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(54) **Title:** APPARATUS AND METHOD FOR COMMUNICATION BETWEEN DOWNHOLE COMPONENTS

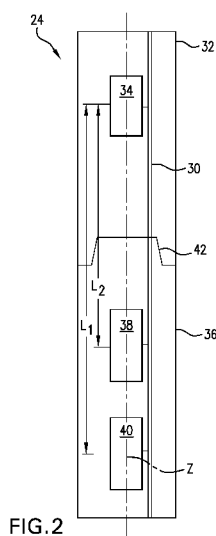


FIG. 2

(57) **Abstract:** A method of synchronization between downhole components includes: generating a dual tone synchronization signal by a signal generator in a first downhole component disposed in a borehole in an earth formation, the dual tone signal including a first constituent periodic signal having a first frequency f_1 and a second constituent periodic signal having a second frequency f_2 that is different from the first frequency; transmitting the synchronization signal to a second downhole component disposed in the borehole; receiving the synchronization signal by a signal processor in the second downhole component, calculating a phase difference between the first constituent signal and the second constituent signal, and calculating a transmission delay based on the phase difference; and synchronizing operation of the first and second downhole components based on the delay.



APPARATUS AND METHOD FOR COMMUNICATION BETWEEN DOWNHOLE COMPONENTS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Application No. 13/735404, filed on January 7, 2013, which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] Various techniques are used to measure formation properties, such as transient electromagnetic (EM) measurement techniques. Transient EM methods such as transient logging while drilling (LWD), especially using “look-ahead” capability, have been shown to have great use in geologic formation evaluation and measurement. Transient EM techniques involve disposing a tool including at least one transmitter and receiver, and transmitting transient pulses of current into a formation. The induced electromagnetic field and decay responses are measured. For proper operation of the transient EM tool, the transmitter and receiver must be well synchronized, i.e., the receiver data acquisition should start at the same instant of the transmit trigger, to within an error of, e.g., a few hundred nanoseconds.

[0003] It has been conventional to the industry to assemble a LWD or wireline tool string from individual modules (also referred to as subassemblies or “subs”) which perform various functions and carry out various measurements while the string has been lowered in the borehole. However, even though these subs are mechanically attached to each other and share common power, the string communication abilities remains limited. For instance, in operations such as LWD or production logging where a single conductor carries power and telemetry signals, the telemetry uses a unique master controller which respectively sends commands to a particular sub and/or accepts a reply. This type of data transfer in general denies the modules the ability to communicate directly with each other which in turn may severely limit some applications, e.g., multicomponent transient EM (TEM) and multicomponent induction applications.

SUMMARY

[0004] A method of synchronization between downhole components includes: generating a dual tone synchronization signal by a signal generator in a first downhole

component disposed in a borehole in an earth formation, the dual tone signal including a first constituent periodic signal having a first frequency f_1 and a second constituent periodic signal having a second frequency f_2 that is different from the first frequency; transmitting the synchronization signal to a second downhole component disposed in the borehole; receiving the synchronization signal by a signal processor in the second downhole component, calculating a phase difference between the first constituent signal and the second constituent signal, and calculating a transmission delay based on the phase difference; and synchronizing operation of the first and second downhole components based on the delay.

[0005] An apparatus for communicating between downhole components includes: an interface coupled to a first downhole component, the interface configured to communicatively couple the first downhole component to a transmission line and transmit signals to a second downhole component over the transmission line, the interface including a current loop transmitter configured to convert voltage signals from the first downhole component to current signals and transmit the current signals on a current loop formed by the transmission line.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The following descriptions should not be considered limiting in any way. With reference to the accompanying drawings, like elements are numbered alike:

[0007] FIG. 1 depicts an embodiment of a drilling, formation evaluation and/or production system;

[0008] FIG. 2 depicts an embodiment of a portion of a borehole string including transient electromagnetic (TEM) transmitter and receiver subassemblies;

[0009] FIG. 3 depicts an embodiment of a communication assembly;

[0010] FIG. 4 depicts an embodiment of an interface of the communication assembly of FIG. 3;

[0011] FIG. 5 depicts an embodiment of a one-way dual tone synchronization signal;

[0012] FIG. 6 is a state diagram showing the operation of a TEM transmitter subassembly during a synchronization and measurement operation;

[0013] FIG. 7 is a state diagram showing the operation of a TEM receiver subassembly during a synchronization and measurement operation;

[0014] FIG. 8 depicts an embodiment of a subassembly current loop communication configuration;

[0015] FIG. 9 depicts an embodiment of the configuration of FIG. 8 in a half-duplex arrangement; and

[0016] FIG. 10 depicts an embodiment of the configuration of FIG. 8 in a full-duplex arrangement.

DETAILED DESCRIPTION

[0017] Apparatuses and methods are provided for performing downhole operations such as electromagnetic (EM) measurement operations, including logging-while-drilling (LWD) and/or wireline operations. The apparatuses and methods also provide for direct communication between downhole components over a power and/or communication line extending along a borehole string. An exemplary method is provided for performing transient EM (TEM) logging operations, and for direct communication between downhole components. An exemplary apparatus and method provides for direct communication between subassemblies for, e.g., synchronization between a master subassembly (e.g., an EM transmitter) and another subassembly (e.g., an EM receiver). In one embodiment, synchronization is performed via a dual frequency one-way time delay measurement method. An embodiment of a communication apparatus or assembly includes interfaces for implementing a data channel in a bus or other transmission line for sending high-speed data from the master subassembly to affected subassemblies without interfering with other telemetry and power signals (e.g., between downhole components and surface units) already present on the transmission line.

[0018] Referring to FIG. 1, an exemplary embodiment of a well drilling, logging and/or production system 10 includes a borehole string 12 that is shown disposed in a wellbore or borehole 14 that penetrates at least one earth formation 16 during a drilling or other downhole operation. A surface structure 18 includes various components such as a wellhead, derrick and/or rotary table for deploying and supporting the borehole string. In one embodiment, the borehole string 12 is a drillstring including one or more drill pipe sections that extend downward into the borehole 14, and is connected to a drilling assembly 20. In one embodiment, system 10 includes any number of downhole tools or other components 24 for various processes including communication, measurement, drilling, geosteering, and formation evaluation (FE) for measuring versus depth and/or time one or more physical quantities in or around a borehole. The tool 24 may be included in or

embodied as a bottomhole assembly (BHA) 22, drillstring component or other suitable carrier. In the embodiment shown in FIG. 1, various tools and other components are configured as subassemblies or “subs” that are connected together and/or with other portions of the string 12.

[0019] The BHA 22 and/or other portions of the borehole string 12 include sensor devices configured to measure various parameters of the formation and/or borehole. In one embodiment, the sensor devices include one or more transmitters and receivers configured to transmit and receive electromagnetic signals for measurement of formation properties such as composition, resistivity and permeability. An exemplary measurement technique is a transient EM (TEM) technique.

[0020] In one embodiment, the tool 24, BHA 22 and/or sensor devices include and/or are configured to communicate with a processor to receive, measure and/or estimate directional and other characteristics of the downhole components, borehole and/or the formation. For example, the tool 24 is equipped with transmission equipment including a power and/or data transmission line 30 to communicate with a processor such as a downhole processor 26 or a surface processing unit 28. Such transmission equipment may take any desired form, and different transmission media and connections may be used. Examples of connections include wired, fiber optic, acoustic, wireless connections and mud pulse telemetry.

[0021] FIG. 2 illustrates an embodiment of the downhole tool 24. In this embodiment, the tool 24 includes one or more sections or assemblies for performing electromagnetic (EM) measurements. For example, the tool 24 is configured as a transient EM (TEM) tool, which may be configured as a logging while drilling (LWD) tool. The TEM tool includes a transmitter that periodically produces fast magnetic dipole reversals that induce eddy currents in the surrounding earth formation. These eddy currents induce voltage in one or more receiver sensors. The received voltage signals are processed to produce a model of the geometrical structure of the resistivity surrounding the borehole. Such models may be used to estimate characteristics of the formation or may be used for steering a drill bit to locate the borehole for maximum hydrocarbon production.

[0022] In one embodiment, the downhole tool 24 includes separate subassemblies or “subs” that incorporate the transmitter and receiver(s). For example, a transmitter sub 32 houses an EM transmitter 34 (including, e.g., a transmitter antenna or coil) and associated electronics, which is configured to transmit EM pulses into the formation and is connected to the transmission line 30. The transmitter sub 32 is connected to a receiver sub 36 that houses

one or more EM receivers 38 and 40 (e.g., receiver coils) and associated electronics, which is configured to receive EM signals from the formation and is also connected to the transmission line 30. The subs 32 and 36 are connected together via connection mechanism 42 (e.g. a pin-box connector). An electric source, which may be disposed downhole or at a surface location, is configured to apply electric current to the transmitter 34 through, e.g., the transmission line 30. Although the subs 32 and 36 are shown in direct connection, they are not so limited, as other subs, pipe sections or tools may be connected between them.

[0023] Although the tool 24, EM transmitter 34 and EM receivers 38 and 40 are described as being incorporated in downhole subs, they may be incorporated into any suitable downhole component, module or other carrier. A "carrier" as described herein means any device, device component, combination of devices, media and/or member that may be used to convey, house, support or otherwise facilitate the use of another device, device component, combination of devices, media and/or member. Exemplary non-limiting carriers include drill strings of the coiled tubing type, of the jointed pipe type and any combination or portion thereof. Other carrier examples include casing pipes, wirelines, wireline sondes, slickline sondes, drop shots, downhole subs, bottom-hole assemblies, and drill strings.

[0024] In one embodiment, the transmitter and the receivers are disposed axially relative to one another. An "axial" location refers to a location along the Z axis that extends along a length of the tool 24 and/or borehole 14. The receiver 40 is positioned at a selected axial distance L_1 from the transmitter 34, and the receiver 38 is positioned at a shorter axial distance L_2 from the transmitter.

[0025] Referring to FIGS. 3 and 4, in one embodiment, the tool 24 includes a communication or telemetry system or apparatus 44 for communication between downhole components or subassemblies that utilizes the data and/or power transmission line 30. In the embodiment shown in FIG. 3, the transmission line 30 is a single conductor bus capable of transmitting power and communications. For example, the transmission line 30 is configured to transmit DC voltage and communications. An exemplary communication scheme incorporates a communications signal (e.g., using frequency shift keying modulation) having a 250 kHz carrier. Digital transmission can be accomplished at, e.g., a 9600 baud rate. The transmission line 30, in this example, powers separate subassemblies on the string 12 by the transmission line 30 with return current through the string 12.

[0026] The EM transmitter sub 32 and the EM receiver sub 34 each include a communication assembly that connects the EM transmitter/receiver electronics to the transmission line 30. For example, the EM transmitter sub 32 includes a synchronization signal generation assembly 46 and the EM receiver sub 34 includes a synchronization signal processing assembly 48. An interface 50 is included in each communication assembly that adds a communication channel to the transmission line 30.

[0027] In one embodiment, each interface 50 is a relatively narrow-band high frequency interface (e.g., around 4 MHz) added between the sub electronics and the transmission line 30. In one embodiment, shown in FIG. 4, the interface 50 is designed with a trap or high frequency band-pass filter 52 to block signals having frequencies corresponding to carrier frequencies used in the transmission line's main communication channel (e.g., around 250 kHz), so that the channel does not interfere with other communications transmitted over the transmission line 30.

[0028] In one embodiment, one of the subassemblies (e.g., the EM transmitter sub 32) is configured as a master subassembly and has the capability to inject signals into the interface 50 to be broadcast to selected subassemblies or individual receivers (e.g., the EM receiver sub 36 or one of the EM receivers 38, 40) over the transmission line 30. The injected narrow-band (e.g., 4 MHz) signals can be either synchronization signals for time synchronization purposes or data transmission signals over the injected carrier.

[0029] For example, the transmitter communication assembly 46 includes a modem 54 for modulating data signals 56 from the transmitter, and a synchronization (sync) signal generator 58 for transmitting synchronization signals. The receiver sub 36 (or each receiver 38 and 40) includes a modem 54 for demodulating data signals and a sync processor 60 for receiving and processing synchronization signals.

[0030] In one embodiment, for time synchronization between transmitters and receivers, the sync generator 58 includes a dual tone signal generator capable of generating tones with fixed phase difference. The sync generator outputs a signal generated by two constituent signals having a fixed initial phase relationship. Each constituent signal has a different frequency or tone. In one embodiment, the constituent signals each have a frequency that falls within the frequency band of the channel added to the transmission line 30 by the interface 50.

[0031] In order to receive the dual tone signal, the sync processor 60 includes a phase sensitive receiver connected to the added channel of the transmission line 30. The sync processor 60 is configured to measure or calculate the difference in phase of the two tones

transmitted by the master subassembly. In one example, the signal processing assembly 48 includes a digitizer followed by a Fourier transform processing routine that measures phase difference of the received tones.

[0032] It is noted that the subassemblies are not limited to the embodiments and configurations described herein. For example, the EM receiver sub 36, described as a synchronization signal receiver in FIG. 3, may be configured as a communication signal transmitter and/or master for communicating the with other subassemblies and/or the EM transmitter sub 32. Likewise, the EM transmitter sub 32 may be configured as a communication signal receiver. In other embodiments, the subassemblies 32, 36 and/or other subassemblies may be configured to both transmit and receive communication signals over the communication line 30. As described herein, “communication signals” refer to signals transmitted directly between downhole components over the transmission line 30, and can be distinguished from power and/or telemetry signals transmitted between downhole components and a surface and/or control unit.

[0033] FIGS. 5-7 illustrate a method for synchronizing components of a borehole string or carrier using signals transmitted over a downhole transmission line, using a one-way synchronization signal. The method includes one or more stages described herein. The method may be performed by one or more processors or other devices capable of receiving and processing measurement data. In one embodiment, the method includes the execution of all of stages in the order described. However, certain stages may be omitted, stages may be added, or the order of the stages changed.

[0034] In the first stage, the borehole string 12, including downhole components such as the EM transmitter sub 32 and the EM receiver sub 36, is lowered in the borehole. The string 12 may be lowered, for example, during a drilling operation, LWD operation or via a wireline.

[0035] In the second stage, the master component (e.g., the EM transmitter sub 32), transmits a synchronization signal to another downhole component (e.g., the EM receiver sub 36). In one embodiment, the master component transmits a trigger signal to the downhole component in addition to the synchronization signal. The trigger signal is a signal indicating a time value associated with the master component. For example, the trigger signal indicates the time value at which the EM

transmitter sub 32 commences transmission of transient EM signals into the formation.

[0036] An exemplary synchronization signal is shown in FIG. 5, which illustrates a dual tone signal 62 including frequencies f_1 and f_2 that is sent from the EM transmitter sub 32 that includes two signals having different frequencies and having a fixed phase relationship. As shown in FIG. 5, the dual tone signal forms a two-tone envelope. Signal 64 is the dual tone signal as received by the EM receiver sub 36 and is used to calculate a transmission delay based on the phase difference, $\phi(f_2) - \phi(f_1)$, between the two frequencies. The trigger signal indicates the time as measured by the transmitter in which the transmitter fired an EM pulse into the formation. For example, the trigger signal indicates that the EM pulse was fired by the transmitter at a time corresponding to a zero-crossing point of a selected cycle of the dual tone envelope, although any temporal point on the dual tone signal may be used to correspond to the trigger time.

[0037] FIG. 6 is a state diagram 70 showing an example of the EM transmitter sub operation during the second stage. At state 71, the sync generator 58 is enabled to generate a dual tone signal with zero phase between tones. After a selected number (N1) of dual tone cycles (state 72), the transient EM transmitter 34 is triggered to emit a series of EM pulses into the formation (state 73). The dual tone signal is transmitted to the EM receiver sub 36 along with a trigger signal indicating the trigger point (e.g., zero crossing at N1 cycle). In state 74, the EM transmitter sub 32 collects data indicating the axis and polarity of each dipole reversal for each pulse. This polarity and axis information is also transmitted to the receiver subassembly over the transmission line 30, using the modem 54 (state 75 and 76).

[0038] In the third stage, the other downhole component (e.g., EM receiver sub 36) receives the trigger signal and the synchronization signal. The time of the trigger is noted, i.e., its position in the synchronization signal, and recording of TEM voltage signals from the formation by the EM receiver 38 or 40 is commenced. In one embodiment, the EM receiver sub 36 includes a circular buffer, and the trigger causes the EM receiver sub 36 to store data from the buffer at the trigger time and record subsequent data as needed. The EM receiver sub 36 also analyzes the synchronization to calculate the time delay τ that corresponds to the amount of time required to transmit the trigger to the EM receiver sub 36. This delay is used to adjust the trigger time for the receiver data so that the received TEM data is synchronized with the transmitter.

[0039] In one embodiment, the receiver calculates the delay τ based on the phase difference between the two tones or frequencies f_1 and f_2 . For example, a fast Fourier

transform (FFT) is used to calculate the phase difference $\phi(f_2) - \phi(f_1)$. The delay may then be calculated based on:

$$\tau = \frac{\phi(f_2) - \phi(f_1)}{2\pi(f_2 - f_1)}.$$

[0040] FIG. 7 is a state diagram 80 showing an example of the receiver subassembly operation during the third stage. In state 81, the EM receiver sub 36 is idle and awaiting a synchronization signal. The EM receiver sub 36 may also receive a trigger signal indicating the trigger point. Upon receiving a dual tone signal, the EM receiver sub 36 waits for N1 cycles, notes the end time of the trigger and commences FFT processing to calculate the delay (state 82). At this point, the EM receiver sub 36 commences recording voltage signals, and may also store data recorded in a buffer. In state 83, the EM receiver sub 36 enables the modem 54 and awaits receipt of data from the EM transmitter sub 32 indicating, e.g., dipole shape, polarity and sensor axis for each pulse. After all TEM voltage signal data has been acquired and information data received, the voltage signal data is matched to the delay and the voltage data is processed (or transmitted to a remote processor) to analyze the formation, e.g., by generating or updating a formation model.

[0041] In the fourth stage, a measurement operation is performed using the transmitter and receiver subassemblies. The measured voltage signals may be transformed, e.g., using a Fourier transform. The measured or transformed signals may be inverted or otherwise analyzed to estimate characteristics of the formation and/or borehole for the purpose of, e.g., formation evaluation and geosteering. For example, measured or transformed frequency domain TEM signals are inverted to provide estimations of formation properties, such as resistivities and distances to interfaces or boundaries in the formation.

[0042] FIGS. 8-10 illustrate embodiments of an interface 50 that allows for electrical and communicative coupling between downhole tools or other components (e.g., the EM transmitter sub 32 and the EM receiver sub 36) and a communication line such as the bus 30. In many configurations, borehole strings such as LWD and wireline tool string include individual subs, modules or other components that are mechanically attached to each other and receive power from the communication line such as the transmission line 30, which may include one or more electrical conductors and/or other components such as optical fibers. The communication line allows the

subs to be in communication with a master controller (e.g., the surface processing unit 28) for sending data, receiving commands from the controller and sending replies. The interface 50 allows individual subs to directly communicate with one another, in contrast to forcing the subs to communicate via the master controller. The interface allows communication modules installed in different and separate subs in the downhole string to communicate directly with each other utilizing an existing single conductor bus or other telemetry configuration without interfering with pre-existing telemetry and power signals already present on the bus.

[0043] In one embodiment, the EM transmitter sub 32 and the EM receiver sub 36 each include a current loop transmitter and/or current loop receiver that form part of a current loop communication system for direct communication between the EM transmitter sub 32 and the EM receiver sub 36 over the communication line. The current loop transmitter is configured to receive a voltage signal (e.g., data, commands or other communications) from the EM transmitter or receiver, convert the sensor signal to a current and inject the current into a current loop formed by the communication line. The current signal generated by the current loop transmitter is tuned to a frequency that is different than the communication line's pre-existing carrier frequency or frequencies.

[0044] An example of a current loop communication configuration is shown in the circuit diagram of FIG. 8. In this example, downhole components such as the EM transmitter sub 32 and the EM receiver sub 36 each include a current loop transceiver 90 connected to the sub electronics and having the capability to both transmit and receive current signals. Each transceiver has a termination network L1, C4, X1, C1 and R1, which is designed to present a low impedance to the transmission line 30 at the carrier frequency (e.g. 4 MHz), but presents a high impedance to the line at all other frequencies (e.g. the preexisting telemetry system 250 kHz carrier frequency).

[0045] A first transceiver 90 (e.g., in the EM transmitter 34) converts voltage signals to current via the low impedance looking into the termination network of a second transceiver 90 through the transmission line 30 and transmits the current to the second transceiver 90 over the communication line 30. The second transceiver 90 (e.g., in the EM receiver 36) receives the current signal and converts the current signal to a voltage signal to be detected by the subassembly electronics. The communication line 30 in this configuration forms part of a current loop at the carrier frequency that includes, e.g., a power supply from the surface processing unit 28, the communication line 30 and return through the borehole string.

[0046] In one embodiment, each transceiver 90 includes circuitry for resonant decoupling of the transceiver from telemetry/power signals transmitted over the

communication line 30. For example, resonant decoupling is achieved for the transceivers via a decoupling capacitor 92 (“C1” in the transmitter sub and “C2” in the receiver sub) and a transformer 94 (“X1” in the transmitter sub and “X2” in the receiver sub). The capacitors 92 allow for elimination of passing DC voltage acting on the bus 30 to the transformer primary winding which could cause excessive power losses and saturate the transformer's core.

[0047] In one embodiment, each transformer 94, together with an inductor 96 (“L1” or “L2”) and an additional capacitor 98 (“C3” or “C4”) forms a high quality band pass filter that can be tuned to the transceiver's operating frequency (e.g., 4 MHz). This also allows for effective suppression of low frequency telemetry signals that may be propagated to the transceiver inputs.

[0048] If the input impedance of a current loop receiver “R” were maintained high, a change of the communication line's impedance could de-tune the above mentioned band pass filter. This impedance change could occur if more downhole subs have been connected to the bus and/or their power/telemetry characteristics changed.

[0049] In one embodiment, to mitigate this issue, the current loop receiver module includes a very low impedance front-end amplifier, i.e., operating as a current amplifier, or in transimpedance mode. In this embodiment, the input impedance of the current loop receiver at the transceiver frequency is negligible while remain sufficiently high for telemetry signals. The transceivers' information is delivered from the current loop transmitter to the current loop receiver by current owing from the current loop transmitter output to the current loop receiver input, and the amount of current diverted to connected extra subs will be in reverse proportion to the ratio of their input impedances to the impedance of the current loop receiver. In this way, additional subs or components added to the communication line 30 do not result in an appreciable change in performance of the current loop.

[0050] The current loop communication system can be configured as a one-way system, where a first component includes only a current loop transmitter and is configured to transmit current signals to a second component that includes only a current loop receiver. In other embodiments, the communication system is configured as a half-duplex or a full-duplex system.

[0051] FIG. 9 shows an exemplary half-duplex arrangement, in which both modules send and receive data at the same frequency, but do so one way at a time.

For example, each transceiver 90 includes circuitry for receiving signals (receiving circuitry 100) and transmitting current signals (transmitting circuitry 102), which are connected to the communication line 30 via a solid state switch 104. Initially and when in stand-by mode, the receiver 100 is connected to the communication line 30. Optionally, one of the transceivers operates as a master and another as a slave. When either of the transceivers 90 needs to transmit data, the switch is actuated (via, e.g., a controller 106 following commands from respective tool's electronics) to connect the transmitting circuitry 102 to the communication line 30.

[0052] FIG. 10 shows an exemplary full-duplex arrangement, in which both modules can exchange data independently and asynchronously. In this example, the receiver 100 in the first component and the transmitter 102 in the second component operate at a first frequency F1, and the receiver 100 in the second component and the transmitter 102 in the first component operate at a first frequency F2.

[0053] The apparatuses and methods described herein provide various advantages over prior art techniques, including providing a method for effective synchronization between downhole components over existing communication/power lines.

[0054] The dual tone synchronization method overcomes disadvantages inherent in prior art methods. For example, for transient EM tools, synchronization of the receiver using the rising edge of voltage signals induced in receiver coils (due to current in the formation induced by the EM transmitter) is possible, however the conductivity of the formation between the transmitter and receiver tends to distort and lengthen the rise time of the rising edge, making synchronization variable, inaccurate and unreliable. Furthermore, this synchronization method can be badly affected by random noise. Algorithms for distinguishing the axis and polarity of dipole reversals by the receiver will likely be complicated and may be unreliable, thus reducing the reliability of a synchronization method using the receiver voltage signals.

[0055] The dual tone synchronization methods overcome these deficiencies and provide an accurate method for time synchronization of transmitters and receivers, e.g., that are placed on separate subassemblies. In addition, the method may be a one-way syncing method that doesn't require two-way communication and handshaking among the affected subassemblies.

[0056] The communication systems and interfaces described herein provide for direct communication between subassemblies by implementing a data channel in a bus or other transmission line that allows for sending high-speed data between subassemblies without

interfering with other telemetry and power signals (e.g., between downhole components and surface units) already present on the transmission line. The systems thus are compatible with current tools without requiring engineering modifications to unaffected tools on the string, and allow for transmission of digital communication so that receiver information can be transmitted to the affected subassemblies. In the case of the transient EM tool, the transmit subassembly needs to send the transmit axis and transmit polarity associated with each dipole reversal.

[0057] For example, in the transient EM tool the transmitter and receiver are located on separate subassemblies that have very limited communication capabilities between them. Typically, separate subassemblies on the drill string are powered by a single common wire or other communication line. It is possible for subassemblies to communicate over this bus over a narrow band data channel around 250 kHz. This channel is not suitable for passing sync signals from transmitter to receiver, since the data channel is dedicated to tool control and data acquisition, and cannot be preempted to pass sync signals. The communication systems and interfaces described herein address these deficiencies by providing for direct communication between subassemblies over the communication line via one or more separate data channels that do not interfere with power and/or telemetry channels.

[0058] Generally, some of the teachings herein are reduced to an algorithm that is stored on machine-readable media. The algorithm is implemented by a computer and provides operators with desired output.

[0059] The systems described herein may be incorporated in a computer coupled to various downhole components, subassemblies and/or surface processing units. Exemplary components include, without limitation, at least one processor, storage, memory, input devices, output devices and the like. As these components are known to those skilled in the art, these are not depicted in any detail herein. The computer may be disposed in at least one of a surface processing unit and a downhole component.

[0060] In support of the teachings herein, various analyses and/or analytical components may be used, including digital and/or analog systems. The system may have components such as a processor, storage media, memory, input, output, communications link (wired, wireless, pulsed mud, optical or other), user interfaces, software programs, signal processors (digital or analog) and other such components (such as resistors, capacitors, inductors and others) to provide for operation and

analyses of the apparatus and methods disclosed herein in any of several manners well-appreciated in the art. It is considered that these teachings may be, but need not be, implemented in conjunction with a set of computer executable instructions stored on a computer readable medium, including memory (ROMs, RAMs), optical (CD-ROMs), or magnetic (disks, hard drives), or any other type that when executed causes a computer to implement the method of the present invention. These instructions may provide for equipment operation, control, data collection and analysis and other functions deemed relevant by a system designer, owner, user or other such personnel, in addition to the functions described in this disclosure.

[0061] While the invention has been described with reference to exemplary embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications will be appreciated by those skilled in the art to adapt a particular instrument, situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

CLAIMS

What is claimed is:

1. A method of synchronization between downhole components, the method comprising:
 - generating a dual tone synchronization signal by a signal generator in a first downhole component disposed in a borehole in an earth formation, the dual tone signal including a first constituent periodic signal having a first frequency f_1 and a second constituent periodic signal having a second frequency f_2 that is different from the first frequency;
 - transmitting the synchronization signal to a second downhole component disposed in the borehole;
 - receiving the synchronization signal by a signal processor in the second downhole component, calculating a phase difference between the first constituent signal and the second constituent signal, and calculating a transmission delay based on the phase difference; and
 - synchronizing operation of the first and second downhole components based on the delay.
2. The method of claim 1, wherein the synchronization signal is transmitted directly to the second downhole component over a transmission line connected between the downhole components and a surface unit.
3. The method of claim 2, wherein the transmission line is a single conductor power and telemetry bus.
4. The method of claim 2, wherein the synchronization signal is transmitted in a first frequency band that is different than a second frequency band used to transmit communications between the surface unit and the downhole components.
5. The method of claim 1, further comprising transmitting a trigger signal from the first downhole component to the second downhole component, the trigger signal indicating a time value measured by the first downhole component.
6. The method of claim 5, wherein the time value is a zero crossing point at a selected cycle of the synchronization signal.
7. The method of claim 5, wherein the first downhole component includes a transient electromagnetic (TEM) transmitter, the second downhole

component includes a TEM receiver, and the trigger signal indicates a time at which the TEM transmitter commences transmitting TEM signals into the earth formation.

8. The method of claim 1, wherein the first downhole component and the second downhole component are connected via a current loop communication system.

9. The method of claim 8, wherein the first downhole component includes a current loop transmitter configured to convert voltage signals from the first downhole component to current signals and transmit the current signals over a current loop formed by the transmission line.

10. An apparatus for communicating between downhole components, comprising: an interface coupled to a first downhole component, the interface configured to communicatively couple the first downhole component to a transmission line and transmit signals to a second downhole component over the transmission line, the interface including a current loop transmitter configured to convert voltage signals from the first downhole component to current signals and transmit the current signals on a current loop formed by the transmission line.

11. The apparatus of claim 10, further comprising a second interface coupled to the second downhole component, the second interface including a current loop receiver configured to convert current signals received from the first downhole component over the transmission line to voltage signals.

12. The apparatus of claim 10, wherein the current loop is formed by the transmission line coupled to a surface power source and a return path formed by a borehole string that includes the downhole components.

13. The apparatus of claim 12, wherein the transmission line is a single conductor power and telemetry bus.

14. The apparatus of claim 12, wherein the current loop transmitter is configured to transmit the current signals in a first frequency band that is different than a second frequency band used to transmit communications between the surface unit and the downhole components.

15. The apparatus of claim 14, wherein the current loop transmitter includes a resonant decoupling device configured to prevent coupling of signals in the second frequency band with the current loop transmitter.

16. The apparatus of claim 14, wherein the current loop transmitter includes a band pass filter tuned to frequencies in the first frequency band.

17. The apparatus of claim 11, wherein the first interface and the second interface are configured to both transmit and receive current loop signals.
18. The apparatus of claim 17, wherein the first interface and the second interface are configured as a half-duplex system to allow for two-way communication.
19. The apparatus of claim 17, wherein the first interface and the second interface are configured as a full-duplex system to allow for simultaneous two-way communication.
20. The apparatus of claim 10, wherein the first downhole component includes a signal generator configured to generate a dual tone synchronization signal, the dual tone signal including a first constituent periodic signal having a first frequency f_1 and a second constituent periodic signal having a second frequency f_2 that is different from the first frequency, and the second downhole component includes a processor configured to receive the synchronization signal, calculating a phase difference between the first constituent signal and the second constituent signal, and calculate a transmission delay based on the phase difference.

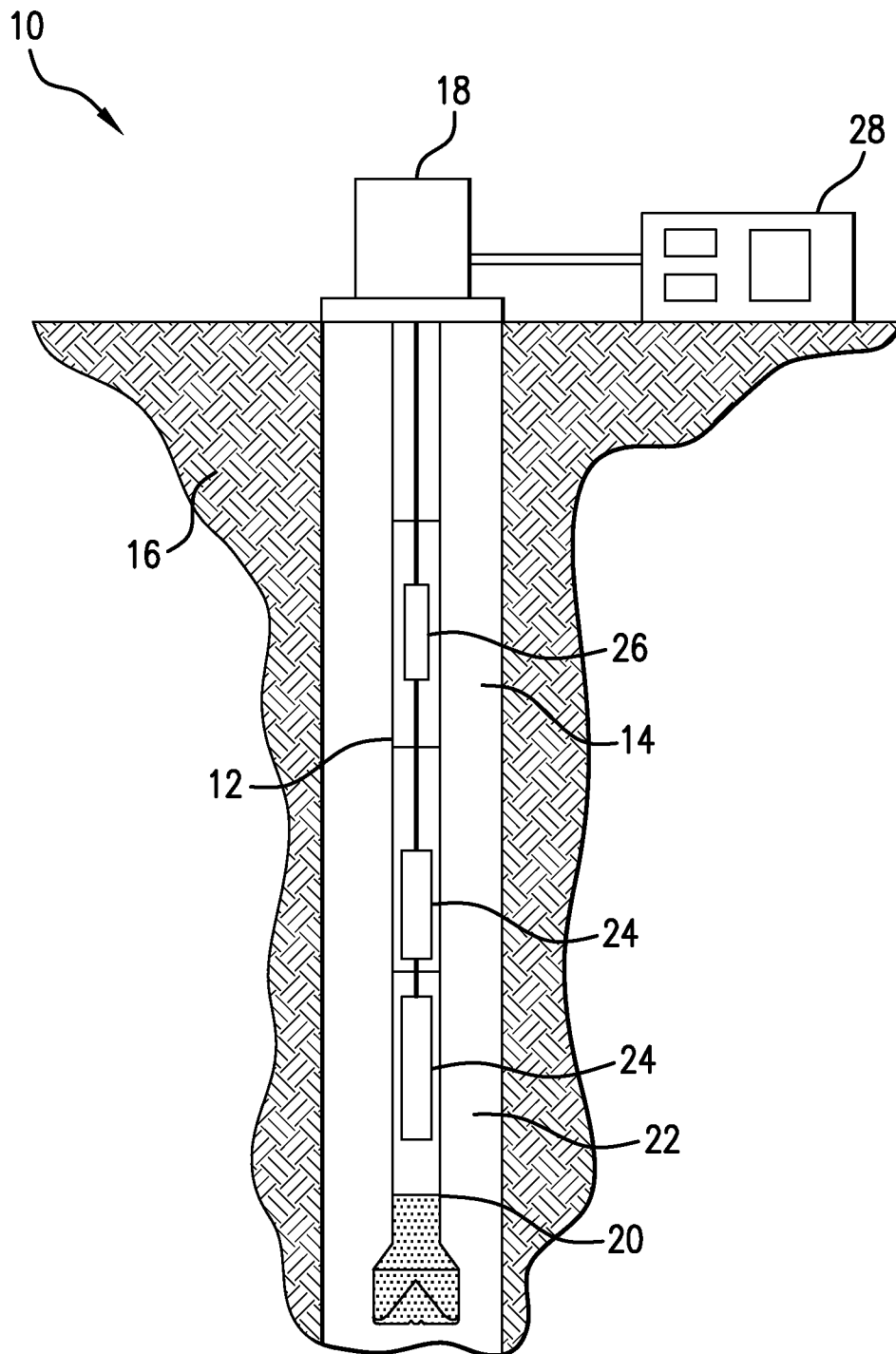


FIG. 1

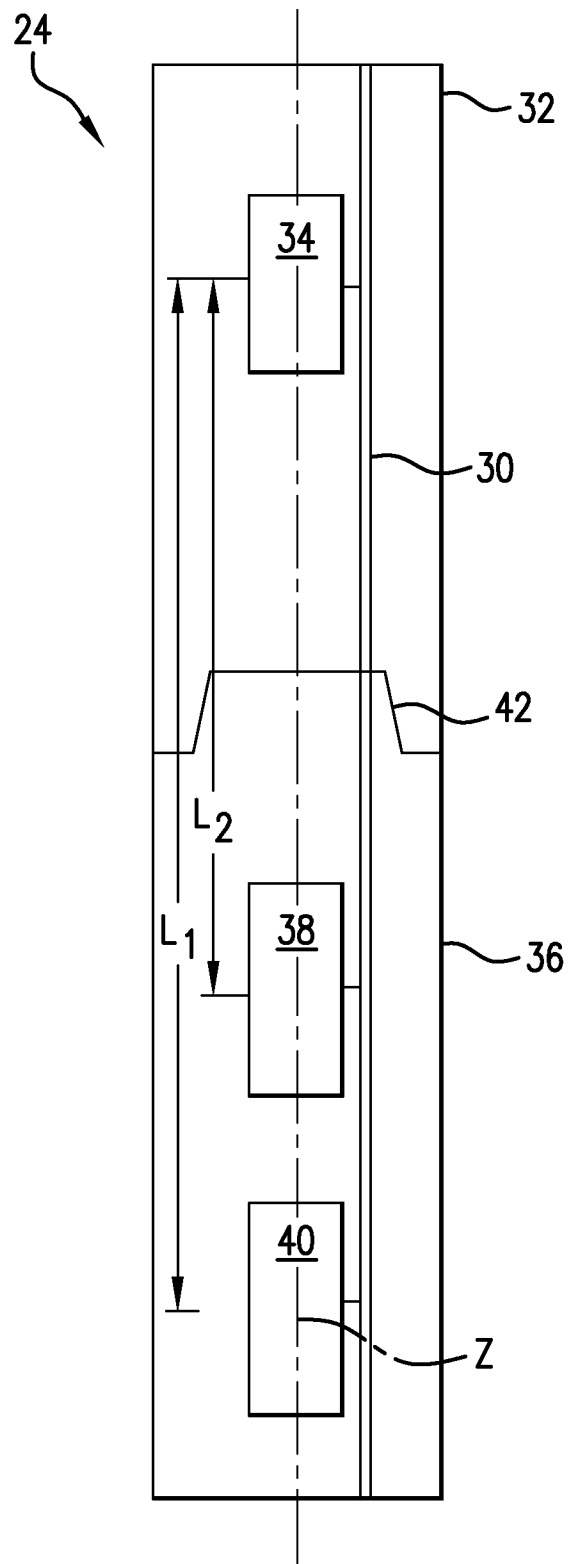
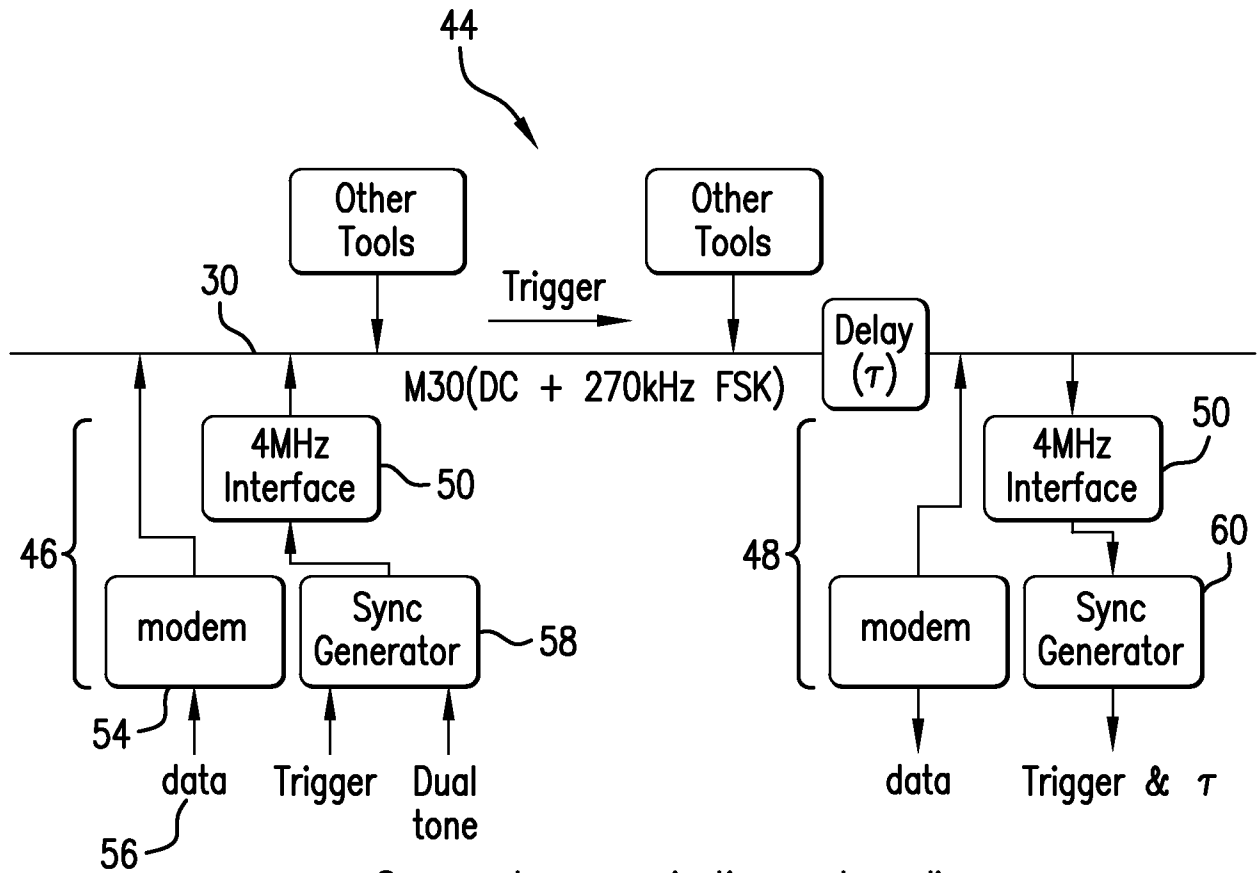
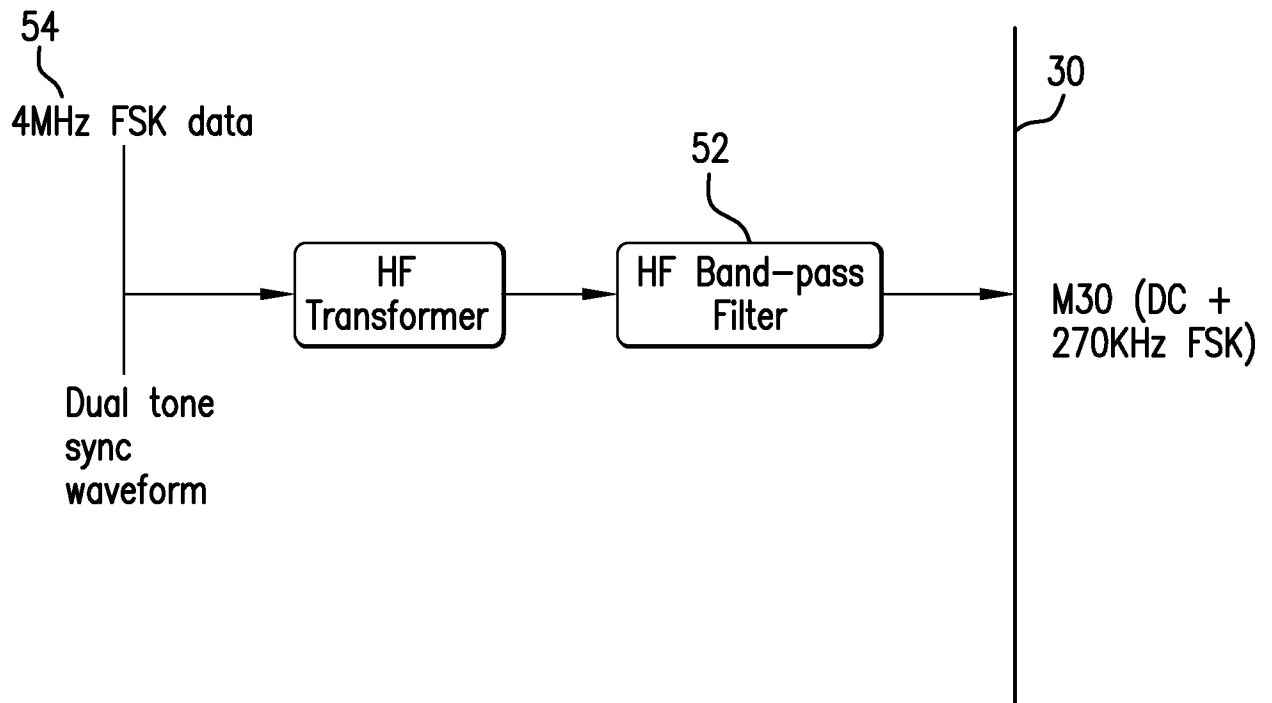


FIG. 2



Sync and communication system diagram

FIG.3



Adam bus 4 MHz interface

FIG.4

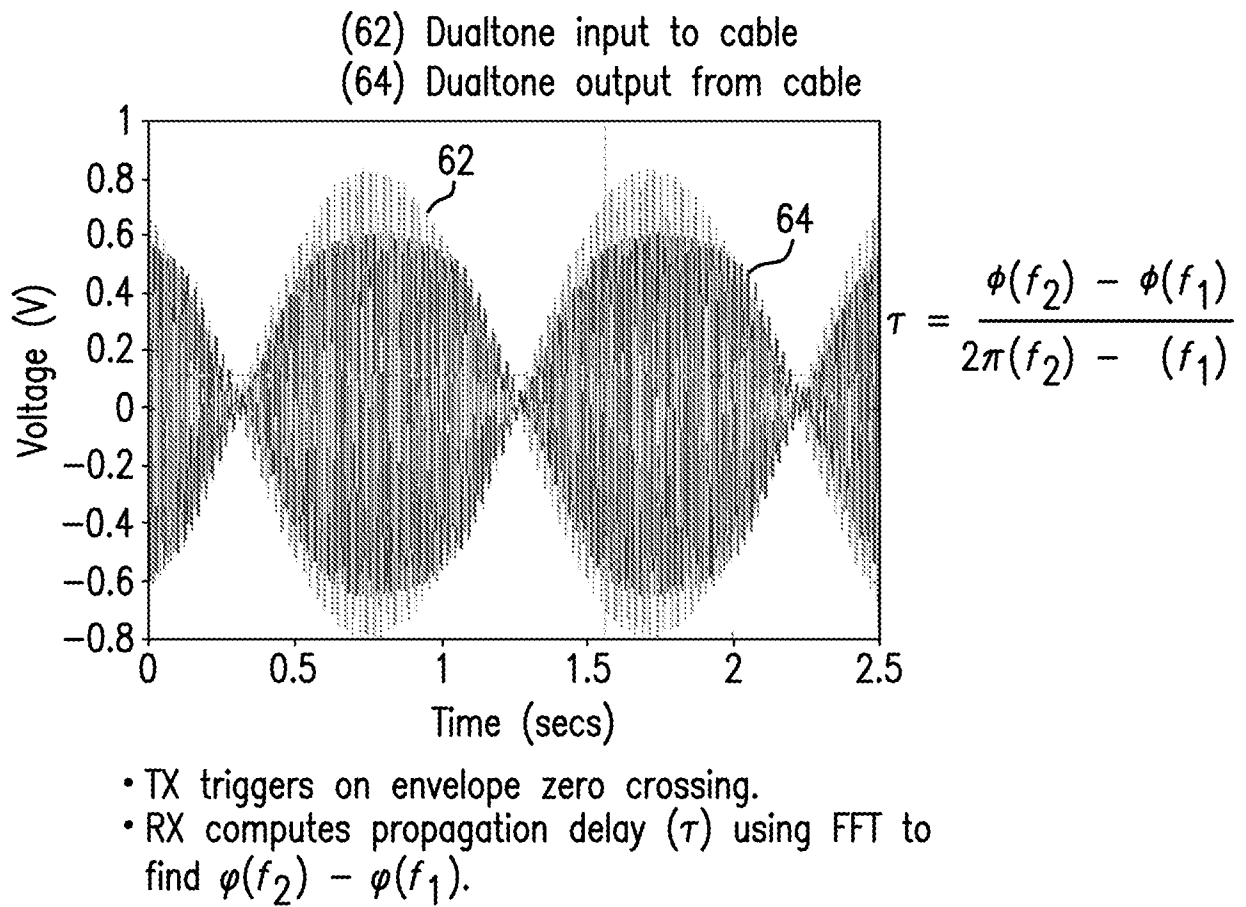


FIG.5

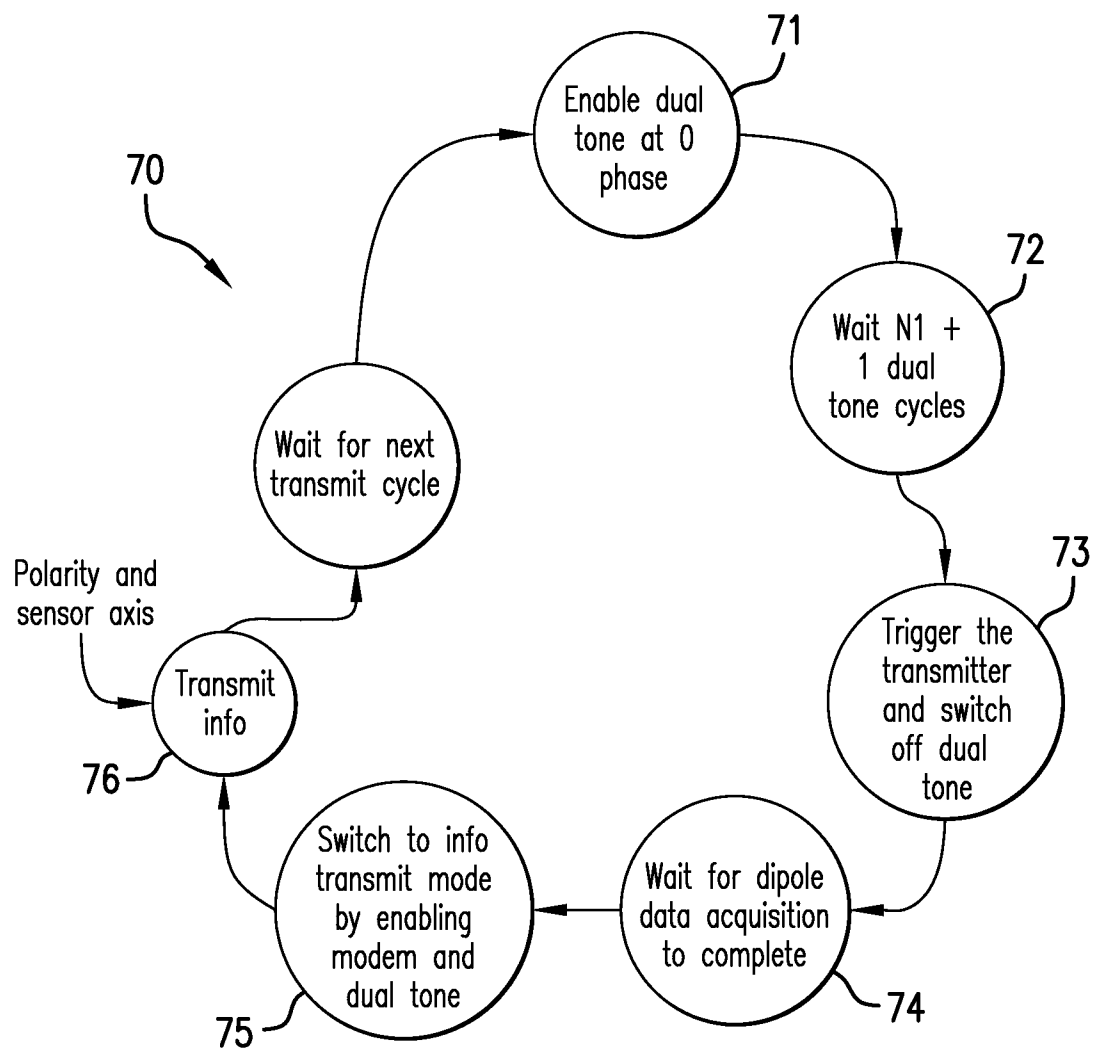


FIG.6

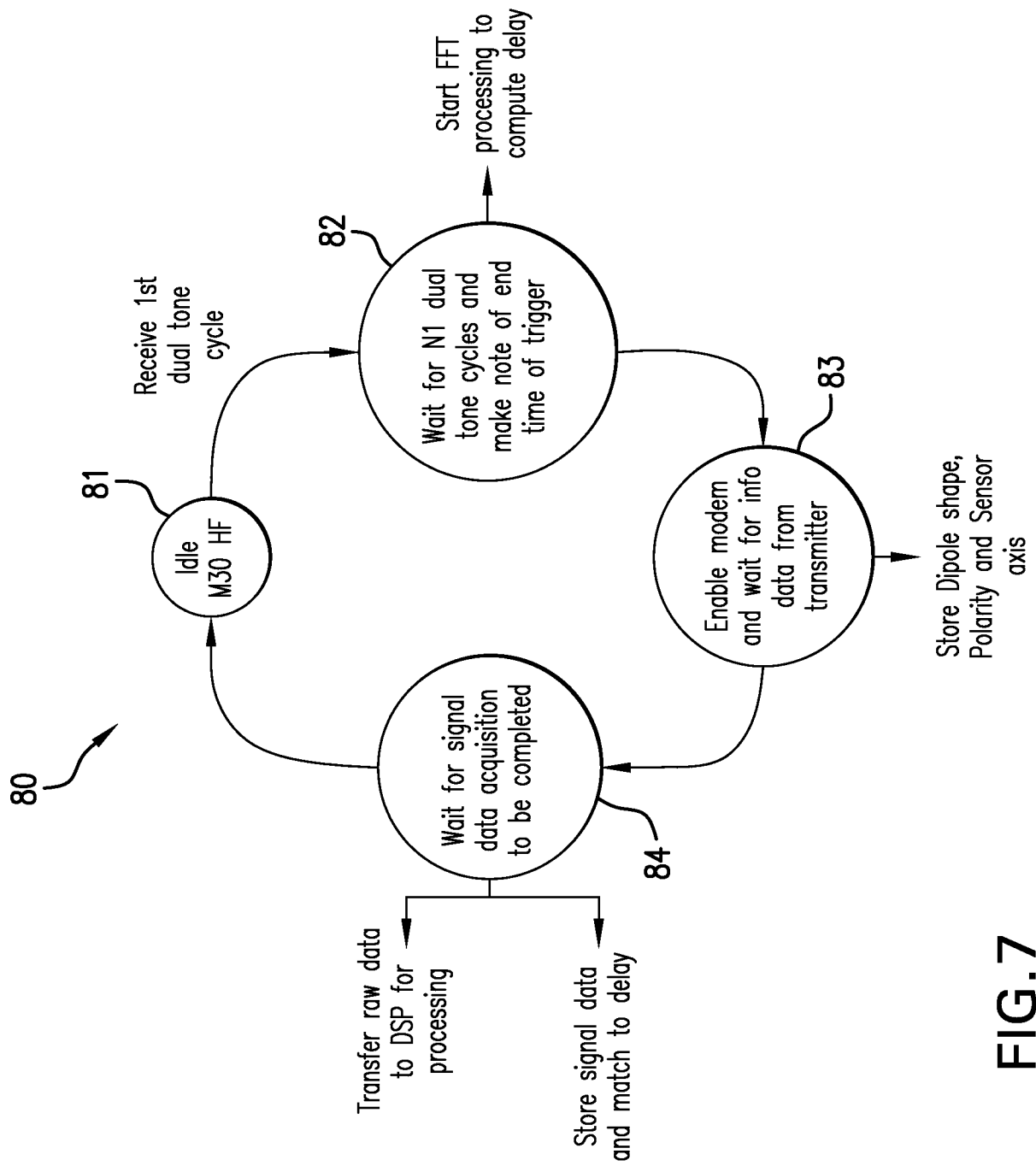


FIG.7

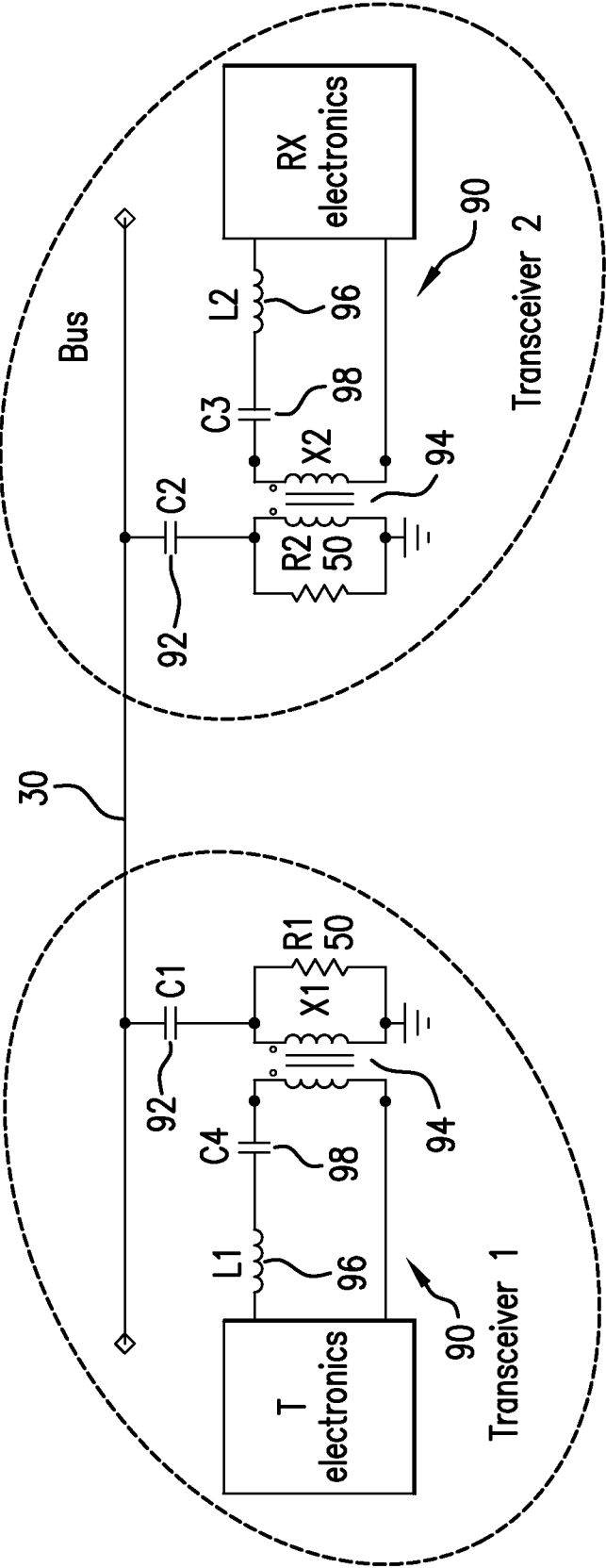


FIG.8

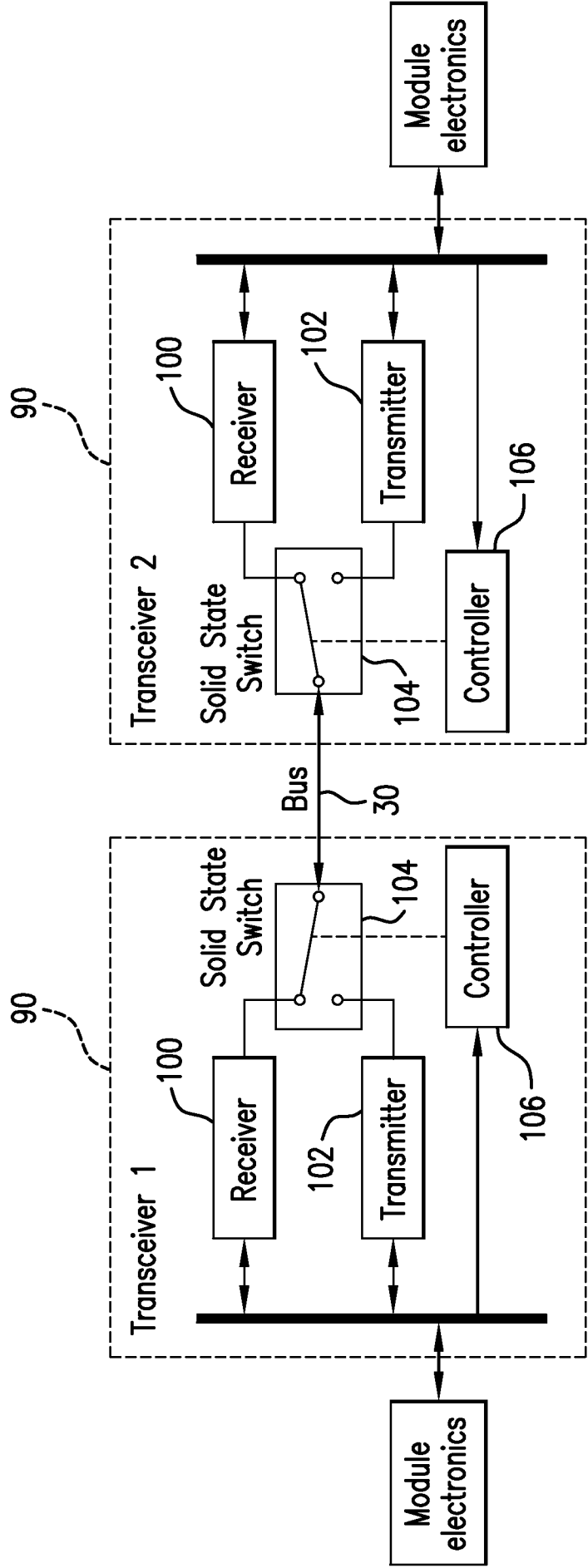


FIG.9

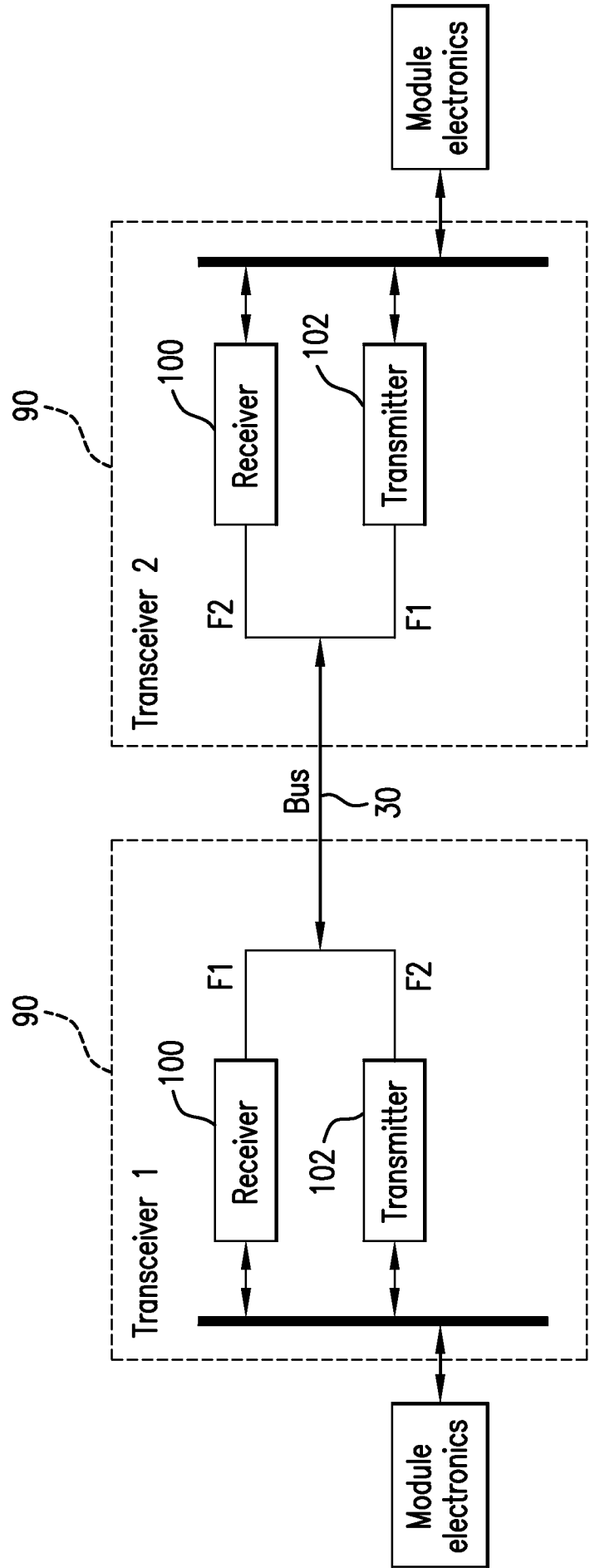


FIG.10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/010449**A. CLASSIFICATION OF SUBJECT MATTER****E21B 47/12(2006.01)i, E21B 47/13(2012.01)i**

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

E21B 47/12; G01V 3/00; E21B 43/00; H04L 7/02; E21B 47/14; E21B 47/13

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: synchronization, downhole component, dual tone, signal generator, frequency, interface, and current loop transmitter

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2011-0309948 A1 (MONTGOMERY et al.) 22 December 2011 See paragraphs [0056]–[0059], [0120]–[0138] and claims 18–20.	1–20
A	US 2012-0250461 A1 (MILLOT et al.) 04 October 2012 See paragraphs [0058]–[0081] and figures 4A–5B.	1–20
A	US 5452761 A (BEARD et al.) 26 September 1995 See abstract, column 2, line 62 - column 4, line 8 and figure 1.	1–20
A	US 2010-0302060 A1 (MONTGOMERY et al.) 02 December 2010 See abstract and paragraphs [0028]–[0034].	1–20
A	US 2012-0026003 A1 (LAYTON, JAMES E.) 02 February 2012 See abstract and claims 1–6, 13–17.	1–20



Further documents are listed in the continuation of Box C.



See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

28 April 2014 (28.04.2014)

Date of mailing of the international search report

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2014/010449

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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