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(54) **Title:** HYBRID WIRELESS/WIRED TRANSPONDER AND HYBRID RADIO-OVER-FIBER COMMUNICATION SYSTEM USING SAME

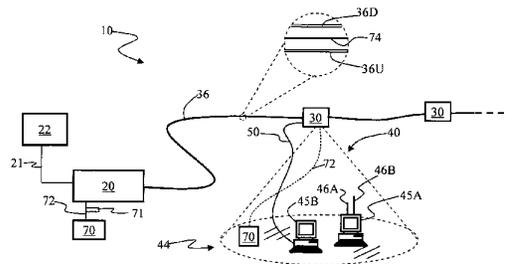


FIG. 1

(57) **Abstract:** A radio-over-fiber (RoF) hybrid wired/wireless transponder is disclosed that is configured to provide both wireless and wired communication between a hybrid head-end and one or more client devices. The hybrid transponder includes optical-to-electrical (O/E) and electrical-to-optical (E/O) conversion capability and is configured to frequency multiplex/demultiplex electrical "wired" signals and electrical "wireless" signals. The electrical wireless signals are wirelessly communicated to the client device(s) via a multiple-input/multiple-output (MIMO) antenna system within a cellular coverage area. The electrical wired signals are communicated to the client device(s) via a wireline cable that plugs into a wireline cable port on the transponder. The hybrid RoF system includes a hybrid head-end capable of transmitting and receiving wired and wireless optical signals, and an optical fiber cable that is optically coupled to the hybrid head-end and to at least one hybrid transponder. Drop-down transponder configurations that allow for easy wired and wireless connectivity between the client device(s) to the transponder(s) are also disclosed.

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HYBRID WIRELESS/WIRED TRANSPONDER AND HYBRID RADIO-OVER-FIBER COMMUNICATION SYSTEM USING SAME

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention relates generally to wireless and wired communication systems, and in particular relates to radio-over-fiber (RoF) communication systems that employ wired and/or wireless technology.

Technical Background

[0002] Wireless communication is rapidly growing, with ever-increasing demands for high-speed mobile data communication. As an example, so-called “wireless fidelity” or “WiFi” systems and wireless local area networks (WLANs) are being deployed in many different types of areas (coffee shops, airports, libraries, etc.). Wireless communication systems communicate with wireless devices called “clients,” which must reside within the wireless range or “cell coverage area” in order to communicate with the access point device.

[0003] One approach to deploying a wireless communication system involves the use of “cells,” which are radio-frequency (RF) coverage areas. Cells can have relatively large radii (e.g., 1000 m) or can have relatively small radii (“picocells”) in the range from about a few meters up to about 20 meters. Because a picocell covers a small area, there are typically only a few users (clients) per picocell. Picocells also allow for selective wireless coverage in small regions that otherwise would have poor signal strength when covered by larger cells created by conventional base stations.

[0004] The essential components that make up a RoF wireless cellular system are a head-end controller (“head end”), one or more optical fiber cables, and one or more transponders. The optical fiber cables are connected at one end to the head-end controller. The transponders are optically coupled to the optical fiber cables along the length of the cables. The optical fiber cables have downlink and uplink optical fibers that carry RoF optical signals between the transponders and the head end. The transponders convert RoF optical signals to electrical signals and vice versa to create the corresponding one or more cells. The transponders include one or more antennas that transmit and receive RF free-space

electromagnetic (EM) signals to and from the client devices within the corresponding cell. Combining a number of transponders creates an array of cells that cover an area called a "cellular coverage area." A closely packed array of picocells forms a picocellular coverage area that provides high per-user data-throughput.

[0005] While RoF wireless cellular and picocellular systems are robust, it is desirable to be able to provide state-of-the-art wireless and wired services to end-users -- for instance, in present day technology terms, a wireless RoF infrastructure with IEEE 802.11a/b/g/n along with Gigabit Wireline Ethernet, and a wired infrastructure with IEEE 802.3/u./z (where IEEE 802.3 is 10 Mbps, IEEE 802.3u is 100 Mbps and IEEE 802.3z is 1 Gbps). The traditional way of achieving this is through two separate wireless and wired network infrastructures, which is costly and complicated to deploy and maintain.

[0006] What is needed is an approach that allows for both wireless and wired services to be provided to end-users without the complexity and cost of having to deploy two separate communication systems.

SUMMARY OF THE INVENTION

[0007] One aspect of the invention is a hybrid transponder for distributing wireless and wired signals from a hybrid head end to at least one client device. The hybrid transponder includes a hybrid converter adapted to convert wireless and wired optical signals from the head-end unit to corresponding wired and wireless electrical signals, and vice versa. The hybrid transponder also includes a frequency multiplexer/demultiplexer (M/D) electrically connected to the converter and adapted to multiplex and demultiplex the wired and wireless electrical signals. An antenna system is electrically connected to the frequency M/D via a signal-directing element configured to allow the antenna system to transmit and receive wireless signals from the at least one client device. A wireline cable port, such as a standard Ethernet port, is electrically connected to the frequency M/D and is adapted to connect to a wireline cable (e.g., an Ethernet cable) to carry wired electrical signals to and from the at least one client device. Further embodiments of the present invention comprise wireline cables and cable ports that carry optical signals to and from the at least one client device. The hybrid transponder thus allows for both wired and wireless communication between one or more client devices and the hybrid head end. In an example embodiment, one client device wirelessly communicates via the hybrid transponder while another client device wire-

communicates via the hybrid transponder. In another example embodiment, the same client device both wire-communicates and wirelessly communicates via the hybrid transponder.

[0008] Another aspect of the invention is a method of providing wired and wireless connectivity to at least one client device from a hybrid head-end. The method includes deploying at least one hybrid transponder optically coupled to the head-end unit and adapted to convert optical wired and wireless signals from the hybrid head-end into corresponding electrical wired and wireless signals. The method also includes, in the at least one hybrid transponder, directing the electrical wireless signals to a multiple-input/multiple-output (MIMO) antenna system so as to wirelessly communicate with the at least one client device. The method also included directing the electrical wired signals to a wireline cable port and to the client device via a wireline cable operably connecting the transponder to the at least one client device.

[0009] Another aspect of the invention is a hybrid RoF communication system capable of providing wireless and wired connectivity to at least one client device. The system includes a hybrid head-end adapted to transmit and receive wired and wireless optical signals over an optical fiber cable. At least one hybrid transponder is optically coupled to the optical fiber cable and is configured to convert wired and wireless optical signals to corresponding wired and wireless electrical signals and vice versa. The hybrid transponder is configured to wirelessly transmit the wireless electrical signals to the at least one client device via an antenna system, and to wire-transmit the wired signals to the at least one client device via a wireline cable that operably connects the hybrid transponder to the at least one client device. In an example embodiment, the system provides a wired connection to one client device and a wireless connection to another client device that both reside within a cell of the system.

[0010] Additional features and advantages of the invention are set forth in the detailed description that follows, and will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description that follows, the claims, as well as the appended drawings.

[0011] It is to be understood that both the foregoing general description and the following detailed description present embodiments of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated into and constitute a part of this specification. The drawings

illustrate various embodiments of the invention and, together with the description, serve to explain the principles and operations of the invention.

[0012] Accordingly, various basic electronic circuit elements and signal-conditioning components, such as bias tees, RF filters, amplifiers, power dividers, etc., are not all shown in the Figures for ease of explanation and illustration. The application of such basic electronic circuit elements and components to the devices and systems of the present invention will be apparent to one skilled in the art.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. 1 is a schematic diagram of a generalized embodiment of a hybrid RoF wireless/wired communication system (“hybrid RoF system”) according to the present invention showing a hybrid head-end optically coupled to at least one hybrid transponder via an optical fiber cable, and showing a cell (picocell) formed by one of the hybrid transponders and two client devices within the picocell;

[0014] FIG. 2 is a detailed schematic diagram of an example embodiment of the hybrid head-end of the hybrid RoF system of FIG. 1;

[0015] FIG. 3 and FIG. 4 are the same as FIG. 2, and respectively show the various downlink and uplink wireless and wired signals;

[0016] FIG. 5 is a detailed schematic diagram of an example embodiment of the hybrid transponder of the system of FIG. 1, showing the various optical and electrical downlink wireless and wired signals transmitted to and received from the hybrid head-end, and also showing the wireline cable that provides wired communication to a client device;

[0017] FIG. 6 is a schematic diagram illustrating a hybrid transponder incorporated with the optical fiber cable that has downlink and uplink optical fibers, and showing an Ethernet-type wireline cable port in the transponder;

[0018] FIG. 7 is the schematic diagram of FIG. 5, but showing the various uplink optical and electrical wireless and wired signals;

[0019] FIG. 8 is a schematic diagram of the transponder end of the hybrid RoF system of the present invention, showing two transponders and three client devices, including a multiple-input/multiple-output (MIMO) client device in wireless communication with one or both hybrid transponders, and two other client devices in wired communication with the respective hybrid transponders;

[0020] FIG. 9 is a detailed schematic diagram of an example embodiment of a MIMO hybrid transponder;

[0021] FIG. 10 is a schematic diagram of the transponder end of the hybrid RoF system of the present invention that includes the MIMO hybrid transponder of FIG. 9, illustrating the hybrid transponder providing MIMO wireless communication with one of the client devices as well as wired communication with the other two client devices;

[0022] FIG. 11 is a schematic diagram of the transponder end of the hybrid RoF system of the present invention illustrating an example embodiment wherein some of the upstream hybrid transponders are connected to a remote power/data extender unit;

[0023] FIG. 12A is a schematic diagram of the transponder-end of the hybrid RoF system of the present invention, illustrating an example embodiment of a drop-down configuration wherein the hybrid transponder drops down from the ceiling into a room from an optical fiber cable installed above the ceiling;

[0024] FIG. 12B is similar to FIG. 12A, and illustrates an example embodiment wherein one client device wirelessly communicates through the hybrid transponder while another client device wire-communicates through the hybrid transponder;

[0025] FIG. 13 is a schematic diagram similar to FIG. 12, illustrating an example embodiment of a drop down configuration wherein the hybrid transponder remains above the ceiling and wherein the wireline cable can plug into the transponder's wireline cable port and also plug into the client device to establish wired and/or wireless communication between the head-end and the client device;

[0026] FIG. 14A is similar to FIG. 13 but shows two client devices, and illustrates an example embodiment wherein the wireline cable is connected directly to the transponder rather than to a wireline cable port in the hybrid transponder;

[0027] FIG. 14B is similar to FIG. 14A and illustrates an example embodiment wherein a first wireline cable connects the transponder to a wall outlet, and a second wireline cable connects the client device to the wall outlet; and

[0028] FIG. 15 is a close-up view of the hybrid transponder and wireline cable, showing the wireline cable connected directly to the transponder at the amplifier/filter electronics unit ("A/F electronics").

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0029] Reference is now made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. Whenever possible, the same or analogous reference numbers are used throughout the drawings to refer to the same or like parts.

[0030] The present invention is directed to a hybrid wireless/wired RoF communication system (hereinafter “hybrid RoF system” for short) that provides both wireless and wired network connectivity. The system is designed to provide a wireless connection with MIMO capability, such as IEEE 802.11n, along with a high-data-rate wired connection, such as Wireline Ethernet or a fiber optic wireline cable. An example of the hybrid RoF system of the present invention combines wireless and wired network infrastructures into a single hybrid RoF system (e.g., network) with multimode optical fibers carrying IEEE 802.11a/b/g/n, and ultra wide band (UWB) signals, along with base-band gigabit wireline Ethernet signals (e.g., IEEE 802.3z @ 1 Gbps).

[0031] In the description below, a “wireless” signal is that associated with providing wireless communication, and a “wired” signal is that associated with providing baseband wired communication. Both “wireless” and “wired” signals can be electrical or optical, while the wireless signals can additionally be free-space electromagnetic signals of the type normally associated with “wireless” (i.e., non-wired) communications.

[0032] Also in the description below, the acronym LAN stands for “local area network,” and the acronym WLAN stands for “wireless local area network.”

Generalized optical-fiber-based wireless system

[0033] FIG. 1 is a schematic diagram of a generalized embodiment of a hybrid RoF system 10 according to the present invention. Hybrid RoF system 10 includes a hybrid head-end 20, at least one hybrid transponder unit (“transponder”) 30 configured to handle both wireless and wired signals, and an optical fiber cable 36 that optically couples the hybrid head-end to the at least one hybrid transponder. Hybrid head-end 20 is operably connected via a communication link 21 to an external source 22, such as an optical communication network or other network architecture backbone, the Internet, etc.

[0034] As shown in the close-up view in FIG. 1, in an example embodiment optical fiber cable 36 includes one or more optical fibers, and in a particular example embodiment

includes a downlink optical fiber **36D** and an uplink optical fiber **36U**. In an example embodiment, the present invention employs multi-mode optical fibers for the downlink and uplink optical fibers **36D** and **36U**. In a more specific example embodiment, OM3 50 μm multi-mode optical fibers are used for downlink and uplink optical fibers **36D** and **36U**. In another example embodiment downlink optical fiber **36D** and/or uplink optical fiber **36U** can comprise one or more individual optical fibers. In **FIG. 1**, individual optical fibers are shown for downlink and uplink optical fibers **36D** and **36U** by way of example and for ease of illustration.

[0035] In an example embodiment, one of the optical fibers in **36D** and/or in **36U** is used for wireless signals, while another of the optical fibers in **36D** and/or in **36U** is used for wired signals. Likewise, in another example embodiment, one of the optical fibers is used for one type of signal, while the other carries both signal types. For the sake of illustration and ease of discussion, downlink optical fibers in **36D** are assumed to carry downlink optical wireless and wired signals from hybrid head-end **20** to hybrid transponder **30**, while uplink optical fibers in **36U** are assumed to carry uplink optical wireless and wired signals from the hybrid transponder to the hybrid head-end.

[0036] Hybrid RoF system **10** forms at each hybrid transponder **30** a cell **40** substantially centered about the corresponding hybrid transponder. In example embodiments, a cell **40** can be relatively large (e.g., 1000 m radius) or can be a picocell ranging anywhere from about a meter across to about twenty meters across. One or more cells **40** associated with the at least one hybrid transponder form a cellular coverage area **44**. In the remainder of the discussion below, for the sake of illustration, cell **40** is assumed to be a “picocell” and coverage area **44** is assumed to be a “picocell coverage area.”

[0037] Hybrid transponder **30** is also adapted to provide wired communication via a wireline cable **50**, such as an Ethernet wire-based cable or an optical fiber cable. Hybrid head-end **20** is adapted to perform or to facilitate any one of a number of RoF applications, such as radio-frequency identification (RFID), wireless local-area network (WLAN) communication (Ethernet signals), and/or cellular phone service.

[0038] With continuing reference to **FIG. 1**, there is shown within picocell **40** two client devices **45** (**45A** and **45B**), shown in the form of computers by way of example. An example embodiment of client device **45A** includes two antennas **46A** and **46B** (e.g., a multi-antenna wireless card) adapted to receive and/or send free-space electromagnetic signals, while client

device **45B** is wire-connected to the transponder via wireline cable **50**. Client device **45A** is thus adapted for multiple-input/multiple-output (MIMO) communication with hybrid head-end **20** via hybrid transponder **30**.

[0039] In an example embodiment, hybrid RoF system **10** also includes a power supply **70** that generates an electrical power signal **71**. In an example embodiment, power supply **70** is located at and is electrically coupled to head-end unit **20** via an electrical power line **72**, and powers the power-consuming elements therein. In an example embodiment, an electrical power line **74** runs through hybrid head-end **20** and over to the at least one hybrid transponder **30** and powers not only the power-consuming elements in the hybrid head-end but also the power-consuming elements in at least one hybrid transponder, such as the O/E and E/O converters, as described below. In an example embodiment, electrical power line **74** includes two wires **74A** and **74B** that carry a single voltage and that are electrically coupled to a DC power converter **180** at transponder **30** (DC power converter **180** is discussed in greater detail below in connection with **FIG. 5**).

[0040] In an example embodiment, a power supply **70** is provided locally to one or more of the hybrid transponders and provides electrical power directly to one or more of the local hybrid transponders via electrical power line(s) **72** rather than via optical fiber cable **36**. In an example embodiment, electrical power line **74** (or a branch thereof) is included in wireline cable **50**, thereby allowing hybrid RoF system **10** to provide Power-over-Ethernet via hybrid transponder **30**.

[0041] In an example embodiment, hybrid RoF system **10** employs a known telecommunications wavelength, such as 850 nm, 1300 nm, or 1550 nm. In another example embodiment, hybrid RoF system **10** employs other less common but suitable wavelengths such as 980 nm.

Hybrid head-end

[0042] **FIG. 2** is a detailed schematic diagram of an example embodiment of hybrid head-end **20** of **FIG. 1**. Hybrid head-end **20** includes a switch **100** having first and second input/output (I/O) sides **102** and **104**. I/O side **102** is operably coupled to communication link **21** at an I/O port **103**. In an example embodiment, communication link **21** is or otherwise includes a high-speed (e.g., 10 Gbps) Ethernet link. I/O side **104** includes a number of I/O ports **106**. In an example embodiment, I/O ports **106** are lower-speed ports

(e.g., ten 1 Gbps ports to handle ten Gbps Ethernet signals from different wires carried by communication link **21**). Two I/O ports **106A** and **106B** are shown for the sake of illustration.

[0043] I/O port **106A** is electrically connected to a wireless-signal converter **120**, while I/O port **106B** is electrically connected to a wired-signal converter **130**. In an example embodiment, wireless-signal converter **120** includes an amplifier/filter electronics unit (“A/F electronics”) **122** that amplifies and filters the wireless signals, as explained below. Hybrid head end unit **20** also includes a frequency multiplexer/demultiplexer (M/D) **138** that in an example embodiment includes a frequency combiner **140** and a frequency splitter **150**. Frequency M/D **138** is electrically connected to A/F electronics **122** and converter **130**.

[0044] Hybrid head end **20** also includes an electrical-to-optical (E/O) converter **160** electrically coupled to frequency combiner **140** of frequency M/D **138**. E/O converter **160** is adapted to receive electrical signals from frequency combiner **140** and convert them to corresponding optical signals, as discussed in greater detail below. In an example embodiment, E/O converter **160** includes a laser suitable for delivering sufficient dynamic range for RoF applications, and optionally includes a laser driver/amplifier (not shown) electrically coupled to the laser. Examples of suitable lasers for E/O converter **160** include laser diodes, distributed feedback (DFB) lasers, Fabry-Perot (FP) lasers, and vertical cavity surface emitting lasers (VCSELs), such as 850 nm commercially available VCSELs specified for 10 Gbps data transmission. E/O converter **160** is optically coupled to optical fiber cable **36** and downlink optical fiber(s) **36D** carried therein.

[0045] Hybrid head-end **20** also includes an optical-to-electrical (O/E) converter **162** electrically coupled to frequency splitter **150** of frequency M/D **138** and to optical fiber cable **36** and uplink optical fiber **36U** carried therein. O/E converter **162** is adapted to receive optical signals and convert them to corresponding electrical signals. In an example embodiment, O/E converter **162** is or otherwise includes a photodetector, or a photodetector electrically coupled to a linear amplifier. E/O converter **160** and O/E converter **162** constitute a converter pair unit (“converter unit”) **166** that converts electrical signals to optical signals and vice versa.

[0046] With reference now to **FIG. 3**, in an example embodiment of the operation of hybrid head-end **20**, communication link **21** carries signals S_{21} that include downlink and uplink digital signals SD_{21} and SU_{21} . Downlink digital signals SD_{21} originate, for example,

from an external source **22**. Digital signals **S₂₁** may include a variety of different signal types, such as data, voice, video, etc. Certain types of these signals, such as high-bandwidth video signals, have relatively high data rates and so are best transmitted to an end-user via a wired connection. On the other hand, certain ones of these signals have relatively low data rates, such as low-bandwidth voice signals, and so can be transmitted to an end-user via a wireless signal.

[0047] Downlink signals **SD₂₁** enter hybrid head-end **20** and encounter switch **100**. Switch **100** is adapted to direct certain signals **SD₂₁** most suitable for wireless transmission to wireless-signal converter **120** and to direct the other signals **SD₂₁** suitable for wired transmission to wired-signal converter **130**. Wireless-signal converter **120** receives the signals **SD₂₁** directed to it and converts them into downlink “wireless signals” **S1D**. Specifically, wireless-signal converter **120** phase modulates and/or amplitude modulates signals **SD₂₁** onto an RF carrier signal, e.g., a 2.4 GHz or 5 GHz RF carrier signal, resulting in downlink wireless signals **S1D**. Wireless-signal converter **120** also amplifies and filters wireless signals **S1D** using A/F electronics **122**. In an example embodiment, wireless-signal converter **120** is configured to adapt the transmission protocol for wireless communication (e.g., Ethernet wireless protocol 802.3 to wireless LAN protocol 802.11).

[0048] Meanwhile, wired-signal converter **130** receives the signals **SD₂₁** directed to it and processes (e.g., filters) these signals to make them compatible for transmission over the hybrid system. For example, downlink signals **SD₂₁** are twisted-pair transmit Ethernet data signals, and wired-signal converter **130** interfaces signals **SD₂₁** to make them compatible with the corresponding single-ended signal versions, while rejecting any power-over-Ethernet DC signals that may be present. This results in downlink wired signals **S2D**.

[0049] Generally, wireless signals **S1D** have a higher frequency than wired signals **S2D** so that these two signal types can be frequency multiplexed and demultiplexed. Accordingly, wireless signals **S1D** and wired signals **S2D** proceed to frequency M/D **138** and frequency combiner **140** therein, which combines (multiplexes) the different-frequency signals **S1D** and **S2D** onto a common electrical line connected to E/O converter **160** in converter pair unit **166**. E/O converter **160** then converts downlink electrical wireless signals **S1D** into a corresponding optical signals **S1D'** and converts downlink electrical wired signal **S2D** into a corresponding optical signal **S2D'**. In an example embodiment, E/O converter **160** is configured to modulate the wireless and wired optical signals onto a single optical carrier.

Both wireless and wired optical signals **S1D'** and **S2D'** are carried by downlink optical fiber **36D** and travel to hybrid transponder **30**.

[0050] With reference now to **FIG. 4**, hybrid head-end **20** also receives uplink optical wireless signals **S1U'** and uplink optical wired signals **S2U'** from transponder **30**, as described below. These signals travel from hybrid transponder **30** over uplink optical fiber **36U** and are received by O/E converter **162** in converter unit **166**, which converts these signals into corresponding uplink electrical wireless and wired signals **S1U** and **S2U**. Frequency splitter **150** in frequency M/D **138** splits (i.e., demultiplexes) these signals to follow two different electrical paths wherein that wireless signal **S1U** travels to wireless-signal converter **120**, while wired signal **S2U** travels to wired-signal converter **130**. Wireless-signal converter **120** then operates on the wireless signal **S2U** it receives and extracts signals **SU₂₁** from the RF carrier. Likewise, wired-signal converter **130** processes wired signals **S2U** it receives to form signals **SU₂₁**. For example, wired signals **S2U** are converted by wired-signal converter **130** to twisted pair receive Ethernet data signals.

[0051] Signals **SU₂₁** from converters **120** and **130** then travel to switch **100**, which directs these signals onto communication link **21**. In an example embodiment, not all signals **SU₂₁** are directed to communication link **21**. For example, repeater-cellular signals would not need to go through switch **100** but rather would be directed to a separate processing unit (not shown).

Hybrid transponder

[0052] **FIG. 5** is a schematic diagram of an example embodiment of hybrid transponder **30** according to the present invention. **FIG. 6** is a schematic diagram of hybrid transponder **30** shown incorporated with optical fiber cable **36**.

[0053] Hybrid transponder **30** of the present invention differs from the typical access point device associated with wireless communication systems in that the preferred embodiment of the transponder has just a few signal-conditioning elements and no digital information processing capability with respect to the transmitted/received wired and wireless signals. This allows hybrid transponder **30** to be very compact and virtually maintenance free. In addition, the preferred example embodiment of hybrid transponder **30** consumes very little power, is transparent to signals, and does not require a local power source. Hybrid

transponder **30** also is configured to provide a wired connection to client device **45** either within picocell **40** of the particular hybrid transponder, or outside of this picocell.

[0054] Hybrid transponder **30** includes a converter unit **166** wherein O/E converter **162** is optically coupled to downlink optical fiber **36D** while E/O converter **160** is optically coupled to uplink optical fiber **36U**. O/E converter **162** is electrically connected to a frequency M/D **138** and specifically frequency splitter **150** therein. E/O converter **160** is also electrically connected to frequency M/D **138** and specifically to frequency combiner **140** therein. Both frequency splitter **150** and frequency combiner **140** are electrically connected to A/F electronics **122**. Frequency splitter **150** of frequency M/D **138** is also electrically connected to port **P1** of a three-port signal-directing element **200** having additional ports **P2** and **P3**. In an example embodiment, signal-directing element **200** is a circulator.

[0055] An antenna system **210** is electrically connected to input/output port **P2** of signal-directing element **200**, while frequency combiner **140** of frequency M/D **138** is electrically connected to output port **P3**. In an example embodiment, antenna system **210** includes one or more patch antennas, such as disclosed in U.S. Patent Application Serial No. 11/504,999 filed on August 16, 2006 and assigned to the present assignee. Also in an example embodiment, antenna system **210** is configured for MIMO communication with one or more client devices within picocell **40** (or more generally within the picocell coverage area **44** formed by one or more transponders). Antenna system **210** is discussed in greater detail below.

[0056] A/F electronics **122** is electrically coupled to a wireline cable port **220**, which in an example embodiment is or otherwise includes an Ethernet cable port. Cable port **220** is adapted to receive a cable connector **230** of a wireline cable **50**, such as an Ethernet cable connector (plug) and Ethernet cable, that leads to a wired client **45** (see FIG. 1). In an example embodiment, cable port **220** is a gigabit Ethernet wireline port and wireline cable **50** is an Ethernet cable. In an example embodiment, electrical power line **74** is operably accessible at cable port **220** and wireline cable **50** includes a section of electrical power line **74** so as to provide Power-over-Ethernet via transponder **30** at the wireline cable port.

[0057] In an example embodiment, aforementioned DC power converter **180** is electrically coupled to converter unit **166** and changes the voltage or levels of electrical power signal **71** to the power level(s) required by the power-consuming components in transponder **30**. In an example embodiment, DC power converter **180** is either a DC/DC power converter, or an AC/DC power converter, depending on the type of power signal **71** carried by electrical

power line 74. In an example embodiment, electrical power line 74 includes standard electrical-power-carrying electrical wire(s), e.g., 18-26 AWG (American Wire Gauge) used in standard telecommunications and other applications.

[0058] With reference again also to FIG. 1, in another example embodiment, electrical power line 72 (dashed line) runs from a local power supply 70 to hybrid transponder 30 (e.g., through a section of optical communication link 36 or straight to the hybrid transponder) rather than from or through head end 20 via optical fiber cable 36, such as electrical power line 74. In another example embodiment, electrical power line 72 or 74 includes more than two wires and carries multiple voltages.

Hybrid transponder operation

[0059] Hybrid transponder 30 is configured to provide both a wireless and wired connection to at least one client device 45. Thus, with reference to FIG. 5, in the operation of hybrid transponder 30, downlink optical wireless and wired signals S1D' and S2D' travel from head end unit 20 over downlink optical fiber 36D to O/E converter 162 in converter unit 166 of the hybrid transponder. O/E converter 162 converts optical signal S1D' and S2D' back into their electrical counterparts S1D and S2D. Electrical signals S1D and S2D travel to frequency M/D 138 and to frequency splitter 150 therein, which demultiplexes these signals, with wireless signal S1D sent to signal-directing element 200, and wired signal S2D sent to A/F electronics 122 and then to wireline cable port 220.

[0060] Signal-directing element 200 directs signal S1D to antenna system 210, causing it to transmit a corresponding downlink free-space electromagnetic wireless signal S1D". Because client device 45A is within picocell 40, signal S1D" is received by client device antenna 46A or 46B (say, antenna 46A), which antennas may both be part of a wireless card, or a cell phone antenna, for example. Antenna 46A converts electromagnetic signal S1D" into its counterpart electrical signal S1D in the client device (signal S1D is not shown therein). Client device 45A then processes electrical signal S1D, e.g., stores the signal information in memory, displays the information as an e-mail or text message, etc. Meanwhile, wired signals S2D travel over wireline cable 50 to client device 45B (see FIG. 1) and are processed therein.

[0061] With reference now to FIG. 7, in an example embodiment, client device 45A (FIG. 1) generates an uplink electrical wireless signal S1U (not shown in the client device),

which is converted into a corresponding free-space electromagnetic signal **S1U**” by antenna **46A**. Because client device **45A** is located within picocell **40**, electromagnetic signal **S1U**” is detected by transponder antenna system **210**, which converts this signal back into electrical signal **S1U**. Meanwhile, client device **45B** also transmits wired uplink signals **S2U** to hybrid transponder **30** via wireline cable **50**.

[0062] Signal **S1U** is then directed by signal-directing element **200** out of port **P3** to frequency M/D **138** and frequency combiner **140** therein. Meanwhile, signal **S2U** is amplified and filtered by A/F electronics **122** and provided to frequency M/D **138** and to frequency combiner **140** therein. Frequency combiner **140** combines (multiplexes) signals **S1U** and **S2U** and provides them to E/O converter **160**. E/O converter **160** converts these electrical signals into corresponding optical signals **S1U'** and **S2U'**. These optical signals then travel over uplink optical fiber **36U** to hybrid head-end unit **20**, where they are received and processed in the manner described above.

MIMO operation

[0063] In a preferred embodiment, hybrid RoF system **10** is configured to support MIMO operation. **FIG. 8** is a schematic diagram of the transponder end of hybrid RoF system **10** illustrating an example embodiment of the system, where client device **45A** includes two antennas **46A** and **46B**. This configuration allows for 2x2 MIMO wireless communication with client **45A** while also providing wired communication with clients **45B** and **45C** with downlink and uplink electrical wired signals **S2D** and **S2U**.

[0064] Hybrid RoF system **10** can be set to one of a number of various MIMO configurations, such as 1x2, 2x1, 2x3, 3x2, 3x3, 3x4, 4x3, 4x4, etc., depending on particular antenna system **210** configurations and the number of antennas available on the particular client device(s). An example embodiment of a client device having multiple antennas and MIMO capability is a laptop computer with a multiple-antenna MIMO wireless card.

[0065] Generally speaking, in a MIMO application downlink electrical wireless signals **S1D** and corresponding uplink signals **S1U** are in the form of bit streams. For MIMO applications, each transponder antenna system and each client antenna system serve as both transmitting and receiving antennas that transmit and receive bit-stream segments. Alternatively, there can be separate antennas for transmitting and receiving. For uplink MIMO communication, each transponder antenna system **210** receives the various portions of

the entire uplink electromagnetic free-space wireless signal **S1U**" (i.e., the bit stream segments) transmitted by each transmitter antenna **46A** and **46BA** so that a jumbled bit stream is received at each receiver antenna. Likewise, for downlink MIMO communication, each antenna **46A** and **46B** receives the various portions of the corresponding downlink signal **S1D**" (i.e., the bit stream segment) transmitted from each transmitter antenna system **210**. Thus, hybrid head-end station **20** provides the downlink signal **S1D** simultaneously to the different hybrid transponders **30**, though the downlink signal bit stream is divided up among the hybrid transponders according to the MIMO signal processing. Likewise, the client device simultaneously transmits the uplink signal bit streams to the different antenna systems **210**, though the uplink signal bit stream is divided up among the client device antennas according to the MIMO signal processing.

[0066] In an example embodiment, hybrid head-end **20** is adapted to perform MIMO signal processing of the electrical downlink and uplink signal bit streams by carrying out mathematical algorithms that properly divide a given downlink bit stream signal into the separate downlink bit stream signals for each transponder antenna system **210** to achieve MIMO gain. Likewise, hybrid head-end **20** is adapted to properly recombine the otherwise jumbled uplink signal bit streams received by each antenna system **210**. Client device **45A** also preferably has MIMO signal processing capabilities so that it can communicate with antenna systems **210** using MIMO techniques.

[0067] An example MIMO signal processing approach suitable for use in the present invention is discussed, for example, in the article by Arogyaswami et al., entitled "An overview of MIMO communications—a key to gigabit wireless," Proceedings of the IEEE, Vol. 92, No. 2, February 2004, which article is incorporated by reference herein. In an example embodiment, wireless-signal converter **120** includes a MIMO chip **124** adapted to perform the aforementioned MIMO signal processing. An example MIMO chip suitable for use in head-end unit **20** to provide MIMO capability is a 802.11n-compatible MIMO chip, such as is available from Broadcom, Inc., Irvine, CA, as part number BCM2055.

[0068] By using the MIMO communication method, independent downlink and uplink signals (bit streams) are transmitted from two or more transponder antenna systems **210**, which leads to an improvement of the bit rate of up to N times, where N is the smaller of either the number of transponder antenna systems **210** used or client antennas **45** used. The MIMO method allows picocellular wireless systems employing single-antenna transponders

to satisfy the higher data transmission rates anticipated by future wireless communication standards, such as IEEE wireless communication standards (e.g., IEEE 802.11n).

[0069] FIG. 9 is a schematic diagram of an example embodiment of hybrid transponder 30 according to the present invention that is configured to provide 2xN MIMO capability.

Transponder 30 includes two antenna systems 210. FIG. 10 is a schematic diagram of the hybrid transponder 30 of FIG. 9 as used to perform MIMO wireless communication with client device 45A as well as wired communication with neighboring client devices 45B and 45C. The MIMO wireless communication includes downlink free-space electromagnetic signals S1D” and their counterpart uplink free-space electromagnetic signals S1U”. These signals are processed in the manner described above.

[0070] In FIG. 10, in an example embodiment optical fiber cable 36 includes two sets of downlink and uplink optical fibers 36D and 36U to handle two different wireless signals (e.g., wireless signals having different frequencies). In an alternative example embodiment, hybrid transponder 30 of FIG. 9 and hybrid head-end 20 (FIG. 3) are configured to frequency multiplex the different-frequency downlink and uplink wireless signals onto the same downlink and uplink optical fibers.

Data and power-reach extension

[0071] An example of hybrid RoF system 10 extends the maximum power and data reach of a traditional cellular (e.g., picocellular) network by allowing a connection to a powered wall socket and converting wired signals to wireless signals for the next section of traditional “picocell” cable. FIG. 11 is a schematic diagram of the transponder end of RoF network system 10 illustrating an example embodiment wherein electrical power is provided locally rather than entirely from head end 20 via electrical power line 74 carried by optical fiber cable 36 (FIG. 1), and wherein wired signals (e.g., Ethernet wireline signals) are converted to wireless signals upstream of hybrid head end 20.

[0072] The example embodiment of hybrid RoF system 10 of FIG. 11 includes a power/data extender unit 260 that includes a power supply 70 that provides electrical power via electrical power signal carried by a (multi-wire) local electrical power line 72. Local electrical power line 72 carries electrical power to hybrid transponders 30 on an upper cable span 302, which is farthest from hybrid head-end 20, while the hybrid transponders on a lower cable span 301 closer to hybrid head-end 20 are powered by power line 74 carried by

link **36**. In an example embodiment of power extension, power supply **70** is powered by (or is itself) an electrical outlet **308** via an electrical cord **310** and plug **312**.

[0073] In an example embodiment of data extension, power/data extender unit **260** includes a wired-to-wireless converter unit (e.g., a WLAN router) **322** adapted to convert downlink wired signals **S2D** (e.g., Ethernet-coded wireline signals) carried on lower cable span **301** into multiple downlink wireless signals **S1D** in upper cable span **302**. Likewise, power/data extender unit **260** is adapted to convert uplink wireless signals **S1U** carried on upper cable span **302** to uplink wired signals **S2U** that travel back to hybrid head-end **20** via lower cable span **301**.

Drop-down configurations

[0074] An advantage of the hybrid RoF system **10** of the present invention is that it can be installed in the same manner as a wireless picocellular system is installed, with transponders hanging down to desktop height at a corner of a room for easy access to the wireline Ethernet connection. In such an office environment, a user has broadband wireless connectivity anywhere in the office, along with a wired “worry free” fast wireline Ethernet connectivity--all from a single hybrid transponder.

[0075] **FIG. 12A** is a schematic diagram of the transponder end of hybrid RoF system **10** wherein hybrid transponder **30** drops down via optical fiber cable **36** into a room **400** (e.g., an office, library space, etc.) from above a ceiling **402**. A client device **45** is shown resting upon a table **406** in room **400**. This drop-down configuration allows for wireless communication with client device **45** as well as for convenient wired communication via wireline cable **50**. The MIMO antenna system **210** shown in **FIG. 12A** includes patch antennas for the sake of illustration. The drop-down configuration of **FIG. 12A** allows for a system user to easily plug wireline cable **50** into client device **45** as well as into port **220** of transponder **30** to obtain a wired connection.

[0076] **FIG. 12B** is similar to **FIG. 12A**, and illustrates an example embodiment wherein one client device **45** wirelessly communicates through hybrid transponder **30** while another client device **45** wire-communicates through the hybrid transponder via wireline cable **50**.

[0077] **FIG. 13** is a schematic diagram similar to **FIG. 12**, illustrating an example embodiment wherein hybrid transponder **30** remains above ceiling **402** and wireline cable **50** plugs into wireline cable port **220**. Wireline cable **50** drops down through ceiling **402** (e.g.,

through a hole 410 formed therein) so that it can be plugged into client device 45. This configuration hides transponder 30 and is convenient so long as access to the transponder is available, or if wireline cable 50 is plugged into the hybrid transponder and dropped down from the ceiling so that the user need not have to plug wireline cable 50 into the hybrid transponder.

[0078] FIG. 14A is a schematic diagram similar to FIG. 13, except that wireline cable port 220 is not provided. Rather, wireline cable 50 is connected directly to hybrid transponder 30, e.g., at amplifier/filter unit 122, as illustrated in the close-up partial view of the hybrid transponder shown in FIG. 15. FIG. 14A also illustrates an example embodiment wherein one client device 45 wirelessly communicates through hybrid transponder 30 while another client device 45 wire-communicates through the hybrid transponder.

[0079] FIG. 14B is a schematic diagram similar to FIG. 14A, illustrating an example embodiment wherein a first wireline cable 50 connects transponder 30 to a wall outlet 420 in wall 403, and a second wireline cable 50 connects one of the client devices 45 to the wall outlet. In an example embodiment, wall outlet 420 includes two or more sockets (e.g., RJ-type sockets) 422 so that a number of client devices can be wire-connected to transponder 30.

Advantages

[0080] Hybrid transponder 30 and the hybrid RoF system 10 that includes at least one of the hybrid transponders offer a number of advantages over transponders and RoF communication systems that separately provide wireless and wired connectivity. For example, hybrid RoF system 10 eliminates the need for separate wired and wireless network infrastructure and instead provides wireless and wired connectivity in a single integrated architecture. In addition, any new network deployment can be carried out with one fiber cable network. Further, the hybrid nature of the system has lower installation costs relative to having separate wired and wireless infrastructure deployments. Also, the hybrid RoF system of the present invention facilitates the migration from wired to wireless connections on a user-by-user basis without having to overlay new cabling.

[0081] Hybrid RoF system 10 also provides improved connection reliability achieved through the guaranteed wireline connection provided at desired locations. Hybrid RoF system 10 also extends the maximum data reach of a traditional cellular network through the use of the additional wireline data being converted to a wireless data stream for the next

section of traditional RoF cable. Hybrid RoF system **10** also extends the maximum power reach of the traditional cellular network through local powering of the drop down Wireline Ethernet cable.

[0082] Both the wired and wireless features of the present invention can be easily upgraded as technology progresses. For example, MIMO capability can be updated as needed, such as from 1x2 MIMO to 2x3 MIMO or to 4x6 MIMO, etc., using cell bonding, as described in U.S. Patent Application Serial No. 11/357,640 filed February 17, 2006, which is incorporated by reference herein.

[0083] Hybrid RoF system **10** is also relatively easy to deploy into an existing building infrastructure. For example, it can be deployed in the same manner as optical fiber cables are deployed atop ceiling tiles rather than, for example, within building walls.

[0084] It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. A hybrid transponder for distributing wireless and wired signals from a hybrid head-end to at least one client device, comprising:
 - a hybrid converter adapted to convert wireless and wired optical signals from the head-end unit to wired and wireless electrical signals and vice versa;
 - a frequency multiplexer/demultiplexer (M/D) electrically connected to the converter and adapted to multiplex and demultiplex the wired and wireless electrical signals;
 - an antenna system electrically connected to the frequency M/D via a signal-directing element configured to allow the antenna system to transmit and receive wireless signals from the at least one client device; and
 - a wireline cable port electrically connected to the frequency M/D and adapted to connect to a wireline cable to carry signals to and from the at least one client device.
2. The hybrid transponder of claim 1, further including an amplifier/filter (A/F) electronics unit arranged between the wireline cable port and the frequency M/D.
3. The hybrid transponder of claims 1-2, wherein the transponder includes the wireline cable connected to the wireline cable port.
4. The hybrid transponder of claims 1-3, wherein the antenna system is adapted for communicating with the at least one client device using multiple-input/multiple-output (MIMO) communication.
5. The hybrid transponder of claims 1-4, wherein the antenna system includes at least one patch antenna.
6. A hybrid RoF communication system, comprising:
 - at least one hybrid transponder according to claims 1-5;
 - an optical fiber cable optically coupled to the at least one transponder and that is adapted to carry the wireless and wired optical signals.

7. The hybrid RoF communication system of claim 6, wherein the optical fiber cable includes downlink and uplink optical fibers.
8. The hybrid RoF communication system of claims 6-7, further including the hybrid head-end optically coupled to the optical fiber cable.
9. The hybrid RoF communication system of claims 6-8, wherein the antenna system is adapted to communicate with the at least one client device using multiple-input/multiple-output (MIMO) communication.
10. The hybrid RoF communication system of claims 6-9, wherein one of the at least one client device is wire-connected to the at least one transponder via an Ethernet cable connected to the wireline cable port.
11. The hybrid RoF communication system of claims 6-10, wherein the at least one client device resides in a room having a ceiling, and wherein the at least one transponder is deployed either below the ceiling or above the ceiling.
12. The hybrid RoF communication system according to claims 6-11, wherein the optical fiber cable includes an electrical power line adapted to carry electrical power from the head-end unit to the at least one transponder.
13. The hybrid RoF communication system according to claim 12, further including a power/data extender unit operably coupled to the optical fiber cable and adapted to provide electrical power to one or more of the at least one transponders and to convert downstream optical wired signals to upstream optical wireless signals.
14. A method of providing wired and wireless connectivity to at least one client device from a hybrid head-end, comprising:
 - deploying at least one hybrid transponder optically coupled to the head-end unit and adapted to convert optical wired and wireless signals from the hybrid head-end into electrical wired and wireless signals; and
 - in the at least one hybrid transponder,

- (i) directing the electrical wireless signals to a multiple-input/multiple-output (MIMO) antenna system so as to wirelessly communicate with the at least one client device; and
 - (ii) directing the electrical wired signals to a wireline cable port and to the client device via a wireline cable operably connecting the transponder to the at least one client device.
15. The method of claim 14, wherein the wired signals include gigabit Ethernet signals.
16. The method of claims 14-15, including sending the wired and wireless optical signals from the hybrid head-end on a single optical carrier.
17. A hybrid RoF communication system capable of providing wireless and wired connectivity to at least one client device, comprising:
a hybrid head-end adapted to transmit and receive wired and wireless optical signals over an optical fiber cable;
at least one hybrid transponder optically coupled to the optical fiber cable and configured to convert wired and wireless optical signals to corresponding wired and wireless electrical signals and vice versa, the hybrid transponder further configured to wirelessly transmit the wireless electrical signals to the at least one client device via an antenna system and to wire-transmit the wired signals to the at least one client device via a wireline cable that operably connects the hybrid transponder to the at least one client device.
18. The system of claim 17, wherein the antenna system and the at least one client device are configured for multiple-input/multiple-output (MIMO) communication within a picocell coverage area formed by the at least one hybrid transponder.
19. The system of claims 17-18, wherein the optical fiber cable includes:
a downlink optical fiber that carries downlink wired and wireless optical signals from the hybrid head-end to the at least one hybrid transponder; and
an uplink optical fiber that carries uplink wired and wireless optical signals from the at least one hybrid transponder to the hybrid head-end.

20. The system of claims 17-19, wherein the optical fiber cable includes an electrical power line that carries electrical power to one or more of the at least one hybrid transponder from a power supply, wherein the power supply is electrically connected to the electrical power line either via the head-end station or directly to the optical fiber communication link.

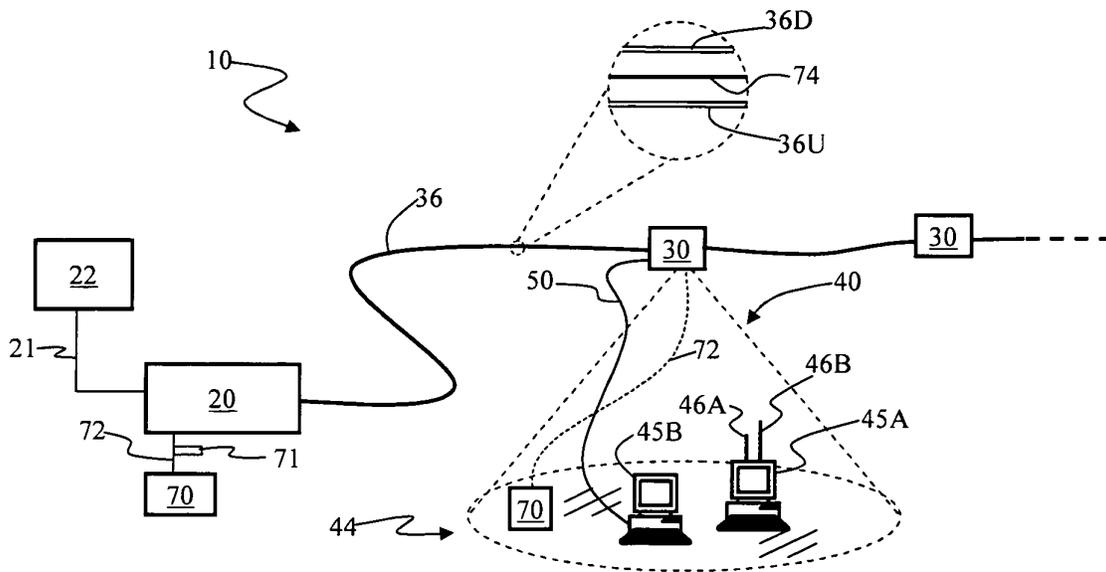


FIG. 1

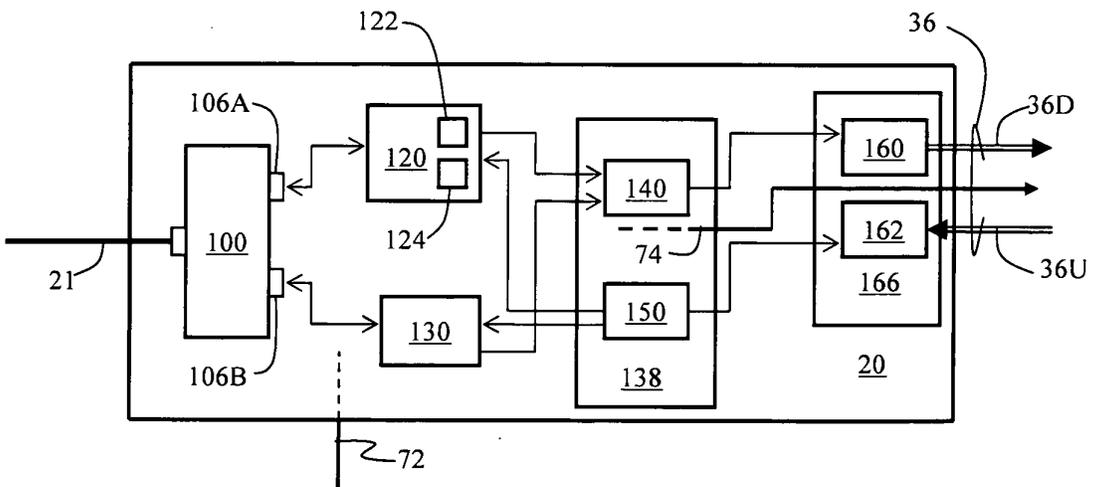


FIG. 2

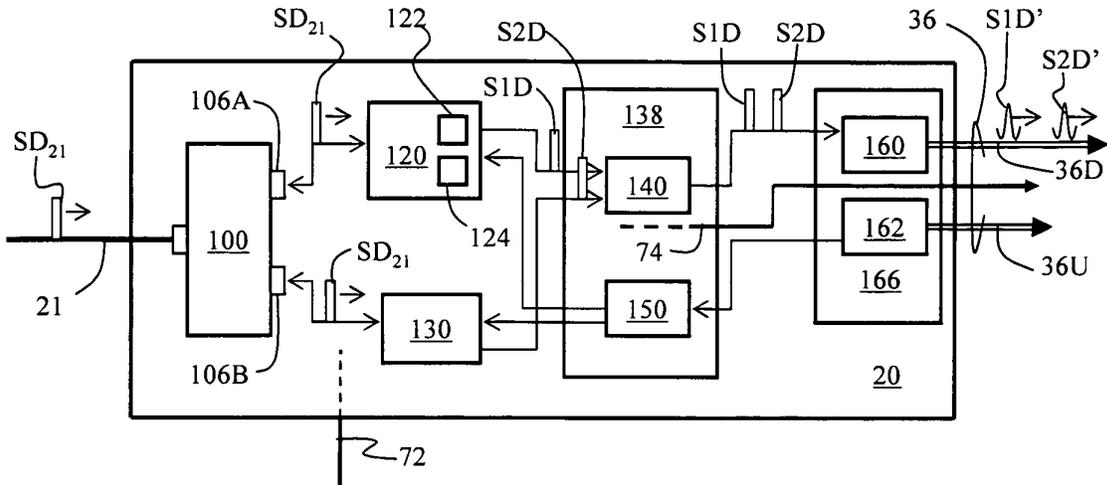


FIG. 3

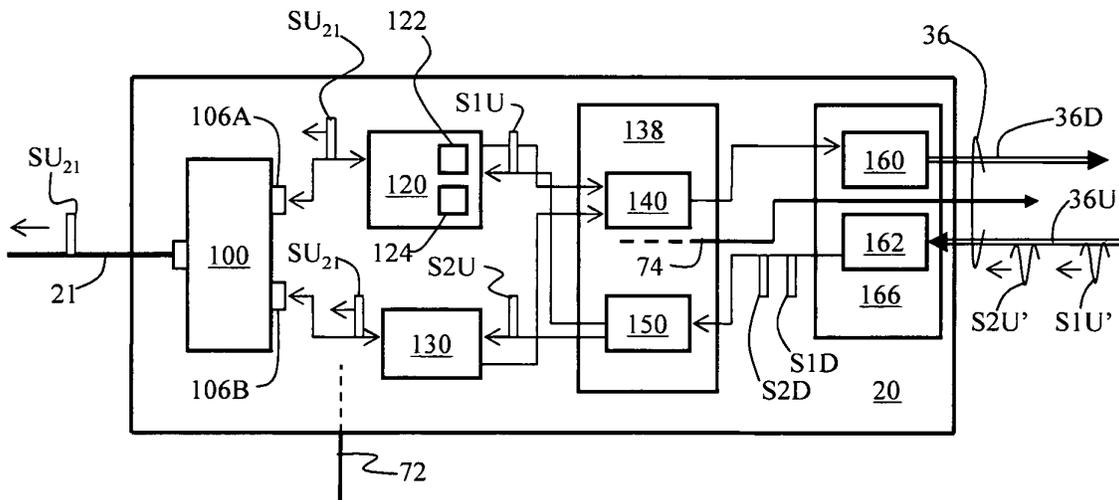


FIG. 4

3/10

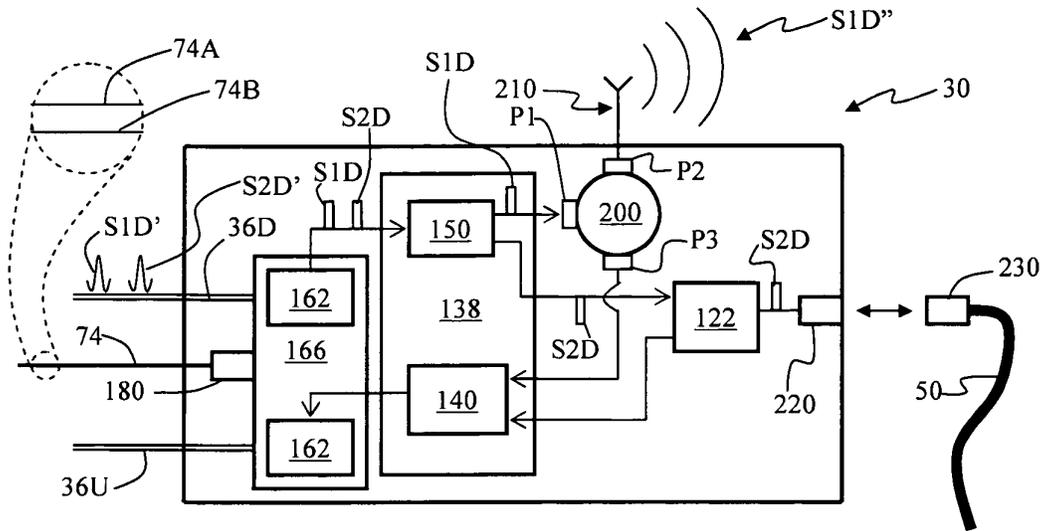


FIG. 5

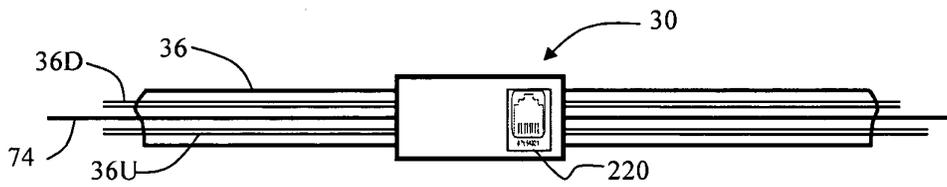


FIG. 6

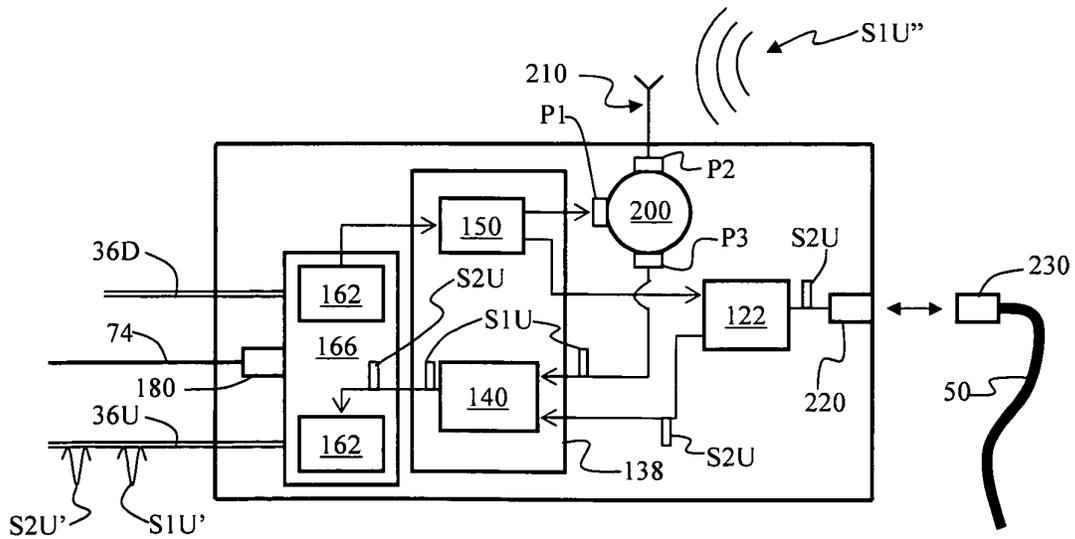


FIG. 7

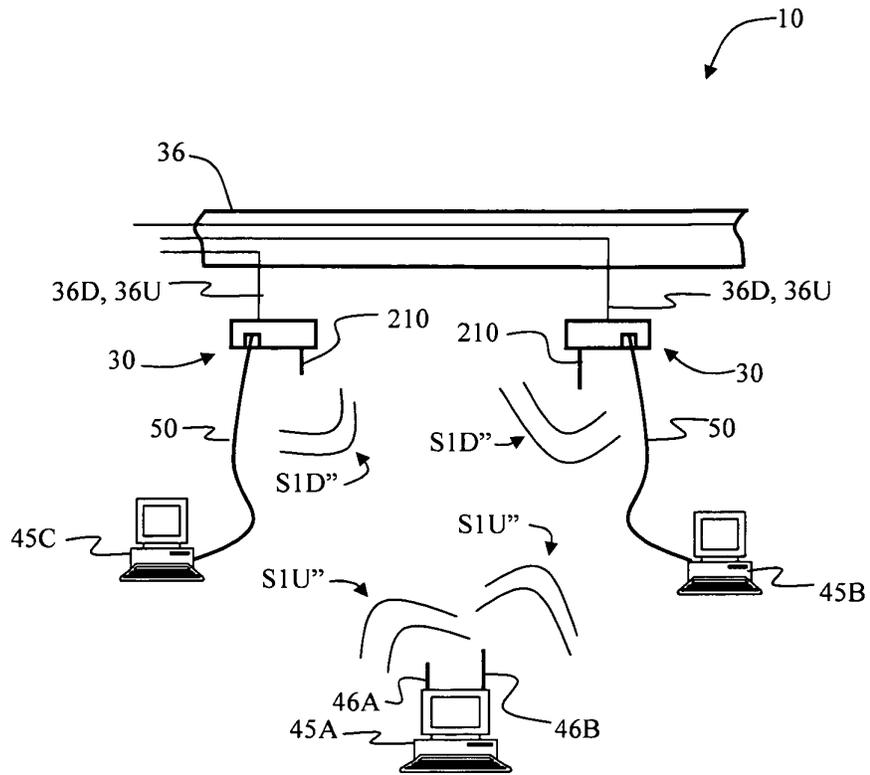


FIG. 8

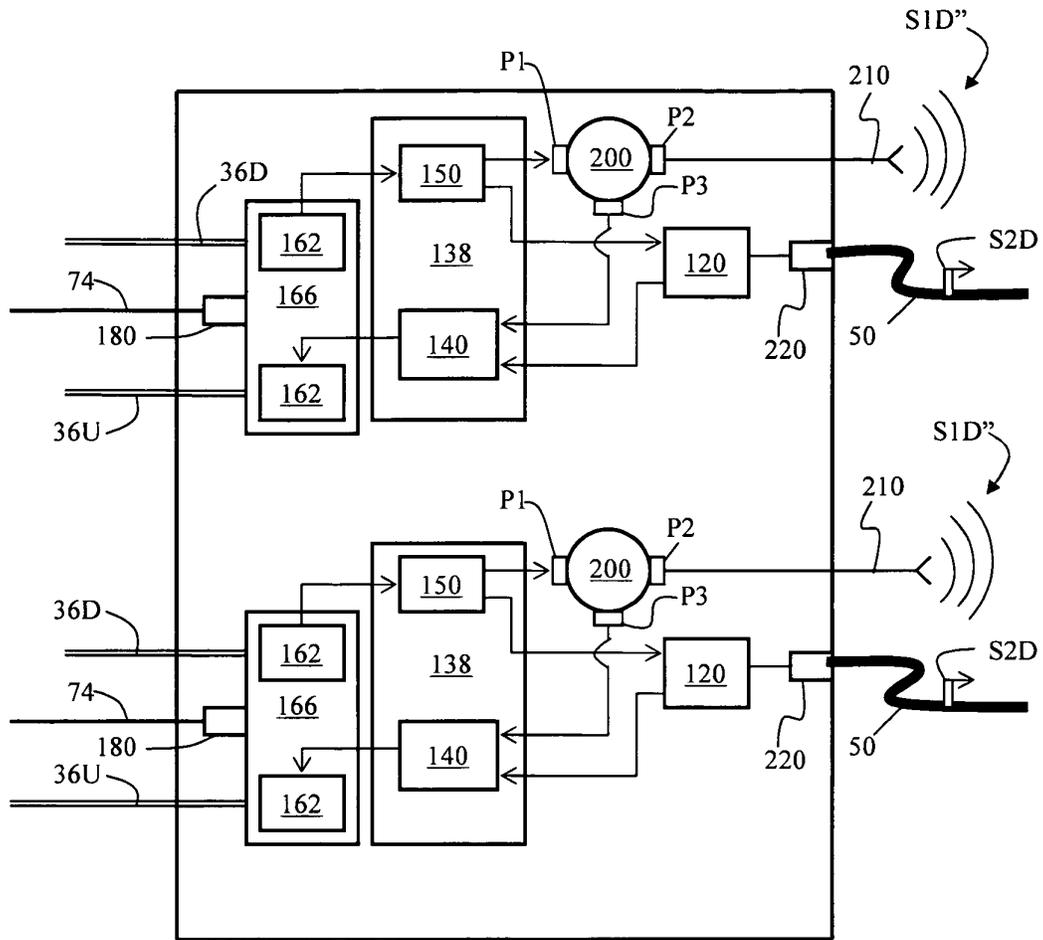


FIG. 9

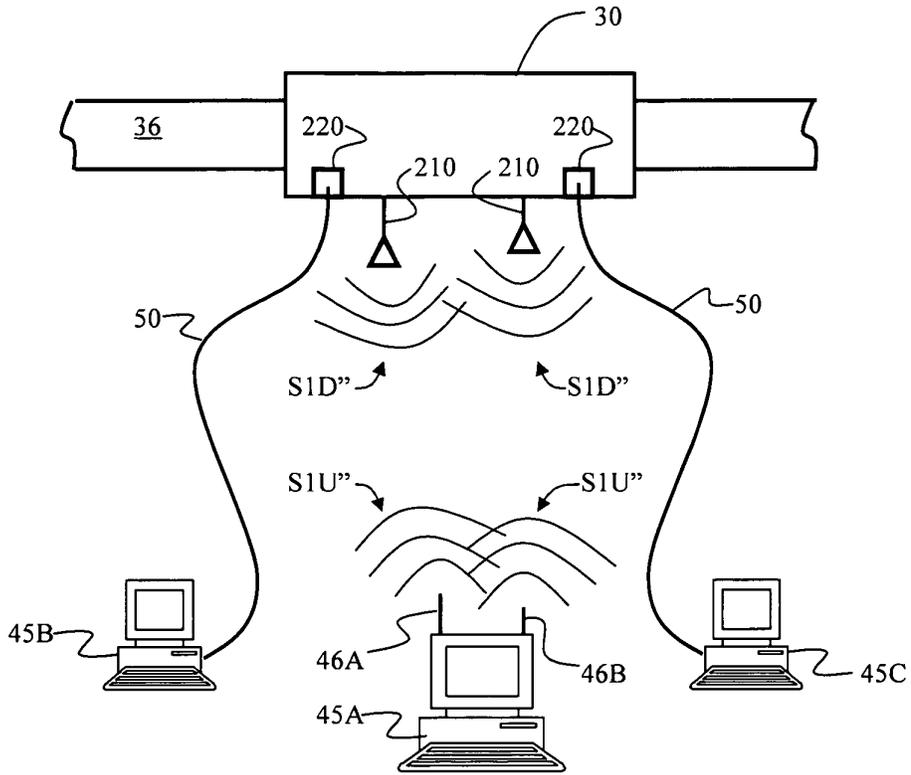


FIG. 10

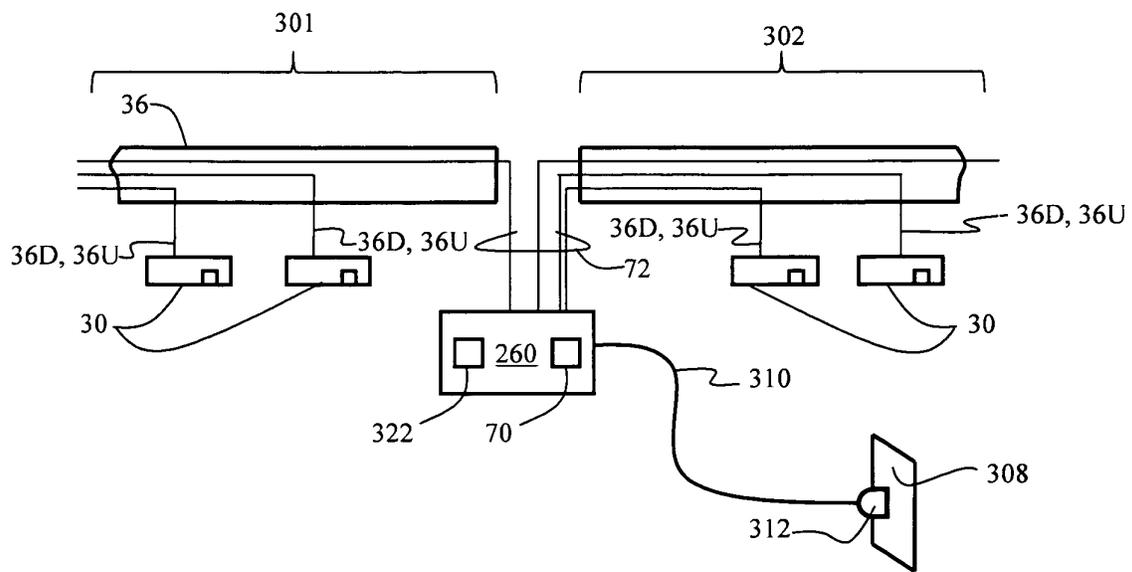


FIG. 11

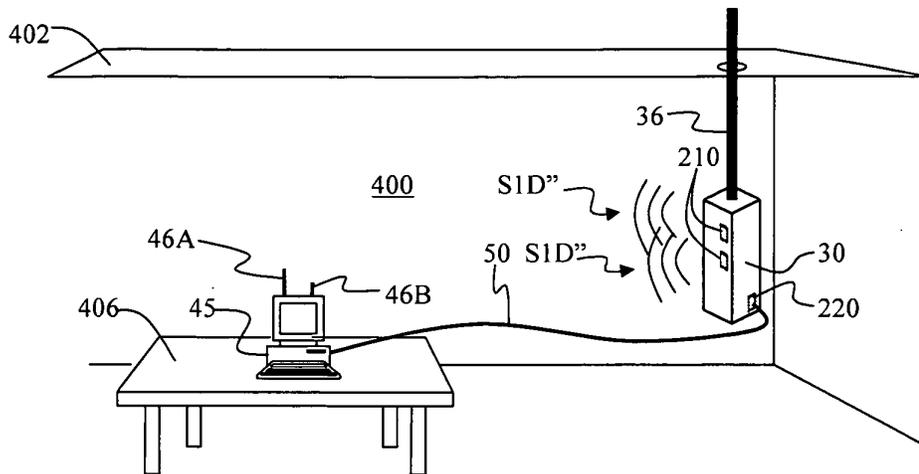


FIG. 12A

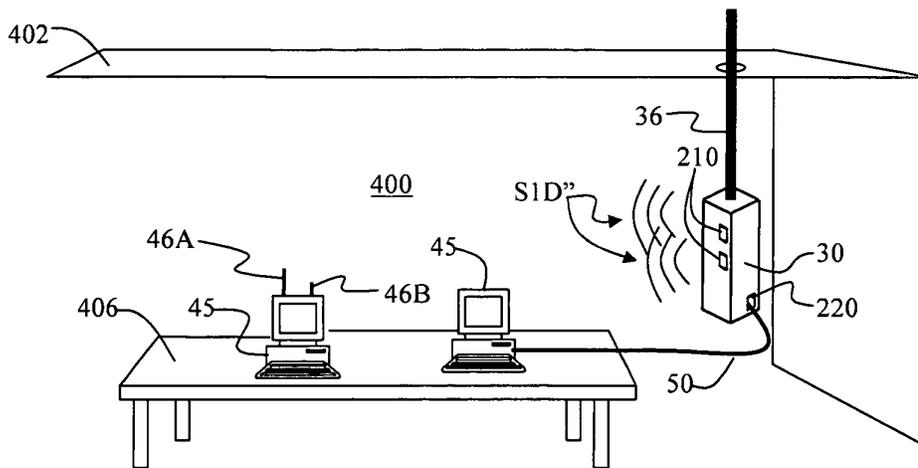


FIG. 12B

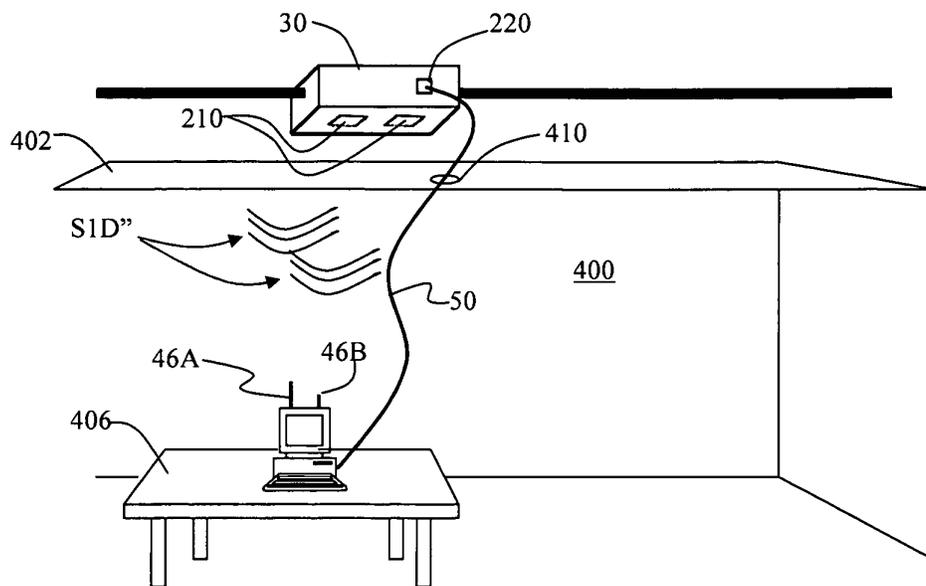


FIG. 13

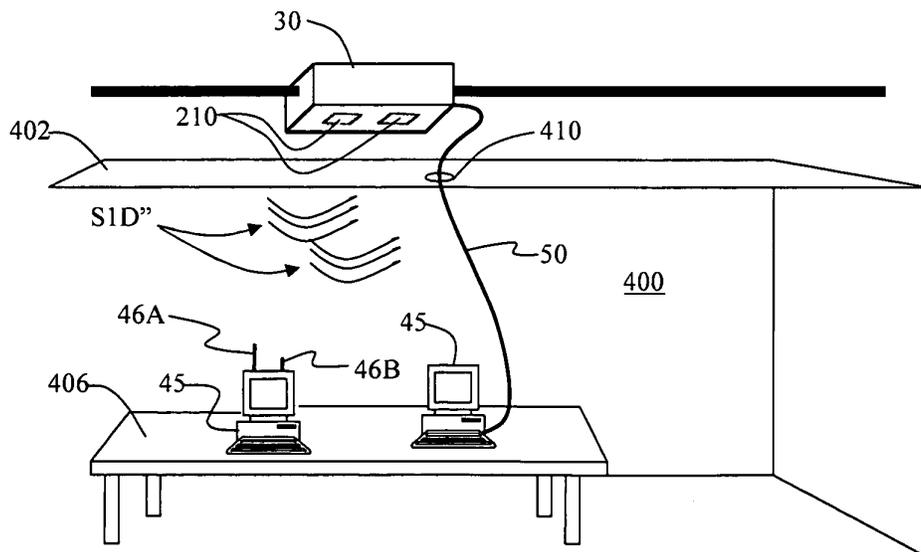


FIG. 14A

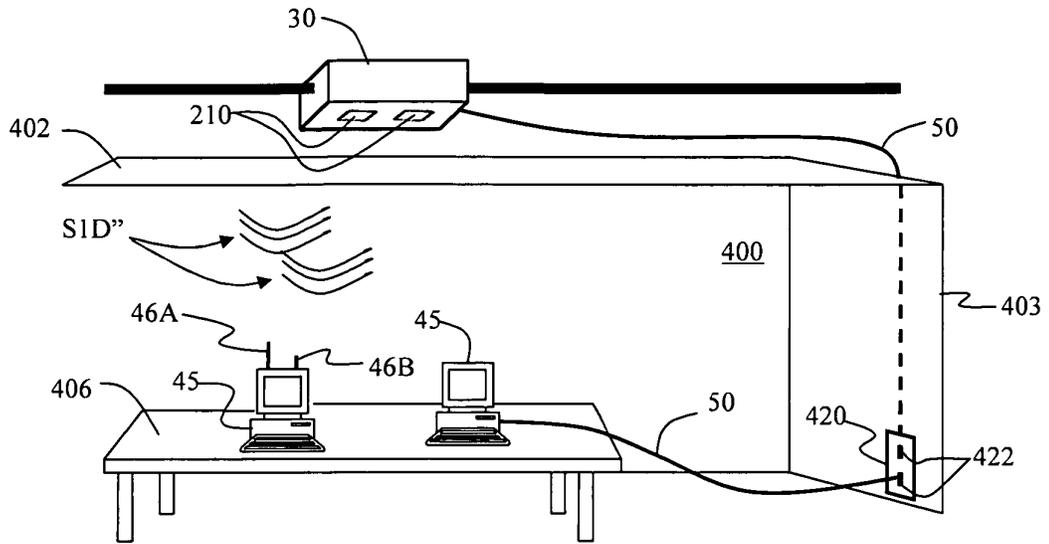


FIG. 14B

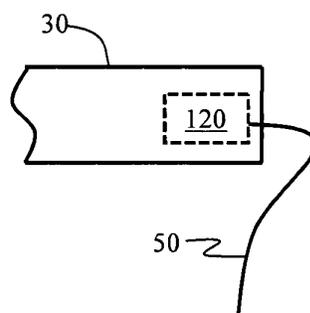


FIG. 15