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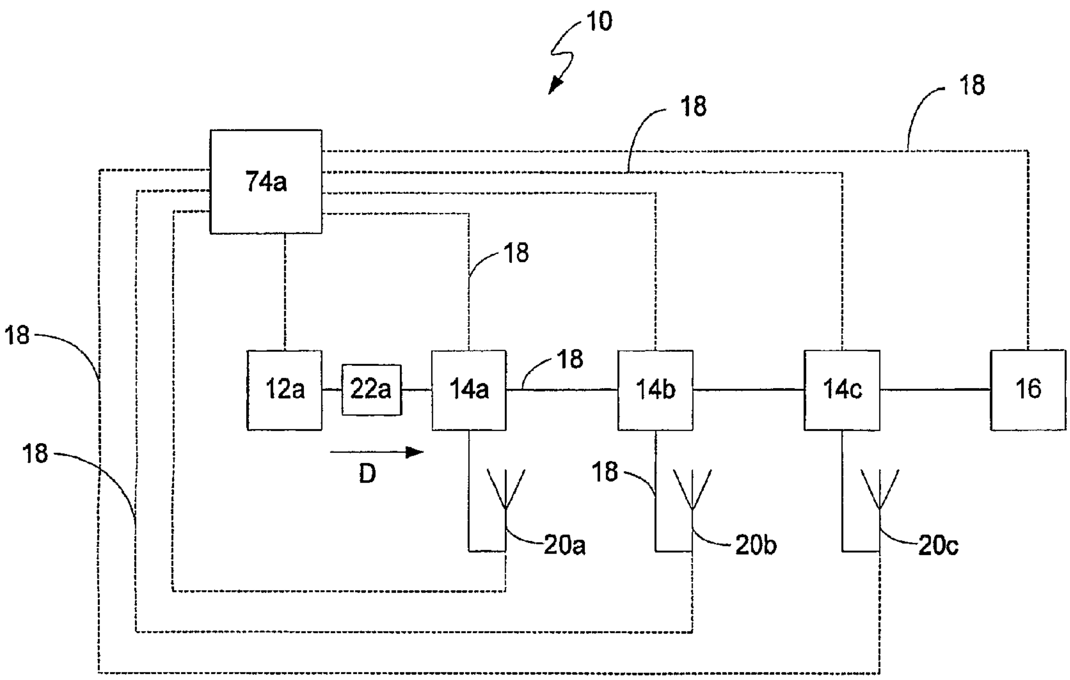
(54) **Title:** RF POWER TRANSMISSION NETWORK AND METHOD



(57) **Abstract:** Disclosed is an RF power transmission network. The network includes at least one RF power transmitter, at least one power tapping component, and at least one load. The at least one RF power transmitter, the at least one power tapping component, and the at least one load are connected in series. The RF power transmitter sends power through the network. The power is radiated from the network to be received by a device to be charged, re-charged, or directly powered by the power.

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RF POWER TRANSMISSION NETWORK AND METHOD

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention is directed to a series radio frequency (RF) power transmission network.

Description of Related Art

[0002] As processor capabilities have expanded and power requirements have decreased, there has been an ongoing explosion of devices that operate completely independent of wires or power cords. These "untethered" devices range from cell phones and wireless keyboards to building sensors and active Radio Frequency Identification (RFID) tags.

[0003] Engineers and designers of these untethered devices continue to have to deal with the limitations of portable power sources, primarily using batteries as the key design parameter. While the performance of processors and portable devices has been doubling every 18-24 months (driven by Moore's law), battery technology in terms of capacity has only been growing at 6% per year.

[0004] Even with power conscious designs and the latest in battery technology, many devices do not meet the lifetime cost and maintenance requirements for applications that require a large number of untethered devices, such as logistics and building automation. Today's devices that need two-way communication require scheduled maintenance every three to 18 months to replace or recharge the device's power source (typically a battery). One-way devices that simply broadcast their status without receiving any signals, such as automated utility meter readers, have a better battery life typically requiring replacement within 10 years. For both device types, scheduled power-source maintenance is costly and can be disruptive to the entire system that a device is intended to monitor and/or control. Unscheduled maintenance trips are even more costly and disruptive. On a macro level, the relatively high cost associated with the internal battery also reduces the practical, or economically viable, number of devices that can be deployed.

[0005] The ideal solution to the power problem for untethered devices is a device or system that can collect and harness sufficient energy from the environment. The harnessed energy would then either directly power an untethered device or augment a power supply. However, this ideal solution may not always be practical to implement due to low energy in the environment and site restrictions that limit the ability to use a dedicated energy supply.

[0006] A need exists for a system that takes these factors into account and provides a solution for both the ideal situation and also for more restrictive circumstances.

[0007] Previous inventions have focused on a parallel network for power distribution, for example, U.S. Provisional Patent Application Nos. 60/683,991 and 60/763,582, both entitled Power Transmission Network and incorporated by reference herein. These inventions did not explore a network in series because, for many applications exploiting this technology, losses from transmission lines, series switches, directional couplers (DC), and connectors are unacceptable. However, in certain applications, these losses are acceptable or may be minimized, for example, a small network with a coaxial cable infrastructure, such as a desk area, or using a new or existing low-loss coaxial cable infrastructure in a building for distributing RF power.

BRIEF SUMMARY OF THE INVENTION

[0008] It is an object of this invention to provide an RF power network in series, where the RF power network is suitable to be implemented as a portion of a system that provides RF power to a device in order to charge or re-charge the device or to directly power the device.

[0009] A series network has several advantages when compared to a parallel network for certain applications. As an example, the amount of transmission line can be reduced by the use of a series network. In a parallel network, a transmission line is typically connected from the RF power transmitter to each antenna. In a series network, each antenna removes an amount of power from a series connected transmission line. Another advantage of a series RF power transmission network is that the network is easily scalable. As an example, additional antennas may be added to the network by adding additional power tapping components in the series or by adding additional power tapping components to the end of the network, thus increasing the length of the series.

[0010] A method and apparatus for high efficiency rectification for various loads, which is suitable for receiving the RF power distributed by the present invention, has been discussed in detail in U.S. Provisional Patent Application No. 60/729,792, which is incorporated herein by reference.

[0011] The present invention pertains to an RF power transmission network. The network comprises a first RF power transmitter for generating power. The network comprises at least one power tapping component electrically connected in series to the first RF power transmitter for separating the power received from the first power transmitter into at least a first portion and a second portion. The network comprises at least one antenna electrically connected to the at least one power tapping component for receiving the first portion and transmitting power.

[0012] The present invention pertains to a system for power transmission. The system comprises a first RF power transmitter for generating power. The system comprises at least one power tapping component electrically connected in series to the first RF power transmitter for separating the power received from the first RF power transmitter into at least a first portion and a second portion. The system comprises at least one antenna electrically connected to the at least one power tapping component for receiving the first portion and transmitting power. The system comprises a device to be powered. The system comprises a receiving antenna electrically connected to the device and configured to receive the transmitted power.

[0013] The present invention pertains to a method for RF power transmission. The method comprises the steps of generating power with a first RF power transmitter. There is the step of separating the power received from the first power transmitter into at least a first portion and a second portion with at least one power tapping component electrically connected in series to the first RF power transmitter. There is the step of receiving the first portion by at least one antenna electrically connected to the at least one power tapping component. There is the step of transmitting power with the at least one antenna.

[0014] The present invention pertains to an apparatus for wireless power transmission to a receiver having a wireless power harvester which produces direct current. The apparatus comprises a combiner having a first input having a first power. The apparatus comprises a second input having a second power. The apparatus comprises an output having an output power that is a combination of the first power and the second power and greater than the first power and the second power individually. The apparatus comprises an antenna electrically connected to the output through which the output power is transmitted to the receiver.

[0015] The present invention pertains to an apparatus for wireless power transmission to a receiver having a wireless power harvester which produces direct current. The apparatus comprises a field adjustable coupler to increase or decrease power to a desired level having a mainline and a secondary line a distance d from the mainline. The apparatus comprises an adjustable mechanism that varies the distance d. The apparatus comprises an antenna through which the power is transmitted to the receiver.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0016] Fig. 1 is an illustration of a simple series network according to the present invention;

[0017] Fig. 2 is an illustration of a multiple input series network according to the present invention;

[0018] Fig. 3 is an illustration of a coupler that may be used with the present invention;

[0019] Fig. 4 is an illustration of a three transmitter network according to the present invention;

[0020] Fig. 5 is an illustration of a power distributor for use with the present invention.

[0021] Fig. 6 is an illustration of an adjustable directional coupler that may be used with the present invention;

[0022] Figs. 7 and 8 are illustrations of a multiple path networks according to the present invention;

[0023] Fig. 9 is an illustration of a switching network according to the present invention;

[0024] Fig. 10 is an illustration of a second switching network according to the present invention; and

[0025] Fig. 11 is an illustration of a desk top installation of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0026] A complete understanding of the invention will be obtained from the following description when taken in connection with the accompanying drawing figures wherein like reference characters identify like parts throughout.

[0027] For purposes of the description hereinafter, the terms "upper", "lower", "right", "left", "vertical", "horizontal", "top", "bottom", and derivatives thereof shall relate to the invention as it is oriented in the drawing figures. However, it is to be understood that the invention may assume various alternative variations and step sequences, except where expressly specified to the contrary. It is also to be understood that the specific devices and processes illustrated in the attached drawings, and described in the following specification, are simply exemplary embodiments of the invention. Hence, specific dimensions and other physical characteristics related to the embodiments disclosed herein are not to be considered as limiting.

[0028] The present invention pertains to an RF power transmission network 10, as shown in figure 1. The network 10 comprises a first RF power transmitter 12a for generating power. The network 10 comprises at least one power tapping component 14a electrically connected in series to the first RF power transmitter 12a for separating the power received from the first power transmitter 12a into at least a first portion and a second portion. The network comprises at least one antenna 20a electrically connected to the at least one power tapping component 14a for receiving the first portion and transmitting power.

[0029] The at least one power tapping component 14a can be a directional coupler 36, as shown in figure 3. The network 10 can include a second RF power transmitter 12b electrically connected in series to the at least one power tapping component 14a, as shown in figure 2. The network 10 can include at least one controller 74a electrically connected to one or more of the first RF power transmitter 12a, the at least one power tapping component 14a, the at least one antenna 20a, and the second RF power transmitter 12b. The at least one power tapping component 14a can be a bi-directional coupler 36. Alternatively, the at least one power tapping component can be a power distributor 52, as shown in figure 4.

[0030] The network 10 can include at least one additional RF power transmitter 12b electrically connected in series to the at least one power tapping component 14a, as shown in figure 2. The network 10 can include at least one controller 74a electrically connected to one or more of the first RF power transmitter 12a, the at least one power tapping component 14a, the at least one antenna 20a, and the at least one additional RF power transmitter 12b. The network 10 can include a terminating load 16. The network 10 can include at least one transmission line 18. In one embodiment, the power transmitted from the first RF power transmitter 12a does not include data.

[0031] The network 10 can include at least one controller 74a electrically connected to one or more of the first RF power transmitter 12a, the at least one power tapping component 14a, and the at least one antenna 20a. At least one controller 74a of the at least one controllers can be electrically connected to at least one other controller 74b of the at least one controllers. The network 10 can be configured to transmit the power via the at least one antenna 20a in pulses.

[0032] At least one of the at least one power tapping component 14 can be a switch 82a, as shown in figure 9. The switch 82a can be controlled via a control line. The switch 82a can be controlled by sensing power. The sensed power can be pulses of power. The pulses of power can vary in duration. The pulses of power can vary in timing. The switch 82a can be controlled via a communications signal. The communications signal can be sent via coaxial cable.

[0033] The antenna 20a can be a transmission line 18, as shown in figure 1. At least a portion of the power received from the first RF power transmitter 12a can be used by the at least one power tapping component 14a as operational power. The network 10 can include a second power tapping component 14b electrically connected in series to the at least one power tapping component 14a, with the at least one power tapping component 14a disposed between the first RF power transmitter 12a and the second power tapping component 14b. The second power tapping component 14b receives the second portion from the at least one power tapping component 14a and separates it into at least a third portion and a fourth portion.

[0034] The first RF transmitter 12a may only include a first connector which electrically connects the first RF power transmitter 12a to the at least one power tapping component 14a; and the at least one power tapping component 14a includes a second connector which electrically connects the at least one power tapping component to the second power tapping component 14b.

[0035] The present invention pertains to a system 100 for power transmission, as shown in figure 11. The system comprises a first RF power transmitter 12a for generating power. The system comprises at least one power tapping component 14a electrically connected in series to the first RF power transmitter 12a for separating the power received from the first RF power transmitter 12a into at least a first portion and a second portion. The system comprises at least one antenna 20a electrically connected to the at least one power tapping component 14a for receiving the first portion and transmitting power. The system comprises a device 94 to be powered. The system comprises a receiving antenna 92 electrically connected to the device 94 and configured to receive the transmitted power.

[0036] The network 10 can include at least one controller 74a electrically connected to one or more of the RF power transmitter, the at least one power tapping component 14a, and the at least one antenna 20a, as shown in figure 1. At least one of the at least one power tapping components can be a switch 82a, as shown in figure 9. The system 100 can be configured to transmit the power via the at least one antenna 20a in pulses. At least a portion of the power received from the first RF power transmitter 12a can be used by the at least one power tapping component 14a as operational power. In one embodiment, power transmitted from the first RF power transmitter 12a does not include data.

[0037] The network 10 can include a second power tapping component 14b electrically connected in series to the at least one power tapping component 14a, with the at least one power tapping component 14a disposed between the first RF power transmitter 12a and the second power tapping component 14b, as shown in figure 11. The second power tapping component 14b receives the second portion from the at least one power tapping component 14a and separates it into at least a third portion and a fourth portion; and a second antenna 20b electrically connected to the second power tapping component 14b for receiving the third portion and transmitting power.

[0038] As shown in figure 3, there is an apparatus for wireless power transmission to a receiver having a wireless power harvester which produces direct current. The apparatus comprises a combiner 38 having a first input 40a having a first power. The apparatus comprises a second input 40b having a second power. The apparatus comprises an output having an output power that is a combination of the first power and the second power and greater than the first power and the second power individually. The apparatus comprises an antenna 20a electrically connected to the output through which the output power is transmitted to the receiver.

[0039] As shown in figure 6, there is an apparatus for wireless power transmission to a receiver having a wireless power harvester which produces direct current. The apparatus comprises a field adjustable coupler 60 to increase or decrease power to a desired level having a mainline 62 and a secondary line 64 a distance d from the mainline 62. The apparatus comprises an adjustable mechanism that varies the distance d. The apparatus comprises an antenna 20a through which the power is transmitted to the receiver.

[0040] The present invention pertains to a method for RF power transmission. The method comprises the steps of generating power with a first RF power transmitter 12a, as shown in figure 11. There is the step of separating the power received from the first power transmitter 12a into at least a first portion and a second portion with at least one power tapping component electrically 14a connected in series to the first RF power transmitter 12a. There is the step of receiving the first portion by at least one antenna 20a electrically connected to the at least one power tapping component 14a. There is the step of transmitting power with the at least one antenna 20a.

[0041] The method can include the steps of receiving the power transmitted wirelessly from the at least one antenna 20a at a receiving antenna 92 electrically connected to a device 94 and configured to receive the transmitted power; and converting the power received by the receiving antenna 92 with a power harvester disposed in the device 94 electrically connected to the device 94. The method can include the steps of adding a second power tapping component 14b electrically connected in series to the at least one power tapping component, with the at least one power tapping component 14a disposed between the first RF power transmitter 12a and the second power tapping component 14b. The second power tapping component 14b receives the second portion from the at least one power tapping component 14a and separates it into at least a third portion and a fourth portion. There can be the step of receiving the third portion at a second antenna 20b electrically connected to the second power tapping component 14b. There can be the step of transmitting power from the second antenna 20b.

Single input series network

[0042] Referring generally to Fig. 1, a single input ("simple") series power distribution/transmission network 10, according to the present invention, includes a single RF power transmitter 12a and at least one power tapping component (PTC) 14a. The single input series network 10 terminates with a load 16. The PTCs 14a-c are connected in series.

[0043] Power travels in a direction D from the RF power transmitter 12a. Thus, in the single input series network 10, there is a single power direction. As illustrated in Fig. 1, power travels from left to right.

[0044] Connections 18 (generally referred to as transmission line herein) in the network 10 are made via a coaxial cable, transmission line, waveguide, or other suitable means. A load 16 may include, but is not limited to, an antenna, terminator, coupler, directional coupler, bi-directional coupler, splitter, combiner, power distributor, circulator, attenuator, or any other component that acts as a load. The transmission line 18 or the last PTC 14c should be terminated to eliminate reflections using a load 16. It should be noted that the circulator, as well as the splitter and the combiner could also feed the reflected power back into a series connection.

[0045] A PTC 14a removes power from a transmission line 18 (or other connection) and supplies the removed power to another component, such as a load 16, an antenna 20a, or other transmission line 18. Preferably, a PTC 14a passes any remaining power to the next component in the series, such as a load 16, an antenna 20a, another PTC 14b, or other transmission line 18.

[0046] Preferably, a PTC 14a has three or more input/outputs (connectors) in which power is input, output (accepted), and/or output (passed). For example, a PTC 14a has an input, a first output for accepted power, and a second output for passed power. The PTC 14a receives power at the input. The PTC 14a separates the power into a first portion and a second portion. The first portion is "accepted" and sent to the first output, for example, to an antenna 20a (discussed below). The second portion is "passed" and sent to the next component in the series, for example, another PTC 14b.

[0047] A PTC 14a may be a directional coupler, as illustrated in Fig. 1. A directional coupler may be implemented with a splitter or a combiner.

[0048] One output of each PTC 14ac is preferably connected to an antenna 20ac, respectively. Each antenna 20ac radiates power into a coverage area (or volume). A coverage area is defined by a minimum electric and/or magnetic field strength. As an example, a coverage area may be defined as an area (or space) in which the electric field strength radiated is greater than two volts per meter (2 V/m). The coverage area from a given antenna 20a may or may not overlap other coverage areas from other antennas 20b, 20c. Other outputs of each PTC 14ac may be connected to a load 16 and other transmission lines 18.

[0049] When the PTCs 14ac are implemented as directional couplers, the directional couplers may be designed to tap (or remove) a certain percentage (dB) from the transmission line 18. For example, a -20dB coupler and a 1000 Watt(W) input result with a 10W output to the terminating load 16. The directional couplers in the network 10 may all have the same coupling (e.g., -20dB) or may be designed on a case-to-case basis to use standard coupling (e.g., -3, -6, -10 dB) or non-standard coupling (e.g., -3.4, -8, -9.8 dB).

[0050] A circulator 22a or isolator may be connected between the RF power transmitter 12 and the first PTC 14a in the series in order to protect against reflected power that would cause damage to the RF power transmitter 12a.

[0051] Fig. 1 illustrates the single input series network 10 with an RF power transmitter 12a, a circulator 22a, three PTCs 14ac (implemented as directional couplers) each connected to an antenna 20ac, respectively, and a terminating load 16.

[0052] In use, the RF power transmitter 12a supplies power along a transmission line(s) 18 to each PTC 14ac in the network 10. Each PTC 14ac taps power from the line and sends the power to the respective connected antennas 20ac, load16. The antennas 20ac, load 16 radiate the power to coverage areas corresponding to each antenna 20ac, load 16. When in a coverage area, a device to be powered receives the radiated power. The received power is used to charge or re-charge the device or to directly power the device.

Dual input series network

[0053] Referring generally to Fig. 2, a dual input series power distribution/transmission network 10, according to the present invention, includes a first RF power transmitter 12a at a first end 32 of the network 30 and a second RF power transmitter 12b at a second end 34 of the network 10. One or more PTCs 14 are located in series between the first RF power transmitter 12a and the second RF power transmitter 12b.

[0054] Preferably, each PTC 14 is also connected to a respective antenna 20ac. Each antenna 20ac radiates power into a coverage area. The coverage area from a given antenna 20a may or may not overlap other coverage areas from other antennas 20b, 20c.

[0055] The PTCs 14ac may be bi-directional couplers that couple waves in both directions. This allows for dual power directions - a first power direction A stemming from the first RF power transmitter 12a and a second power direction B stemming from the second RF power transmitter 12b.

[0056] A first circulator 22a may be connected next to the first RF power transmitter 12a to be between the first RF power transmitter 12a and the PTC 14a next in line in the series in order to protect against reflected power that would cause damage to the first RF power transmitter 12a. Likewise, a second circulator 22b may be located between the second RF power transmitter 12b and the corresponding PTC 14b next in line in the series.

[0057] The first RF power transmitter 12a and the second RF power transmitter 12b may be on the same frequency. Due to component tolerances, however, they will actually be on slightly different frequencies and will drift in and out of phase, averaging to a finite value. This issue is discussed in detail in U.S. Patent Application No. 11/699,148 and U.S. Provisional Patent Application No. 60/763,582, both entitled Power Transmission Network, which are incorporated herein by reference. The first RF power transmitter 12a and the second RF power transmitter 12b may also be designed to be on different frequencies or on separate channels.

[0058] An advantage of a network 10 with dual (or multiple, discussed below) RF power transmitters 12a, 12b is that the network 10 distributes loss along the transmission line 18 rather than concentrating the loss at one end (as with a single input series network 10). Another advantage is that less power is needed for each RF power transmitter 12a, 12b. For example, a single transmitter 12a could input 1000W, or two transmitters 12a, 12b could input 500W each. The two inputs of 500W would be the cheaper network 10, in terms of power and component costs, etc. The RF power transmitters 12a, 12b may have different power levels if found to be advantageous.

[0059] Figure 2 illustrates a dual input series network 10 having a first RF power transmitter 12a, a first circulator 22a, three PTCs 14ac (implemented as bi-directional couplers) each connected to an antenna 20a, a second circulator 22b, and a second RF power transmitter 12b.

[0060] In use, the RF power transmitters 12a and 12b supply power along a transmission line(s) 18 to each PTC 14ac in the network 10. Each PTC 14ac taps power from the line and sends the power to the connected antenna 20ac, respectively. The antennas 20ac radiate the power to coverage areas corresponding to each antenna 20ac. When in a coverage area, a device to be powered receives the radiated power. The received power is used to charge or re-charge the device or to directly power the device.

[0061] Referring to Fig. 3, a given bi-directional coupler 36 may need a combiner 38 to combine the power from each power direction A, B. A first input 40a having a first initial power enters the bi-directional coupler 36 from the first power direction A. A second input 40b having a second initial power enters the bi-directional coupler 36 from the second power direction B. A tap of the first input (for example, -20dB) and a tap of the second input (for example, -20dB) are combined in the combiner 38 to output a combined power 42 to the antenna 22a or another transmission line 18 (or a combination of the two).

[0062] The first input leaving the bi-directional coupler 36, which may be an input to another bi-directional coupler 36, has been decreased by the amount of power tapped and by an amount of loss from the coupler 36 itself (insertion loss). The same holds for the second input leaving the bi-directional coupler 36. In other words, when the first input 40a exits the bi-directional coupler 36, the amount of power now present equals the initial power minus the amount tapped minus power lost within the coupler 36 (insertion loss).

[0063] Alternatively, the bi-directional coupler 36 may be designed to not sense direction of the power, therefore not requiring a combiner 38. Therefore, the PTC 14a (bi-directional coupler in this case) may be termed simply a coupler.

Multiple input series network

[0064] Referring generally to Fig. 4, a multiple input series power distribution/transmission network 10, according to the present invention, includes a first RF power transmitter 12a, a second RF power transmitter 12b, and at least a third RF power transmitter 12c connected via a power distributor 52, for example, in a star or cluster pattern. One or more PTCs 14ac may be located in series between the first, second, and/or third RF power transmitter 12a-c and the power distributor 52.

[0065] Preferably, each PTC 14ac is also connected to an antenna 20ac, respectively. Each antenna 20ac radiates power into a coverage area. The coverage area from a given antenna 20a may or may not overlap other coverage areas from other antennas 20b, 20c.

[0066] The PTCs 14ac may be bi-directional couplers that couple waves in two directions. The power distributor 52 couples waves (or routes power) in multiple directions. This allows for multiple power directions - a first power direction A stemming from the first RF power transmitter 12a, a second power direction B stemming from the second RF power transmitter 12b, and a third power direction C stemming from the third RF power transmitter 12c. The power distributor 52 may be a combiner or a splitter. Compared to the dual input series network 10 (illustrated in Fig. 2), in the multiple input series network 10, the network 10 not only includes a first input 40a from the first RF power transmitter 12a and a second input 40b from the second RF power transmitter 12b, but also includes at least a third input 40c from the third RF power transmitter 12c.

[0067] Referring to Fig. 5, the number of ports on the power distributor 52 may be increased by using 1 to N splitters, giving N+1 ports on the power distributor

52. Each of the outputs on one splitter 54a is connected to one of the outputs of another splitter 54b. For example, as illustrated in figure 5, a three port power distributor 52 includes three 1 to 2 splitters 54a-c. Power from direction A enters a first port 56a, is split by splitter 54a, and is directed to splitters 54b and 54c. Power from direction B enters a second port 56b, is split by splitter 54b, and is directed to splitters 54a and 54c. Power from direction C enters a third port 56c, is split by splitter 54c, and is directed to splitters 54a and 54b.

[0068] The multiple input series network 10, shown in figure 4, may include additional RF power transmitters and/or additional power distributors connected in various configurations. In other words, the network 10 may be expanded such that more than one power distributor 52 connects multiple RF power transmitters 12ac. Thus, the network 10 may include multiple star patterns or clusters.

[0069] Figure 4 illustrates a multiple input series network 10 having a first RF power transmitter 12a, a second RF power transmitter 12b, a third RF power transmitter 12c, and a power distributor 52. A first PTC 14a (implemented as a bi-directional coupler) is connected between the first RF power transmitter 12a and the power distributor 52. A second PTC 14b is connected between the second RF power transmitter 12b and the power distributor 52. A third PTC 14c is connected between the third RF power transmitter 12c and the power distributor 52. Each PTC 14ac is also connected to an antenna 20a.

[0070] In use, the RF power transmitters 12a-c supply power along a transmission line 18 to each PTC 14 in the network 10. Each PTC 14ac taps power from the line and sends the power to the connected antenna 20ac, respectively. The antennas 20ac radiate the power to coverage areas corresponding to each antenna 20ac. When in a coverage area, a device to be powered receives the radiated power. The received power is used to charge or re-charge the device or to directly power the device.

<u>Adjustable PTC</u>

[0071] In general, the amount of power exiting a PTC 14a is equal to the amount of power which entered the PTC 14a reduced by the amount of power which was tapped by the PTC 14a. Thus, the initial amount of power from an RF power transmitter 12a is reduced each time it passes through a PTC 14ac.

[0072] For example, a network includes two PTCs implemented as -20dB couplers. If the input to the first coupler is 100W, the amount tapped would be 1W (i.e., 100W / 100 = 1W) and the amount of power exiting would be 99W (i.e., 100W - 1W = 99W). When the 99W reaches the second -20dB coupler, the amount tapped would be 0.99W (99W / 100 = 0.99W) and the amount exiting the second coupler would be 98.01W.

[0073] Referring generally to Fig. 6, in order to make all outputs equal or at a desired level, a field adjustable PTC 60 may be utilized with the present invention. The field adjustable PTC 60 allows the power to be increased or decreased to a desired level by changing a coupling factor.

[0074] For example, the PTC 60 is a bi-directional coupler. In order to make the bi-directional coupler adjustable an adjustment mechanism, such as but not limited to, a screw or electrical controller is introduced to vary the distance or electrical properties. The coupling factor is dependent on a distance d between a mainline 62 and a secondary line 64 of the bi-directional coupler or the electrical properties of the coupler. It should be noted that changing a length of the coupler would also vary the properties.

[0075] By including a field adjustable PTC 60 in the network 10, the power coupled to each antenna throughout the network 10 may be maintained at an approximately constant level.

[0076] Referring to Figs. 7 and 8, multiple paths may be present in a network. For example, referring to Fig. 7, a network 10 includes an RF power transmitter 12a connected in series with a first PTC 14a (implemented as a directional coupler) and a power splitter 54 (1 to 2). A first output of the power splitter 54 is connected to a second PTC 14b and terminates with a first terminating antenna (load) 16b. A second output of the power splitter 54 is connected to a third PTC 14c in series with a fourth PTC 14d and terminates with a second terminating antenna (load) 16d. The first, second, third, and fourth PTCs 14a-d are each connected to an antenna (a first antenna 20a, second antenna 20b, third antenna 20c, and fourth antenna 20d, respectively) and couple power to the respective antenna 20a-d in order to radiate power into various coverage areas. When in a coverage area, a device to be powered receives the radiated power. The received power is used to charge or re-charge the device or to directly power the device.

[0077] For another example, referring to Fig. 8, a network 10 includes an RF power transmitter 12a connected in series with a circulator 22 connected to a first PTC 14a (implemented as directional coupler). The first PTC 14a is connected in series to a second PTC 14b and a third PTC 14c and terminates with a first terminating antenna (load) 16c. The first PTC 14a is also connected in series to a fourth PTC 14d, and a fifth PTC 14e, and terminates with a second terminating antenna (load) 16e. The fourth PTC 14d is also connected to a sixth PTC 14f and terminates with a third terminating load 16f. The second, third, fifth, and sixth PTCs 14b, 14c, 14e, and 14f are each connected to an antenna (second antenna 20b, third antenna 20c, fifth antenna 20e, and sixth antenna 20f respectively) for radiating power into various coverage areas. It should be noted that a given PTC may not have an associated antenna for radiating power. When in a coverage area, a device to be powered receives the radiated power. The received power is used to charge or re-charge the device or to directly power the device.

Other embodiments

[0078] Referring generally to Fig. 9, the invention, according to any embodiment, may be implemented as a switching network 10 (a network containing at least one switch 82). In the switching network 10, the PTC 14a, or at least one of the PTCs, is a switch 82a or contains a switch 82a. The components are connected in series.

[0079] The switch 82a may be, but is not limited to, electromechanical or solid state, such as a relay or PIN diode, respectively. The switch 82a may have any configuration suitable for the network 10, such as, but not limited to, SPST, DPDT, SP3T, etc.

[0080] Preferably, the switch 82a is also connected to an antenna 20a. The antenna 20a radiates power into a coverage area. The coverage area from a given antenna 20a may or may not overlap other coverage areas from other antennas 20b, 20c.

[0081] Preferably, the switch 82a either accepts or passes the power. When power is accepted, power is supplied to a particular component of the network 10, such as the antenna 20a. When power is passed, power is supplied to the next component in series. It should be noted that for PTCs 14 without a direct antenna connection, the switch 82a may pass power to one or more components sequentially or simultaneously.

[0082] Since each switch 82a, 82b either accepts or passes power, the network 10 may be designed to pulse power. In other words, any antenna 20a, 20b connected to a switch 82a, 82b may be turned on and off as desired. For example, one antenna 20a of the network may be turned on at a time. Pulsing networks were described in U.S. Patent Application No. 11/356,892 and U.S. Provisional Patent Application No. 60/758,018, both entitled Pulsing Transmission Network and incorporated herein by reference.

[0083] The switch 82a may be controlled by any suitable means. The switch 82a may be controlled by the RF power transmitter 12a using a control line 18. The control line may send communications and/or power to the switch 82a. The switch 82a may have a timer or a clock (e.g., a "smart switch"). A communication signal may be sent over a coaxial cable 18 at the same frequency or a separate frequency in order to tell the switch 82a when to switch. DC power may be sent over the transmission line to power the PTC 14a, in this case, the switch 82a, or any other component in the network. Additionally, any PTC or power distributing component may derive power from the transmission line by consuming some of the RF power, preferably, by rectifying the RF power to DC power.

[0084] The switch 82a may sense supplied pulses of power from an RF power transmitter 12a to determine when to switch. Pulses may be designed to create node identifications that signal the switch 82a to switch. The pulses may have differing frequencies (timings) or consist of varying durations (long and short pulses).

[0085] The switch 82a may sense for power. When power is detected at an input, the switch 82a may cause a pulse of power, and then pass power through for a period of time before pulsing again.

[0086] Preferably, the switch 82a may sense the supplied pulses, the pulses forming a node identification, or power by tapping a portion of the power from the transmission line 18 and rectifying the RF power to DC power in order supply switching information to the switch 82a or switch controller 74a (discussed below). The rectified DC power informs the switch 82a or switching controller 74a that the RF power transmitter 12a is supplying pulses, sending a node identification, or sending power.

[0087] Additionally, the switch 82a may sense if DC power is available on the transmission line 18 along with the RF power. The DC power may be used to directly power the switch 82a or switch controller 74 or may be used as in input to the switch controller 74. If the DC power is used to directly power the switch 82a, a controller in the RF power transmitter 12a may control the switch(s) 82a, 82b by placing and removing DC power from the transmission line 18 in a pulsing manner.

[0088] It should be noted that any outputs of the switch 82a which are not active (i.e., connected to an antenna or other component of the network) may be open circuited or may be connected to a load 16 to ensure that unactive antennas do not significantly influence the radiation from the active antenna.

[0089] As illustrated in Fig. 9, for example, a single input series switching network 10 includes an RF power transmitter 12a, a first switch 82a, a second switch 82b, and a terminating antenna 16. The first switch 82a is connected to a first antenna 20a. The second switch 82b is connected to a second antenna 20b.

[0090] The first switch 82a may accept the power from the RF power transmitter 12a and send the power to the first antenna 20a. Alternatively, the first switch 82a may pass the power to the second switch 82b. The second switch 82b may accept the power and send the power to the second antenna 20b. Alternatively, the second switch 82b may pass the power to the terminating antenna 16. In this configuration, at any given time, the first antenna 20a, the second antenna 20b, or the terminating antenna 16 is radiating RF energy. The network 10 may be designed to pulse power from each of the first antenna 20a, second antenna 20a, and terminating antennas 16. The network 10 may be designed in such a way that for a given period of time, no antenna is transmitting power. This may be accomplished by turning the RF power transmitter 12a power down or off or by terminating the power into a load.

[0091] The network 10 may be configured to radiate RF energy from one or more antenna at any given time. As illustrated in Fig. 10, for example, a single input series switching network 10 includes an RF power transmitter 12a, a first PTC 14a, a second PTC 14b, a third PTC 14c. A first switch 82a is connected to the first PTC 14a and a first antenna 20a. A second switch 82b is connected to the second PTC 14b and a second antenna 20b. A third switch 82c is connected to the third PTC 14c and a third antenna 20c. A fourth switch 82d is also connected to the third PTC 14c. The fourth switch is connected to a fourth antenna 20d and a terminating antenna 16.

[0092] The first PTC 14a supplies power to the first switch 82a and the second PTC 14b. The first switch 82a may accept the power and supply the power to the first antenna 20a. Alternatively, the first switch 82a may pass the power to a terminating load (not shown) or open circuit.

[0093] The second PTC 14b supplies power to the second switch 82b and the third PTC 14c. The second switch 82b may accept the power and supply the power to the second antenna 20b. Alternatively, the second switch 82b may pass the power to a terminating load (not shown) or open circuit.

[0094] The third PTC 14b supplies power to the third switch 82c and the fourth switch 82d. The third switch 82c may accept the power and supply the power to the third antenna 20c. Alternatively, the third switch 82c may pass the power to a terminating load (not shown) or open circuit. The fourth switch 82d may accept the power and supply the power to the fourth antenna 20d or pass the power to the terminating antenna 16.

[0095] In this configuration, more than one antenna 20a-d may be active at any desired time. In a given installation of a network 10, the configuration of PTCs and switches should be determined by the desired coverage areas to be obtained from RF energy radiating from the antennas.

[0096] Referring generally to Figs. 1, 2, 4, and 7-11 the invention, according to any of the embodiments, may include a controller 74a to control the operation of the network. Referring to Fig. 1, the controller 74a is connected to one or more of the components of the network 10. The controller 74a may be used to change the frequency, polarization, or radiation pattern of the antennas 20ac. The controller 74a may be used to create pulses of power from the network 10.

[0097] Referring to Fig. 2, more than one controller 74a is utilized to control the components of the network 10. A controller 74a may be in communication with one or more other controllers 74a of the network 10.

[0098] Referring to Fig. 10, a controller 74a is connected to a switching network 10. The controller 74a is utilized to control (or assist in controlling) the switching of the switches 82a-d.

[0099] Referring to Fig. 11, an implementation of a series power distribution/transmission network 10 is illustrated. The network includes an RF power transmitter 12a connected to a first PTC 14a, a second PTC 14b, a third PTC 14c, and a terminating antenna 16. The RF power transmitter 12a and the first, second, and third PTCs 14a-c are connected in series. Each of the first, second, and third PTCs 14a-c are connected to an antenna 20a-c, respectively (illustrated as dipoles although any antenna or radiating device may be used with this or any embodiment herein). The antennas 20a-c and 16 radiate power to a receiving antenna 92 (illustrated as a dipole) of a device 94 to be powered. The device 94 preferably includes a power harvester that converts the RF power into a form useable by the device 94.

[00100] A small scale version of the invention, for example, as shown in Fig. 11, helps to reduce the average power transmitted by a single antenna, thereby reducing safety concerns. This may be important in desktop applications. For example, the device 94 may receive power contribution from multiple antennas 20a-c, 16. The antennas 20a-c, 16 may be positioned in a U-shape or be mounted on a flexible unit so that the user may affix them to the desk area.

[00101] A tapping coupler may be used in the present invention to eliminate connector loss. This issue is discussed in detail in U.S. Patent No. 6,771,143, which is incorporated herein by reference.

[00102] A network according to the present invention preferably uses a low loss coaxial cable, transmission line, or waveguide 18.

[00103] If a leaky coaxial cable 16 is used in the network, antennas may not be necessary. In this configuration, the coaxial cable 16 would radiate the power.

[00104] The various embodiments discussed above, and envisioned as encompassed by the present invention, may be implemented separately or in combinations with each other (in whole or in part).

[00105] The invention should not be confused with power transfer by inductive coupling, which requires the device to be relatively close to the power transmission source. The RFID Handbook by the author Klaus Finkenzeller defines the inductive coupling region as distance between the transmitter and receiver of less than 0.16 times lambda where lambda is the wavelength of the RF wave. The invention can be implemented in the near-field (sometimes referred to as inductive) region as well as the far-field region. The far-field region is distances greater than 0.16 times lambda.

[00106] In any embodiment of the present invention, the RF power transmitted may be limited to include power only, that is, data is not present in the signal. If data is required by the application, the data is, preferably, transmitted in a separate band and/or has a separate receiver.

[00107] It will be understood by those skilled in the art that while the foregoing description sets forth in detail preferred embodiments of the present invention, modifications, additions, and changes might be made thereto without departing from the spirit and scope of the invention.

CLAIMS

THE INVENTION CLAIMED IS:

1. An RF power transmission network, comprising:

a first RF power transmitter for generating power;

at least one power tapping component electrically connected in series to the first RF power transmitter for separating the power received from the first power transmitter into at least a first portion and a second portion; and

at least one antenna electrically connected to the at least one power tapping component for receiving the first portion and transmitting power.

2. The network according to claim 1, wherein the at least one power tapping component is a directional coupler.

3. The network according to claim 1, further including a second RF power transmitter electrically connected in series to the at least one power tapping component.

4. The network according to claim 3, further including at least one controller electrically connected to one or more of the first RF power transmitter, the at least one power tapping component, the at least one antenna, and the second RF power transmitter.

5. The network according to claim 3, wherein the at least one power tapping component is a bi-directional coupler.

6. The network according to claim 3, wherein the directional coupler is a field adjustable directional coupler.

7. The network according to claim 3, wherein the at least one power tapping component is a power distributor.

8. The network according to claim 3, further including at least one additional RF power transmitter electrically connected in series to the at least one power tapping component.

9. The network according to claim 8, further including at least one controller electrically connected to one or more of the first RF power transmitter, the at least one power tapping component, the at least one antenna, and the at least one additional RF power transmitter.

10. The network according to claim 1, further including a terminating load.

11. The network according to claim 1, further including at least one transmission line.

12. The network according to claim 1, wherein power transmitted from the first RF power transmitter does not include data.

13. The network according to claim 1, further including at least one controller electrically connected to one or more of the first RF power transmitter, the at least one power tapping component, and the at least one antenna.

14. The network according to claim 13, wherein at least one of the at least one controllers is electrically connected to at least one other of the at least one controllers.

15. The network according to claim 1, wherein the network is configured to transmit the power via the at least one antenna in pulses.

16. The network according to claim 1, wherein at least one of the at least one power tapping components is a switch.

17. The network according to claim 16, wherein the switch is controlled via a control line.

18. The network according to claim 16, wherein the switch is controlled by sensing power.

19. The network according to claim 18, wherein the sensed power is pulses of power.

20. The network according to claim 19, wherein the pulses of power vary in duration.

21. The network according to claim 19, wherein the pulses of power vary in timing.

22. The network according to claim 16, wherein the switch is controlled via a communications signal.

23. The network according to claim 22, wherein the communications signal is sent via coaxial cable.

24. The network according to claim 1, wherein the antenna is a transmission line.

25. The network according to claim 1, wherein at least a portion of the power received from the first RF power transmitter is used by the at least one power tapping component as operational power.

26. The network according to claim 1, further including a second power tapping component electrically connected in series to the at least one power tapping component, with the at least one power tapping component disposed between the first RF power transmitter and the second power tapping component, the second power tapping component receives the second portion from the at least one power tapping component and separates it into at least a third portion and a fourth portion.

27. The network according to claim 26 wherein the first RF transmitter only includes a first connector which electrically connects the first RF power transmitter to the at least one power tapping component; and the at least one power tapping component includes a second connector which electrically connects the at least one power tapping component to the second power tapping component.

28. A system for power transmission, comprising:

a first RF power transmitter for generating power;

at least one power tapping component electrically connected in series to the first RF power transmitter for separating the power received from the first RF power transmitter into at least a first portion and a second portion;

at least one antenna electrically connected to the at least one power tapping component for receiving the first portion and transmitting power;

a device to be powered; and

a receiving antenna electrically connected to the device and configured to receive the transmitted power.

29. The system according to claim 28, further including at least one controller electrically connected to one or more of the RF power transmitter, the at least one power tapping component, and the at least one antenna.

30. The network according to claim 28, wherein at least one of the at least one power tapping components is a switch.

31. The network according to claim 28, wherein the system is configured to transmit the power via the at least one antenna in pulses.

33. The network according to claim 28, wherein at least a portion of the power received from the first RF power transmitter is used by the at least one power tapping component as operational power.

34. The network according to claim 28, wherein power transmitted from the first RF power transmitter does not include data.

35. The network according to claim 28 including a second power tapping component electrically connected in series to the at least one power tapping

component, with the at least one power tapping component disposed between the first RF power transmitter and the second power tapping component, the second power tapping component receives the second portion from the at least one power tapping component and separates it into at least a third portion and a fourth portion; and a second antenna electrically connected to the second power tapping component for receiving the third portion and transmitting power.

36. A method for RF power transmission comprising the steps of:

generating power with a first RF power transmitter;

separating the power received from the first power transmitter into at least a first portion and a second portion with at least one power tapping component electrically connected in series to the first RF power transmitter;

receiving the first portion by at least one antenna electrically connected to the at least one power tapping component; and

transmitting power with the at least one antenna.

37. A method according to claim 36 including the steps of receiving the power transmitted wirelessly from the at least one antenna at a receiving antenna electrically connected to a device and configured to receive the transmitted power; and converting the power received by the receiving antenna with a power harvester electrically connected to the device.

38. A method according to claim 37 including the steps of adding a second power tapping component electrically connected in series to the at least one power tapping component, with the at least one power tapping component disposed between the first RF power transmitter and the second power tapping component, the second power tapping component receives the second portion from the at least one power tapping component and separates it into at least a third portion and a fourth portion;

receiving the third portion at a second antenna electrically connected to the second power tapping component; and

transmitting power from the second antenna.

39. An apparatus for wireless power transmission to a receiver having a wireless power Harvester which produces direct current comprising:

a combiner having a first input having a first power;

a second input having a second power;

an output having an output power that is a combination of the first power and the second power and greater than the first power in the second power individually; and

an antenna electrically connected to the output through which the output power is transmitted to the receiver.

40. An apparatus for wireless power transmission to a receiver having a wireless power harvester which produces direct current comprising:

a field adjustable coupler to increase or decrease power to a desired level having a mainline and a secondary line a distance d from the mainline;

an adjustable mechanism that varies the distance d; and

an antenna through which the power is transmitted to the receiver.

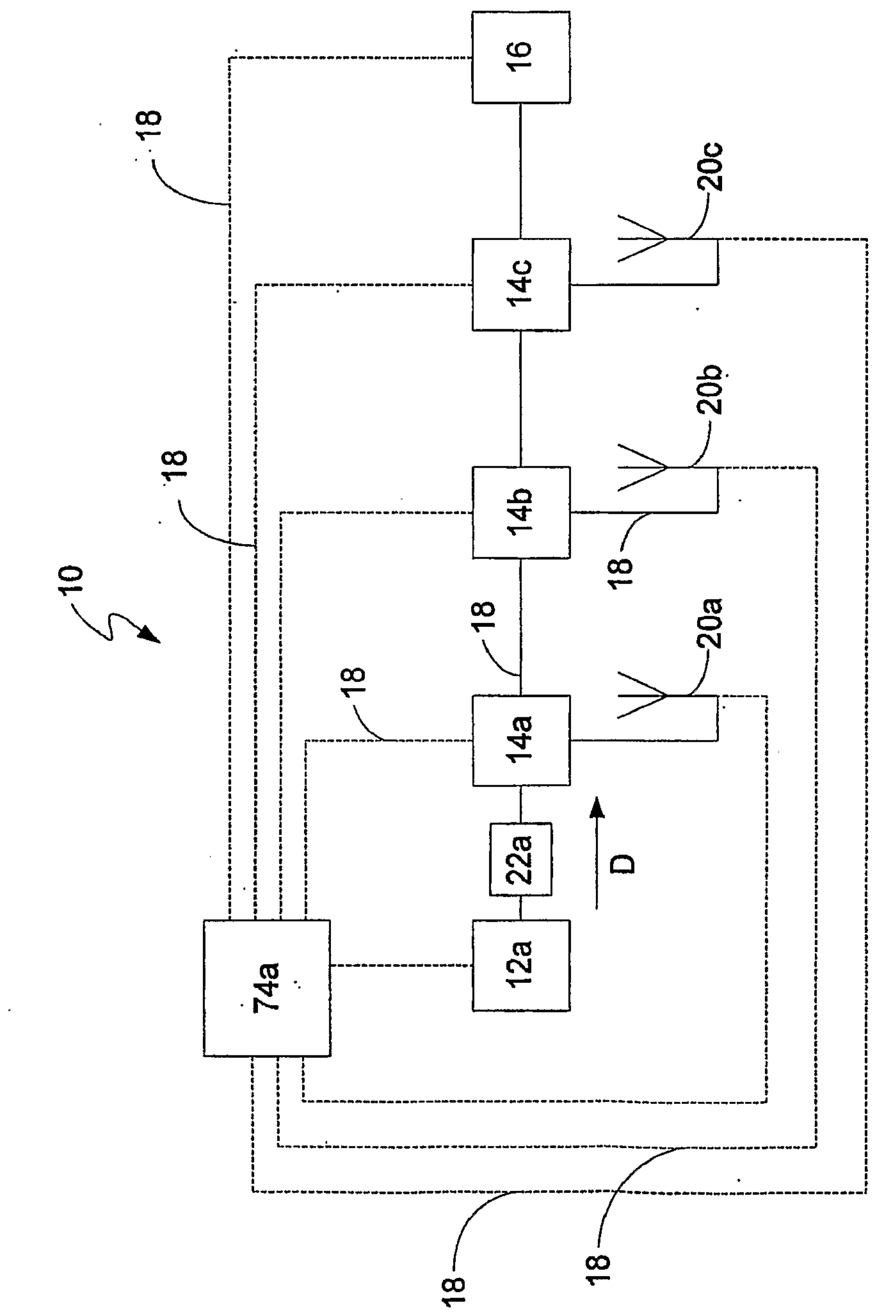
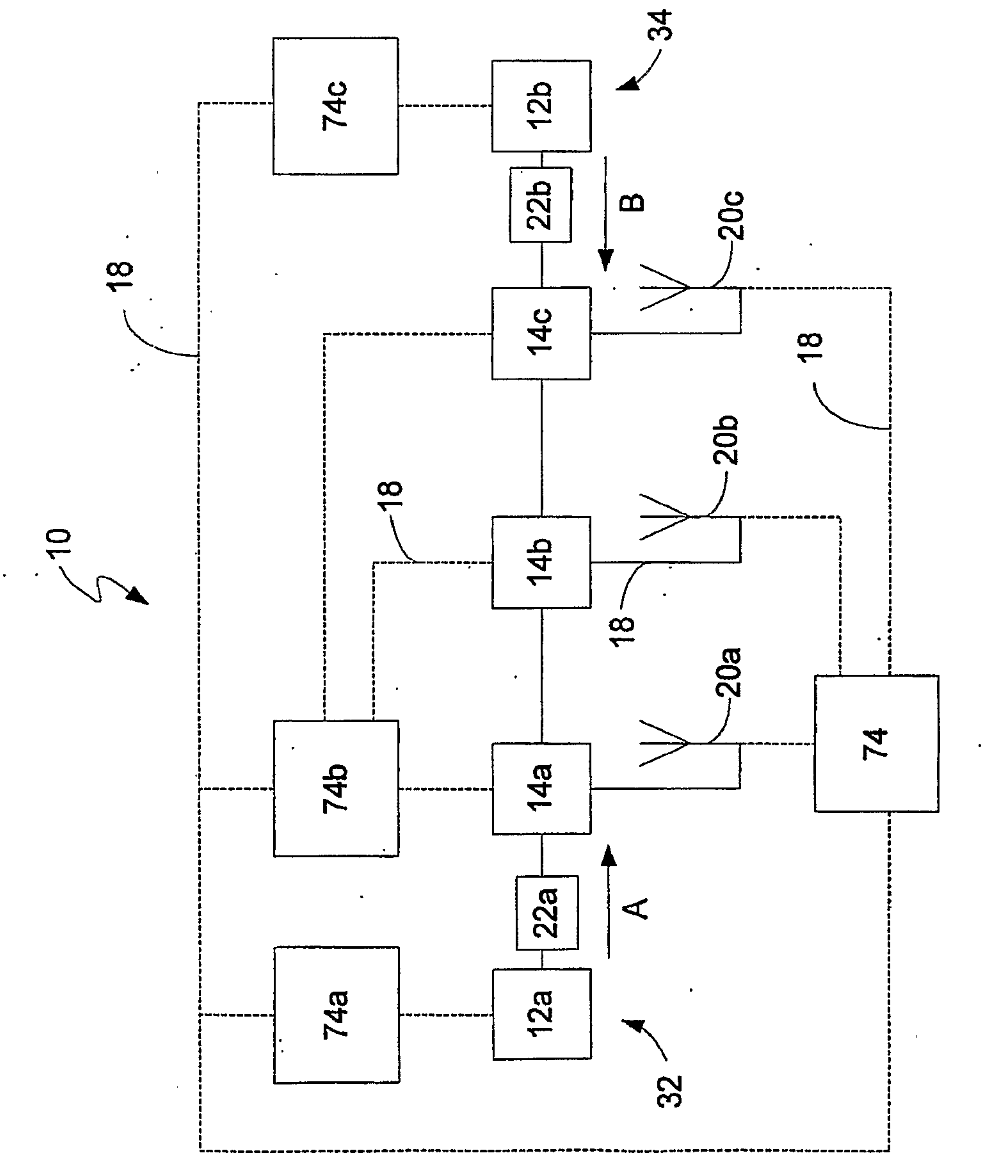


Fig. 1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74c
12b
34
22b
B
20c
14c
18
18
20b
14b
18
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20a
74
22a
A
74a
12a
32

Fig. 2

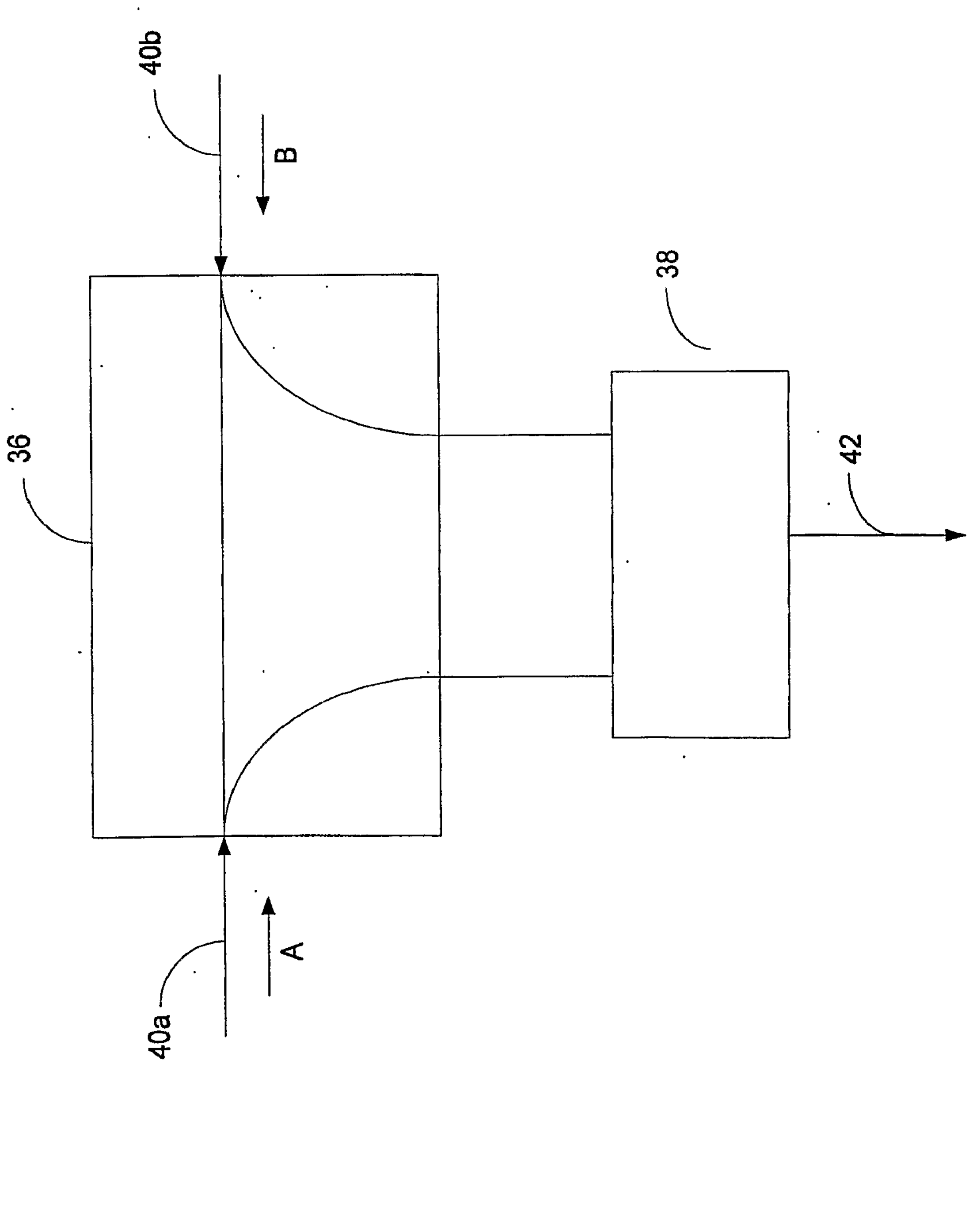

Fig. 3

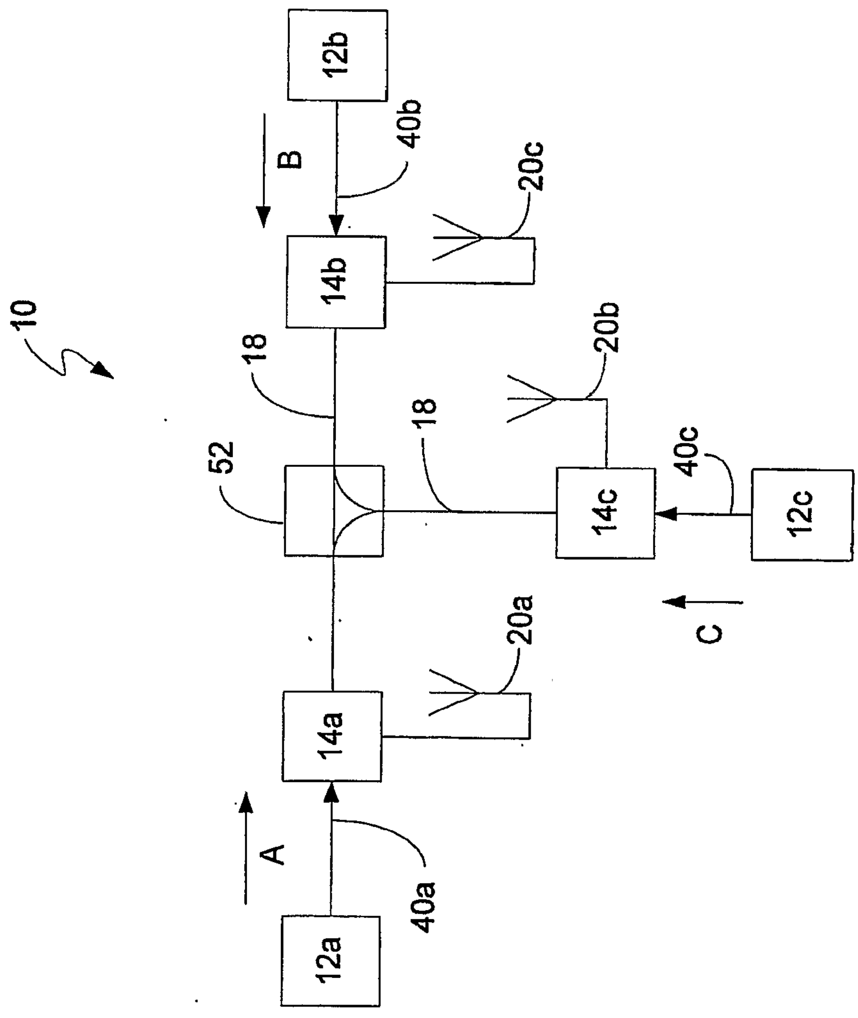

Fig. 4

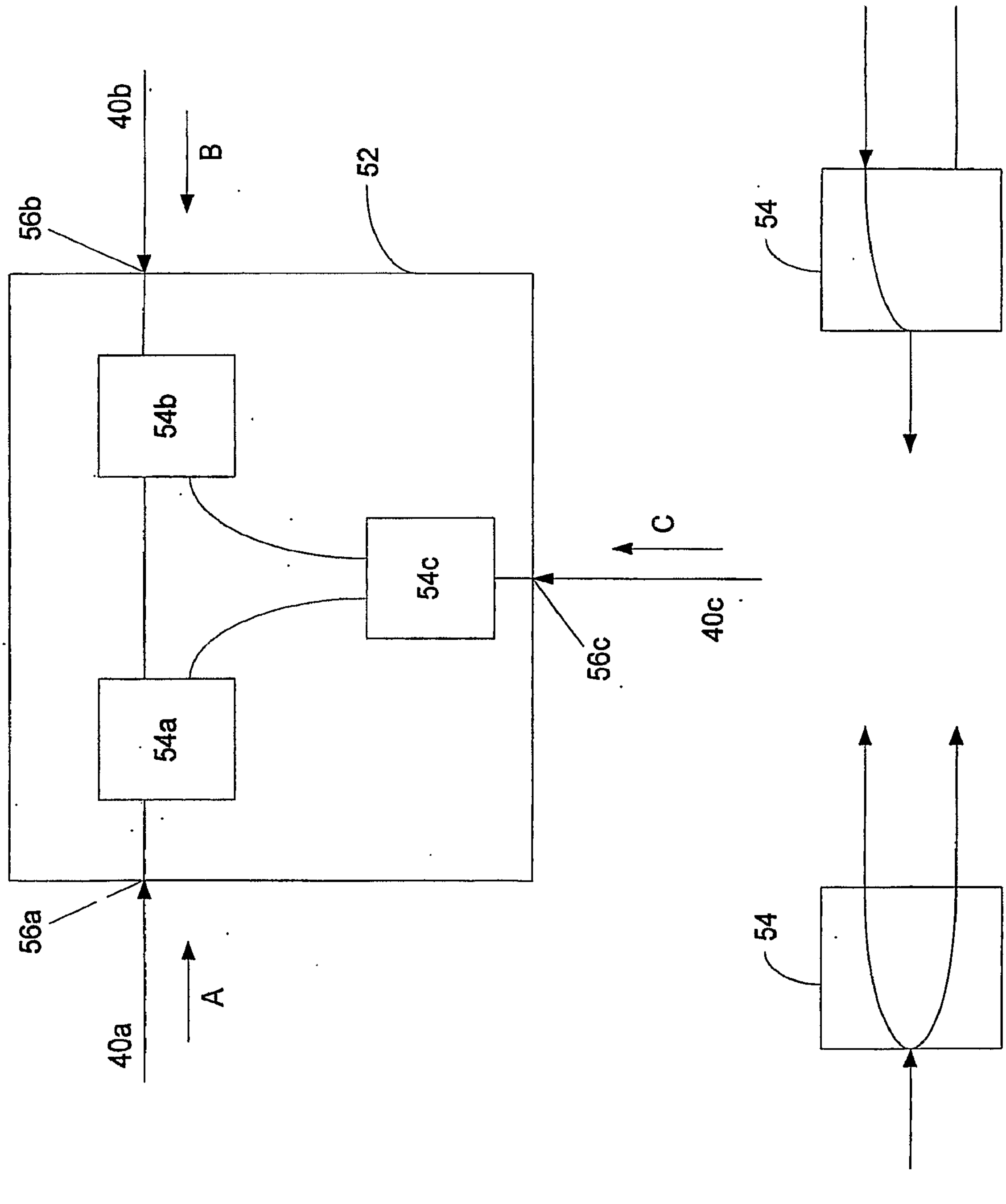

Fig. 5

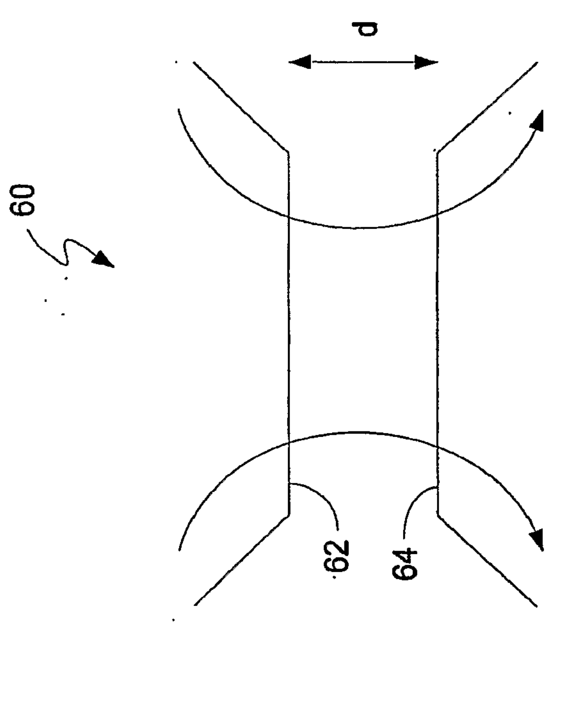

Fig. 6

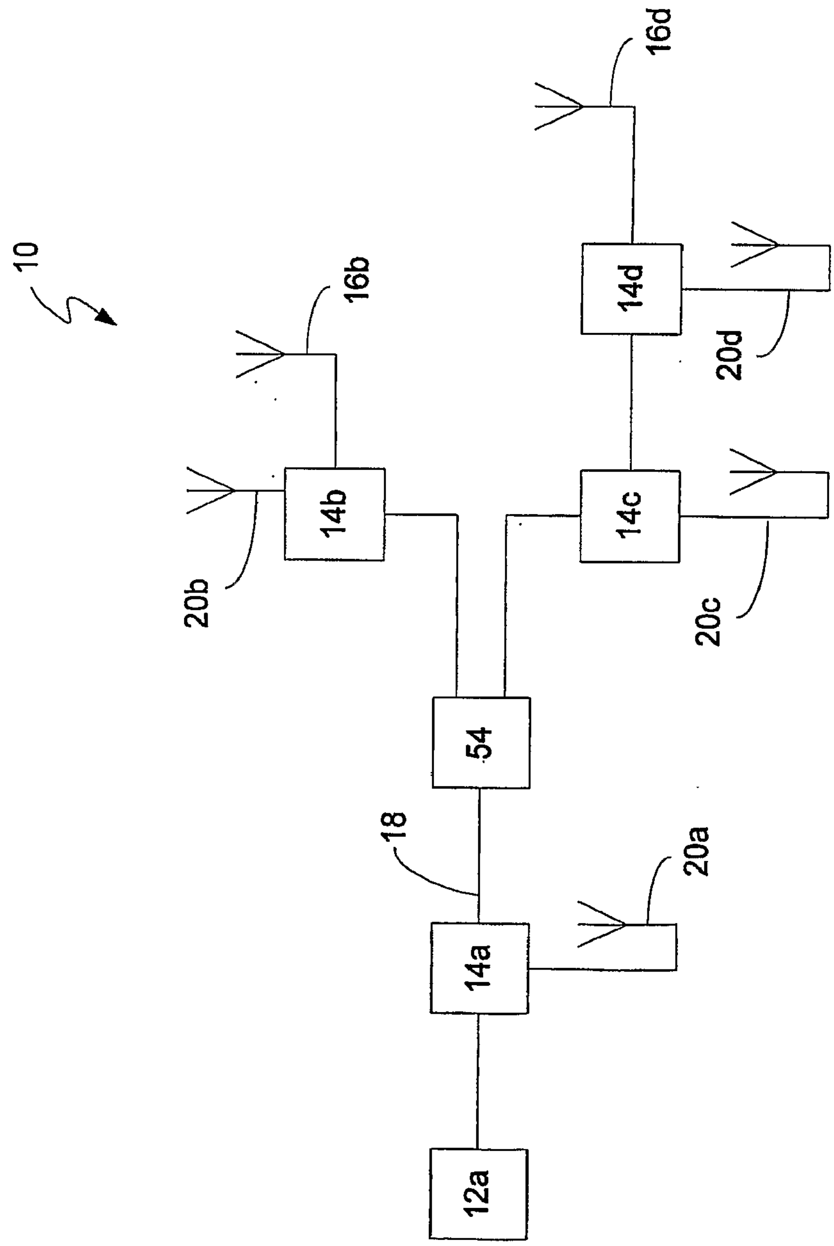

Fig. 7

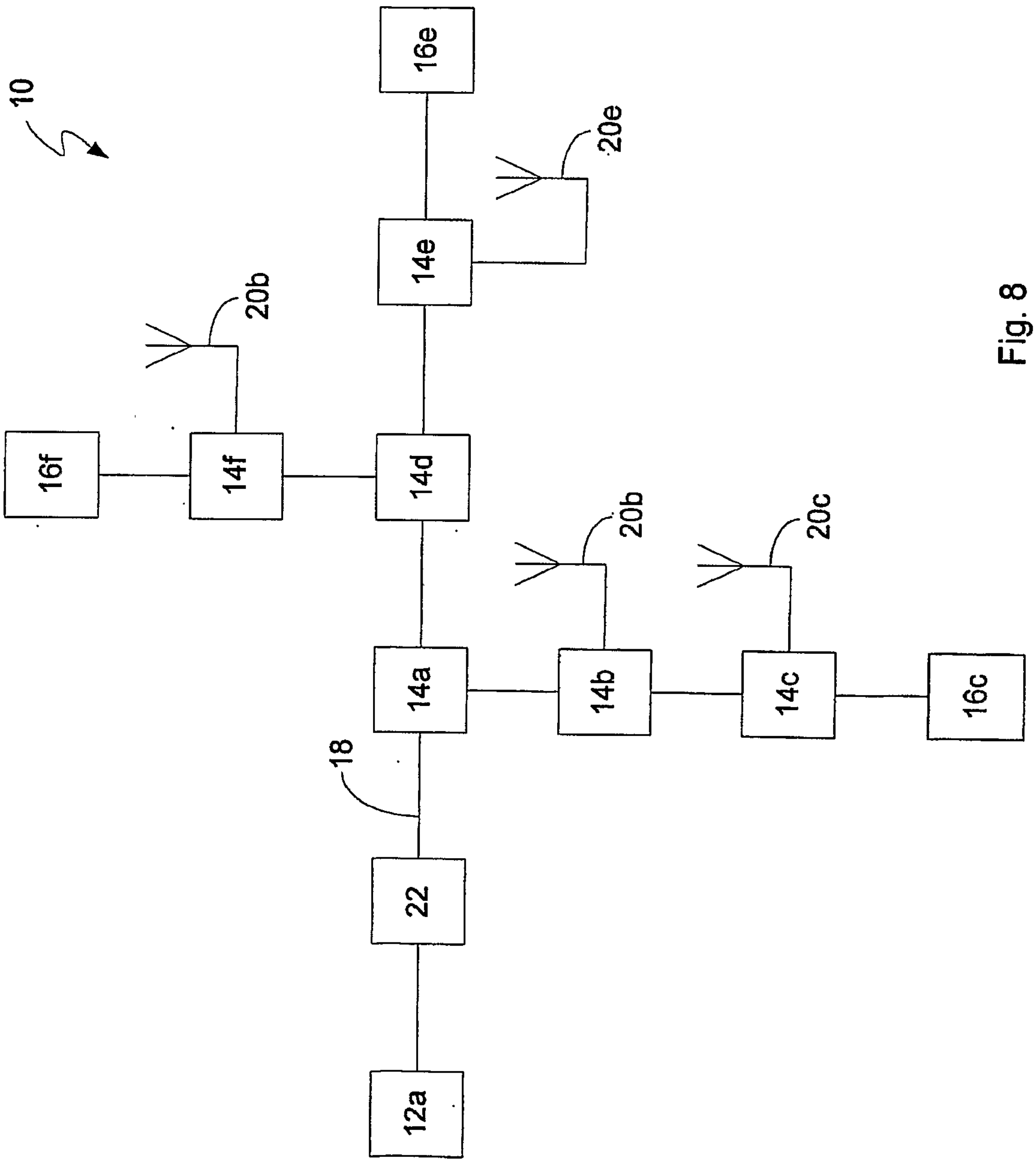

Fig. 8

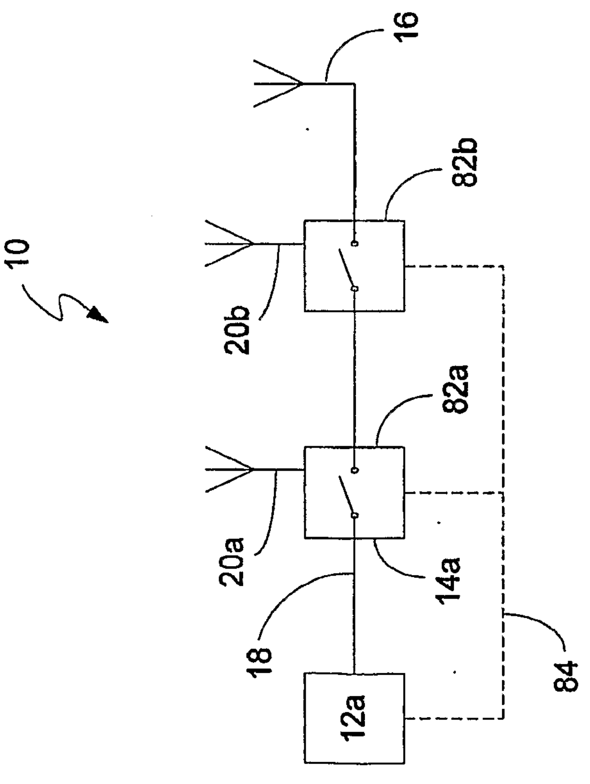

Fig. 9

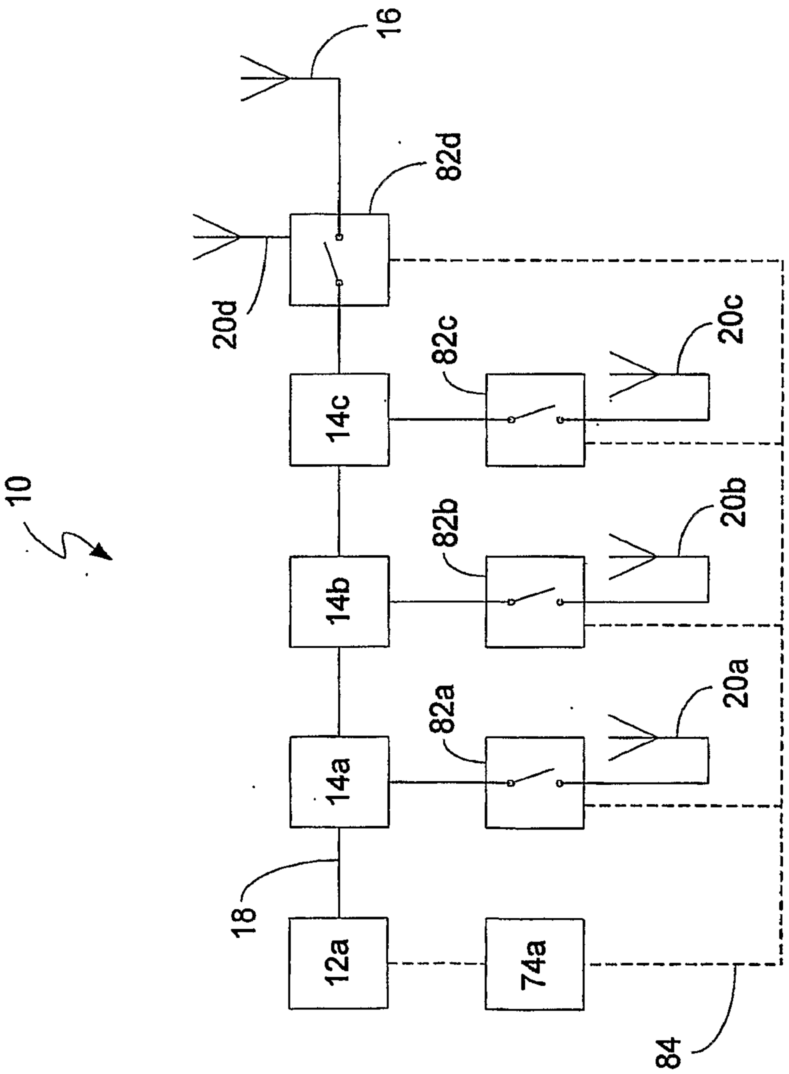

Fig. 10

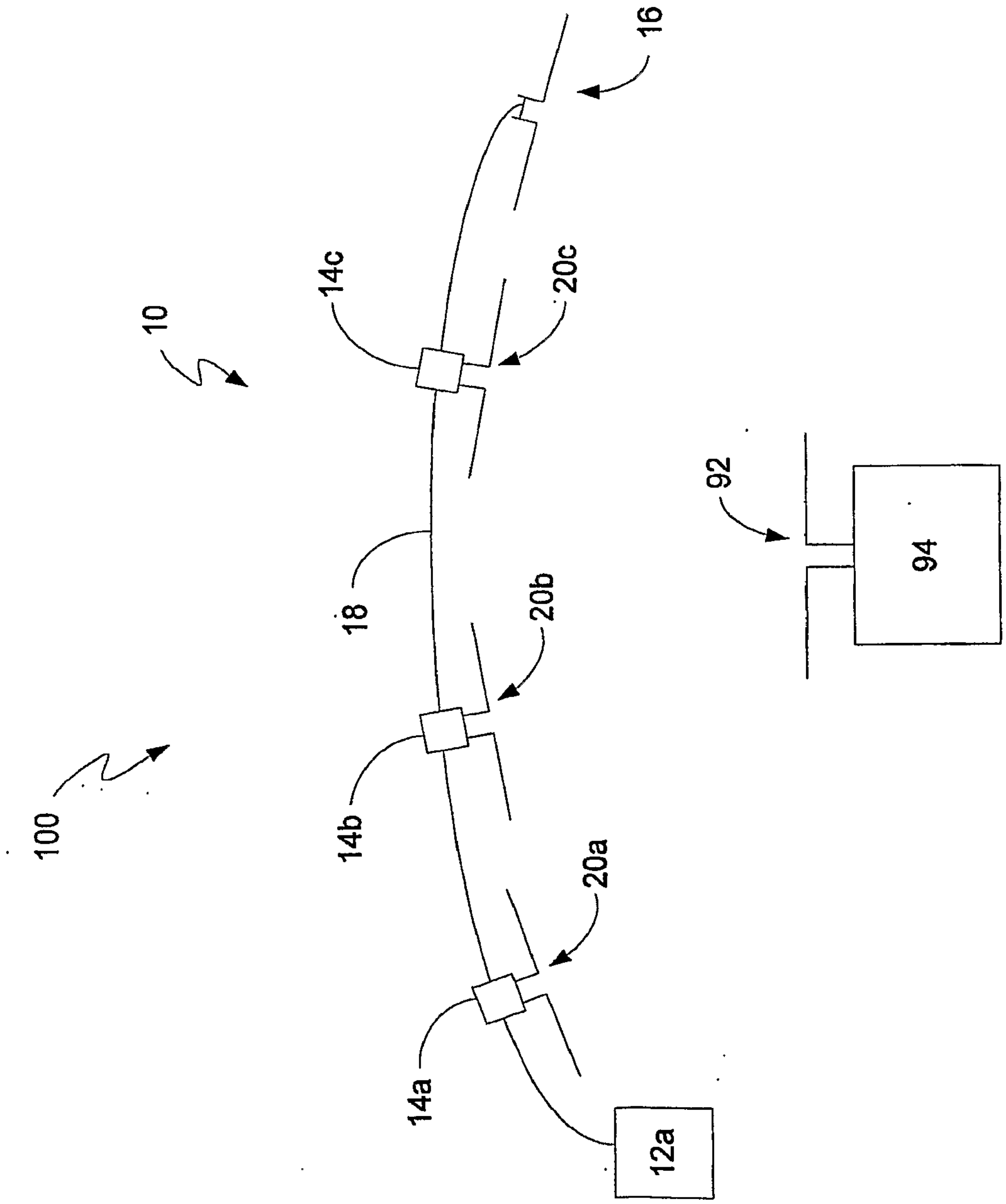

Fig. 11