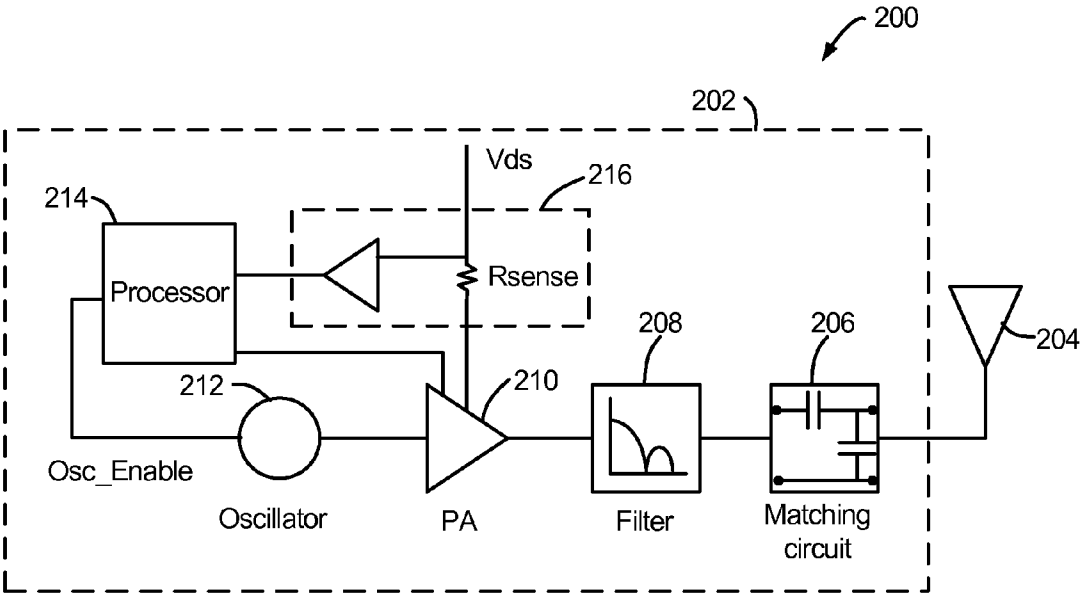

200
202
Vds
216
214
Processor
Rsense
208
206
204
212
210
Osc_Enable
Oscillator
PA
Filter
Matching circuit

FIG. 10

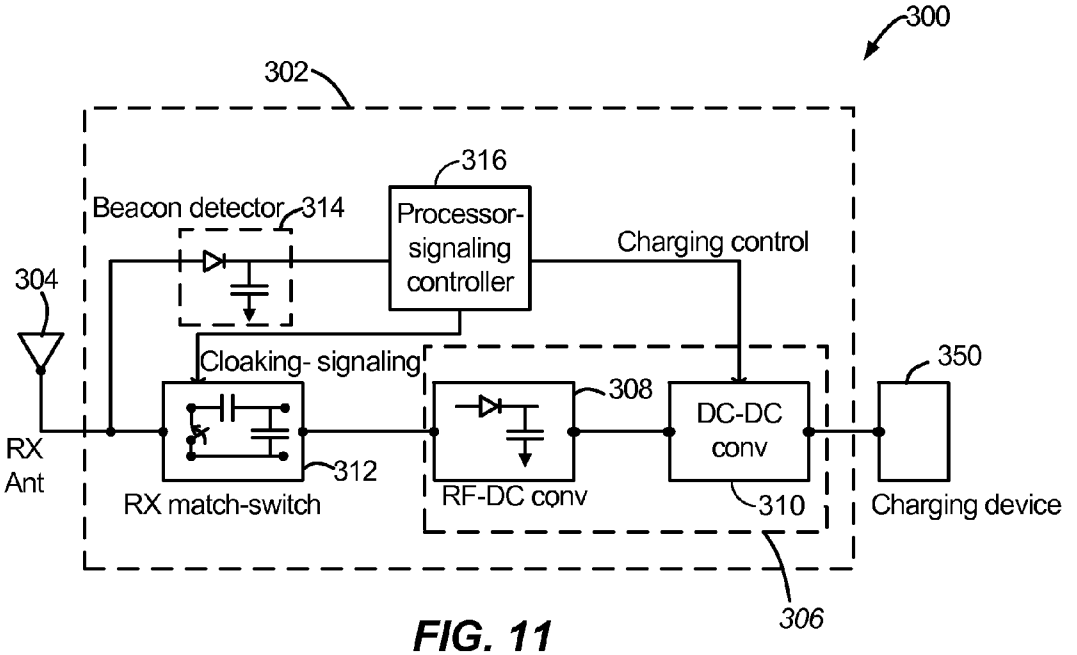

300
302
316
Beacon detector
314
Processor-signaling controller
Charging control
304
Cloaking- signaling
350
308
DC-DC conv
RX Ant
312
RX match-switch
RF-DC conv
310
Charging device
306

FIG. 11

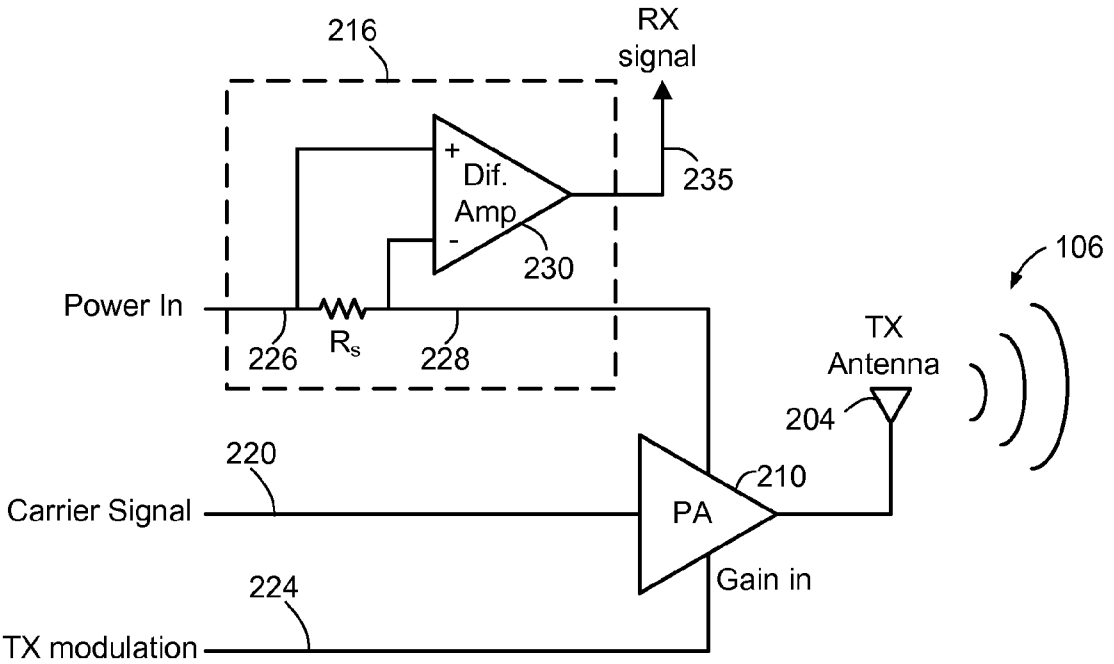

216
RX
signal
+
Dif.
Amp
-
235
230
106
Power In
226
R_s
228
TX
Antenna
204
220
210
Carrier Signal
PA
Gain in
224
TX modulation

FIG. 12

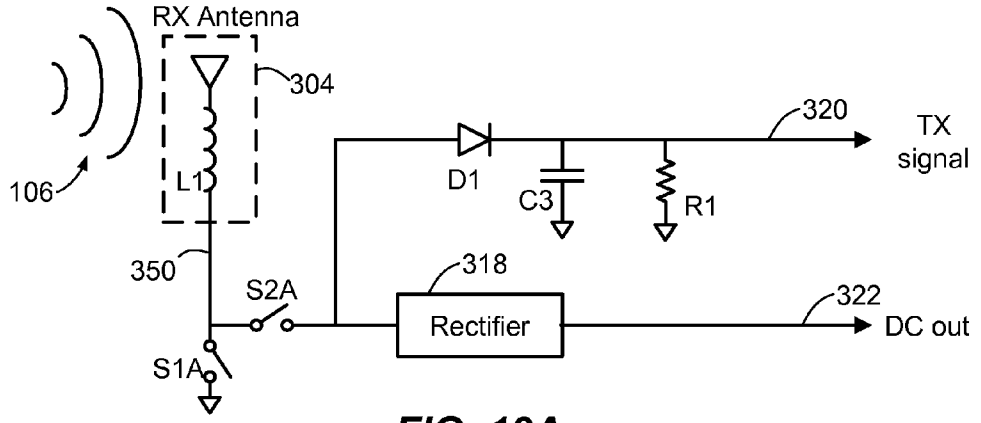


FIG. 13A

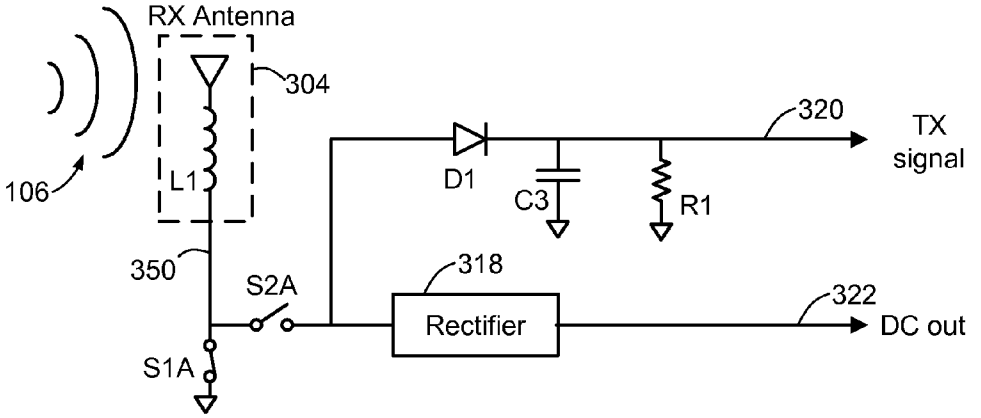


FIG. 13B

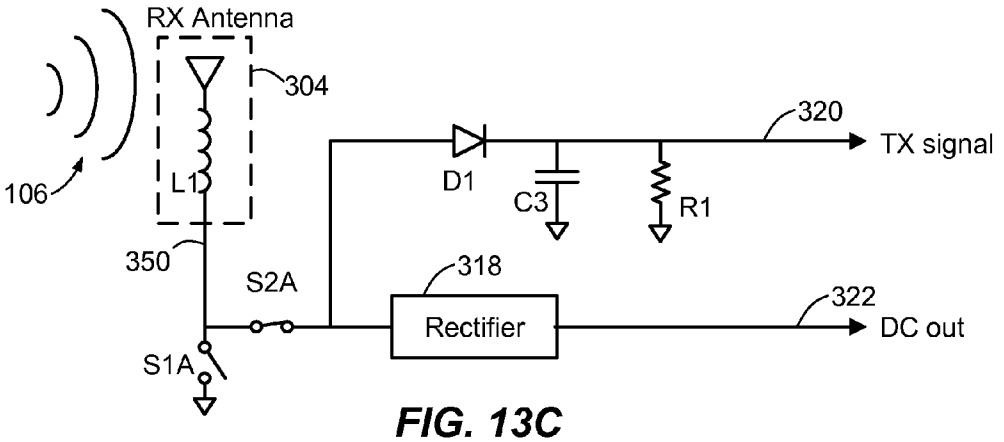


FIG. 13C

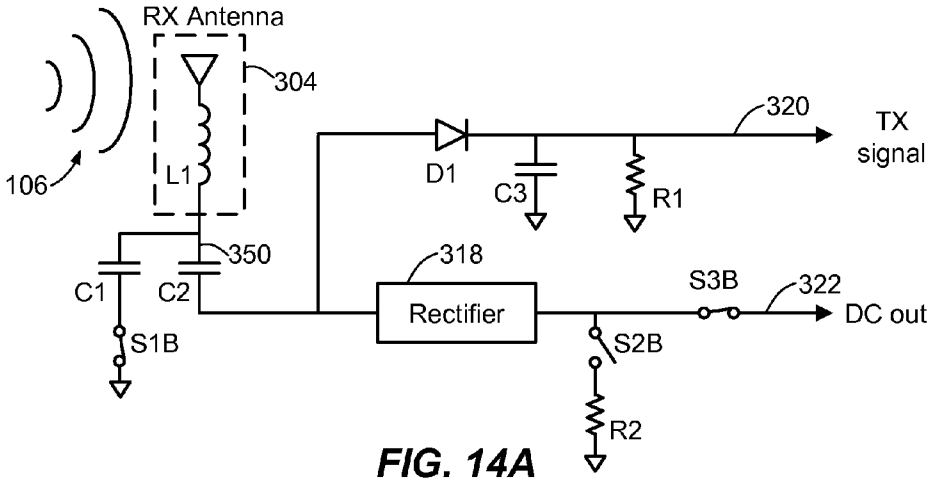


FIG. 14A

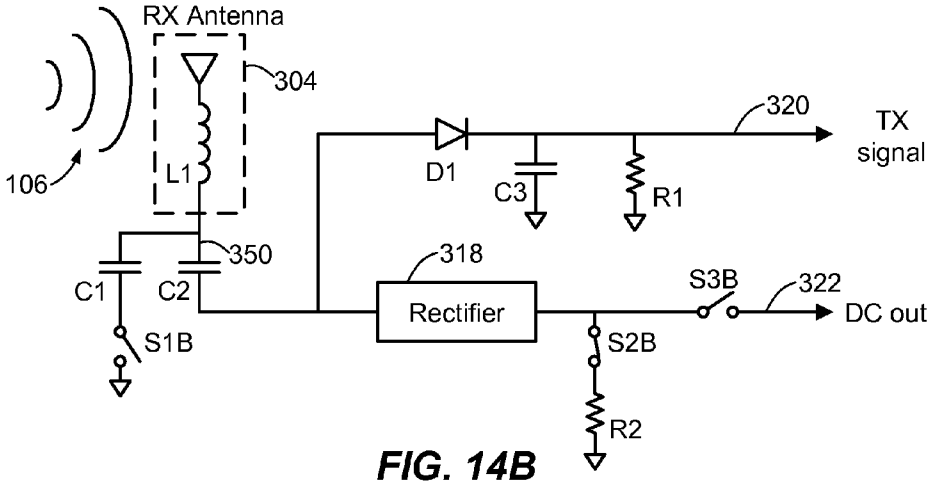


FIG. 14B

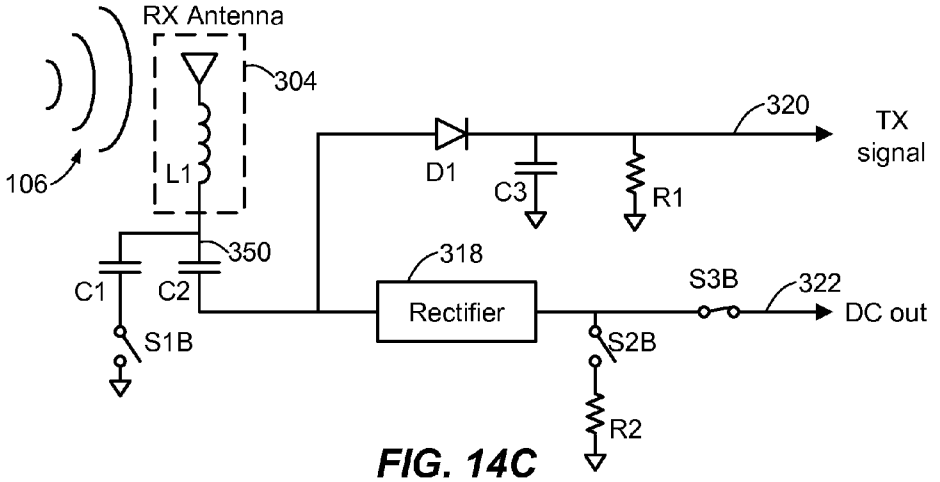


FIG. 14C

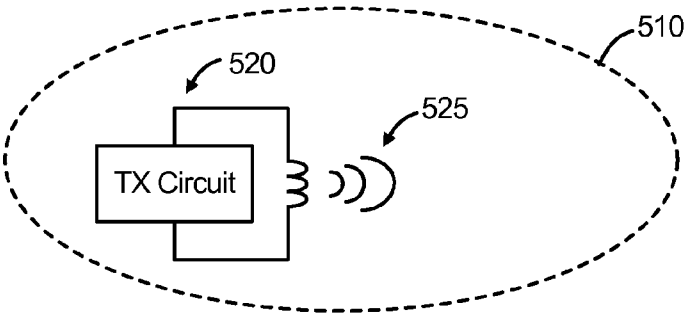


FIG. 15A

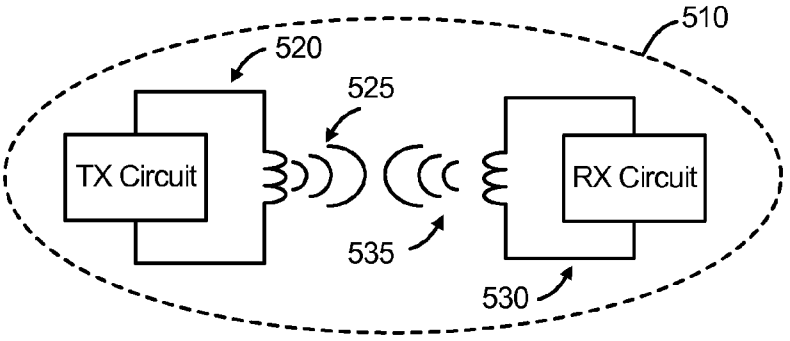


FIG. 15B

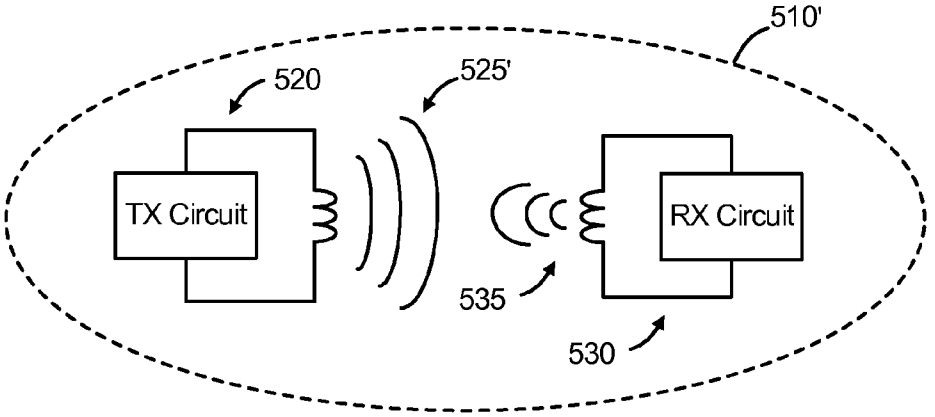


FIG. 15C

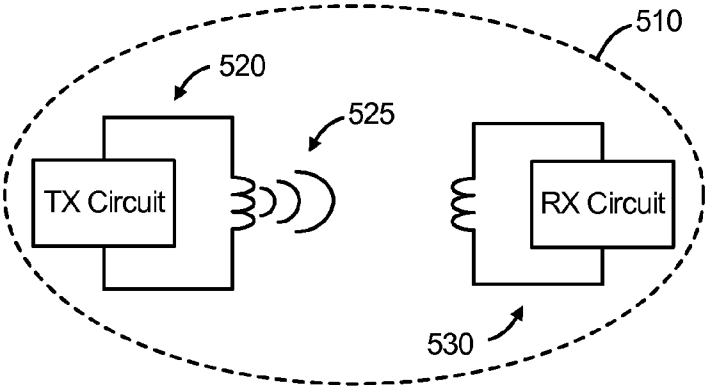


FIG. 15D

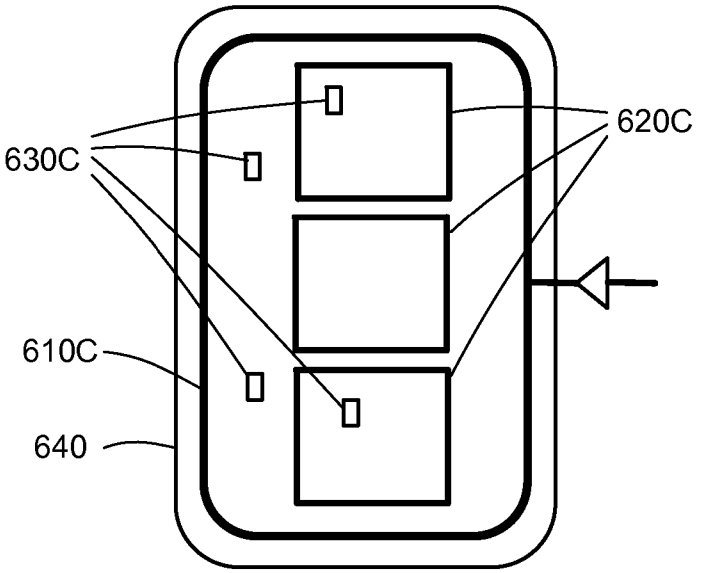


FIG. 16A

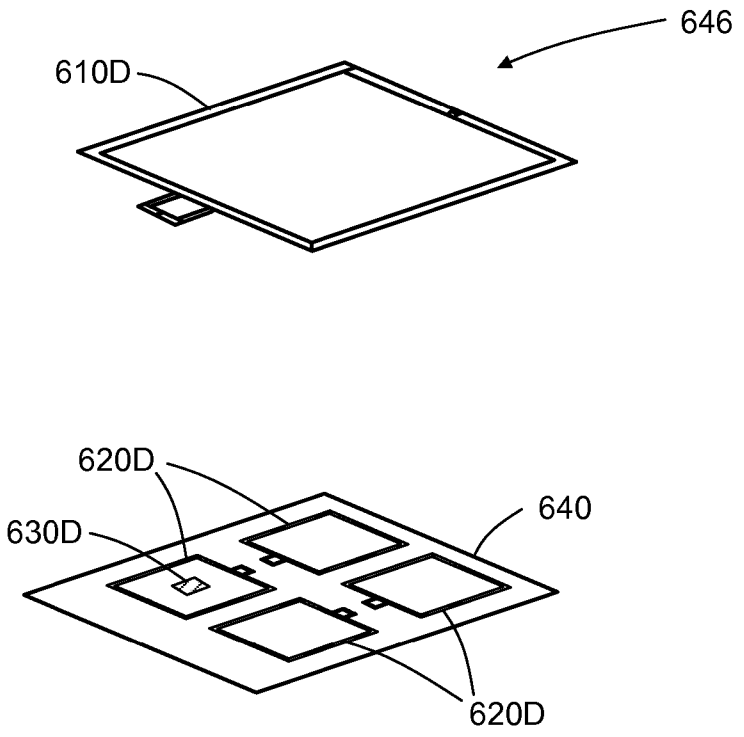


FIG. 16B

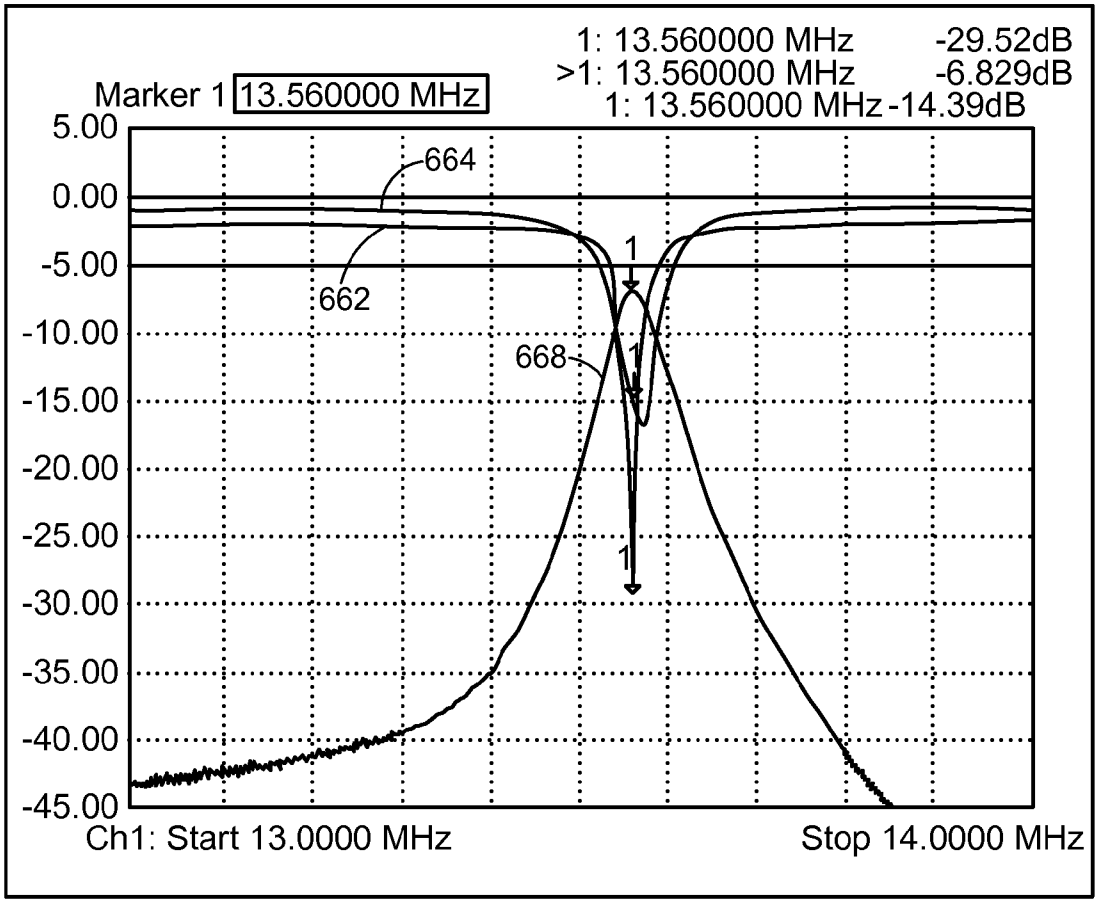

1: 13.560000 MHz -29.52dB
>1: 13.560000 MHz -6.829dB
1: 13.560000 MHz -14.39dB
Marker 1 13.560000 MHz
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
-35.00
-40.00
-45.00
664
662
668
1
Ch1: Start 13.0000 MHz
Stop 14.0000 MHz

FIG. 17

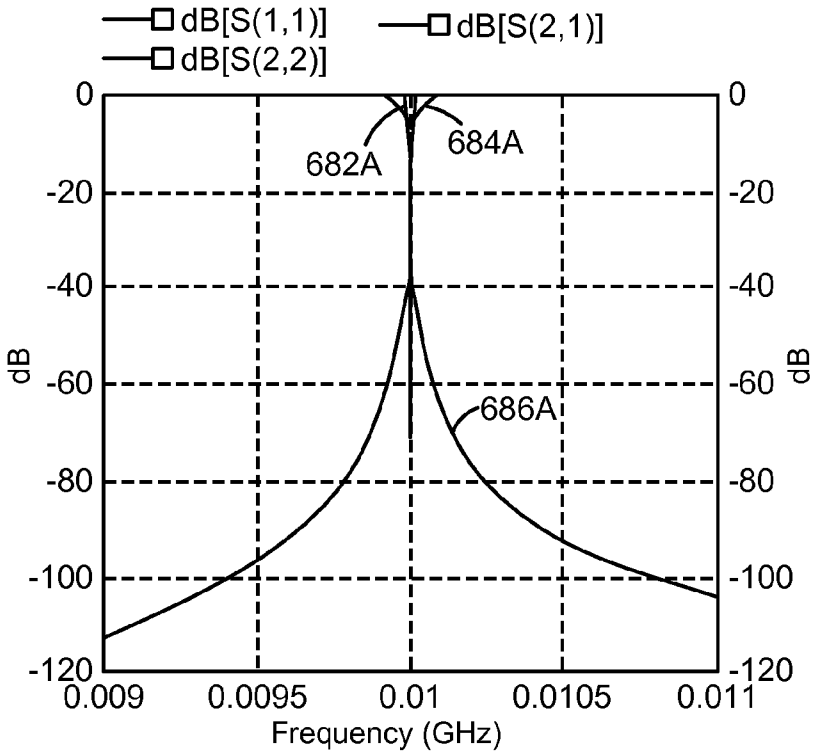


FIG. 18A

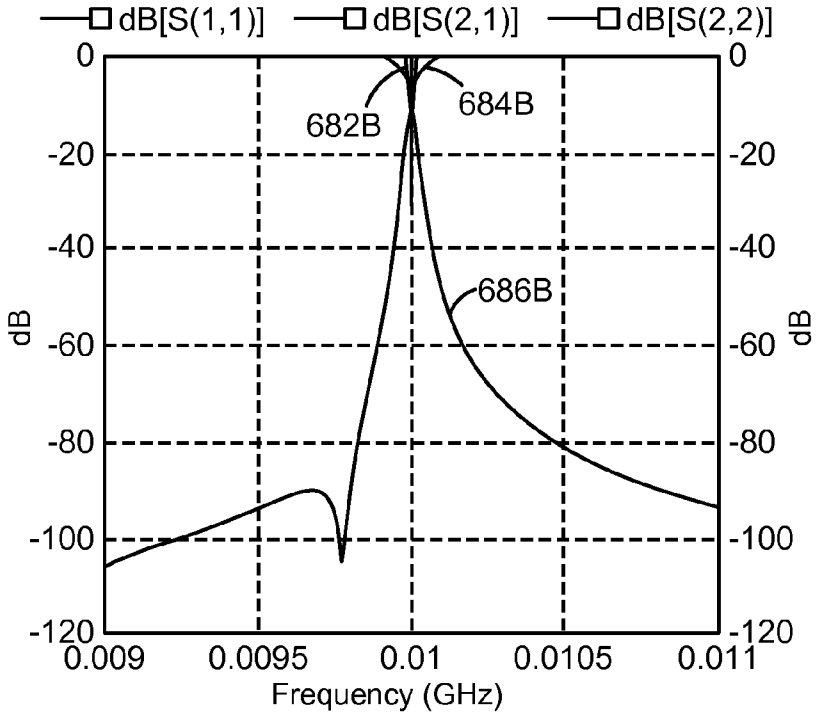


FIG. 18B

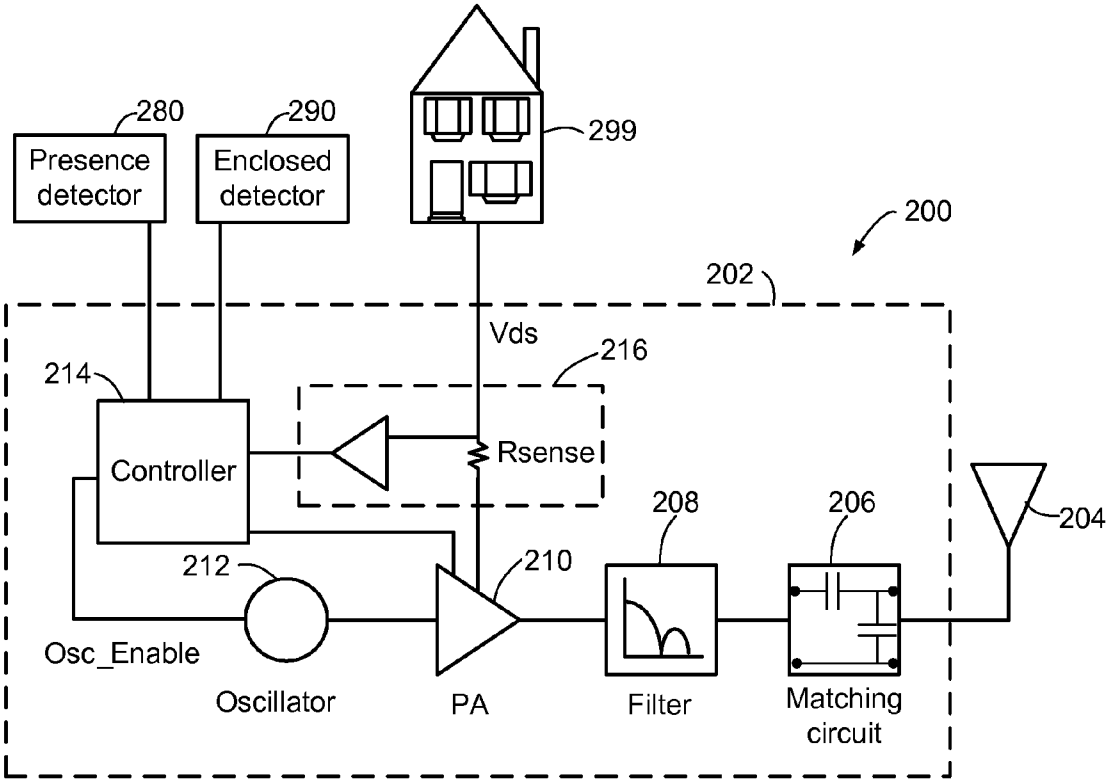

280
290
299
Presence detector
Enclosed detector
200
202
Vds
216
214
Controller
Rsense
208
206
204
212
210
Osc_Enable
Oscillator
PA
Filter
Matching circuit

FIG. 19

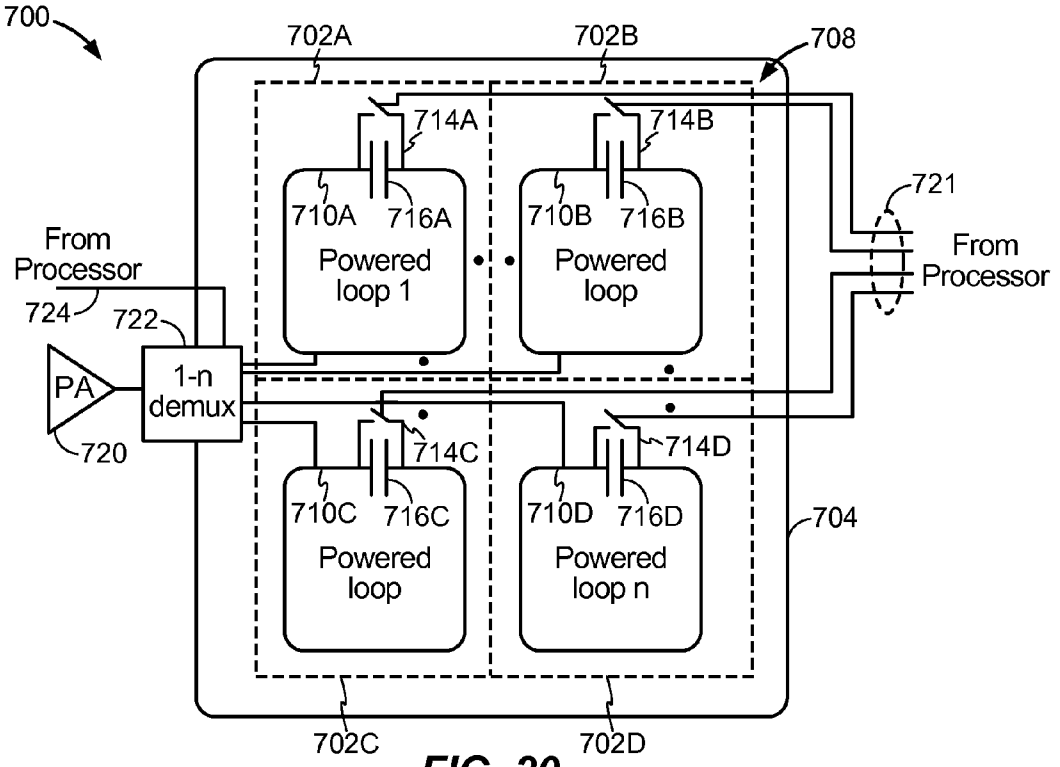

700
702A
702B
708
714A
714B
710A
716A
710B
716B
721
From Processor
Powered loop 1
Powered loop
From Processor
724
722
PA
1-n demux
720
714C
714D
710C
716C
710D
716D
704
Powered loop
Powered loop n
702C
702D

FIG. 20

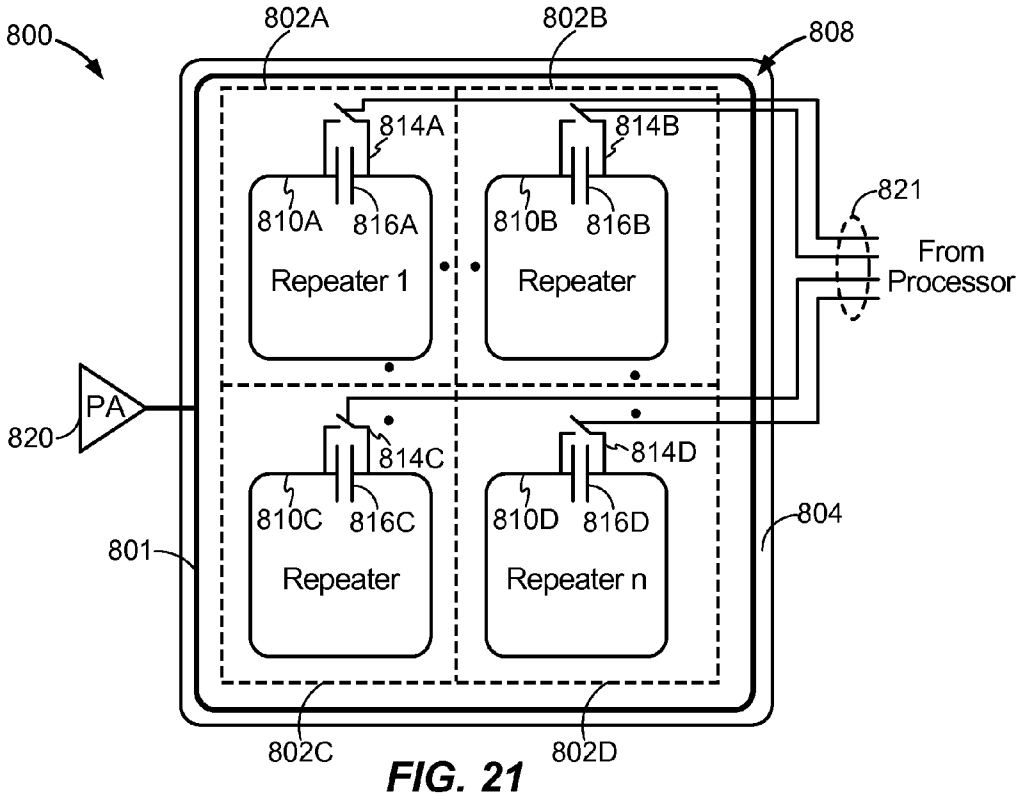

800
802A
802B
808
814A
814B
810A
816A
810B
816B
821
From Processor
Repeater 1
Repeater
PA
820
814C
814D
810C
816C
810D
816D
804
801
Repeater
Repeater n
802C
802D

FIG. 21

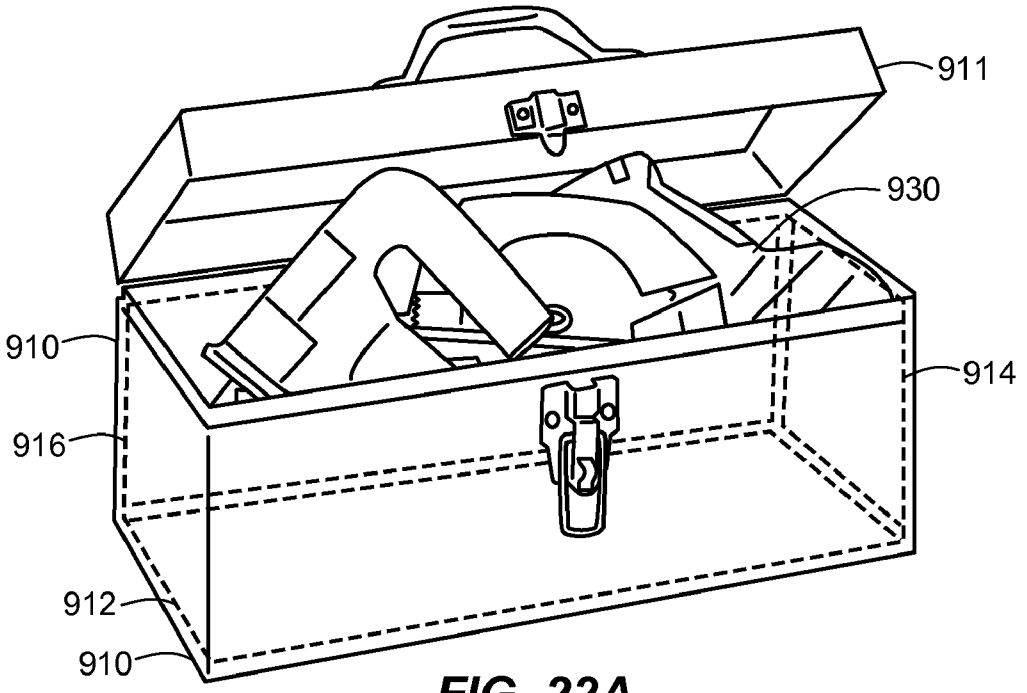


FIG. 22A

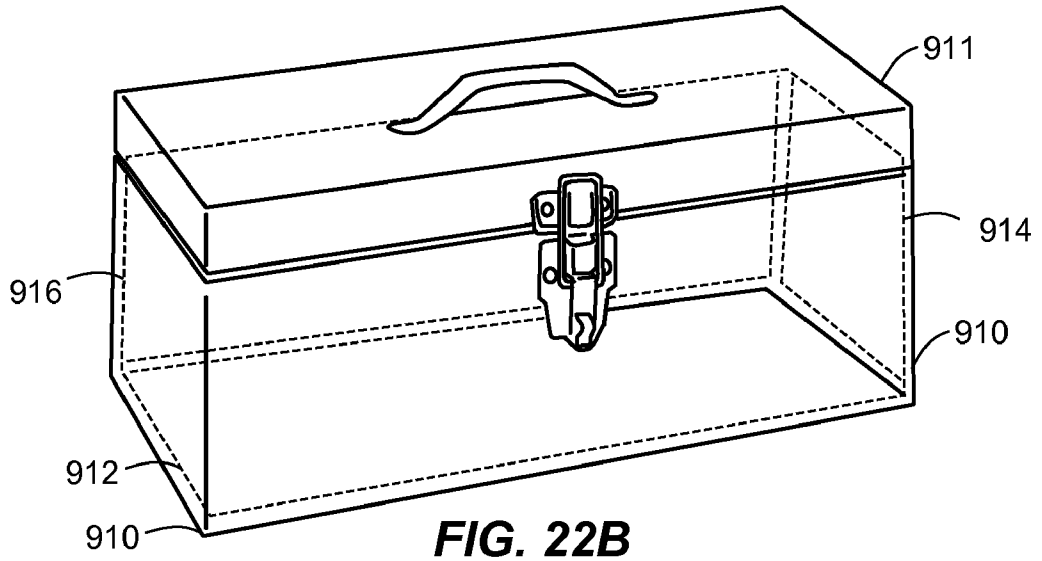


FIG. 22B

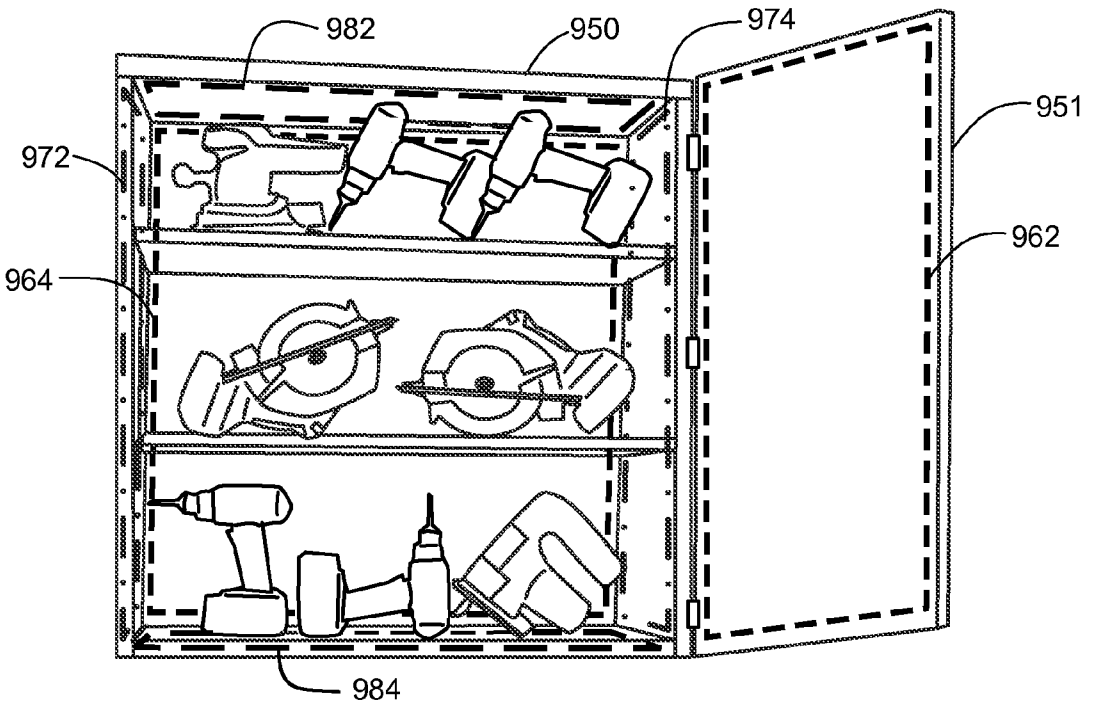


FIG. 23A

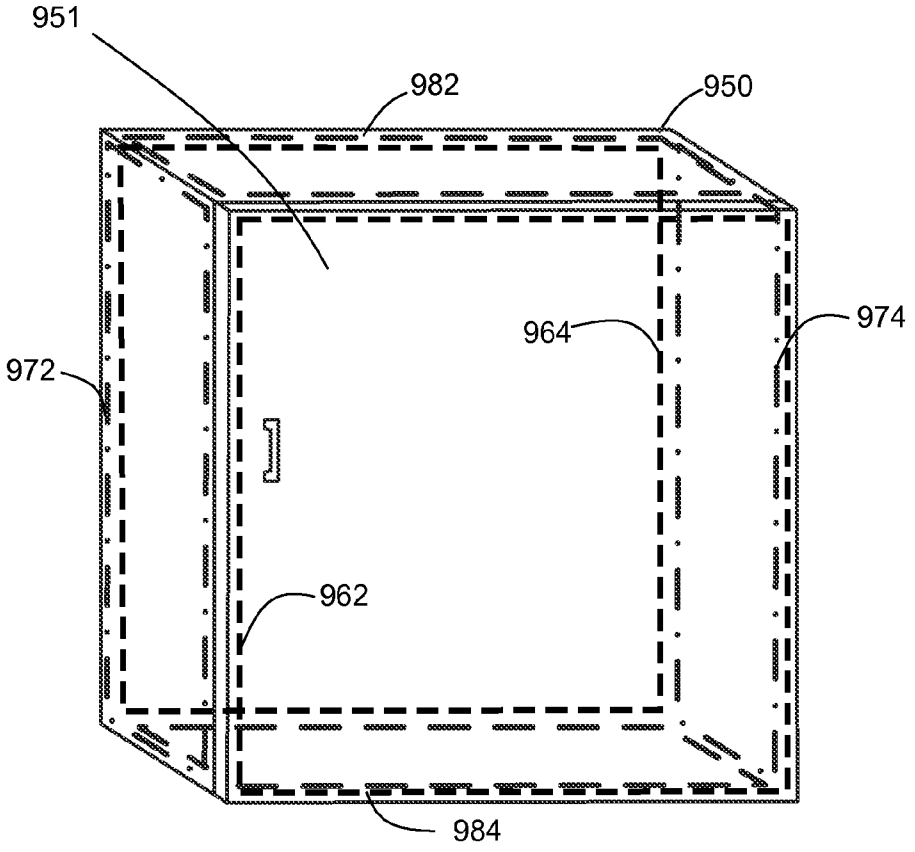


FIG. 23B

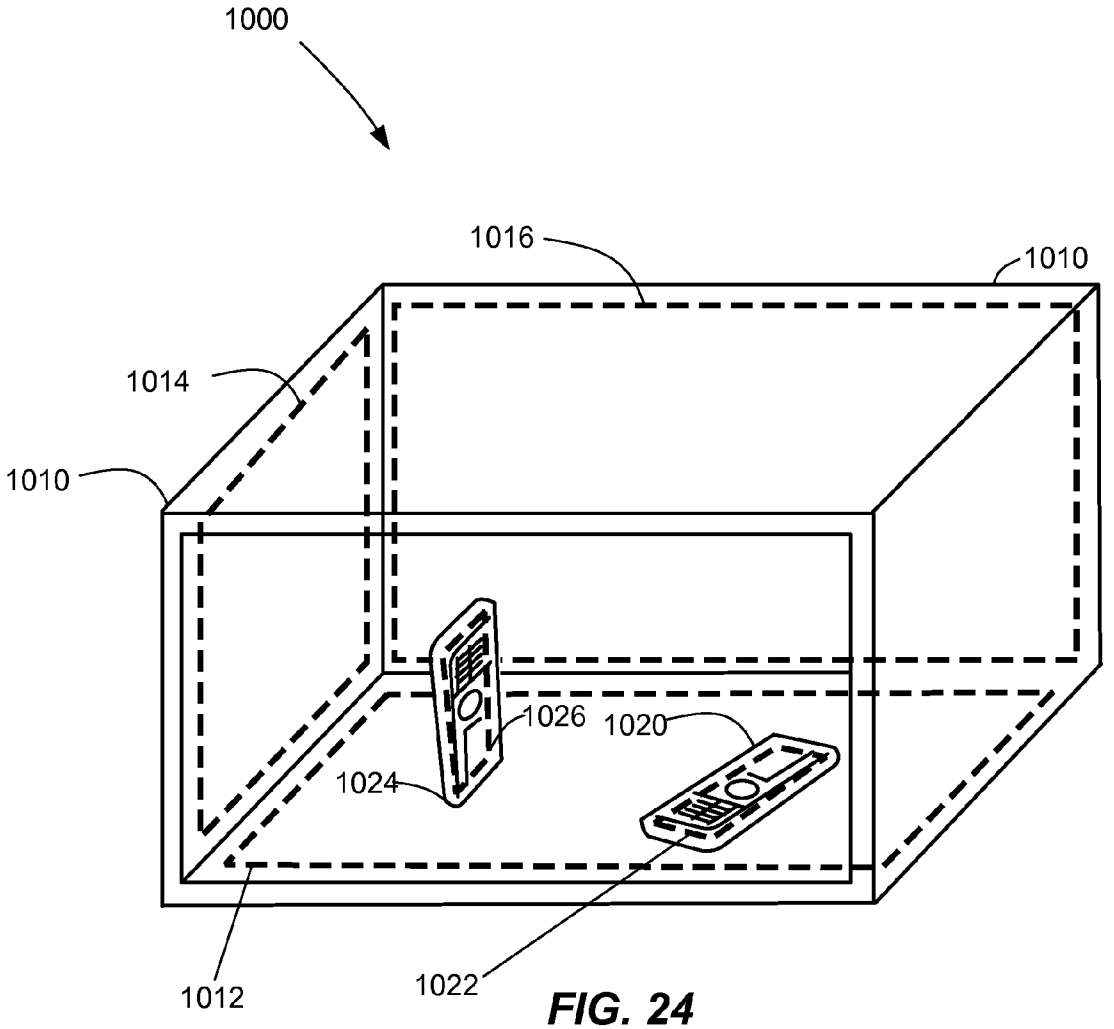


FIG. 24

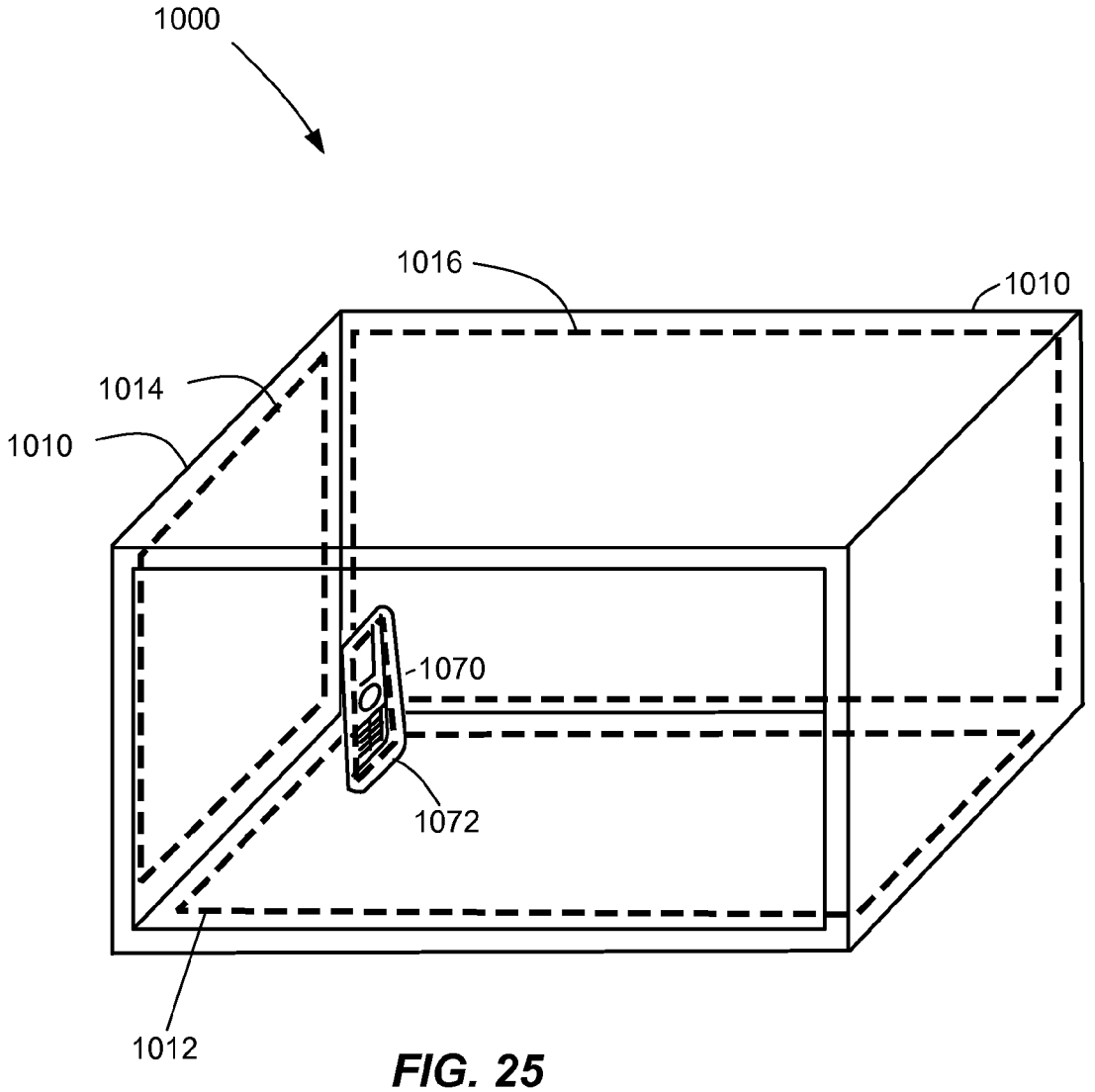


FIG. 25

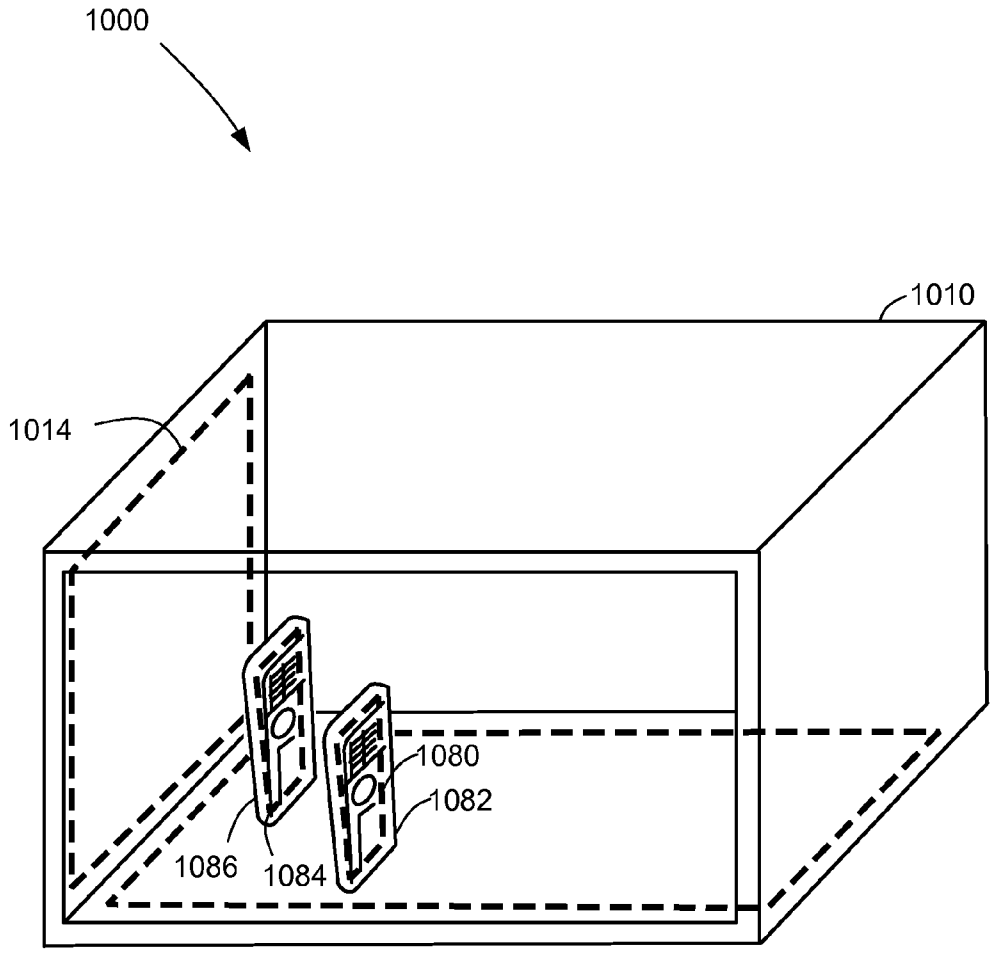


FIG. 26

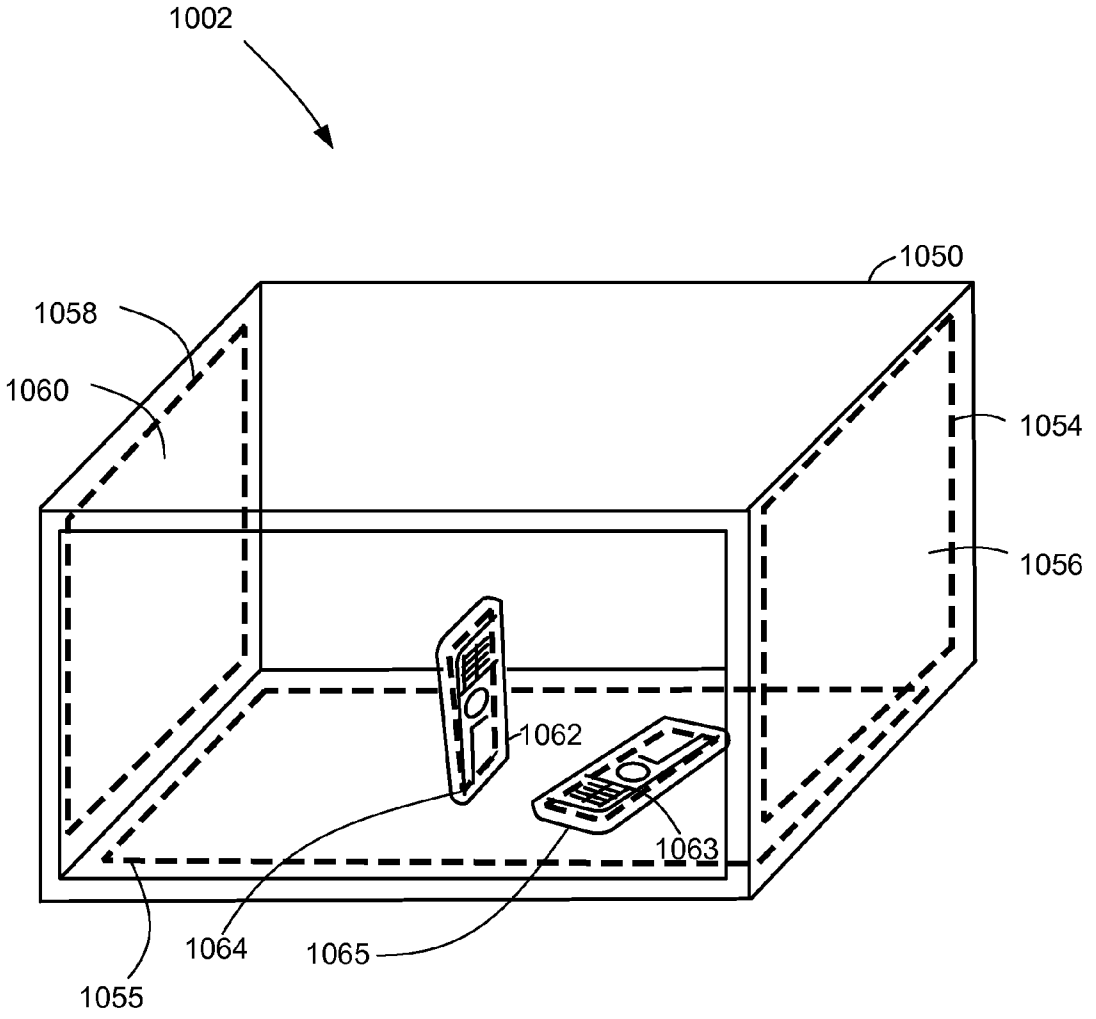


FIG. 27

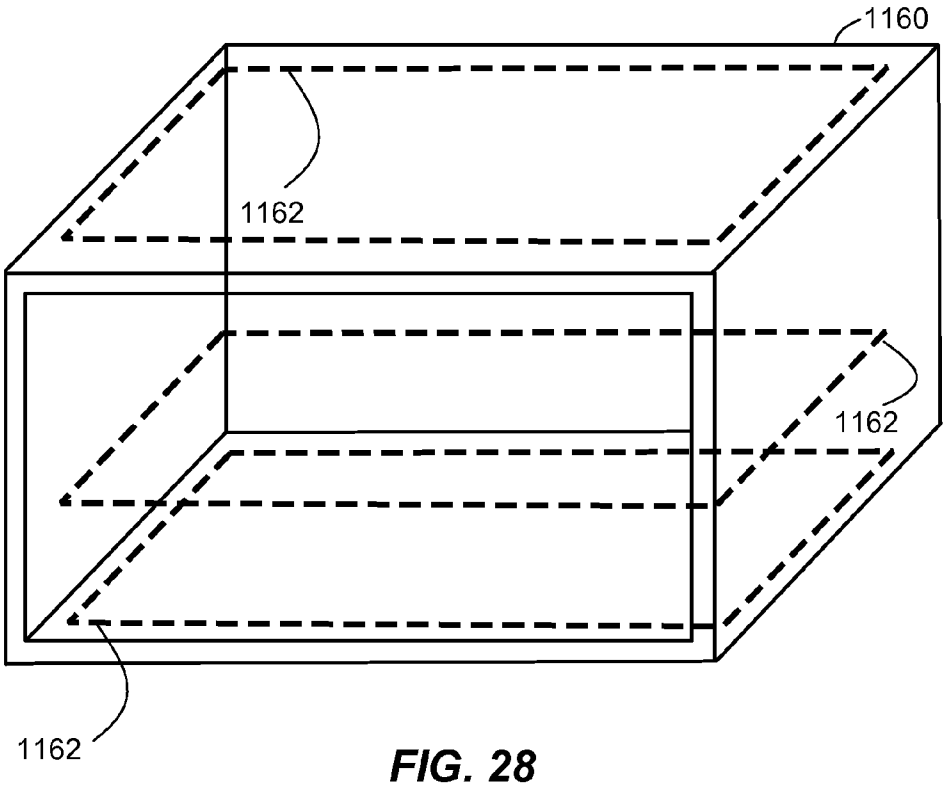


FIG. 28

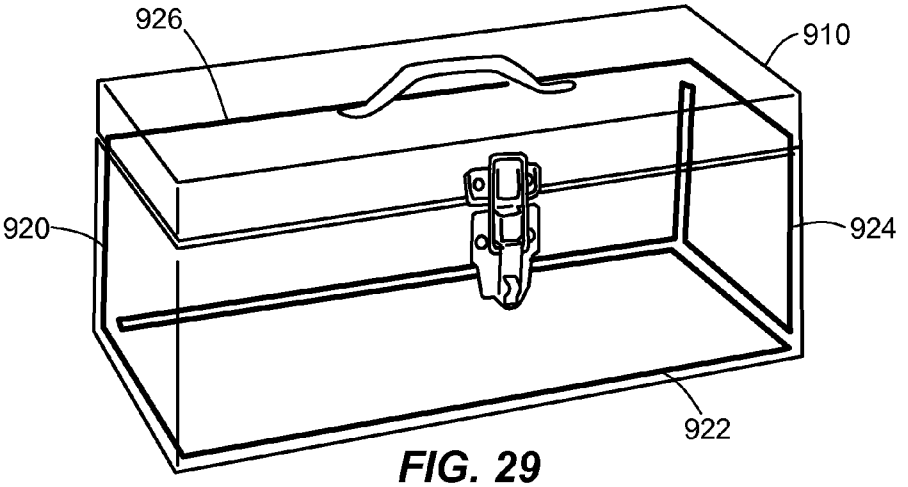


FIG. 29

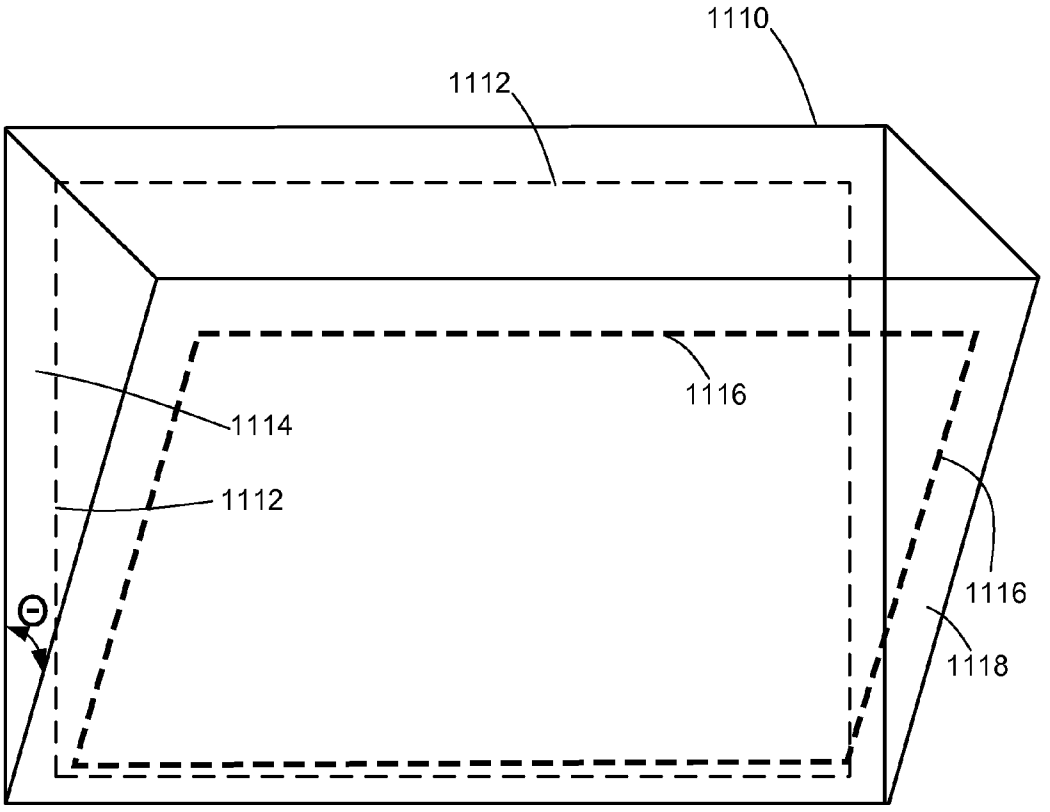


FIG. 30

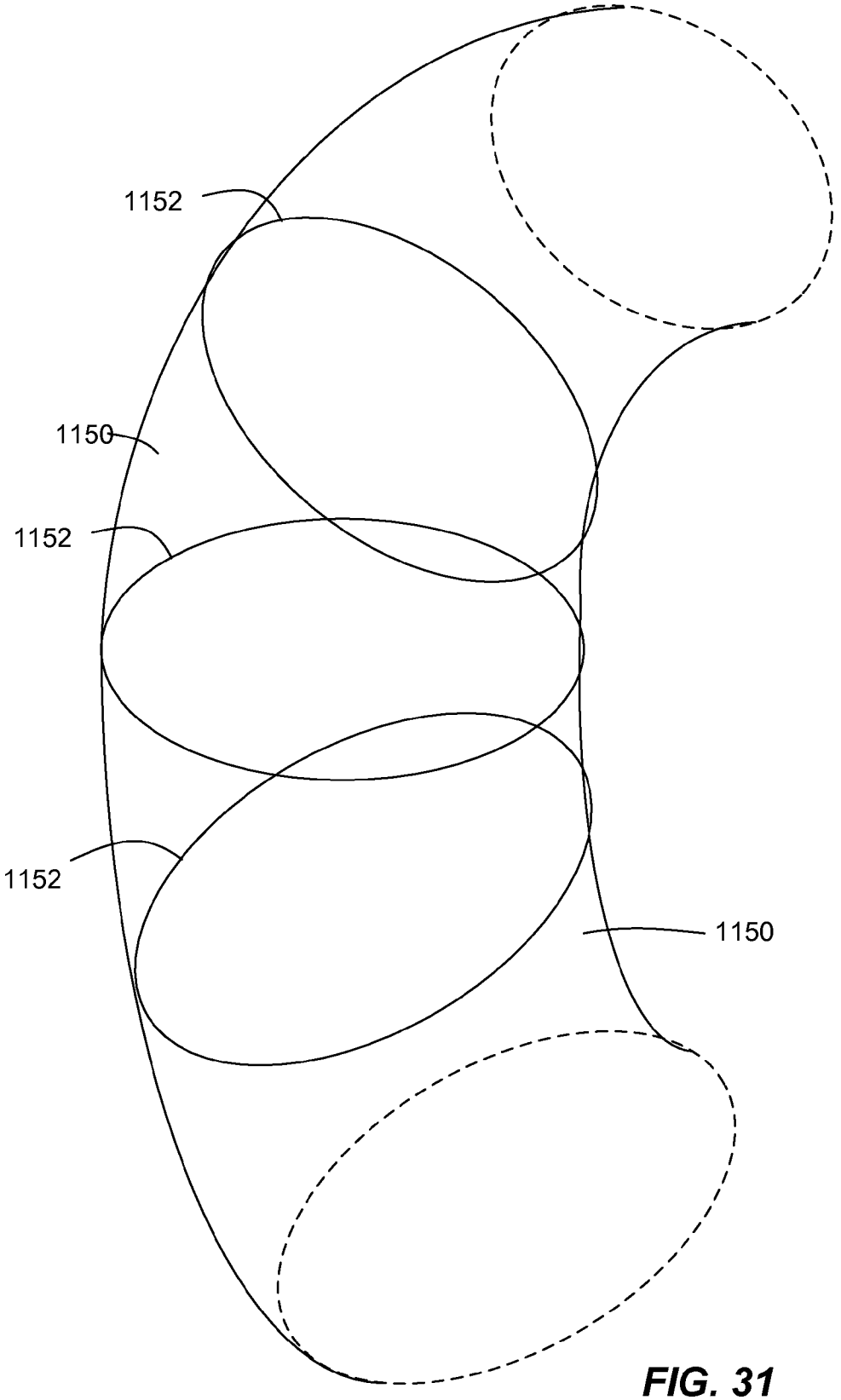


FIG. 31

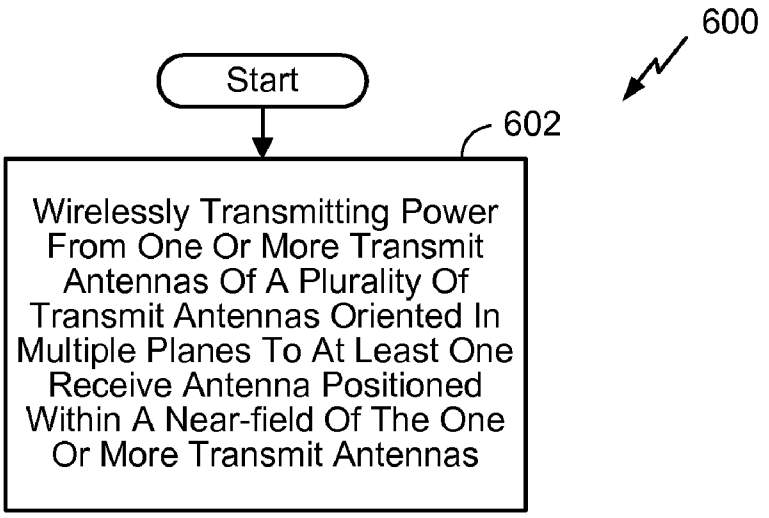

600
Start
602
Wirelessly Transmitting Power From One Or More Transmit Antennas Of A Plurality Of Transmit Antennas Oriented In Multiple Planes To At Least One Receive Antenna Positioned Within A Near-field Of The One Or More Transmit Antennas

FIG. 32

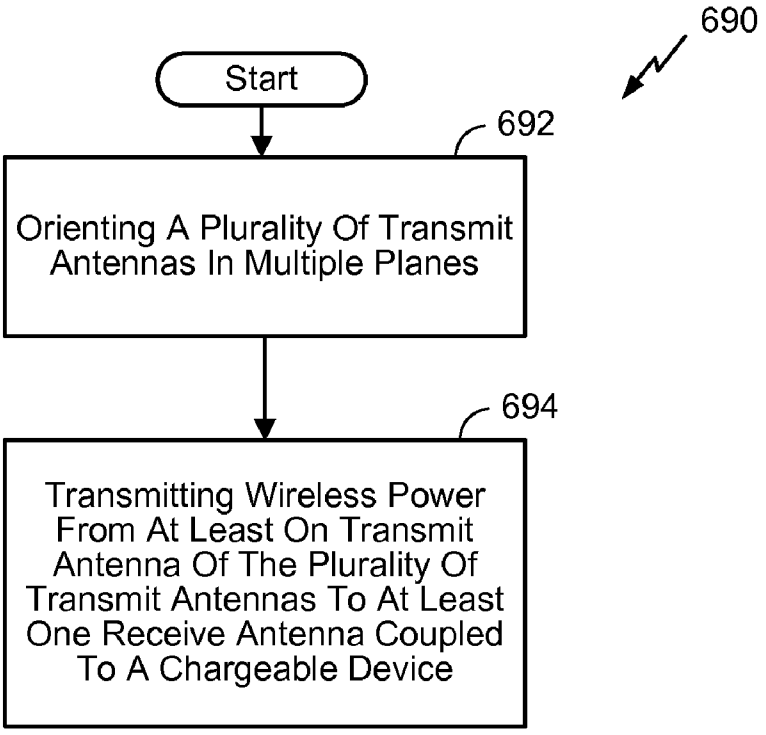

690
Start
692
Orienting A Plurality Of Transmit Antennas In Multiple Planes
694
Transmitting Wireless Power From At Least On Transmit Antenna Of The Plurality Of Transmit Antennas To At Least One Receive Antenna Coupled To A Chargeable Device

FIG. 33

SYSTEMS AND METHODS RELATING TO MULTI-DIMENSIONAL WIRELESS CHARGING

CLAIM OF PRIORITY UNDER 35 U.S.C. §119

[0001] This application claims priority under 35 U.S.C. §119(e) to:

[0002] U.S. Provisional Patent Application No. 61/151,290 entitled "MULTI-DIMENSIONAL WIRELESS CHARGING" filed on Feb. 10, 2009, the disclosure of which is hereby incorporated by reference in its entirety; and

[0003] U.S. Provisional Patent Application No. 61/244,391 entitled "MULTI-ANTENNA TRANSMITTER FOR WIRELESS CHARGING" filed on Sep. 21, 2009, the disclosure of which is hereby incorporated by reference in its entirety.

BACKGROUND

[0004] 1. Field

[0005] The present invention relates generally to wireless charging, and more specifically to devices, systems, and methods related to multi-dimensional wireless charging.

[0006] 2. Background

[0007] Typically, each battery powered device requires its own charger and power source, which is usually an AC power outlet. This becomes unwieldy when many devices need charging.

[0008] Approaches are being developed that use over the air power transmission between a transmitter and the device to be charged. These generally fall into two categories. One is based on the coupling of plane wave radiation (also called far-field radiation) between a transmit antenna and receive antenna on the device to be charged which collects the radiated power and rectifies it for charging the battery. Antennas are generally of resonant length in order to improve the coupling efficiency. This approach suffers from the fact that the power coupling falls off quickly with distance between the antennas. So charging over reasonable distances (e.g., >1-2 m) becomes difficult. Additionally, since the system radiates plane waves, unintentional radiation can interfere with other systems if not properly controlled through filtering.

[0009] Other approaches are based on inductive coupling between a transmit antenna embedded, for example, in a "charging" mat or surface and a receive antenna plus rectifying circuit embedded in the host device to be charged. This approach has the disadvantage that the spacing between transmit and receive antennas must be very close (e.g. mms). Though this approach does have the capability to simultaneously charge multiple devices in the same area, this area is typically small, hence the user must locate the devices to a specific area.

[0010] When placing one or more devices in a wireless charger (e.g. near-field magnetic resonance, inductive coupling, etc.) the orientation between the receiver and the charger may vary. For example, when charging a medical device while disinfecting it in a solution bath or when charging tools while working under water. When a device is dropped into a container with fluid inside, the angle in which the device lands on the bottom of the container would depend on the way its mass is distributed. As another non-limiting example, when the charger takes the form of a box or a bowl, carelessly throwing the device into it, which is very convenient to the user, does not guarantee the position the device will end up in. The charger may also be integrated into a large container or cabinet that can hold many devices, such as a tool storage chest, a toy chest, or an enclosure designed specifically for wireless charging. The receiver integration into these devices may be inconsistent because the devices have different form factors and may be placed in different orientations relative to the wireless power transmitter.

[0011] Existing designs of wireless chargers may perform best under a predefined orientation and deliver lower power levels if the orientation between the charger and the receiver is different. In addition, when the charged device is placed in a position where only a portion of the wireless power can be delivered to it, charging times may increase. Some solutions design the charger in a way that the user have to place the device in a special cradle or holder that positions the device to be charged in an advantageous orientation, which is less convenient than placing it in the charger without thought, or one that cannot hold multiple devices.

[0012] Therefore, there is a need to provide systems and methods relating to multi-dimensional wireless charging.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1** shows a simplified block diagram of a wireless power transfer system.

[0014] FIG. **2** shows a simplified schematic diagram of a wireless power transfer system.

[0015] FIG. **3** shows a schematic diagram of a loop antenna for use in exemplary embodiments of the present invention.

[0016] FIG. **4** shows simulation results indicating coupling strength between transmit and receive antennas.

[0017] FIGS. **5**A and **5**B show layouts of loop antennas for transmit and receive antennas according to exemplary embodiments of the present invention.

[0018] FIG. **6** shows simulation results indicating coupling strength between transmit and receive antennas relative to various circumference sizes for the square and circular transmit antennas illustrated in FIGS. **5**A and **5**B.

[0019] FIG. **7** shows simulation results indicating coupling strength between transmit and receive antennas relative to various surface areas for the square and circular transmit antennas illustrated in FIGS. **5**A and **5**B.

[0020] FIG. **8** shows various placement points for a receive antenna relative to a transmit antenna to illustrate coupling strengths in coplanar and coaxial placements.

[0021] FIG. **9** shows simulation results indicating coupling strength for coaxial placement at various distances between the transmit and receive antennas.

[0022] FIG. **10** is a simplified block diagram of a transmitter, in accordance with an exemplary embodiment of the present invention.

[0023] FIG. **11** is a simplified block diagram of a receiver, in accordance with an exemplary embodiment of the present invention.

[0024] FIG. **12** shows a simplified schematic of a portion of transmit circuitry for carrying out messaging between a transmitter and a receiver.

[0025] FIGS. **13**A-**13**C shows a simplified schematic of a portion of receive circuitry in various states to illustrate messaging between a receiver and a transmitter.

[0026] FIGS. **14**A-**14**C shows a simplified schematic of a portion of alternative receive circuitry in various states to illustrate messaging between a receiver and a transmitter.

[0027] FIGS. **15**A-**15**D are simplified block diagrams illustrating a beacon power mode for transmitting power between a transmitter and a receiver.

[0028] FIG. **16**A illustrates a large transmit antenna with a three different smaller repeater antennas disposed coplanar with, and within a perimeter of, the transmit antenna.

[0029] FIG. **16**B illustrates a large transmit antenna with smaller repeater antennas with offset coaxial placements and offset coplanar placements relative to the transmit antenna.

[0030] FIG. **17** shows simulation results indicating coupling strength between a transmit antenna, a repeater antenna and a receive antenna.

[0031] FIG. **18**A shows simulation results indicating coupling strength between a transmit antenna and receive antenna with no repeater antennas.

[0032] FIG. **18**B shows simulation results indicating coupling strength between a transmit antenna and receive antenna with a repeater antenna.

[0033] FIG. **19** is a simplified block diagram of a transmitter according to one or more exemplary embodiments of the present invention.

[0034] FIG. **20** is a simplified block diagram of an enlarged area wireless charging apparatus, in accordance with an exemplary embodiment of the present invention.

[0035] FIG. **21** is a simplified block diagram of an enlarged area wireless charging apparatus, in accordance with another exemplary embodiment of the present invention.

[0036] FIGS. **22**A and **22**B illustrate a charging system including a plurality of transmit antennas coupled to a charging apparatus and oriented in multiple planes, according to an exemplary embodiment of the present invention.

[0037] FIGS. **23**A and **23**B illustrate another charging system including a plurality of transmit antennas coupled to a chargeable apparatus and oriented in multiple planes, according to an exemplary embodiment of the present invention.

[0038] FIG. **24** illustrates a charging system including a plurality of transmit antennas oriented in multiple planes, according to an exemplary embodiment of the present invention.

[0039] FIG. **25** illustrates another charging system including a plurality of transmit antennas oriented in multiple planes, according to an exemplary embodiment of the present invention.

[0040] FIG. **26** illustrates another charging system including a plurality of transmit antennas oriented in multiple planes, according to an exemplary embodiment of the present invention.

[0041] FIG. **27** illustrates yet another charging system including a plurality of transmit antennas oriented in multiple planes, according to an exemplary embodiment of the present invention.

[0042] FIG. **28** illustrates another charging system including a plurality of parallel transmit antennas, according to an exemplary embodiment of the present invention.

[0043] FIG. **29** illustrates a continuous loop transmit antenna including multiple facets in substantially orthogonal directions, in accordance with an exemplary embodiment of the present invention.

[0044] FIG. **30** illustrates another charging system including a plurality of transmit antennas oriented in multiple planes, according to an exemplary embodiment of the present invention.

[0045] FIG. **31** illustrates yet another charging system including a plurality of transmit antennas oriented in multiple planes, in accordance with an exemplary embodiment of the present invention.

[0046] FIG. **32** is a flowchart illustrating a method, in accordance with an exemplary embodiment of the present invention.

[0047] FIG. **33** is a flowchart illustrating another method, according to an exemplary embodiment of the present invention.

DETAILED DESCRIPTION

[0048] The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments.

[0049] The detailed description set forth below in connection with the appended drawings is intended as a description of exemplary embodiments of the present invention and is not intended to represent the only embodiments in which the present invention can be practiced. The term "exemplary" used throughout this description means "serving as an example, instance, or illustration," and should not necessarily be construed as preferred or advantageous over other exemplary embodiments. The detailed description includes specific details for the purpose of providing a thorough understanding of the exemplary embodiments of the invention. It will be apparent to those skilled in the art that the exemplary embodiments of the invention may be practiced without these specific details. In some instances, well-known structures and devices are shown in block diagram form in order to avoid obscuring the novelty of the exemplary embodiments presented herein.

[0050] The words "wireless power" is used herein to mean any form of energy associated with electric fields, magnetic fields, electromagnetic fields, or otherwise that is transmitted between from a transmitter to a receiver without the use of physical electromagnetic conductors.

[0051] FIG. **1** illustrates wireless transmission or charging system **100**, in accordance with various exemplary embodiments of the present invention. Input power **102** is provided to a transmitter **104** for generating a radiated field **106** for providing energy transfer. A receiver **108** couples to the radiated field **106** and generates an output power **110** for storing or consumption by a device (not shown) coupled to the output power **110**. Both the transmitter **104** and the receiver **108** are separated by a distance **112**. In one exemplary embodiment, transmitter **104** and receiver **108** are configured according to a mutual resonant relationship and when the resonant frequency of receiver **108** and the resonant frequency of transmitter **104** are exactly identical, transmission losses between the transmitter **104** and the receiver **108** are minimal when the receiver **108** is located in the "near-field" of the radiated field **106**.

[0052] Transmitter **104** further includes a transmit antenna **114** for providing a means for energy transmission and receiver **108** further includes a receive antenna **118** for providing a means for energy reception. The transmit and receive antennas are sized according to applications and devices to be associated therewith. As stated, an efficient energy transfer occurs by coupling a large portion of the energy in the near-field of the transmitting antenna to a receiving antenna rather than propagating most of the energy in an electromagnetic wave to the far field. When in this near-field a coupling mode

may be developed between the transmit antenna **114** and the receive antenna **118**. The area around the antennas **114** and **118** where this near-field coupling may occur is referred to herein as a coupling-mode region.

[0053] FIG. **2** shows a simplified schematic diagram of a wireless power transfer system. The transmitter **104** includes an oscillator **122**, a power amplifier **124** and a filter and matching circuit **126**. The oscillator is configured to generate at a desired frequency, which may be adjusted in response to adjustment signal **123**. The oscillator signal may be amplified by the power amplifier **124** with an amplification amount responsive to control signal **125**. The filter and matching circuit **126** may be included to filter out harmonics or other unwanted frequencies and match the impedance of the transmitter **104** to the transmit antenna **114**.

[0054] The receiver may include a matching circuit **132** and a rectifier and switching circuit to generate a DC power output to charge a battery **136** as shown in FIG. **2** or power a device coupled to the receiver (not shown). The matching circuit **132** may be included to match the impedance of the receiver **108** to the receive antenna **118**.

[0055] As illustrated in FIG. **3**, antennas used in exemplary embodiments may be configured as a "loop" antenna **150**, which may also be referred to herein as a "magnetic" antenna. Loop antennas may be configured to include an air core or a physical core such as a ferrite core. Air core loop antennas may be more tolerable to extraneous physical devices placed in the vicinity of the core. Furthermore, an air core loop antenna allows the placement of other components within the core area. In addition, an air core loop may more readily enable placement of the receive antenna **118** (FIG. **2**) within a plane of the transmit antenna **114** (FIG. **2**) where the coupled-mode region of the transmit antenna **114** (FIG. **2**) may be more powerful.

[0056] As stated, efficient transfer of energy between the transmitter **104** and receiver **108** occurs during matched or nearly matched resonance between the transmitter **104** and the receiver **108**. However, even when resonance between the transmitter **104** and receiver **108** are not matched, energy may be transferred at a lower efficiency. Transfer of energy occurs by coupling energy from the near-field of the transmitting antenna to the receiving antenna residing in the neighborhood where this near-field is established rather than propagating the energy from the transmitting antenna into free space.

[0057] The resonant frequency of the loop or magnetic antennas is based on the inductance and capacitance. Inductance in a loop antenna is generally simply the inductance created by the loop, whereas, capacitance is generally added to the loop antenna's inductance to create a resonant structure at a desired resonant frequency. As a non-limiting example, capacitor **152** and capacitor **154** may be added to the antenna to create a resonant circuit that generates resonant signal **156**. Accordingly, for larger diameter loop antennas, the size of capacitance needed to induce resonance decreases as the diameter or inductance of the loop increases. Furthermore, as the diameter of the loop or magnetic antenna increases, the efficient energy transfer area of the near-field increases. Of course, other resonant circuits are possible. As another non-limiting example, a capacitor may be placed in parallel between the two terminals of the loop antenna. In addition, those of ordinary skill in the art will recognize that for transmit antennas the resonant signal **156** may be an input to the loop antenna **150**.

[0058] Exemplary embodiments of the invention include coupling power between two antennas that are in the near-fields of each other. As stated, the near-field is an area around the antenna in which electromagnetic fields exist but may not propagate or radiate away from the antenna. They are typically confined to a volume that is near the physical volume of the antenna. In the exemplary embodiments of the invention, magnetic type antennas such as single and multi-turn loop antennas are used for both transmit (Tx) and receive (Rx) antenna systems since magnetic near-field amplitudes tend to be higher for magnetic type antennas in comparison to the electric near-fields of an electric-type antenna (e.g., a small dipole). This allows for potentially higher coupling between the pair. Furthermore, "electric" antennas (e.g., dipoles and monopoles) or a combination of magnetic and electric antennas is also contemplated.

[0059] The Tx antenna can be operated at a frequency that is low enough and with an antenna size that is large enough to achieve good coupling (e.g., >−4 dB) to a small Rx antenna at significantly larger distances than allowed by far field and inductive approaches mentioned earlier. If the Tx antenna is sized correctly, high coupling levels (e.g., −2 to −4 dB) can be achieved when the Rx antenna on a host device is placed within a coupling-mode region (i.e., in the near-field) of the driven Tx loop antenna.

[0060] FIG. **4** shows simulation results indicating coupling strength between transmit and receive antennas. Curves **170** and **172** indicate a measure of acceptance of power by the transmit and receive antennas, respectively. In other words, with a large negative number there is a very close impedance match and most of the power is accepted and, as a result, radiated by the transmit antenna. Conversely, a small negative number indicates that much of the power is reflected back from the antenna because there is not a close impedance match at the given frequency. In FIG. **4**, the transmit antenna and the receive antenna are tuned to have a resonant frequency of about 13.56 MHz.

[0061] Curve **170** illustrates the amount of power transmitted from the transmit antenna at various frequencies. Thus, at points **1***a* and **3***a*, corresponding to about 13.528 MHz and 13.593 MHz, much of the power is reflected and not transmitted out of the transmit antenna. However, at point **2***a*, corresponding to about 13.56 MHz, it can be seen that a large amount of the power is accepted and transmitted out of the antenna.

[0062] Similarly, curve **172** illustrates the amount of power received by the receive antenna at various frequencies. Thus, at points **1***b* and **3***b*, corresponding to about 13.528 MHz and 13.593 MHz, much of the power is reflected and not conveyed through the receive antenna and into the receiver. However, at point **2***b* corresponding to about 13.56 MHz, it can be seen that a large amount of the power is accepted by the receive antenna and conveyed into the receiver.

[0063] Curve **174** indicates the amount of power received at the receiver after being sent from the transmitter through the transmit antenna, received through the receive antenna and conveyed to the receiver. Thus, at points **1***c* and **3***c*, corresponding to about 13.528 MHz and 13.593 MHz, much of the power sent out of the transmitter is not available at the receiver because (1) the transmit antenna rejects much of the power sent to it from the transmitter and (2) the coupling between the transmit antenna and the receive antenna is less efficient as the frequencies move away from the resonant frequency. However, at point **2***c* corresponding to about 13.56

MHz, it can be seen that a large amount of the power sent from the transmitter is available at the receiver, indicating a high degree of coupling between the transmit antenna and the receive antenna.

[0064] FIGS. **5**A and **5**B show layouts of loop antennas for transmit and receive antennas according to exemplary embodiments of the present invention. Loop antennas may be configured in a number of different ways, with single loops or multiple loops at wide variety of sizes. In addition, the loops may be a number of different shapes, such as, for example only, circular, elliptical, square, and rectangular. FIG. **5**A illustrates a large square loop transmit antenna **114**S and a small square loop receive antenna **118** placed in the same plane as the transmit antenna **114**S and near the center of the transmit antenna **114**S. FIG. **5**B illustrates a large circular loop transmit antenna **114**C and a small square loop receive antenna **118'** placed in the same plane as the transmit antenna **114**C and near the center of the transmit antenna **114**C. The square loop transmit antenna **114**S has side lengths of "a" while the circular loop transmit antenna **114**C has a diameter of "." For a square loop, it can be shown that there is an equivalent circular loop whose diameter may be defined as: $\Phi_{eq}=4a/\pi$.

[0065] FIG. **6** shows simulation results indicating coupling strength between transmit and receive antennas relative to various circumferences for the square and circular transmit antennas illustrated in FIGS. **4**A and **4**B. Thus, curve **180** shows coupling strength between the circular loop transmit antennas **114**C and the receive antenna **118** at various circumference sizes for the circular loop transmit antenna **114**C. Similarly, curve **182** shows coupling strength between the square loop transmit antennas **114**S and the receive antenna **118'** at various equivalent circumference sizes for the transmit loop transmit antenna **114**S.

[0066] FIG. **7** shows simulation results indicating coupling strength between transmit and receive antennas relative to various surface areas for the square and circular transmit antennas illustrated in FIGS. **5**A and **5**B. Thus, curve **190** shows coupling strength between the circular loop transmit antennas **114**C and the receive antenna **118** at various surface areas for the circular loop transmit antenna **114**C. Similarly, curve **192** shows coupling strength between the square loop transmit antennas **114**S and the receive antenna **118'** at various surface areas for the transmit loop transmit antenna **114**S.

[0067] FIG. **8** shows various placement points for a receive antenna relative to a transmit antenna to illustrate coupling strengths in coplanar and coaxial placements. "Coplanar," as used herein, means that the transmit antenna and receive antenna have planes that are substantially aligned (i.e., have surface normals pointing in substantially the same direction) and with no distance (or a small distance) between the planes of the transmit antenna and the receive antenna. "Coaxial," as used herein, means that the transmit antenna and receive antenna have planes that are substantially aligned (i.e., have surface normals pointing in substantially the same direction) and the distance between the two planes is not trivial and furthermore, the surface normal of the transmit antenna and the receive antenna lie substantially along the same vector, or the two normals are in echelon.

[0068] As examples, points p**1**, p**2**, p**3**, and p**7** are all coplanar placement points for a receive antenna relative to a transmit antenna. As another example, point p**5** and p**6** are coaxial placement points for a receive antenna relative to a transmit antenna. The table below shows coupling strength (S**21**) and coupling efficiency (expressed as a percentage of power transmitted from the transmit antenna that reached the receive antenna) at the various placement points (p**1**-p**7**) illustrated in FIG. **8**.

TABLE 1

Position	Distance from plane (cm)	S21 efficiency (%)	Efficiency (TX DC power in to RX DC power out)
p1	0	46.8	28
p2	0	55.0	36
p3	0	57.5	35
p4	2.5	49.0	30
p5	17.5	24.5	15
p6	17.5	0.3	0.2
p7	0	5.9	3.4

[0069] As can be seen, the coplanar placement points p**1**, p**2**, and p**3**, all show relatively high coupling efficiencies. Placement point p**7** is also a coplanar placement point, but is outside of the transmit loop antenna. While placement point p**7** does not have a high coupling efficiency, it is clear that there is some coupling and the coupling-mode region extends beyond the perimeter of the transmit loop antenna.

[0070] Placement point p**5** is coaxial with the transmit antenna and shows substantial coupling efficiency. The coupling efficiency for placement point p**5** is not as high as the coupling efficiencies for the coplanar placement points. However, the coupling efficiency for placement point p**5** is high enough that substantial power can be conveyed between the transmit antenna and a receive antenna in a coaxial placement.

[0071] Placement point p**4** is within the circumference of the transmit antenna but at a slight distance above the plane of the transmit antenna in a position that may be referred to as an offset coaxial placement (i.e., with surface normals in substantially the same direction but at different locations) or offset coplanar (i.e., with surface normals in substantially the same direction but with planes that are offset relative to each other). From the table it can be seen that with an offset distance of 2.5 cm, placement point p**4** still has relatively good coupling efficiency.

[0072] Placement point p**6** illustrates a placement point outside the circumference of the transmit antenna and at a substantial distance above the plane of the transmit antenna. As can be seen from the table, placement point p**7** shows little coupling efficiency between the transmit and receive antennas.

[0073] FIG. **9** shows simulation results indicating coupling strength for coaxial placement at various distances between the transmit and receive antennas. The simulations for FIG. **9** are for square transmit and receive antennas in a coaxial placement, both with sides of about 1.2 meters and at a transmit frequency of 10 MHz. It can be seen that the coupling strength remains quite high and uniform at distances of less than about 0.5 meters.

[0074] FIG. **10** is a simplified block diagram of a transmitter, in accordance with an exemplary embodiment of the present invention. A transmitter **200** includes transmit circuitry **202** and a transmit antenna **204**. Generally, transmit circuitry **202** provides RF power to the transmit antenna **204** by providing an oscillating signal resulting in generation of

near-field energy about the transmit antenna **204**. By way of example, transmitter **200** may operate at the 13.56 MHz ISM band.

[0075] Exemplary transmit circuitry **202** includes a fixed impedance matching circuit **206** for matching the impedance of the transmit circuitry **202** (e.g., 50 ohms) to the transmit antenna **204** and a low pass filter (LPF) **208** configured to reduce harmonic emissions to levels to prevent self-jamming of devices coupled to receivers **108** (FIG. **1**). Other exemplary embodiments may include different filter topologies, including but not limited to, notch filters that attenuate specific frequencies while passing others and may include an adaptive impedance match, that can be varied based on measurable transmit metrics, such as output power to the antenna or DC current draw by the power amplifier. Transmit circuitry **202** further includes a power amplifier **210** configured to drive an RF signal as determined by an oscillator **212**. The transmit circuitry may be comprised of discrete devices or circuits, or alternately, may be comprised of an integrated assembly. An exemplary RF power output from transmit antenna **204** may be on the order of 2.5 Watts.

[0076] Transmit circuitry **202** further includes a processor **214** for enabling the oscillator **212** during transmit phases (or duty cycles) for specific receivers, for adjusting the frequency of the oscillator, and for adjusting the output power level for implementing a communication protocol for interacting with neighboring devices through their attached receivers.

[0077] The transmit circuitry **202** may further include a load sensing circuit **216** for detecting the presence or absence of active receivers in the vicinity of the near-field generated by transmit antenna **204**. By way of example, a load sensing circuit **216** monitors the current flowing to the power amplifier **210**, which is affected by the presence or absence of active receivers in the vicinity of the near-field generated by transmit antenna **204**. Detection of changes to the loading on the power amplifier **210** are monitored by processor **214** for use in determining whether to enable the oscillator **212** for transmitting energy to communicate with an active receiver.

[0078] Transmit antenna **204** may be implemented as an antenna strip with the thickness, width and metal type selected to keep resistive losses low. In a conventional implementation, the transmit antenna **204** can generally be configured for association with a larger structure such as a table, mat, lamp or other less portable configuration. Accordingly, the transmit antenna **204** generally will not need "turns" in order to be of a practical dimension. An exemplary implementation of a transmit antenna **204** may be "electrically small" (i.e., fraction of the wavelength) and tuned to resonate at lower usable frequencies by using capacitors to define the resonant frequency. In an exemplary application where the transmit antenna **204** may be larger in diameter, or length of side if a square loop, (e.g., 0.50 meters) relative to the receive antenna, the transmit antenna **204** will not necessarily need a large number of turns to obtain a reasonable capacitance.

[0079] FIG. **11** is a block diagram of a receiver, in accordance with an exemplary embodiment of the present invention. A receiver **300** includes receive circuitry **302** and a receive antenna **304**. Receiver **300** further couples to device **350** for providing received power thereto. It should be noted that receiver **300** is illustrated as being external to device **350** but may be integrated into device **350**. Generally, energy is propagated wirelessly to receive antenna **304** and then coupled through receive circuitry **302** to device **350**.

[0080] Receive antenna **304** is tuned to resonate at the same frequency, or near the same frequency, as transmit antenna **204** (FIG. **10**). Receive antenna **304** may be similarly dimensioned with transmit antenna **204** or may be differently sized based upon the dimensions of an associated device **350**. By way of example, device **350** may be a portable electronic device having diametric or length dimension smaller that the diameter of length of transmit antenna **204**. In such an example, receive antenna **304** may be implemented as a multi-turn antenna in order to reduce the capacitance value of a tuning capacitor (not shown) and increase the receive antenna's impedance. By way of example, receive antenna **304** may be placed around the substantial circumference of device **350** in order to maximize the antenna diameter and reduce the number of loop turns (i.e., windings) of the receive antenna and the inter-winding capacitance.

[0081] Receive circuitry **302** provides an impedance match to the receive antenna **304**. Receive circuitry **302** includes power conversion circuitry **306** for converting a received RF energy source into charging power for use by device **350**. Power conversion circuitry **306** includes an RF-to-DC converter **308** and may also in include a DC-to-DC converter **310**. RF-to-DC converter **308** rectifies the RF energy signal received at receive antenna **304** into a non-alternating power while DC-to-DC converter **310** converts the rectified RF energy signal into an energy potential (e.g., voltage) that is compatible with device **350**. Various RF-to-DC converters are contemplated including partial and full rectifiers, regulators, bridges, doublers, as well as linear and switching converters.

[0082] Receive circuitry **302** may further include switching circuitry **312** for connecting receive antenna **304** to the power conversion circuitry **306** or alternatively for disconnecting the power conversion circuitry **306**. Disconnecting receive antenna **304** from power conversion circuitry **306** not only suspends charging of device **350**, but also changes the "load" as "seen" by the transmitter **200** (FIG. **2**) as is explained more fully below. As disclosed above, transmitter **200** includes load sensing circuit **216** which detects fluctuations in the bias current provided to transmitter power amplifier **210**. Accordingly, transmitter **200** has a mechanism for determining when receivers are present in the transmitter's near-field.

[0083] When multiple receivers **300** are present in a transmitter's near-field, it may be desirable to time-multiplex the loading and unloading of one or more receivers to enable other receivers to more efficiently couple to the transmitter. A receiver may also be cloaked in order to eliminate coupling to other nearby receivers or to reduce loading on nearby transmitters. This "unloading" of a receiver is also known herein as a "cloaking" Furthermore, this switching between unloading and loading controlled by receiver **300** and detected by transmitter **200** provides a communication mechanism from receiver **300** to transmitter **200** as is explained more fully below. Additionally, a protocol can be associated with the switching which enables the sending of a message from receiver **300** to transmitter **200**. By way of example, a switching speed may be on the order of 100 μsec.

[0084] In an exemplary embodiment, communication between the transmitter and the receiver refers to a Device Sensing and Charging Control Mechanism, rather than conventional two-way communication. In other words, the transmitter uses on/off keying of the transmitted signal to adjust whether energy is available in the near-filed. The receivers interpret these changes in energy as a message from the transmitter. From the receiver side, the receiver uses tuning

and de-tuning of the receive antenna to adjust how much power is being accepted from the near-field. The transmitter can detect this difference in power used from the near-field and interpret these changes as a message from the receiver.

[0085] Receive circuitry **302** may further include signaling detector and beacon circuitry **314** used to identify received energy fluctuations, which may correspond to informational signaling from the transmitter to the receiver. Furthermore, signaling and beacon circuitry **314** may also be used to detect the transmission of a reduced RF signal energy (i.e., a beacon signal) and to rectify the reduced RF signal energy into a nominal power for awakening either un-powered or power-depleted circuits within receive circuitry **302** in order to configure receive circuitry **302** for wireless charging.

[0086] Receive circuitry **302** further includes processor **316** for coordinating the processes of receiver **300** described herein including the control of switching circuitry **312** described herein. Cloaking of receiver **300** may also occur upon the occurrence of other events including detection of an external wired charging source (e.g., wall/USB power) providing charging power to device **350**. Processor **316**, in addition to controlling the cloaking of the receiver, may also monitor beacon circuitry **314** to determine a beacon state and extract messages sent from the transmitter. Processor **316** may also adjust DC-to-DC converter **310** for improved performance.

[0087] FIG. **12** shows a simplified schematic of a portion of transmit circuitry for carrying out messaging between a transmitter and a receiver. In some exemplary embodiments of the present invention, a means for communication may be enabled between the transmitter and the receiver. In FIG. **12** a power amplifier **210** drives the transmit antenna **204** to generate the radiated field. The power amplifier is driven by a carrier signal **220** that is oscillating at a desired frequency for the transmit antenna **204**. A transmit modulation signal **224** is used to control the output of the power amplifier **210**.

[0088] The transmit circuitry can send signals to receivers by using an ON/OFF keying process on the power amplifier **210**. In other words, when the transmit modulation signal **224** is asserted, the power amplifier **210** will drive the frequency of the carrier signal **220** out on the transmit antenna **204**. When the transmit modulation signal **224** is negated, the power amplifier will not drive out any frequency on the transmit antenna **204**.

[0089] The transmit circuitry of FIG. **12** also includes a load sensing circuit **216** that supplies power to the power amplifier **210** and generates a receive signal **235** output. In the load sensing circuit **216** a voltage drop across resistor R_s develops between the power in signal **226** and the power supply **228** to the power amplifier **210**. Any change in the power consumed by the power amplifier **210** will cause a change in the voltage drop that will be amplified by differential amplifier **230**. When the transmit antenna is in coupled mode with a receive antenna in a receiver (not shown in FIG. **12**) the amount of current drawn by the power amplifier **210** will change. In other words, if no coupled mode resonance exist for the transmit antenna **210**, the power required to drive the radiated field will be first amount. If a coupled mode resonance exists, the amount of power consumed by the power amplifier **210** will go up because much of the power is being coupled into the receive antenna. Thus, the receive signal **235** can indicate the presence of a receive antenna coupled to the transmit antenna **235** and can also detect signals sent from the receive antenna, as explained below. Additionally, a change in receiver current draw will be observable in the transmitter's power amplifier current draw, and this change can be used to detect signals from the receive antennas, as explained below.

[0090] FIGS. **13A-13C** shows a simplified schematic of a portion of receive circuitry in various states to illustrate messaging between a receiver and a transmitter. All of FIGS. **13A-13C** show the same circuit elements with the difference being state of the various switches. A receive antenna **304** includes a characteristic inductance L**1**, which drives node **350**. Node **350** is selectively coupled to ground through switch S**1**A. Node **350** is also selectively coupled to diode D**1** and rectifier **318** through switch S**1**B. The rectifier **318** supplies a DC power signal **322** to a receive device (not shown) to power the receive device, charge a battery, or a combination thereof. The diode D**1** is coupled to a transmit signal **320** which is filtered to remove harmonics and unwanted frequencies with capacitor C**3** and resistor R**1**. Thus the combination of D**1**, C**3**, and R**1** can generate a signal on the transmit signal **320** that mimics the transmit modulation generated by the transmit modulation signal **224** discussed above with reference to the transmitter in FIG. **12**.

[0091] Exemplary embodiments of the invention includes modulation of the receive device's current draw and modulation of the receive antenna's impedance to accomplish reverse link signaling. With reference to both FIG. **13**A and FIG. **12**, as the power draw of the receive device changes, the load sensing circuit **216** detects the resulting power changes on the transmit antenna and from these changes can generate the receive signal **235**.

[0092] In the exemplary embodiments of FIGS. **13A-13C**, the current draw through the transmitter can be changed by modifying the state of switches S**1**A and S**2**A. In FIG. **13**A, switch S**1**A and switch S**2**A are both open creating a "DC open state" and essentially removing the load from the transmit antenna **204**. This reduces the current seen by the transmitter.

[0093] In FIG. **13**B, switch S**1**A is closed and switch S**2**A is open creating a "DC short state" for the receive antenna **304**. Thus the state in FIG. **13**B can be used to increase the current seen in the transmitter.

[0094] In FIG. **13**C, switch S**1**A is open and switch S**2**A is closed creating a normal receive mode (also referred to herein as a "DC operating state") wherein power can be supplied by the DC out signal **322** and a transmit signal **320** can be detected. In the state shown in FIG. **13**C the receiver receives a normal amount of power, thus consuming more or less power from the transmit antenna than the DC open state or the DC short state.

[0095] Reverse link signaling may be accomplished by switching between the DC operating state (FIG. **13**C) and the DC short state (FIG. **13**B). Reverse link signaling also may be accomplished by switching between the DC operating state (FIG. **13**C) and the DC open state (FIG. **13**A).

[0096] FIGS. **14A-14C** shows a simplified schematic of a portion of alternative receive circuitry in various states to illustrate messaging between a receiver and a transmitter.

[0097] All of FIGS. **14A-14C** show the same circuit elements with the difference being state of the various switches. A receive antenna **304** includes a characteristic inductance L**1**, which drives node **350**. Node **350** is selectively coupled to ground through capacitor C**1** and switch S**1**B. Node **350** is also AC coupled to diode D**1** and rectifier **318** through capacitor C**2**. The diode D**1** is coupled to a transmit signal **320** which

is filtered to remove harmonics and unwanted frequencies with capacitor C3 and resistor R1. Thus the combination of D1, C3, and R1 can generate a signal on the transmit signal **320** that mimics the transmit modulation generated by the transmit modulation signal **224** discussed above with reference to the transmitter in FIG. **12**.

[0098] The rectifier **318** is connected to switch S2B, which is connected in series with resistor R2 and ground. The rectifier **318** also is connected to switch S3B. The other side of switch S3B supplies a DC power signal **322** to a receive device (not shown) to power the receive device, charge a battery, or a combination thereof.

[0099] In FIGS. **13**A-**13**C the DC impedance of the receive antenna **304** is changed by selectively coupling the receive antenna to ground through switch S1B. In contrast, in the exemplary embodiments of FIGS. **14**A-**14**C, the impedance of the antenna can be modified to generate the reverse link signaling by modifying the state of switches S1B, S2B, and S3B to change the AC impedance of the receive antenna **304**. In FIGS. **14**A-**14**C the resonant frequency of the receive antenna **304** may be tuned with capacitor C2. Thus, the AC impedance of the receive antenna **304** may be changed by selectively coupling the receive antenna **304** through capacitor C1 using switch S1B, essentially changing the resonance circuit to a different frequency that will be outside of a range that will optimally couple with the transmit antenna. If the resonance frequency of the receive antenna **304** is near the resonant frequency of the transmit antenna, and the receive antenna **304** is in the near-field of the transmit antenna, a coupling mode may develop wherein the receiver can draw significant power from the radiated field **106**.

[0100] In FIG. **14**A, switch S1B is closed, which de-tunes the antenna and creates an "AC cloaking state," essentially "cloaking" the receive antenna **304** from detection by the transmit antenna **204** because the receive antenna does not resonate at the transmit antenna's frequency. Since the receive antenna will not be in a coupled mode, the state of switches S2B and S3B are not particularly important to the present discussion.

[0101] In FIG. **14**B, switch S1B is open, switch S2B is closed, and switch S3B is open, creating a "tuned dummy-load state" for the receive antenna **304**. Because switch S1B is open, capacitor C1 does not contribute to the resonance circuit and the receive antenna **304** in combination with capacitor C2 will be in a resonance frequency that may match with the resonant frequency of the transmit antenna. The combination of switch S3B open and switch S2B closed creates a relatively high current dummy load for the rectifier, which will draw more power through the receive antenna **304**, which can be sensed by the transmit antenna. In addition, the transmit signal **320** can be detected since the receive antenna is in a state to receive power from the transmit antenna.

[0102] In FIG. **14**C, switch S1B is open, switch S2B is open, and switch S3B is closed, creating a "tuned operating state" for the receive antenna **304**. Because switch S1B is open, capacitor C1 does not contribute to the resonance circuit and the receive antenna **304** in combination with capacitor C2 will be in a resonance frequency that may match with the resonant frequency of the transmit antenna. The combination of switch S2B open and switch S3B closed creates a normal operating state wherein power can be supplied by the DC out signal **322** and a transmit signal **320** can be detected.

[0103] Reverse link signaling may be accomplished by switching between the tuned operating state (FIG. **14**C) and the AC cloaking state (FIG. **14**A). Reverse link signaling also may be accomplished by switching between the tuned dummy-load state (FIG. **14**B) and the AC cloaking state (FIG. **14**A). Reverse link signaling also may be accomplished by switching between the tuned operating state (FIG. **14**C) and the tuned dummy-load state (FIG. **14**B) because there will be a difference in the amount of power consumed by the receiver, which can be detected by the load sensing circuit in the transmitter.

[0104] Of course, those of ordinary skill in the art will recognize that other combinations of switches S1B, S2B, and S3B may be used to create cloaking, generate reverse link signaling and supplying power to the receive device. In addition, the switches S1A and S1B may be added to the circuits of FIGS. **14**A-**14**C to create other possible combinations for cloaking, reverse link signaling, and supplying power to the receive device.

[0105] Thus, when in a coupled mode signals may be sent from the transmitter to the receiver, as discussed above with reference to FIG. **12**. In addition, when in a coupled mode signals may be sent from the receiver to the transmitter, as discussed above with reference to FIGS. **13**A-**13**C and **14**A-**14**C.

[0106] FIGS. **15**A-**15**D are simplified block diagrams illustrating a beacon power mode for transmitting power between a transmitter and a one or more receivers. FIG. **15**A illustrates a transmitter **520** having a low power "beacon" signal **525** when there are no receive devices in the beacon coupling-mode region **510**. The beacon signal **525** may be, as a non-limiting example, such as in the range of ~10 to ~20 mW RF. This signal may be adequate to provide initial power to a device to be charged when it is placed in the coupling-mode region.

[0107] FIG. **15**B illustrates a receive device **530** placed within the beacon coupling-mode region **510** of the transmitter **520** transmitting the beacon signal **525**. If the receive device **530** is on and develops a coupling with the transmitter it will generate a reverse link coupling **535**, which is really just the receiver accepting power from the beacon signal **525**. This additional power, may be sensed by the load sensing circuit **216** (FIG. **12**) of the transmitter. As a result, the transmitter may go into a high power mode.

[0108] FIG. **15**C illustrates the transmitter **520** generating a high power signal **525'** resulting in a high power coupling-mode region **510'**. As long as the receive device **530** is accepting power and, as a result, generating the reverse link coupling **535**, the transmitter will remain in the high power state. While only one receive device **530** is illustrated, multiple receive devices **530** may be present in the coupling-mode region **510**. If there are multiple receive device **530** they will share the amount of power transmitted by the transmitter based on how well each receive device **530** is coupled. For example, the coupling efficiency may be different for each receive device **530** depending on where the device is placed within the coupling-mode region **510** as was explained above with reference to FIGS. **8** and **9**.

[0109] FIG. **15**D illustrates the transmitter **520** generating the beacon signal **525** even when a receive device **530** is in the beacon coupling-mode region **510**. This state may occur when the receive device **530** is shut off, or the device cloaks itself, perhaps because it does not need any more power.

[0110] The receiver and transmitter may communicate on a separate communication channel (e.g., Bluetooth, zigbee, etc). With a separate communication channel, the transmitter

may determine when to switch between beacon mode and high power mode, or create multiple power levels, based on the number of receive devices in the coupling-mode region **510** and their respective power requirements.

[0111] Exemplary embodiments of the invention include enhancing the coupling between a relatively large transmit antenna and a small receive antenna in the near-field power transfer between two antennas through introduction of additional antennas into the system of coupled antennas that will act as repeaters and will enhance the flow of power from the transmitting antenna toward the receiving antenna.

[0112] In exemplary embodiments, one or more extra antennas are used that couple to the transmit antenna and receive antenna in the system. These extra antennas comprise repeater antennas, such as active or passive antennas. A passive antenna may include simply the antenna loop and a capacitive element for tuning a resonant frequency of the antenna. An active element may include, in addition to the antenna loop and one or more tuning capacitors, an amplifier for increasing the strength of a repeated near-field radiation.

[0113] The combination of the transmit antenna and the repeater antennas in the power transfer system may be optimized such that coupling of power to very small receive antennas is enhanced based on factors such as termination loads, tuning components, resonant frequencies, and placement of the repeater antennas relative to the transmit antenna.

[0114] A single transmit antenna exhibits a finite near-field coupling mode region. Accordingly, a user of a device charging through a receiver in the transmit antenna's near-field coupling mode region may require a considerable user access space that would be prohibitive or at least inconvenient. Furthermore, the coupling mode region may diminish quickly as a receive antenna moves away from the transmit antenna.

[0115] A repeater antenna may refocus and reshape a coupling mode region from a transmit antenna to create a second coupling mode region around the repeater antenna, which may be better suited for coupling energy to a receive antenna. Discussed below in FIGS. **16**A-**18**B are some non-limiting examples of embodiments including repeater antennas.

[0116] FIG. **16**A illustrates a large transmit antenna **610**C with three smaller repeater antennas **620**C disposed coplanar with, and within a perimeter of, the transmit antenna **610**C. The transmit antenna **610**C and repeater antennas **620**C are formed on a table **640**. Various devices including receive antennas **630**C are placed at various locations within the transmit antenna **610**C and repeater antennas **620**C. The exemplary embodiment of FIG. **16**A may be able to refocus the coupling mode region generated by the transmit antenna **610**C into smaller and stronger repeated coupling mode regions around each of the repeater antennas **620**C. As a result, a relatively strong repeated near-field radiation is available for the receive antennas **630**C. Some of the receive antennas are placed outside of any repeater antennas **620**C. Recall that the coupled mode region may extend somewhat outside the perimeter of an antenna. Therefore, receive antennas **630**C may be able to receive power from the near-field radiation of the transmit antenna **610**C as well as any nearby repeater antennas **620**C. As a result, receive antennas placed outside of any repeater antennas **620**C, may be still be able to receive power from the near-field radiation of the transmit antenna **610**C as well as any nearby repeater antennas **620**C.

[0117] FIG. **16**B illustrates a large transmit antenna **610**D with smaller repeater antennas **620**D with offset coaxial placements and offset coplanar placements relative to the transmit antenna **610**D. A device including a receive antenna **630**D is placed within the perimeter of one of the repeater antennas **620**D. As a non-limiting example, the transmit antenna **610**D may be disposed on a ceiling **646**, while the repeater antennas **620**D may be disposed on a table **640**. The repeater antennas **620**D in an offset coaxial placement may be able to reshape and enhance the near-field radiation from the transmitter antenna **610**D to repeated near-field radiation around the repeater antennas **620**D. As a result, a relatively strong repeated near-field radiation is available for the receive antenna **630**D placed coplanar with the repeater antennas **620**D.

[0118] FIG. **17** shows simulation results indicating coupling strength between a transmit antenna, a repeater antenna and a receive antenna. The transmit antenna, the repeater antenna, and the receive antenna are tuned to have a resonant frequency of about 13.56 MHz.

[0119] Curve **662** illustrates a measure for the amount of power transmitted from the transmit antenna out of the total power fed to the transmit antenna at various frequencies. Similarly, curve **664** illustrates a measure for the amount of power received by the receive antenna through the repeater antenna out of the total power available in the vicinity of its terminals at various frequencies. Finally, Curve **668** illustrates the amount of power actually coupled between the transmit antenna, through the repeater antenna and into the receive antenna at various frequencies.

[0120] At the peak of curve **668**, corresponding to about 13.56 MHz, it can be seen that a large amount of the power sent from the transmitter is available at the receiver, indicating a high degree of coupling between the combination of the transmit antenna, the repeater antenna and the receive antenna.

[0121] FIG. **18**A show simulation results indicating coupling strength between a transmit antenna and receive antenna disposed in a coaxial placement relative to the transmit antenna with no repeater antennas. The transmit antenna and the receive antenna are tuned to have a resonant frequency of about 10 MHz. The transmit antenna in this simulation is about 1.3 meters on a side and the receive antenna is a multi-loop antenna at about 30 mm on a side. The receive antenna is placed at about 2 meters away from the plane of the transmit antenna. Curve **682**A illustrates a measure for the amount of power transmitted from the transmit antenna out of the total power fed to its terminals at various frequencies. Similarly, curve **684**A illustrates a measure of the amount of power received by the receive antenna out of the total power available in the vicinity of its terminals at various frequencies. Finally, Curve **686**A illustrates the amount of power actually coupled between the transmit antenna and the receive antenna at various frequencies.

[0122] FIG. **18**B show simulation results indicating coupling strength between the transmit and receive antennas of FIG. **18**A when a repeater antenna is included in the system. The transmit antenna and receive antenna are the same size and placement as in FIG. **18**A. The repeater antenna is about 28 cm on a side and placed coplanar with the receive antenna (i.e., about 0.1 meters away from the plane of the transmit antenna). In FIG. **18**B, Curve **682**B illustrates a measure of the amount of power transmitted from the transmit antenna out of the total power fed to its terminals at various frequencies. Curve **684**B illustrates the amount of power received by the receive antenna through the repeater antenna out of the total power available in the vicinity of its terminals at various

frequencies. Finally, Curve **686**B illustrates the amount of power actually coupled between the transmit antenna, through the repeater antenna and into the receive antenna at various frequencies.

[0123] When comparing the coupled power (**686**A and **686**B) from FIGS. **18**A and **18**B it can be seen that without a repeater antenna the coupled power **686**A peaks at about −36 dB. Whereas, with a repeater antenna the coupled power **686**B peaks at about −5 dB. Thus, near the resonant frequency, there is a significant increase in the amount of power available to the receive antenna due to the inclusion of a repeater antenna.

[0124] Exemplary embodiments of the invention include low cost unobtrusive ways to properly manage how the transmitter radiates to single and multiple devices and device types in order to optimize the efficiency by which the transmitter conveys charging power to the individual devices.

[0125] FIG. **19** is a simplified block diagram of a transmitter **200** including a presence detector **280**. The transmitter is similar to that of FIG. **10** and, therefore, does not need to be explained again. However, in FIG. **19** the transmitter **200** may include presence detector **280**, and enclosed detector **290**, or a combination thereof, connected to the controller **214** (also referred to as a processor herein). The controller **214** can adjust an amount of power delivered by the amplifier **210** in response to presence signals from the presence detector **280** and enclosed detector **290**. The transmitter may receive power through an AC-DC converter (not shown) to convert conventional AC power **299**.

[0126] As a non-limiting example, the presence detector **280** may be a motion detector utilized to sense the initial presence of a device to be charged that is inserted into the coverage area of the transmitter. After detection, the transmitter is turned on and the RF power received by the device is used to toggle a switch on the Rx device in a pre-determined manner, which in turn results in changes to the driving point impedance of the transmitter.

[0127] As another non-limiting example, the presence detector **280** may be a detector capable of detecting a human, for example, by infrared detection, motion detection, or other suitable means. In some exemplary embodiments, there may be regulations limiting the amount of power that a transmit antenna may transmit at a specific frequency. In some cases, these regulations are meant to protect humans from electromagnetic radiation. However, there may be environments where transmit antennas are placed in areas not occupied by humans, or occupied infrequently by humans, such as, for example, garages, factory floors, shops, and the like. If these environments are free from humans, it may be permissible to increase the power output of the transmit antennas above the normal power restrictions regulations. In other words, the controller **214** may adjust the power output of the transmit antenna **204** to a regulatory level or lower in response to human presence and adjust the power output of the transmit antenna **204** to a level above the regulatory level when a human is outside a regulatory distance from the electromagnetic field of the transmit antenna **204**.

[0128] In many of the examples below, only one guest device is shown being charged. In practice, a multiplicity of the devices can be charged from a near-field generated by each host.

[0129] In exemplary embodiments, a method by which the Tx circuit does not remain on indefinitely may be used. In this case, the Tx circuit may be programmed to shut off after a user-determined amount of time. This feature prevents the Tx circuit, notably the power amplifier, from running long after the wireless devices in its perimeter are fully charged. This event may be due to the failure of the circuit to detect the signal sent from either the repeater or the Rx coil that a device is fully charged. To prevent the Tx circuit from automatically shutting down if another device is placed in its perimeter, the Tx circuit automatic shut off feature may be activated only after a set period of lack of motion detected in its perimeter. The user may be able to determine the inactivity time interval, and change it as desired. As a non-limiting example, the time interval may be longer than that needed to fully charge a specific type of wireless device under the assumption of the device being initially fully discharged.

[0130] Exemplary embodiments of the invention include using surfaces as the charging stations or "hosts," housing totally, or partially, the transmit antenna and other circuitry necessary for wireless transfer of power to other often smaller devices, equipment, or machines referred to as "guests." As non-limiting examples, these charging stations or hosts could be a window, a wall, and so on. The charging system, which can be at least partially embedded in the aforementioned examples, may either be a retrofit to existing apparatus, or made as part of its initial design and manufacturing.

[0131] Electrically small antennas have low efficiency, often no more than a few percent as explained by the theory of small antennas. The smaller the electric size of an antenna, the lower is its efficiency. The wireless power transfer can become a viable technique replacing wired connection to the electric grid in industrial, commercial, and household applications if power can be sent over meaningful distances to the devices that are in the receiving end of such power transfer system. While this distance is application dependent, a few tens of a centimeter to a few meters can be deemed a suitable range for most applications. Generally, this range reduces the effective frequency for the electric power in the interval between 5 MHz to 100 MHz.

[0132] FIGS. **20** and **21** are plan views of block diagrams of an enlarged area wireless charging apparatus, in accordance with exemplary embodiments. As stated, locating a receiver in a near-field coupling mode region of a transmitter for engaging the receiver in wireless charging may be unduly burdensome by requiring accurate positioning of the receiver in the transmit antenna's near-field coupling mode region. Furthermore, locating a receiver in the near-field coupling mode region of a fixed-location transmit antenna may also be inaccessible by a user of a device coupled to the receiver especially when multiple receivers are respectively coupled to multiple user accessible devices (e.g., laptops, PDAs, wireless devices) where users need concurrent physical access to the devices. For example, a single transmit antenna exhibits a finite near-field coupling mode region. Accordingly, a user of a device charging through a receiver in the transmit antenna's near-field coupling mode region may require a considerable user access space that would be prohibitive or at least inconvenient for another user of another device to also wirelessly charge within the same transmit antenna's near-field coupling mode region and also require separate user access space. For example, two adjacent users of wireless chargeable devices seated at a conference table configured with a single transmit antenna may be inconvenienced or prohibited from accessing their respective devices due to the local nature of the transmitters near-field coupling mode region and the considerable user access space required to interact with the respective

devices. Additionally, requiring a specific wireless charging device and its user to be specifically located may also inconvenience a user of the device.

[0133] Referring to FIG. **20**, an exemplary embodiment of an enlarged area wireless charging apparatus **700** provides for placement of a plurality of adjacently located transmit antenna circuits **702**A-**702**D to define an enlarged wireless charging area **708**. By way of example and not limitation, a transmit antenna circuit includes a transmit antenna **710** having a diameter or side dimension, for example, of around 30-40 centimeters for providing uniform coupling to an receive antenna (not shown) that is associated with or fits in an electronic device (e.g., wireless device, handset, PDA, laptop, etc.). By considering the transmit antenna circuit **702** as a unit or cell of the enlarged area wireless charging apparatus **700**, stacking or adjacently tiling these transmit antenna circuits **702**A-**702**D next to each other on substantially a single planar surface **704** (e.g., on a table top) allows for increasing or enlarging the charging area. The enlarged wireless charging area **708** results in an increased charging region for one or more devices.

[0134] The enlarged area wireless charging apparatus **700** further includes a transmit power amplifier **720** for providing the driving signal to transmit antennas **710**. In configurations where the near-field coupling mode region of one transmit antenna **710** interferes with the near-field coupling mode regions of other transmit antennas **710**, the interfering adjacent transmit antennas **710** are "cloaked" to allow improved wireless charging efficiency of the activated transmit antenna **710**.

[0135] The sequencing of activation of transmit antennas **710** in enlarged area wireless charging apparatus **700** may occur according to a time-domain based sequence. The output of transmit power amplifier **720** is coupled to a multiplexer **722** which time-multiplexes, according to control signal **724** from the transmitter processor, the output signal from the transmit power amplifier **720** to each of the transmit antennas **710**.

[0136] In order to inhibit inducing resonance in adjacent inactive transmit antenna **710** when the power amplifier **720** is driving the active transmit antenna, the inactive antennas may be "cloaked" by altering the resonant frequency of that transmit antenna by, for example, activating the cloaking circuit **714**. By way of implementation, concurrent operation of directly or nearly adjacent transmit antenna circuits **702** may result in interfering effects between concurrently activated and physically nearby or adjacent other transmit antenna circuits **702**. Accordingly, transmit antenna circuit **702** may further include a transmitter cloaking circuit **714** for altering the resonant frequency of transmit antennas **710**.

[0137] The transmitter cloaking circuit may be configured as a switching means (e.g. a switch) for shorting-out or altering the value of reactive elements, for example capacitor **716**, of the transmit antenna **710**. The switching means may be controlled by control signals **721** from the transmitter's processor. In operation, one of the transmit antennas **710** is activated and allowed to resonate while other of transmit antennas **710** are inhibited from resonating, and therefore inhibited from adjacently interfering with the activated transmit antenna **710**. Accordingly, by shorting-out or altering the capacitance of a transmit antenna **710**, the resonant frequency of transmit antenna **710** is altered to prevent resonant coupling from other transmit antennas **710**. Other techniques for altering the resonant frequency are also contemplated.

[0138] In another exemplary embodiment, each of the transmit antenna circuits **702** can determine the presence or absence of receivers within their respective near-field coupling mode regions with the transmitter processor choosing to activate ones of the transmit antenna circuits **702** when receivers are present and ready for wireless charging or forego activating ones of the transmit antenna circuits **702** when receivers are not present or not ready for wireless charging in the respective near-field coupling mode regions. The detection of present or ready receivers may occur according to the receiver detection signaling protocol described herein or may occur according to physical sensing of receivers such as motion sensing, pressure sensing, image sensing or other sensing techniques for determining the presence of a receiver within a transmit antenna's near-field coupling mode region. Furthermore, preferential activation of one or more transmit antenna circuits by providing an enhanced proportional duty cycle to at least one of the plurality of antenna circuits is also contemplated to be within the scope of the present invention.

[0139] Referring to FIG. **21**, an exemplary embodiment of an enlarged area wireless charging apparatus **800** provides for placement of a plurality of adjacently located repeater antenna circuits **802**A-**802**D inside of a transmit antenna **801** defining an enlarged wireless charging area **808**. Transmit antenna **801**, when driven by transmit power amplifier **820**, induces resonant coupling to each of the repeater antennas **810**A-**810**D. By way of example and not limitation, a repeater antenna **810** having a diameter or side dimension, for example, of around 30-40 centimeters provides uniform coupling to a receive antenna (not shown) that is associated with or affixed to an electronic device. By considering the repeater antenna circuit **802** as a unit or cell of the enlarged area wireless charging apparatus **800**, stacking or adjacently tiling these repeater antenna circuits **802**A-**802**D next to each other on substantially a single planar surface **804** (e.g., on a table top) allows for increasing or enlarging the charging area. The enlarged wireless charging area **808** results in an increased charging space for one or more devices.

[0140] The enlarged area wireless charging apparatus **800** includes transmit power amplifier **820** for providing the driving signal to transmit antenna **801**. In configurations where the near-field coupling mode region of one repeater antenna **810** interferes with the near-field coupling mode regions of other repeater antennas **810**, the interfering adjacent repeater antennas **810** are "cloaked" to allow improved wireless charging efficiency of the activated repeater antenna **810**.

[0141] The sequencing of activation of repeater antennas **810** in enlarged area wireless charging apparatus **800** may occur according to a time-domain based sequence. The output of transmit power amplifier **820** is generally constantly coupled (except during receiver signaling as described herein) to transmit antenna **801**. In the present exemplary embodiment, the repeater antennas **810** are time-multiplexed according to control signals **821** from the transmitter processor. By way of implementation, concurrent operation of directly or nearly adjacent repeater antenna circuits **802** may result in interfering effects between concurrently activated and physically nearby or adjacent other repeater antennas circuits **802**. Accordingly, repeater antenna circuit **802** my further include a repeater cloaking circuit **814** for altering the resonant frequency of repeater antennas **810**.

[0142] The repeater cloaking circuit may be configured as a switching means (e.g. a switch) for shorting-out or altering the value of reactive elements, for example capacitor **816**, of

the repeater antenna **810**. The switching means may be controlled by control signals **821** from the transmitter's processor. In operation, one of the repeater antennas **810** is activated and allowed to resonate while other of repeater antennas **810** are inhibited from resonating, and therefore adjacently interfering with the activated repeater antenna **810**. Accordingly, by shorting-out or altering the capacitance of a repeater antenna **810**, the resonant frequency of repeater antenna **810** is altered to prevent resonant coupling from other repeater antennas **810**. Other techniques for altering the resonant frequency are also contemplated.

[0143] In another exemplary embodiment, each of the repeater antenna circuits **802** can determine the presence or absence of receivers within their respective near-field coupling mode regions with the transmitter processor choosing to activate ones of the repeater antenna circuits **802** when receivers are present and ready for wireless charging or forego activating ones of the repeater antenna circuits **802** when receivers are not present or not ready for wireless charging in the respective near-field coupling mode regions. The detection of present or ready receivers may occur according to the receiver detection signaling protocol described herein or may occur according to physical sensing of receivers such as motion sensing, pressure sensing, image sensing or other sensing techniques for determining a receiver to be within a repeater antenna's near-field coupling mode region.

[0144] The various exemplary embodiments of the enlarged area wireless charging apparatus **700** and **800** may further include time domain multiplexing of the input signal being coupled to transmit/repeater antennas **710**, **810** based upon asymmetrically allocating activation time periods to the transmit/repeater antennas based upon factors such as priority charging of certain receivers, varying quantities of receivers in different antennas' near-field coupling mode regions, power requirements of specific devices coupled to the receivers as well as other factors.

[0145] It is known that electrically small antennas have low efficiency, often no more than a few percent as explained by the theory of small antennas, known by those of skill in the art. Generally, the smaller the electric size of an antenna, the lower is its efficiency. Accordingly, wireless power transfer can become a viable technique replacing wired connection to the electric grid in industrial, commercial, and household applications if power can be sent over meaningful distances to the devices that are in the receiving end of such power transfer system. While this distance is application dependent, a few tens of a centimeter to a few meters, for example, can be deemed a suitable range for most applications. Generally, this range reduces the effective frequency for the electric power in the interval, for example, between 5 MHz to 100 MHz.

[0146] As stated, efficient transfer of energy between the transmitter and receiver occurs during matched or nearly matched resonance between the transmitter and the receiver. However, even when resonance between the transmitter and receiver are not matched, energy may be transferred at a lower efficiency. Transfer of energy occurs by coupling energy from the near-field of the transmitting antenna to the receiving antenna residing in the neighborhood where this near-field is established rather than propagating the energy from the transmitting antenna into free space.

[0147] Exemplary embodiments of the invention include coupling power between two antennas that are in the near-fields of each other. As stated, the near-field is an area around the antenna in which electromagnetic fields exist but may not propagate or radiate away from the antenna. They are typically confined to a volume that is near the physical volume of the antenna. In the exemplary embodiments of the invention, magnetic type antennas such as single and multi-turn loop antennas are used for both transmit (Tx) and receive (Rx) antenna systems since magnetic near-field amplitudes tend to be higher for magnetic type antennas in comparison to the electric near-fields of an electric-type antenna (e.g., a small dipole). This allows for potentially higher coupling between the pair. Furthermore, "electric" antennas (e.g., dipoles and monopoles) or a combination of magnetic and electric antennas is also contemplated.

[0148] The Tx antenna can be operated at a frequency that is low enough and with an antenna size that is large enough to achieve good coupling (e.g., >−4 dB) to a small Rx antenna at significantly larger distances than allowed by far field and inductive approaches mentioned earlier. If the Tx antenna is sized correctly, high coupling levels (e.g., −2 to −4 dB) can be achieved when the Rx antenna on a host device is placed within a coupling-mode region (i.e., in the near-field) of the driven Tx loop antenna.

[0149] FIGS. **20** and **21** illustrate multiple loops in a charging area that is substantially planar. However, exemplary embodiments of the present invention are not so limited. Three-dimensional spaces with multiple antennas may be used.

[0150] Exemplary embodiments of the invention include using an apparatus as a charging stations or "host," housing totally, or partially, transmit antennas and other circuitry necessary for wireless transfer of power to other often smaller devices, equipment, or machines referred to as "guests." These charging stations or hosts could be any apparatus having a plurality of surfaces. As non-limiting examples, these charging stations or hosts could be a toolbox, a bag, a container configured to hold a solution, an autoclave, a cabinet, a chest, and so on. The transmit antennas, which can be at least partially embedded in the aforementioned examples, may either be a retrofit to existing apparatus, or made as part of its initial design and manufacturing.

[0151] FIGS. **22**A-**31** illustrate various exemplary embodiments of charging systems including apparatuses having transmit antennas oriented in multiple directions. Multi-dimensional orientation of transmit antennas may increase the power that can be delivered to one or more receive antennas positioned in various orientations in respect to the multiple dimensions of the transmit antennas. The charging systems may be configured so that any number of the transmit antennas can be used at once to wirelessly transmit power to one or more receive antennas positioned within an apparatus. Although various exemplary embodiments depicted below may illustrate transmit antennas oriented in three planes (i.e., three-dimensional wireless charging), embodiments of the present invention are not so limited. Rather, embodiments of the present invention are directed to multi-dimensional wireless charging, wherein transmit antennas may be oriented in any number of planes.

[0152] In the exemplary embodiments described herein, messaging between a receiver and a transmitter may be performed by the techniques described in above with respect to FIGS. **13**A-**15**D. In addition, more sophisticated messaging means may be employed, such as the means described in U.S. patent application Ser. No. 12/249,816, entitled "SIGNALING CHARGING IN WIRELESS POWER ENVIRON-

MENT" filed on Oct. 10, 2008, the contents of which is hereby incorporated herein in its entirety by reference.

[0153] With reference to FIGS. **22**A and **22**B, a multi-dimensional wireless charging apparatus **910** is shown in which a plurality of transmit antennas (i.e., transmit antenna **912**, transmit antenna **914**, and transmit antenna **916**) are coupled to surfaces along a plurality of axes. FIG. **22**A illustrates apparatus **910** with a lid **911** open to show a plurality of chargeable devices **930** disposed therein. FIG. **22**B illustrates apparatus **910** with lid **911** closed. It is noted that transmit antenna **912**, transmit antenna **914**, and transmit antenna **916** may each be coupled to apparatus **910** in a manner so as to prevent the antennas from being shorted by a material of apparatus **910**, its contents, or any combination thereof. As an example, each of transmit antenna **912**, transmit antenna **914**, and transmit antenna **916** may be coated with an insulating material and attached to a surface of apparatus **910**. Furthermore, for example only, apparatus **910** may comprise a non-conductive material.

[0154] As illustrated in each of FIG. **22**A and FIG. **22**B, wireless charging apparatus **910** includes transmit antennas coupled to three sides. Specifically, a first-orientation transmit antenna **912** is coupled to a bottom of apparatus **910**. A second-orientation transmit antenna **914** is coupled to a first side of apparatus **910** and a third-orientation transmit antenna **916** is coupled to a second side of apparatus **910** and is substantially orthogonal to the first-orientation transmit antenna **912**. Any one of the three transmit antennas, any pair of them, or all three at once can be used to wirelessly provide power to one or more receive antennas positioned within apparatus **910** and coupled to a chargeable device. A means such as that discussed above with respect to FIGS. **20** and **21** may be used for selecting and multiplexing between the differently oriented transmit antennas.

[0155] FIGS. **23**A and **23**B illustrate an exemplary embodiment of a cabinet **950** bearing transmit antennas oriented in multiple directions with transmit antennas in opposite panels. FIG. **23**A shows cabinet **950** with an open door **951** and FIG. **23**B shows cabinet **950** with door **951** closed. Transmit antennas **972** and **974** are on opposing sides (i.e., the left and the right respectively) of cabinet **950**. Transmit antennas **962** and **964** are on opposing sides (i.e., the door and the back respectively) of cabinet **950**. Transmit antennas **982** and **984** are on opposing sides (i.e., the top and the bottom respectively) of the cabinet **950**. It is noted that for an apparatus having differing surface lengths (e.g., a rectangular apparatus), different sizes of transmit antennas may be compensated for by respective variations in tank capacitors, as will be understood by a person having ordinary skill in the art. Further, it is noted that each transmit antenna may be coupled to cabinet **950** in a manner so as to prevent the transmit antennas from being shorted by a material of apparatus cabinet **950**, its contents, or any combination thereof. As an example, each may be coated with an insulating material and attached to a surface of cabinet **950**. Furthermore, for example only, cabinet **950** may comprise a non-conductive material.

[0156] FIG. **24** illustrates a charging system **1000**, in accordance with an exemplary embodiment of the present invention. Charging system **1000** includes a charging apparatus **1010** having transmit antennas **1012**, **1014**, and **1016** oriented in multiple directions. As mentioned above, charging apparatus **1010** may comprise any apparatus having a plurality of surfaces, such as, for example only, a toolbox, a bag, or a cabinet. As depicted, a plurality of chargeable devices **1020** and **1024** having respective receive antennas **1022** and **1026** coupled thereto are positioned within charging apparatus **1010**. Although charging system **1000** includes three transmit antennas coupled to charging apparatus **1010** and two chargeable devices positioned therein, embodiments of the present invention are not so limited. Rather, a charging system including a charging apparatus having any number of transmit antennas coupled thereto and any number of chargeable devices positioned therein is within the scope of the present invention.

[0157] According to one exemplary embodiment of the present invention, a charging system having a plurality of transmit antennas oriented in multiple planes may be configured to sequentially transmit power from each transmit antenna. More specifically, the charging system may be configured to sequentially transmit power from each transmit antenna in either a random or a predetermined order continuously until either each chargeable device within the charging apparatus is fully charged or until each chargeable device has been removed from the charging apparatus. As an example, with reference to FIG. **24**, charging system **1000** may be configured to transmit power from transmit antenna **1012** for a first time duration, transmit power from transmit antenna **1014** for a second time duration, and transmit power from transmit antenna **1016** for a third time duration. This process may be repeated indefinitely until each of chargeable device **1020** and chargeable device **1024** are fully charged or until each of chargeable device **1020** and chargeable device **1024** are removed from charging apparatus **1010**. Stated another way, this process may be repeated so long as charging apparatus **1010** includes at least one chargeable device therein and at least one chargeable device therein requires charging. It is noted that the first time duration, the second time duration, and the third time duration may be substantially equal to one another, or the time durations may vary in any suitable manner.

[0158] According to another exemplary embodiment of the present invention, a charging system may be configured to determine an optimal selection of one or more transmit antennas for charging each chargeable device positioned within an associated charging apparatus. More specifically, in the example illustrated in FIG. **24**, charging system **1000** may be configured to define, for each of receive antenna **1026** and receive antenna **1022**, an optimal selection of either a single transmit antenna (i.e., transmit antenna **1012**, transmit antenna **1014**, or transmit antenna **1016**) or any possible combination of transmit antennas (i.e., transmit antenna **1012** and transmit antenna **1014**, transmit antenna **1012** and transmit antenna **1014**, transmit antenna **1014** and transmit antenna **1016**, or transmit antenna **1012**, transmit antenna **1014**, and transmit antenna **1016**) that may lead to the highest power received by the receive antenna and an associated chargeable device. In determining whether a plurality (i.e., a combination) of transmit antennas provides optimal charging for a chargeable device, power levels of each of the plurality of transmit antennas may be varied to further establish an optimal amount of power received by a chargeable device from the combination of transmit antennas. A method of determining an optimal selection of one or more transmit antennas for charging a chargeable device may also be referred to herein as a "single device calibration process."

[0159] A method of determining an optimal selection of one or more transmit antennas for charging a chargeable device (i.e., a single device calibration process), in accor-

dance with an exemplary embodiment of the present invention, will now be described. After identification of a receive antenna coupled to a chargeable device and positioned within a charging apparatus, an associated charging system may be configured to sequentially transmit power to the receive antenna from each transmit antenna coupled to the charging apparatus. Furthermore, the charging system may be configured to sequentially transmit power to the receive antenna from each possible combination of transmit antennas. As noted above, during transmission of power to a receive antenna from a combination of transmit antennas, power levels of the transmit antennas may be varied to further determine an optimal amount of power received by a receive antenna from a combination of transmit antennas.

[0160] After sequentially transmitting power to the receive antenna from each transmit antenna individually and each possible combination of transmit antennas, the charging system may be configured to determine which one or more transmit antennas provide optimal charging for the chargeable device that is coupled to the receive antenna. It is noted that during a calibration process of a receive antenna and an associated chargeable device positioned within a charging apparatus, one or more other receive antennas positioned within the charging apparatus may be "cloaked" to prevent coupling between the one or more other receive antennas and any other receive or transmit antennas coupled to or within an associated charging apparatus.

[0161] With reference to FIG. **24**, an example of a single device calibration process will now be described. After identification of receive antenna **1022**, receive antenna **1026** may be "cloaked" to prevent coupling between either receive antenna **1026** and any transmit antenna (i.e., transmit antennas **1012**, **1014**, or **1016**) or receive antenna **1026** and receive antenna **1022**. Transmit antenna **1012** may then transmit power to receive antenna **1022** and an amount of power received by receive antenna **1022** may be determined. Thereafter, transmit antenna **1014** may transmit power to receive antenna **1022** and an amount of power received by receive antenna **1022** may be determined. Subsequently, transmit antenna **1016** may transmit power to receive antenna **1022** and an amount of power received by receive antenna **1022** may be determined.

[0162] Furthermore, after each individual transmit antenna sequentially transmits power to receive antenna **1022**, transmit antenna **1012** and transmit antenna **1014** may simultaneously transmit power to receive antenna **1022** and an amount of power received by receive antenna **1022** may be determined. During transmission of power from transmit antenna **1012** and transmit antenna **1014**, power levels of each of transmit antenna **1012** and transmit antenna **1014** may be varied to determine an optimal amount of power received by receive antenna **1022** from the combination of transmit antenna **1012** and transmit antenna **1014**. Transmit antenna **1012** and transmit antenna **1016** may then simultaneously transmit power to receive antenna **1022** and an amount of power received by receive antenna **1022** may be determined. During transmission of power from transmit antenna **1012** and transmit antenna **1016**, power levels of each of transmit antenna **1012** and transmit antenna **1016** may be varied to determine an optimal amount of power received by receive antenna **1022** from the combination of transmit antenna **1012** and transmit antenna **1016**. Subsequently, transmit antenna **1014** and transmit antenna **1016** may simultaneously transmit power to receive antenna **1022** and an amount of power received by receive antenna **1022** may be determined. During transmission of power from transmit antenna **1014** and transmit antenna **1016**, power levels of each of transmit antenna **1014** and transmit antenna **1016** may be varied to determine an optimal amount of power received by receive antenna **1022** from the combination of transmit antenna **1014** and transmit antenna **1016**.

[0163] Additionally, transmit antenna **1014**, transmit antenna **1016**, and transmit antenna **1012** may simultaneously transmit power to receive antenna **1022** and an amount of power received by receive antenna **1022** may be determined. During transmission of power from transmit antenna **1012**, transmit antenna **1014**, and transmit antenna **1016**, power levels of each of transmit antenna **1012**, transmit antenna **1014**, and transmit antenna **1016** may be varied to determine an optimal amount of power received by receive antenna **1022** from the combination of transmit antenna **1012**, transmit antenna **1014**, and transmit antenna **1016**. It is noted that an amount of power received by receive antenna **1022** may be determined by any known and suitable method. For example, according to one exemplary embodiment, one or more transmit antennas may sense an amount of power received by receive antenna **1022** by sensing an impedance between the one or more transmit antennas and receive antenna **1022**. According to another exemplary embodiment, upon receipt of power from one or more transmit antennas, receive antenna **1022** may be configured to convey a signal back to the one or more transmit antennas indicative of an amount of power received.

[0164] After sequentially receiving power from each transmit antenna and each possible combination of transmit antennas at various power levels, charging system **1000** may be configured to determine which one or more transmit antennas provide optimal charging for chargeable device **1020**, which is coupled to receive antenna **1022**. Furthermore, as noted above, this calibration process may be repeated for each identified receive antenna positioned within apparatus **1010**. Accordingly, after performing a calibration process for chargeable device **1020**, charging system **1000** may be configured to perform another calibration process to determine an optimal selection of one or more transmit antennas for chargeable device **1024**. In this example, due to the parallel nature of the orientations, it may be determined that transmit antenna **1014** provides optimal charging for chargeable device **1024** and transmit antenna **1012** provides optimal charging for chargeable device **1020**. Furthermore, because a chargeable device and its associated receive antenna may change positions within a charging apparatus, charging system **1000** may be configured to repeat a calibration process periodically for each chargeable device, upon detection of a change in an amount of power received by a receive antenna and an associated chargeable device, or any combination thereof.

[0165] In addition to defining an optimal selection of one or more transmit antennas for charging each chargeable device positioned within charging apparatus **1010**, charging system **1000** may be configured to define an optimal selection of one or more transmit antennas for concurrently charging a plurality of chargeable devices positioned within charging apparatus **1010**. More specifically, with reference to FIG. **24**, charging system **100** may be configured to define an optimal selection of either a single transmit antenna (i.e., transmit antenna **1012**, transmit antenna **1014**, or transmit antenna **1016**) or any possible combination of transmit antennas (i.e.,

transmit antenna **1012** and transmit antenna **1014**, transmit antenna **1012** and transmit antenna **1014**, transmit antenna **1014** and transmit antenna **1016**, or transmit antenna **1012**, transmit antenna **1014**, and transmit antenna **1016**) that may lead to the highest total power received by both receive antenna **1026** and receive antenna **1022**. In determining whether a plurality (i.e., a combination) of transmit antennas provides optimal charging for a plurality of chargeable devices, power levels of each of the plurality of transmit antennas may be varied to further establish an optimal total amount of power received by the chargeable devices from the combination of transmit antennas. A method of determining an optimal selection of one or more transmit antennas for charging a plurality of chargeable devices may also be referred to herein as a "multiple device calibration process."

[0166] A method of determining an optimal selection of one or more transmit antennas for charging a plurality of chargeable devices (i.e., a multiple device calibration process), in accordance with an exemplary embodiment of the present invention, will now be described. After identification of a plurality of receive antennas, each coupled to a chargeable device, an associated charging system may be configured to sequentially transmit power to the receive antennas from each transmit antenna coupled to the charging apparatus. Furthermore, the charging system may be configured to sequentially transmit power to the receive antennas from each possible combination of transmit antennas. As noted above, during transmission of power to a plurality of receive antennas from a combination of transmit antennas, power levels of the transmit antennas may be varied to further determine an optimal total amount of power received by the receive antennas from a combination of transmit antennas. After sequentially transmitting power to the receive antennas from each transmit antenna individually and each possible combination of transmit antennas at various power levels, the charging system may be configured to determine which one or more transmit antennas provide optimal charging for the plurality of chargeable devices, which are each coupled to a receive antenna.

[0167] With reference to FIG. **24**, an example of a multiple device calibration process will now be described. After identification of receive antenna **1022** and receive antenna **1026**, transmit antenna **1012** may transmit power to receive antenna **1022** and receive antenna **1026** and a total amount of power received by receive antenna **1022** and receive antenna **1026** may be determined. Thereafter, transmit antenna **1014** may transmit power to receive antenna **1022** and receive antenna **1026** and a total amount of power received by receive antenna **1022** and receive antenna **1026** may be determined. Subsequently, transmit antenna **1016** may transmit power to receive antenna **1022** and receive antenna **1026** and a total amount of power received by receive antenna **1022** and receive antenna **1026** may be determined.

[0168] Furthermore, after each individual transmit antenna sequentially transmits power to receive antenna **1022** and receive antenna **1026**, transmit antenna **1012** and transmit antenna **1014** may simultaneously transmit power to receive antenna **1022** and receive antenna **1026** and a total amount of power received by receive antenna **1022** and receive antenna **1026** may be determined. During transmission of power from transmit antenna **1012** and transmit antenna **1014**, power levels of each of transmit antenna **1012** and transmit antenna **1014** may be varied to determine an optimal total amount of power received by receive antenna **1022** and receive antenna **1026** from the combination of transmit antenna **1012** and transmit antenna **1014**. Transmit antenna **1012** and transmit antenna **1016** may then simultaneously transmit power to receive antenna **1022** and receive antenna **1026** and a total amount of power received by receive antenna **1022** and receive antenna **1026** may be determined. During transmission of power from transmit antenna **1012** and transmit antenna **1016**, power levels of each of transmit antenna **1012** and transmit antenna **1016** may be varied to determine an optimal total amount of power received by receive antenna **1022** and receive antenna **1026** from the combination of transmit antenna **1012** and transmit antenna **1016**. Subsequently, transmit antenna **1014** and transmit antenna **1016** may simultaneously transmit power to receive antenna **1022** and receive antenna **1026** and a total amount of power received by receive antenna **1022** and receive antenna **1026** may be determined. During transmission of power from transmit antenna **1014** and transmit antenna **1016**, power levels of each of transmit antenna **1014** and transmit antenna **1016** may be varied to determine an optimal total amount of power received by receive antenna **1022** and receive antenna **1026** from the combination of transmit antenna **1014** and transmit antenna **1016**.

[0169] Additionally, transmit antenna **1014**, transmit antenna **1016**, and transmit antenna **1012** may simultaneously transmit power to receive antenna **1022** and receive antenna **1026** and a total amount of power received by receive antenna **1022** and receive antenna **1026** may be determined. During transmission of power from transmit antenna **1012**, transmit antenna **1014**, and transmit antenna **1016**, power levels of each of transmit antenna **1012**, transmit antenna **1014**, and transmit antenna **1016** may be varied to determine an optimal total amount of power received by receive antenna **1022** and receive antenna **1026** from the combination of transmit antenna **1012**, transmit antenna **1014**, and transmit antenna **1016**. It is noted that a total amount of power received by receive antenna **1022** and receive antenna **1026** may be determined by any known and suitable method. For example, according to one exemplary embodiment, one or more transmit antennas may sense an amount of power received by receive antenna **1022** and receive antenna **1026** by sensing an impedance between the one or more transmit antennas and the receive antennas **1022** and **1026**. According to another exemplary embodiment, upon receipt of power from one or more transmit antennas, receive antenna **1022** and receive antenna **1026** may be configured to convey a signal back to the one or more transmit antennas indicative of an amount of power received.

[0170] After sequentially receiving power from each transmit antenna and each possible combination of transmit antennas at various power levels, charging system **1000** may be configured to determine which one or more transmit antennas provide optimal charging for chargeable device **1020**, which is coupled to receive antenna **1022**, and chargeable device **1024**, which is coupled to receive antenna **1026**. Furthermore, because chargeable devices and their associated receive antennas may change positions within a charging apparatus, charging system **1000** may be configured to repeat a calibration process periodically, upon detection of a change in an amount of power received by a receive antenna and an associated chargeable device, or any combination thereof.

[0171] In accordance with various exemplary embodiments of the present invention and, as described more fully below, charging system **1000** may be configured to charge

one or more chargeable devices simultaneously with one or more transmit antennas, charge one or more chargeable devices independently of one or more other chargeable devices in accordance with assigned time periods, or any suitable combination thereof.

[0172] Due to the inherent isolation between transmit antennas oriented in differing planes, it may be possible to simultaneously charge one or more chargeable devices with two or more transmit antennas. For example, with continued reference to FIG. **24**, transmit antenna **1014** may transmit power to receive antenna **1026**, which is substantially parallel to transmit antenna **1014**. Furthermore, transmit antenna **1012**, which is substantially parallel to receive antenna **1022** and substantially perpendicular to transmit antenna **1014**, may simultaneously transmit power to receive antenna **1022**. It is noted that an amount of power transmitted from one or more transmit antennas (e.g., transmit antenna **1012** and/or transmit antenna **1014**) may be adjusted to further optimize an amount of power received by one or more receive antennas (e.g., receive antenna **1022** or receive antenna **1026**). For example, if chargeable device **1024** requires more power than chargeable device **1020**, during simultaneous charging of chargeable device **1020** and chargeable device **1024**, an amount of power transmitted from transmit antenna **1014** may be increased and an amount of power transmitted from transmit antenna **1012** may be decreased.

[0173] According to another exemplary embodiment, a charging system may be configured to simultaneously transmit power from two or more transmit antennas to a receive antenna coupled to a chargeable device. For example, with reference to FIG. **25**, a receive antenna **1070** that is coupled to a chargeable device **1072** may be oriented in a manner within charging apparatus **1010** so as optimal charging may be provided by simultaneously transmitting power from each of transmit antenna **1012** and transmit antenna **1016**. Further, an amount of power transmitted from one or more transmit antennas (e.g., transmit antenna **1012** and/or transmit antenna **1014**) may be adjusted to further optimize an amount of power received by a receive antenna (e.g., receive antenna **1070**). For example, an amount of power transmitted by transmit antenna **1012** may be increased and an amount of power transmitted by transmit antenna **1014** may be decreased to optimize an amount of power received by receive antenna **1070**. It is noted that enabling an amount power transmitted from one or more transmit antennas to be adjusted may allow for reduction of efficiency losses due to the polarization mismatch between the one or more transmit antennas and an arbitrarily placed receive antenna.

[0174] It is further noted that in various exemplary embodiments, the frequency of operations may be sufficiently low such the reasonably-sized, adjacent transmit antennas are within the near-field regions of each other. This may allow for higher coupling levels (−1.5 to −3 dB) than would be possible if the antennas were spaced farther apart. Further, electromagnetic fields radiated by substantially orthogonal and adjacent transmit antennas may be orthogonally polarized, which may improve the isolation between the adjacent antennas and, thus power lost due to unwanted coupling may be reduced.

[0175] In a relatively small wireless charging apparatus, only one transmit antenna in each dimension may be required. On the other hand, a relatively large wireless charging apparatus may include parallel surfaces that are sufficiently spaced from one another so as to prevent interference between the transmit antennas respectively coupled thereto. In this case, a transmit antenna may be embedded in each of the parallel surface so that one or more chargeable devices positioned between the parallel surfaces and in proper alignment may receive power from both transmit antennas. For example, with reference to FIG. **27**, a charging system **1002** comprises a charging apparatus **1050** including a first transmit antenna **1054** embedded in a first surface **1056** and a second transmit antenna **1058** embedded in a second surface **1060**, wherein second surface **1060** is substantially parallel to and sufficiently spaced from first surface **1056** so as to avoid interference between the transmit antennas coupled thereto. Accordingly, a receive antenna **1062** coupled to a chargeable device **1064** may simultaneously receive wireless power from each of transmit antenna **1054** and transmit antenna **1058**. Although FIG. **27** depicts only two parallel antennas, embodiments of the present invention are not so limited. Rather, a charging system may include any number of parallel antennas, wherein the parallel antennas may be configured to simultaneously transmit power to one or more chargeable devices, independently transmit power to one or more chargeable devices, or any combination thereof. For example, with reference to FIG. **28**, a charging apparatus **1160** having a plurality of parallel transmit antennas **1162** is depicted.

[0176] Furthermore, in accordance with another exemplary embodiment, a charging system may be configured to simultaneously transmit power from one transmit antenna to a plurality of chargeable devices. For example, with reference to FIG. **26**, power transmitted by transmit antenna **1014** may be received by each of a receive antenna **1080** and a receive antenna **1084**, each of which is substantially parallel with transmit antenna **1014**.

[0177] Moreover, for a charging apparatus including a plurality of chargeable devices positioned therein, an associated charging system may be configured to assign each chargeable device positioned within the charging apparatus a time period for charging. As an example, with reference again to FIG. **24**, charging system **1000** may be configured to assign receive antenna **1022** a first time period for receiving power and receive antenna **1026** a second time period for receiving power. For example only, charging system **1000** may be configured to assign each device positioned within charging apparatus **1010** a time period of duration 1/N*T, wherein N represents of number of chargeable devices positioned within the charging apparatus and T represents a total charging period. It is noted that defined time periods do not need to be equal in duration. Accordingly, as another example, charging system **1000** may be configured to assign each chargeable device a time period, wherein a duration of a time period assigned to a chargeable device may be dependent on an amount of power needed to fully charge the chargeable device. For example, if chargeable device **1024** requires more power than device **1020**, chargeable device **1024** may be assigned a time period having a longer duration than a time period assigned to device **1020**.

[0178] It is noted that one or more receive antennas may receive power from one or more transmit antennas during a defined time period. For example, with reference again to FIG. **26**, according to one exemplary embodiment, chargeable device **1082** and chargeable device **1086** may each receive power during a common time period. According to another exemplary embodiment, chargeable device **1082** and chargeable device **1086** may receive power during separate time periods. As another example, with reference to FIG. **27**, chargeable device **1064** may receive power from each of

transmit antenna **1058** and transmit antenna **1054** during a first time period and a chargeable device **1065** may receive power from a transmit antenna **1055** during a second time period.

[0179] It is further noted that a time period duration may be determined by any suitable manner. Specifically, a time period duration may be at least partially dependent on a duration of a total charging period, a number of chargeable devices positioned within an associated charging apparatus, a power level of each chargeable device positioned within the associated charging apparatus, or any combination thereof. Further, during a charging time period for charging of one or more chargeable device positioned within a charging apparatus, one or more other receive antennas positioned within the charging apparatus may be "cloaked" to prevent coupling between the one or more other receive antennas and any other receive or transmit antennas coupled to or within an associated charging apparatus.

[0180] FIG. **29** illustrates an alternate configuration of a continuous loop transmit antenna **920** that includes multiple facets in substantially orthogonal directions. In the exemplary embodiment of FIG. **29**, continuous loop transmit antenna **920** includes a first facet **922** along a bottom of a box **913**, a second facet **924** along a side of box **913**, and a third facet **926** along aback of box **913**.

[0181] Although FIGS. **22**A-**29** illustrate transmit antennas embedded in approximately orthogonal surfaces, embodiments of the invention are not so limited. Rather, transmit antennas may be embedded in adjacent surfaces of an apparatus that are separated by an acute angle. For example, with reference to FIG. **30**, a charging apparatus **1150** having a plurality of transmit antennas **1152** is depicted, wherein each transmit antenna is neither parallel nor orthogonal to every other transmit antenna. As another example, with reference to FIG. **31**, a charging apparatus **1110** having a plurality of transmit antennas is depicted. A first-orientation transmit antenna **1112** is disposed on a first side **1114** of charging apparatus **1110** and a second-orientation transmit antenna **1116** is disposed on a second side **1116** of charging apparatus **1110**, wherein first-orientation transmit antenna **1112** and second-orientation transmit antenna **1116** are separated by angle Θ, which may be, for example, forty-five degrees or more.

[0182] FIG. **32** is a flowchart illustrating a method **600**, in accordance with one or more exemplary embodiments. Method **600** may include wirelessly transmitting power from one or more transmit antennas of a plurality of transmit antennas oriented in multiple planes to at least one receive antenna positioned within a near-field of the one or more transmit antennas (depicted by numeral **602**).

[0183] FIG. **33** is a flowchart illustrating another method **690**, according to one or more exemplary embodiments. Method **690** may include orienting a plurality of transmit antennas in multiple planes (depicted by numeral **692**). Furthermore, method **690** may include transmitting wireless power from at least one transmit antenna of the plurality of transmit antennas to at least one receive antenna coupled to a chargeable device (depicted by numeral **694**).

[0184] Various exemplary embodiments of the present invention as described herein may enable one or more chargeable devices positioned within a charging apparatus and oriented in various planes to receive power from one or more transmit antennas coupled to the charging apparatus and oriented in multiple planes. Furthermore, various exemplary embodiments of the present invention may enable for defining an optimal selection of one or more transmit antennas for charging each chargeable device positioned within a charging apparatus. Additionally, various exemplary embodiments of the present invention enable for defining an optimal charging scheme for charging a plurality of devices within a charging apparatus. More specifically, various exemplary embodiments of the present invention enable for defining optimal charging schemes by assigning and varying time periods for charging one or more chargeable devices. Further, power levels of each transmit antenna may be varied. Accordingly, an amount of power delivered to each chargeable device may be increased and, further, the efficiency of a charging system as a whole may be increased.

[0185] Those of skill in the art would understand that information and signals may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[0186] Those of skill would further appreciate that the various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the exemplary embodiments disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the exemplary embodiments of the invention.

[0187] The various illustrative logical blocks, modules, and circuits described in connection with the exemplary embodiments disclosed herein may be implemented or performed with a general purpose processor, a Digital Signal Processor (DSP), an Application Specific Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

[0188] The steps of a method or algorithm described in connection with the exemplary embodiments disclosed herein may be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two. A software module may reside in Random Access Memory (RAM), flash memory, Read Only Memory (ROM), Electrically Programmable ROM (EPROM), Electrically Erasable Programmable ROM (EEPROM), registers, hard disk, a removable disk, a CD-ROM, or any other form of storage medium known in the art. An exemplary storage

medium is coupled to the processor such that the processor can read information from, and write information to, the storage medium. In the alternative, the storage medium may be integral to the processor. The processor and the storage medium may reside in an ASIC. The ASIC may reside in a user terminal. In the alternative, the processor and the storage medium may reside as discrete components in a user terminal.

[0189] In one or more exemplary embodiments, the functions described may be implemented in hardware, software, firmware, or any combination thereof. If implemented in software, the functions may be stored on or transmitted over as one or more instructions or code on a computer-readable medium. Computer-readable media includes both computer storage media and communication media including any medium that facilitates transfer of a computer program from one place to another. A storage media may be any available media that can be accessed by a computer. By way of example, and not limitation, such computer-readable media can comprise RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to carry or store desired program code in the form of instructions or data structures and that can be accessed by a computer. Also, any connection is properly termed a computer-readable medium. For example, if the software is transmitted from a website, server, or other remote source using a coaxial cable, fiber optic cable, twisted pair, digital subscriber line (DSL), or wireless technologies such as infrared, radio, and microwave, then the coaxial cable, fiber optic cable, twisted pair, DSL, or wireless technologies such as infrared, radio, and microwave are included in the definition of medium. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk and blu-ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above should also be included within the scope of computer-readable media.

[0190] The previous description of the disclosed exemplary embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these exemplary embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the exemplary embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

What is claimed is:

1. A charging system, comprising:

a plurality of transmit antennas, wherein at least one transmit antenna of the plurality of transmit antennas is configured to be oriented in a different plane than at least one other transmit antenna of the plurality of transmit antennas;

wherein each transmit antenna of the plurality of transmit antennas is configured for transmitting power within an associated near-field.

2. The charging system of claim **1**, wherein the at least one transmit antenna of the plurality of transmit antennas is configured to be oriented in a plane substantially orthogonal to the at least one other transmit antenna of the plurality of transmit antennas.

3. The charging system of claim **1**, further comprising a charging apparatus, wherein each transmit antenna of the plurality of transmit antennas is coupled to an associated surface of the charging apparatus.

4. The charging system of claim **3**, wherein two or more surfaces of the charging apparatus has a transmit antenna coupled thereto.

5. The charging system of claim **1**, wherein the charging system is configured to identify one or more transmit antennas of the plurality of transmit antennas for charging a chargeable device positioned within the charging apparatus.

6. The charging system of claim **1**, wherein the charging system is configured to identify one or more transmit antennas of the plurality of transmit antennas for charging a plurality of chargeable devices positioned within the charging apparatus.

7. The charging system of claim **1**, wherein the charging system is configured to simultaneously transmit power to at least one receive antenna from a first transmit antenna of the plurality of transmit antennas and a second transmit antenna of the plurality of transmit antennas, wherein the second transmit antenna is parallel to and spaced from the first antenna.

8. The charging system of claim **1**, wherein the charging system comprises a first transmit antenna of the plurality of transmit antennas and a second transmit antenna of the plurality of transmit antennas parallel to and spaced from the first antenna and is configured to identify one of the first transmit antenna and the second transmit antenna for transmitting power to at least one receive antenna positioned between the first transmit antenna and the second transmit antenna.

9. The charging system of claim **1**, wherein the charging system in configured to transmit power from at least one transmit antenna to at least one receive antenna and simultaneously transmit power from at least one other transmit antenna to at least one other receive antenna.

10. The charging system of claim **1**, wherein the charging system is configured to charge each chargeable device positioned within the charging apparatus according to an assigned time period.

11. The charging system of claim **1**, wherein the charging system is configured to charge one or more chargeable devices during a first time period and one or more other chargeable devices during at least one other time period.

12. A charging system, comprising:

a first transmit antenna configured for orientation in a first plane; and

a second transmit antenna configured for orientation in second, different plane;

wherein each of the first transmit antenna and the second transmit antenna is configured for transmitting power to at least one receive antenna positioned within an associated coupling-mode region.

13. The charging system of claim **12**, wherein the first plane is substantially orthogonal to the second plane.

14. The charging system of claim **12**, wherein the first plane is separated from the second plane by an acute angle.

15. The charging system of claim **12**, further comprising at least one other transmit antenna, wherein each transmit antenna of the at least one other transmit antenna is configured to be oriented in a plane other than the first plane or the second plane, each transmit antenna further configured for transmitting power to at least one receive antenna positioned within an associated coupling-mode region.

16. The charging system of claim **12**, wherein the first transmit antenna and the second transmit antenna are configured to simultaneously transmit power to at least one receive antenna.

17. The charging system of claim **12**, wherein the first transmit antenna is configured to transmit power to at least one receive antenna and the second transmit antenna is configured to simultaneously transmit power to at least one other receive antenna.

18. The charging system of claim **12**, wherein the first transmit antenna is configured to be coupled to a first surface of a charging apparatus and the second transmit antenna is configured to be coupled to a second, different surface of the charging apparatus.

19. A method, comprising wirelessly transmitting power from one or more transmit antennas of a plurality of transmit antennas oriented in multiple planes to at least one receive antenna positioned within a near-field of the one or more transmit antennas.

20. The method of claim **19**, wherein transmitting power comprises transmitting power from one or more transmit antennas to at least one receive antenna during a time period and transmitting power from one or more transmit antennas to at least one other receive antenna during another time period.

21. The method of claim **19**, further comprising adjusting a power level of at least one transmit antenna of the one or more transmit antennas.

22. The method of claim **19**, further comprising sequentially transmitting power to a receive antenna from each transmit antenna individually and each possible combination of transmit antennas to identify one or more transmit antennas for charging a chargeable device coupled to the receive antenna.

23. The method of claim **19**, further comprising sequentially transmitting power to a plurality of receive antennas from each transmit antenna individually and each possible combination of transmit antennas to identify one or more transmit antennas for charging a plurality of chargeable device, wherein each chargeable device of the plurality is coupled to an associated receive antenna of the plurality of receive antennas.

24. The method of claim **19**, wherein transmitting power comprises transmitting power to each receive antenna for a time period having a duration defined by:

$$D=1/N*T$$

wherein D is the duration of the time period, N is a number of receive antennas positioned within a near-field of the one or more transmit antennas, and T is a total charging period.

25. The method of claim **19**, further comprising transmitting power from a first transmit antenna during a first time duration, transmitting power from a second transmit antenna during a second time duration, and transmitting power from a third transmit antenna during a third time duration.

26. A wireless power system, the system comprising means for wirelessly transmitting power from one or more transmit antennas of a plurality of transmit antennas oriented in multiple planes to at least one receive antenna positioned within a near-field of the one or more transmit antennas.

27. A method, comprising:

orienting a plurality of transmit antennas in multiple planes; and

transmitting wireless power from at least one transmit antenna of the plurality of transmit antennas to at least one receive antenna coupled to a chargeable device.

28. The method of claim **27**, wherein orienting comprises positioning the plurality of transmit antennas within a charging apparatus, wherein at least one transmit antenna of the plurality of transmit antennas is oriented in a different plane than at least one other transmit antenna of the plurality of transmit antennas.

29. The method of claim **27**, further comprising performing a calibration process on one or more chargeable devices positioned within the charging apparatus.

30. The method of claim **27**, wherein transmitting wireless power comprises transmitting wireless power from at least two adjacent transmit antennas to at least one chargeable device.

31. The method of claim **27**, wherein transmitting wireless power comprises transmitting wireless power from two parallel, spaced transmit antennas to at least one chargeable device positioned therebetween.

32. The method of claim **27**, wherein transmitting wireless power comprises transmitting wireless power from at least one transmit antenna to at least one chargeable device and simultaneously transmitting wireless power from at least one other transmit antenna to at least one other chargeable device.

33. The method of claim **27**, further comprising varying an amount of power transmitted from at least one transmit antenna to at least one receive antenna and varying a duration of a time period for transmitting wireless power from at least one transmit antenna to at least one receive antenna.

34. A wireless power system, the system comprising:

means for capturing renewable energy and conveying another form of energy; and

means for receiving the conveyed another form of energy in at least one transmit antenna; and

means for transmitting power wirelessly from the at least one transmit antenna to at least one other antenna positioned within an associated coupling-mode region.

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