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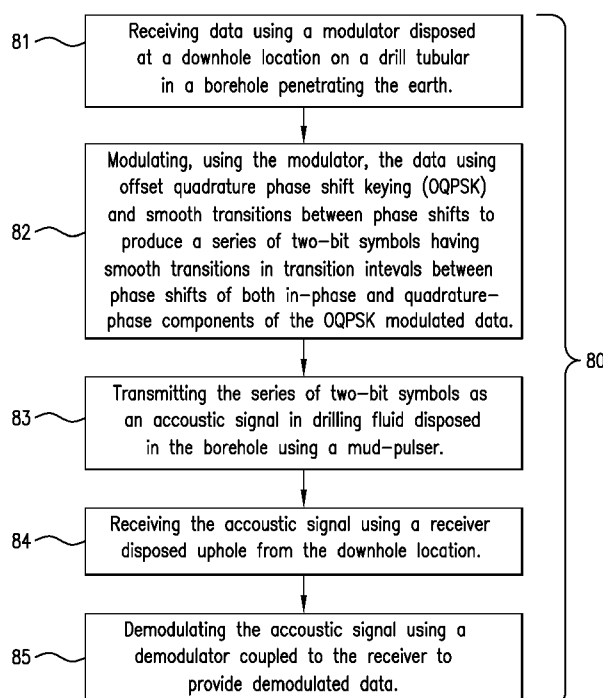
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(54) Title: MODULATION SCHEME FOR HIGH SPEED MUD PULSE TELEMETRY WITH REDUCED POWER REQUIREMENTS



(57) **Abstract:** A method for transmitting data from a down-hole location to a location at the surface of the earth includes: receiving data using a modulator disposed at the downhole location on a drill tubular in a borehole penetrating the earth and modulating the data using offset quadrature phase shift keying (OQPSK) and smooth transitions between phase shifts to produce a series of two-bit symbols having smooth transitions in transition intervals between phase shifts of both in-phase and quadrature-phase components of the OQPSK modulated data. The method further includes transmitting the series of two-bit symbols as an acoustic signal in drilling fluid disposed in the borehole using a mud-pulser, receiving the acoustic signal using a receiver disposed uphole from the downhole location; and demodulating the acoustic signal using a demodulator coupled to the receiver to provide demodulated data.

FIG.8



SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,
GW, KM, ML, MR, NE, SN, TD, TG).

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MODULATION SCHEME FOR HIGH SPEED MUD PULSE TELEMETRY WITH REDUCED POWER REQUIREMENTS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Application No. 14/625813, filed on February 19, 2015, which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] Boreholes are drilled into the earth for many applications such as hydrocarbon production, geothermal production, and carbon dioxide sequestration. In order to efficiently use expensive resources drilling the boreholes, it is important for analysts to acquire detailed information related to the geologic formations being drilled.

[0003] Various types of tools referred to as downhole tools may be conveyed through the boreholes to perform various types of measurements to provide the analysts with the needed information. In order to make efficient use of drilling time, some downhole tools may be disposed on a drill string drilling a borehole so that measurements can be performed while the borehole is being drilled. These types of measurements may be referred to a logging-while-drilling or measurement-while-drilling.

[0004] Once the measurements are obtained, they can be transmitted by telemetry to a receiver at the surface of the earth so that they can be made quickly available to the analysts without having to remove the drill string from the borehole. One type of telemetry for while-drilling applications is mud-pulse telemetry. In mud-pulse telemetry, downhole data is encoded into a digital format and transmitted by acoustic pulses in drilling mud filling the borehole or interior of the drill string. In that energy is expended to transmit the acoustic pulses, it would be appreciated in the drilling industry if method and apparatus were developed to reduce the energy requirements for transmitting data using mud-pulse telemetry.

BRIEF SUMMARY

[0005] Disclosed is a method for transmitting data from a downhole location to a location at the surface of the earth. The method includes: receiving data using a modulator disposed at the downhole location on a drill tubular in a borehole penetrating the earth; modulating, using the modulator, the data using offset quadrature phase shift keying (OQPSK) and smooth transitions between phase shifts to produce a series of two-bit symbols having smooth transitions in transition intervals between phase shifts of both in-phase and

quadrature-phase components of the OQPSK modulated data; transmitting the series of two-bit symbols as an acoustic signal in drilling fluid disposed in the borehole using a mud-pulser; receiving the acoustic signal using a receiver disposed uphole from the downhole location; and demodulating the acoustic signal using a demodulator coupled to the receiver to provide demodulated data.

[0006] Also disclosed is an apparatus for transmitting data from a downhole location on a drill tubular to a location at the surface of the earth. The apparatus includes: a drill tubular disposed in a borehole penetrating the earth and configured to convey drilling fluid; a modulator configured to receive data from the downhole location and to modulate the data using offset quadrature phase shift keying (OQPSK) and smooth transitions between phase shifts to produce a series of two-bit symbols having a smooth transitions in a transition intervals between phase shifts of both in-phase and quadrature-phase components of the OQPSK modulated data; a mud-pulser configured to transmit the series of two-bit symbols as an acoustic signal in drilling fluid disposed in the borehole; a receiver disposed uphole from the downhole location and configured to receive the acoustic signal; and a demodulator coupled to the receiver and configured to demodulate the acoustic signal received by the receiver to provide demodulated data.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The following descriptions should not be considered limiting in any way. With reference to the accompanying drawings, like elements are numbered alike:

[0008] FIG. 1 illustrates a cross-sectional view of an embodiment of a downhole while-drilling tool disposed in a borehole penetrating the earth;

[0009] FIG. 2 depicts aspects of a mud-pulser having a plunger;

[0010] FIGS. 3A-3C, collectively referred to as FIG. 3, depict aspects of a mud-pulser having a rotating or oscillating disc;

[0011] FIG. 4 depicts aspects of offset quadrature phase shift keying (OQPSK);

[0012] FIGS. 5A-5B, collectively referred to as FIG. 5, depicts aspects of smooth transitions in transition intervals between symbols in OQPSK;

[0013] FIG. 6 depicts further aspects of smooth transitions in transition intervals between symbols in OQPSK;

[0014] FIG. 7 is a functional block diagram of one embodiment of the mud-pulse telemetry system 100; and

[0015] FIG. 8 is a flow chart for a method for transmitting data from a downhole location on a drill string to a location at the surface of the earth.

DETAILED DESCRIPTION

[0016] A detailed description of one or more embodiments of the disclosed apparatus and method presented herein by way of exemplification and not limitation with reference to the figures.

[0017] Disclosed are method and apparatus for transmitting data from a downhole tool disposed on a drill string to a receiver at the surface of the earth using mud-pulse telemetry. The method and apparatus use less energy to transmit the same amount of data as prior art techniques.

[0018] FIG. 1 illustrates a cross-sectional view of an embodiment of a downhole tool 10 disposed in a borehole 2 penetrating the earth 3, which includes an earth formation 4. The downhole tool 10 is conveyed through the borehole 2 by a drill tubular 5 such as jointed drill pipe or coiled tubing for example. A drill bit 6 is disposed at the distal end of the drill tubular 5. A drill rig 7 is configured to conduct drilling operations such as rotating the drill tubular 5 and thus the drill bit 6 in order to drill the borehole 2. In addition, the drill rig 8 is configured to pump drilling fluid 13, also referred to as drilling mud, through the drill tubular 5 in order to lubricate the drill bit 6 and flush cuttings from the borehole 2. The downhole tool 10 may include one or more various tools for performing various downhole functions. The tools may include a sensor 8 or formation tester 9 as non-limiting examples. The sensor 8 may be configured to sense various downhole properties such a borehole property, a formation property or a tool property. The formation tester 9 includes an extendable probe 11 configured to seal to a wall of the borehole 2 and extract a sample of formation fluid for analysis downhole or in a surface laboratory. Various sensors in the formation tester may be configured to perform different types of measurements on the sample. Non-limiting examples of the measurements performed by the formation tester 9 or by the sensor 8 include pressure, temperature, density, viscosity, compressibility, radiation, and spectroscopy using optical transmissivity or reflectivity for example.

[0019] Data sensed or collected downhole (i.e., in the borehole) is transmitted to the surface of the earth 3 by a mud-pulser 12 that is configured to transmit an acoustic signal in the drilling fluid 13. At the surface, the acoustic signal is received by a receiver 17. The mud-pulser 12 includes a modulator 14 and downhole electronics 15. The modulator 14 is configured to receive a bit stream that is composed of data received from the various tools in

the downhole tool 10 and to modulate the bit stream into a digital signal. The downhole electronics 15 are configured to operate the mud-pulser 12 to transmit the digital signal as an acoustic pressure signal in the drilling fluid 13. The downhole electronics 15 may also be configured to process data downhole in order to minimize the amount of data needed to be transmitted via the modulator 14. Alternatively or in addition, data processing functions may be performed by a surface computer processing system 16. The downhole tool 10 may also include memory (not shown) for storing measurements that cannot be immediately transmitted to the computer processing system 16 because of limited telemetry bandwidth. A power supply 18 such as a battery or mud turbine powered generator for example supplies power for operation of the mud-pulser 12.

[0020] The receiver 17 is configured to receive the acoustic pressure signal using a transducer 19. The transducer 19 is configured to convert the received acoustic signal into an electrical signal that can be processed. The receiver 17 further includes a demodulator 29 configured to demodulate the acoustic pressure signal into a bit stream that includes the downhole data. The bit stream after further processing is in a format for displaying, storing, or further processing such as by the computer processing system 16. In one or more embodiments, the computer processing system 16 may be configured to perform the demodulating function.

[0021] FIG. 2 depicts further aspects of the mud-pulser 12 in a simplified embodiment. In the embodiment of FIG. 2, the mud-pulser 12 is a plunger-type mud-pulser that includes a plunger 21 that is configured to move back and forth in a reciprocating motion with respect to a seat 22. The reciprocating motion with respect to the seat 22 reduces the flow cross-sectional area so as to increase the pressure drop across the mud-pulser 12 and thereby cause acoustic pulses to be emitted into the drilling fluid 13. An actuator 20 is coupled to the plunger 21 and is configured to cause the reciprocating motion of the piston in accordance with a control signal received from the downhole electronics 15. The desired acoustic pressure signal may be a phase modulated sinusoidal signal. Instantaneous frequency can be changed in order to provide phase. The actuator 20 receives power from the power supply 18. It can be appreciated that the actuator 20 can be implemented in various configurations, such as using a shear valve, in order to emit acoustic pulses into the drilling fluid 13 that travel to the surface of the earth.

[0022] FIG. 3 is a schematic view of an oscillating or rotating shear valve-type pulser 30 for mud pulse telemetry. The pulser assembly 30 is located in the inner bore of a tool housing 101. The housing 101 may be a bored drill collar in the downhole tool (or bottom

hole assembly) 10, or, alternatively, a separate housing adapted to fit into a drill collar bore. The drilling fluid 13 flows through a stator 102 and a rotor 103 and passes through the annulus between pulser housing 108 and the inner diameter of the tool housing 101. The stator 102 (see FIGS. 3A and 3B) is fixed with respect to the tool housing 101 and to the pulser housing 108 and has multiple lengthwise flow passages 120. The rotor 103 (see FIGS. 3A and 3C) is disk shaped with notched blades 130 creating flow passages 125 similar in size and shape to the flow passages 120 in the stator 102. Alternatively, the flow passages 120 and 125 may be holes through the stator 102 and the rotor 103, respectively. The rotor passages 125 are configured such that they can be aligned, at one angular position with the stator passages 120 to create a straight through flow path. The rotor 103 is positioned in close proximity to the stator 102 and is adapted to rotationally oscillate or rotate. An angular displacement of the rotor 103 with respect to the stator 102 changes the effective flow area creating pressure fluctuations in the circulated mud column.

[0023] As disclosed herein, the modulator 14 implements a digital modulation method referred to as Offset Quadrature Phase Shift Keying (OQPSK). FIG. 4 depicts aspects of OQPSK as known in the art of digital radio communications. Due to fast acting electronics and radio waves not having mass, phase shifts such as at T are near-instantaneous and the radio waves have jumps where the first derivative of electromagnetic wave amplitude is not continuous over the phase change. For teaching and comparison purposes, aspects of quadrature phase shift keying (QPSK) from which OQPSK is derived are also depicted and discussed further below. Both OQPSK and QPSK transmit a series of two-bit symbols corresponding to four different signal phases (00, 01, 10, 11).

[0024] QPSK requires changing the phase of the signal via in-phase (I) and the quadrature-phase (Q) for which the possible phase shifts are 0° , $\pm 90^\circ$, and 180° . Increasing the number of phase shifts to what is required for QPSK raises the number of needed transitions. As QPSK has four different symbols, then 16 different phase shifts are required, which correspondingly require different transition frequencies; the transition either from '01' to '10' or vice versa requires a high transition frequency. Increasing the carrier frequency is needed because changing from '01' to '10' or vice versa requires changing the 'I', and 'Q' phases at the same time. Use of OQPSK decreases the power requirements over QPSK by not requiring the high transition frequency while increasing the data transmission rate over other prior art digital modulation techniques such as Binary Phase Shift Keying (BPSK).

[0025] OQPSK depends on introducing a delay (i.e., offset) for one of the two signal phases either the I-phase or the Q-phase. Adding the delay or offset to one phase guarantees that 'I' and 'Q' phases will never change together at the same time, accordingly phase transitions will be limited to 0° and $\pm 90^\circ$ only and does not have a phase shift of 180° as in QPSK. This delay is observed as a delay in the Q-phase as illustrated in FIG. 3. The added delay for the Q-phase will ensure that only one bit can change sign at a given time, which will not allow changing from '01' to '10' or vice versa. Accordingly, the high transition frequency will not be needed any more which enhances the signal spectrum and reduces the power requirements, thus, providing more operational time for a power source having a fixed amount of energy. Based on FIG. 4, OQPSK has more frequent phase shifts than QPSK, but with less degree values. In addition, OQPSK has the same data rate and bit-error-rate (BER) capabilities as QPSK, assuming the same signal power and bandwidth.

[0026] Because the mud-pulser 12 has a moveable element such as the plunger 21, which has mass, the plunger 21 cannot change position or velocity instantaneously or near-instantaneously as electronics for modulating an electromagnetic radio wave. Accordingly, no sudden changes are possible to the acoustic signal or to its first derivative (velocity). The moving element changes its velocity by accelerating for a longer time period, so it can only create a continuous phase moving in the transient between adjacent symbols. Hence, the design of the trajectory of the transient to be followed by the actuator has to be specified. As disclosed herein, OQPSK is implemented for acoustic communication by inserting a transition phase in a transition interval between adjacent symbols as illustrated in FIG. 5. FIG. 5A illustrates an ideal OPSK modulated signal while FIG. 5B illustrates an ideal OQPSK modulated signal and an OQPSK modulated signal with smooth transitions. In the transition intervals illustrated in FIG. 5B, the instantaneous frequency (i.e., frequency representing a two-bit symbol) is changed to perform a phase shift. The solid line in the transition intervals represents an ideal phase shift, while the dotted line in the transition interval represents the phase shift via an increase in instantaneous frequency. Hence, the first time interval has one distinct frequency while the second time interval has another distinct frequency that is lower than the frequency in first time interval in this example performing the phase shift, then in the third time interval the frequency changes back to the frequency from the first time interval with different phase. This results in smooth transitions that have a continuous first derivative of the signal amplitude with respect to time throughout symbol changes. In one or more embodiments, the width or time of the transition interval is fixed so

that the demodulator 29 can regain the information modulated in the acoustic signal at specific points in time. FIG. 6 depicts aspects of an OQPSK modulated signal having three phase shifts with smooth transitions. In the embodiment of FIG. 6, the frequency of the signal in the second and fourth time intervals is half the frequency of the signal in the first and third time intervals.

[0027] There are several advantages to using QPSK or OQPSK over other digital modulation techniques for digital encoding for acoustic signal transmission. While BPSK transmits one bit per symbol, QPSK and OQPSK transmit two bits per symbol corresponding to four different phases (00, 01, 10, 11). Accordingly, the data rate can be doubled at the same symbol rate. QPSK and OQPSK can give the same BER as for BPSK in case of doubling the energy used per symbol, which means the same energy per bit is maintained. Accordingly, increasing the data rate, with the same BER of BPSK comes at the cost of doubled transmitted power.

[0028] However, QPSK has a drawback. As noted above, QPSK requires changing the phase of the signal via in-phase (I) and the quadrature phase (Q) for which the possible phase shifts are 0° , $\pm 90^\circ$, and 180° . Increasing the number of phase shifts to what is required for QPSK raises the number of needed transitions. As QPSK has four different symbols (00, 01, 10, 11), then 16 different phase shifts exist, which require correspondingly different transition frequencies; the transition either from '01' to '10' or vice versa requires a high transition frequency. Increasing the transition frequency is needed, because changing from '01' to '10' or vice versa requires changing the 'I', and 'Q' phases at the same time. OQPSK overcomes this drawback (by not transitioning from '01' to '10' or '10' to '01') in addition to having the same benefits of QPSK such as - a higher possible data transmission rate and similar BER as for BPSK assuming doubling the energy per symbol. Thus, OQPSK decreases the values of the transition frequencies needed for QPSK and consequently decreases the power requirements for OQPSK.

[0029] Accordingly, the power saved by using OQPSK may also be used for increasing the energy used per transmitted bit and thus the signal-to-noise ratio. Higher energy per bit can be achieved by reducing the data transmission rate to be the same as for BPSK, and using the saved power from the reduced transmission rate for increasing the signal power.

[0030] A Forward Error Correction method can be combined with the proposed OQPSK method for reducing bit error rate. Error coding methods add error detection and

correction capabilities to the disclosed telemetry system in order to increase the reliability of the system. Different error coding methods (i.e. block codes, cyclic codes, convolutional codes, and Reed-Solomon) may be combined with OQPSK. As one example, Turbo codes, which are based on convolutional coding, are considered for use with OQPSK. With respect to Turbo/Convolutional code, Convolutional coding can be used to protect the data on the bit level, which performs encoding bit by bit. Accordingly the decoder should not buffer an entire block before generating the associated code-word. Convolutional coding is relevant to the present telemetry system which has bits transmitted and received serially rather than in large block. Convolutional code is specified by three parameters (n , k , K), where k/n is the *code rate* and determines the number of data bits per coded bit. K is called the *constraint length* of the encoder where the encoder has $K-1$ memory elements. The convolutional encoder can be represented in the form of a state diagram that provides outputs S_1 and S_2 where the encoder manipulates the incoming data to provide the S_1 and S_2 outputs. Convolutional codes also can be done in a recursive systematic manner (RSC) in which S_1 is not affected by the encoder, but is the input data stream. Generally, Recursive encoders provide better weight distribution for the code. The difference between them is in the mapping of information bits to code-words. The idea of recursive systematic encoders is used for the turbo coders, where two component RSC encoders in parallel are used separated by an interleaver. The two RSC component encoders are usually identical. The interleaver is used to de-correlate the encoding process of the two encoders. As the number of iteration grows, the decoding performance improves. Alternatively, the two RSC encoders can be replaced also in a series.

[0031] FIG. 7 is a functional block diagram of one embodiment of a mud pulse telemetry system 100. As shown therein, data from downhole sensors (DATA IN) are input to the mud pulse telemetry system 100. The mud pulse telemetry system 100 contains circuits and a processor for processing and transmitting the data to the surface. In the downhole system, the data is compressed. The compression scheme 40 may encompass data scaling and/or any data compression technique known in the art of digital information transmission. Optionally, the compressed data may be error protection encoded (41) by an encoder 41 before it is modulated (42) and converted to an acoustic signal by the transmitter (43) such as a mud-pulser valve. The acoustic signal then propagates to surface through the mud channel 50 where it is received and digitized by the receiver 44 such as a transducer. Optionally, the digitized signal (i.e., electrical digital signal) may then be pre-processed to remove noise (block 45) and reduce signal distortions (block 46) caused by the mud channel

50. Subsequently, the signal is de-modulated (47), error protection decoded (48) by a decoder 48 and decompressed (49) to provide output data (DATA OUT).

[0032] FIG. 8 is a flow chart for a method 80 for transmitting data from a downhole location to a location at the surface of the earth. Block 81 calls for receiving data using a modulator disposed at the downhole location on a drill tubular in a borehole penetrating the earth. Block 82 calls for modulating, using the modulator, the data using offset quadrature phase shift keying (OQPSK) and smooth transitions between phase shifts to produce a series of two-bit symbols having smooth transitions in transition intervals between phase shifts of both in-phase and quadrature-phase components of the OQPSK modulated data. The transition intervals may be of the same time duration or two or more transition intervals may have different time durations. A smooth transition may be characterized by a change of instantaneous frequency of the acoustic signal and one or more of the smooth transitions may be characterized by a continuous first derivative of amplitude with respect to time. Block 83 calls for transmitting the series of two-bit symbols as an acoustic signal in drilling fluid disposed in the borehole using a mud-pulser. Block 84 calls receiving the acoustic signal using a receiver disposed uphole from the downhole location. The term “uphole” relates to the receiver being closer to the surface of the earth via the borehole. Block 85 calls for demodulating the acoustic signal using a demodulator coupled to the receiver to provide demodulated data. The method 80 may also include transmitting the demodulated data to a signal receiving device such as a display or printer for displaying the data to a user or a storage medium or memory for storing the data.

[0033] The method 80 may also include (1) applying forward error correction encoding before modulating the data using an encoder such as at 41 in FIG. 7 and (2) applying forward error correction decoding to the demodulated data uphole of the downhole location using a decoder such as at 48 in FIG. 7. In one or more embodiments, the forward error correction encoding is turbo coding. The method 80 may also include sensing a downhole property using a downhole sensor and transmitting sensed data to the encoder. The method 80 may further include extracting a sample of formation fluid using an extendable probe, sensing a property of the formation fluid using the downhole sensor to provide sensed formation fluid data, and transmitting the sensed formation fluid data to the modulator. The method 80 may also include generating a two-dimensional image representation of the sensed data before transmitting the sensed data to the modulator.

[0034] In support of the teachings herein, various analysis components may be used, including a digital and/or an analog system. For example, the mud-pulse telemetry system

100, the downhole tool 10, the downhole sensor 8, the formation tester 9, the mud-pulser 12, the modulator 14, the downhole electronics 15, the receiver 17, the transducer 19, the demodulator 29, the encoder 41, the decoder 48, and/or the computer processing system 16 may include digital and/or analog systems. The system may have components such as a processor, storage media, memory, input, output, communications link (wired, wireless, optical or other), user interfaces (e.g., a display or printer), 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 non-transitory 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.

[0035] Further, various other components may be included and called upon for providing for aspects of the teachings herein. For example, a power supply (e.g., at least one of a generator, a remote supply and a battery), cooling component, heating component, magnet, electromagnet, sensor, electrode, transmitter, receiver, transceiver, antenna, controller, optical unit, electrical unit or electromechanical unit may be included in support of the various aspects discussed herein or in support of other functions beyond this disclosure.

[0036] Elements of the embodiments have been introduced with either the articles “a” or “an.” The articles are intended to mean that there are one or more of the elements. The terms “including” and “having” and the like are intended to be inclusive such that there may be additional elements other than the elements listed. The conjunction “or” when used with a list of at least two terms is intended to mean any term or combination of terms. The term “configured” relates one or more structural limitations of a device that are required for the device to perform the function or operation for which the device is configured. The terms “first,” “second,” and the like do not denote a particular order, but are used to distinguish different elements.

[0037] The flow diagram depicted herein is just an example. There may be many variations to this diagram or the steps (or operations) described therein without departing from the spirit of the invention. For instance, the steps may be performed in a differing order,

or steps may be added, deleted or modified. All of these variations are considered a part of the claimed invention.

[0038] While one or more embodiments have been shown and described, modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustrations and not limitation.

[0039] It will be recognized that the various components or technologies may provide certain necessary or beneficial functionality or features. Accordingly, these functions and features as may be needed in support of the appended claims and variations thereof, are recognized as being inherently included as a part of the teachings herein and a part of the invention disclosed.

[0040] While the invention has been described with reference to exemplary embodiments, it will be understood 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 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 (80) for transmitting data from a downhole location to a location at the surface of the earth (3), the method (80) characterized by:

receiving data using a modulator (14) disposed at the downhole location on a drill tubular (5) tubular in a borehole (2) penetrating the earth (3) ;

modulating, using the modulator, the data using offset quadrature phase shift keying (OQPSK) and smooth transitions between phase shifts to produce a series of two-bit symbols having smooth transitions in transition intervals between phase shifts of both in-phase and quadrature-phase components of the OQPSK modulated (42) data;

transmitting the series of two-bit symbols as an acoustic signal in drilling fluid disposed in the borehole (2) using a mud-pulser (12) ;

receiving the acoustic signal using a receiver (17, 44) disposed uphole from the downhole location; and

demodulating the acoustic signal using a demodulator (29) coupled to the receiver (17, 44) to provide demodulated (47) data.

2. The method (80) according to claim 1, wherein one or more of the smooth transitions is characterized by a continuous first derivative of amplitude with respect to time.

3. The method (80) according to claim 1, wherein a smooth transition comprises a change of instantaneous frequency of the acoustic signal.

4. The method (80) according to claim 1, wherein each of the transition intervals are of the same duration.

5. The method (80) according to claim 1, wherein at least two transition intervals have different time durations.

6. The method (80) according to claim 1, further comprising applying forward error correction encoding before modulating the data.

7. The method (80) according to claim 6, wherein the forward error correction encoding comprises turbo coding.

8. The method (80) according to claim 6, further comprising applying forward error correction decoding to the demodulated (47) data uphole of the downhole location.

9. The method (80) according to claim 1, further comprising sensing a downhole property using a downhole sensor (8) and transmitting sensed data to the modulator.

10. The method (80) according to claim 9, further comprising extracting a sample of formation fluid using an extendable probe (11) , sensing a property of the formation fluid

using the downhole sensor (8) to provide sensed formation fluid data, and transmitting the sensed formation fluid data to the modulator.

11. An apparatus for transmitting data from a downhole location on a drill tubular (5) tubular to a location at the surface of the earth (3), the apparatus characterized by:

a drill tubular (5) tubular disposed in a borehole (2) penetrating the earth (3) and configured to convey drilling fluid;

a modulator (14) configured to receive data from the downhole location and to modulate the data using offset quadrature phase shift keying (OQPSK) and smooth transitions between phase shifts to produce a series of two-bit symbols having a smooth transitions in a transition intervals between phase shifts of both in-phase and quadrature-phase components of the OQPSK modulated (42) data;

a mud-pulser (12) configured to transmit the series of two-bit symbols as an acoustic signal in drilling fluid disposed in the borehole (2) ;

a receiver (17, 44) disposed uphole from the downhole location and configured to receive the acoustic signal; and

a demodulator (29) coupled to the receiver (17, 44) and configured to demodulate the acoustic signal received by the receiver (17, 44) to provide demodulated (47) data.

12. The apparatus according to claim 11, wherein the mud-pulser (12) comprises a plunger (21) configured to interface with the drilling fluid to transmit the acoustic signal.

13. The apparatus according to claim 11, wherein the mud-pulser (12) comprises a rotating or oscillating disc configured to interface with the drilling fluid to transmit the acoustic signal.

14. The apparatus according to claim 11, further comprising an encoder (41) configured to apply a forward error correcting code before the data is modulated (42) by the modulator.

15. The apparatus according to claim 11, further comprising a sensor (8) disposed on the drill tubular (5) tubular and configured to sense a downhole property and transmit sensed property data to the modulator.

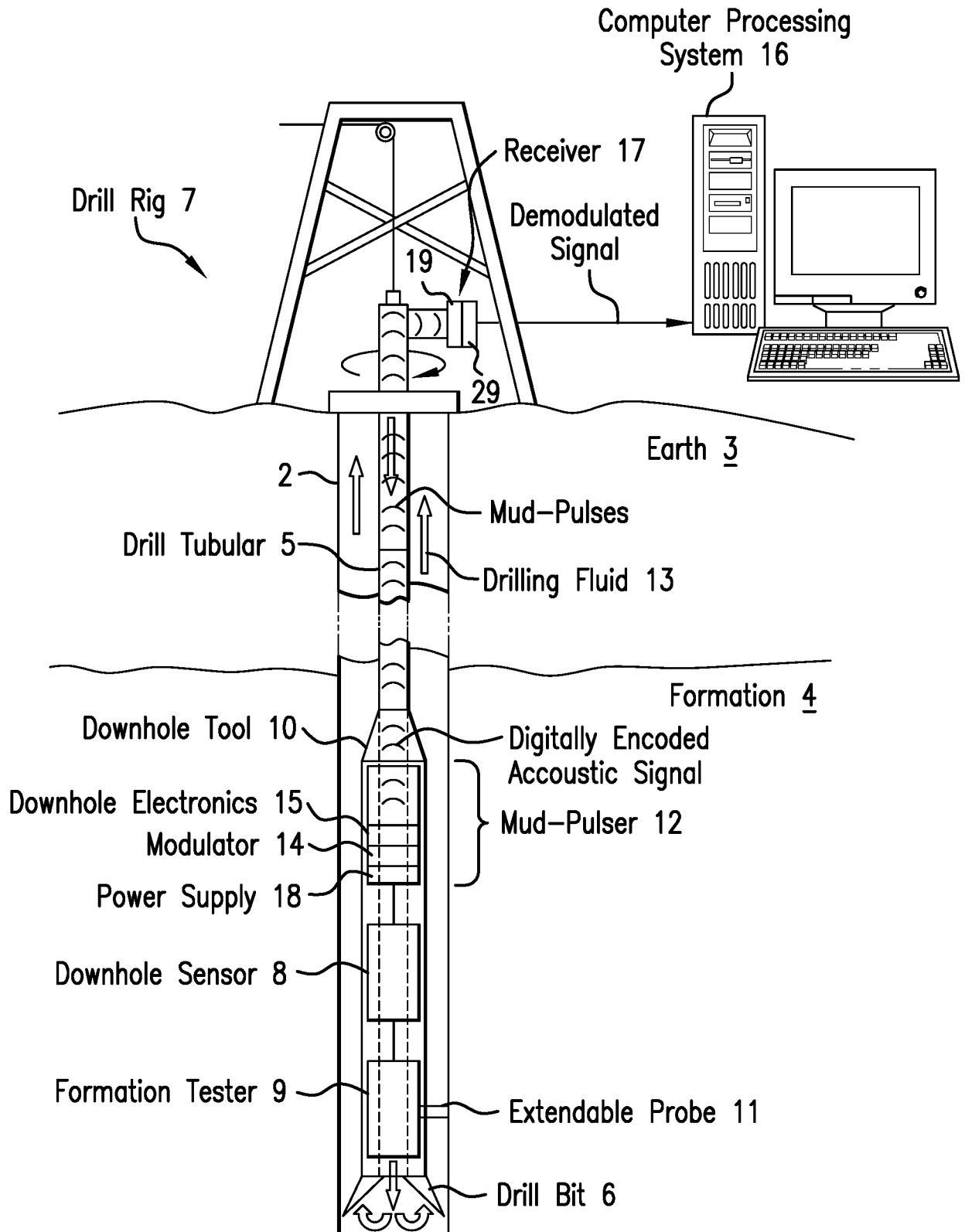


FIG. 1

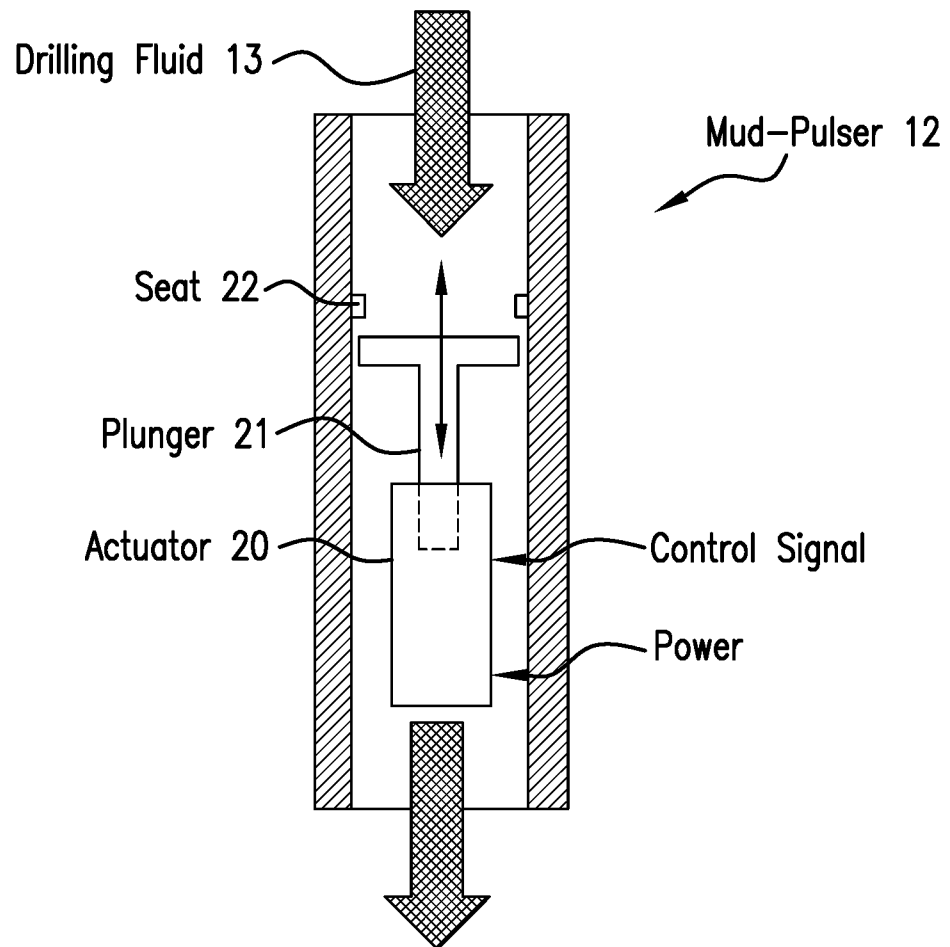


FIG.2

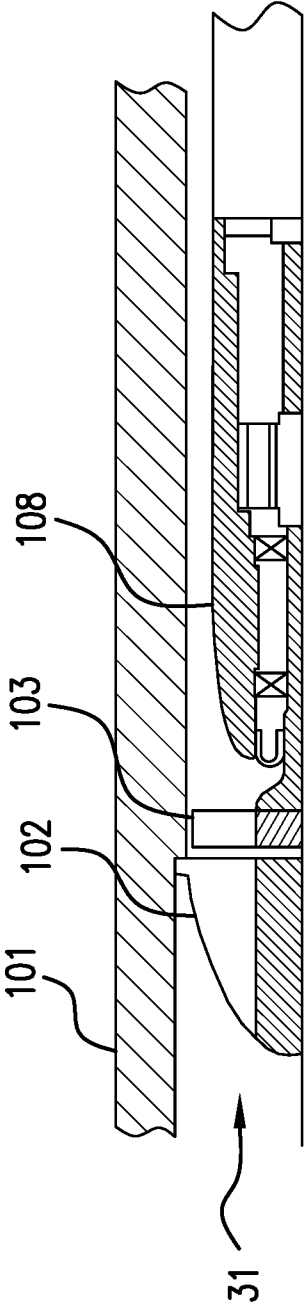


FIG. 3A

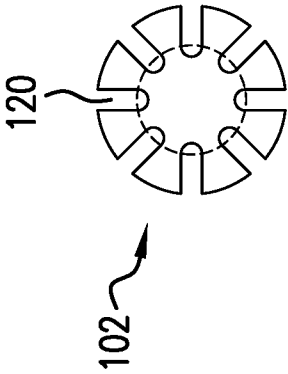


FIG. 3B

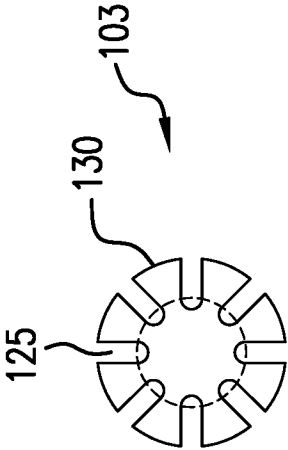


FIG. 3C

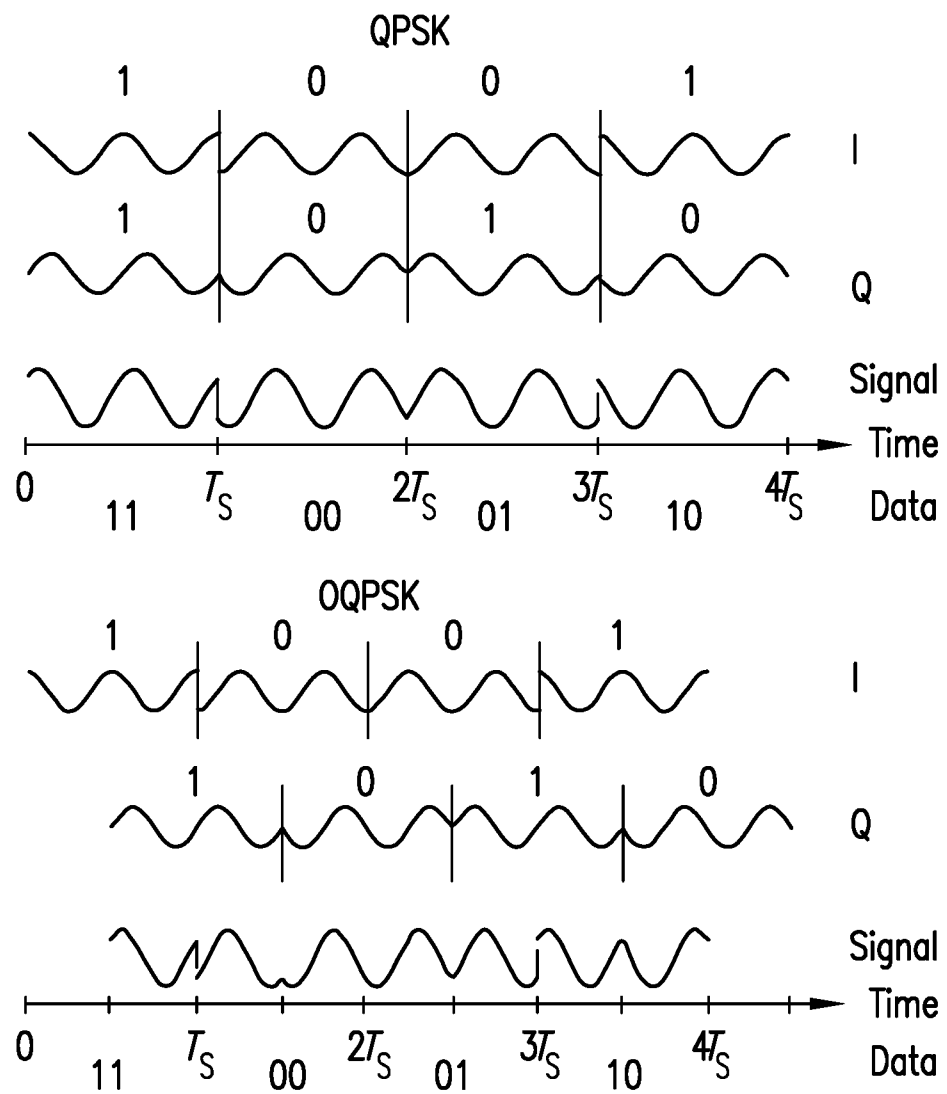


FIG.4

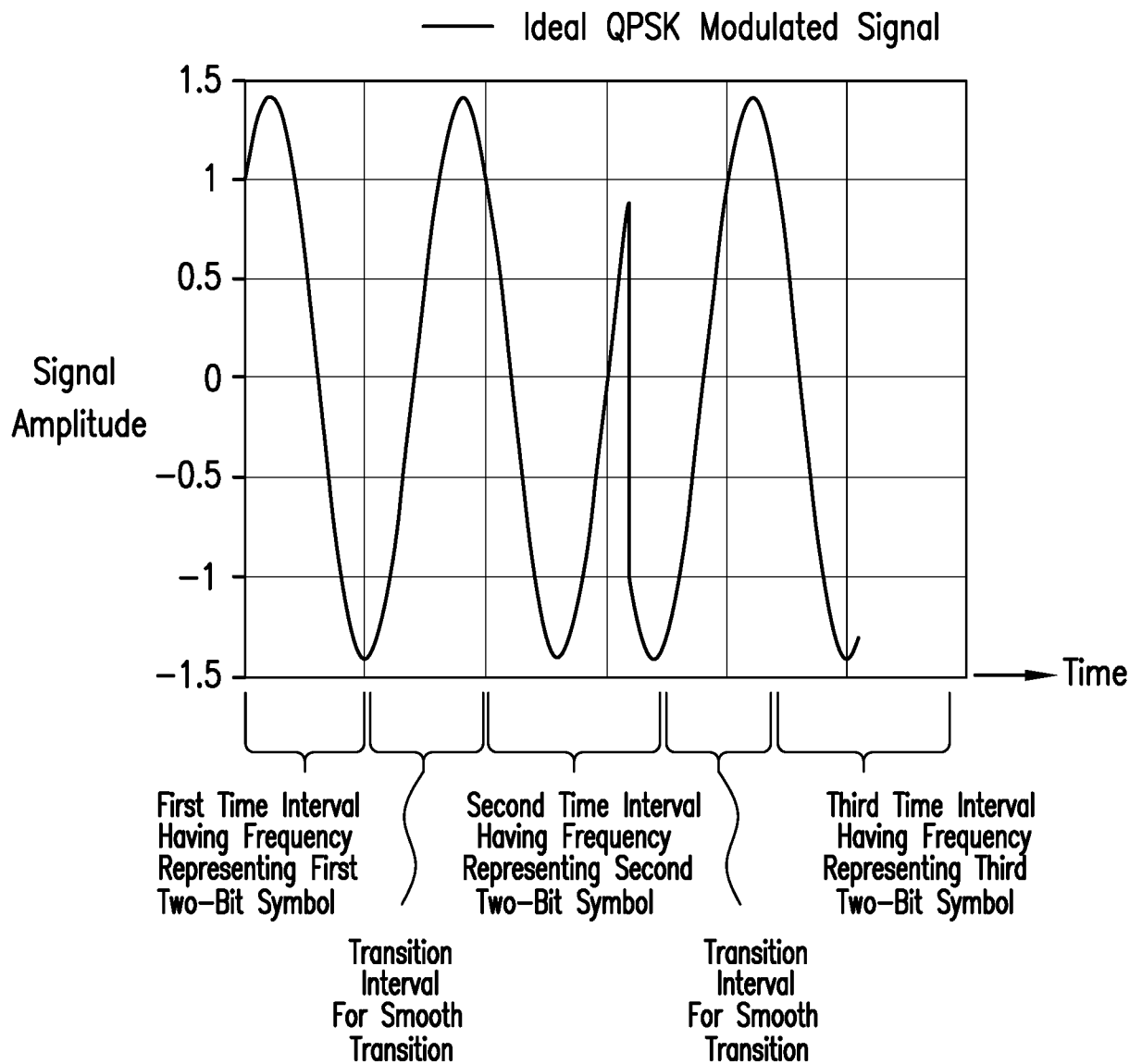


FIG.5A

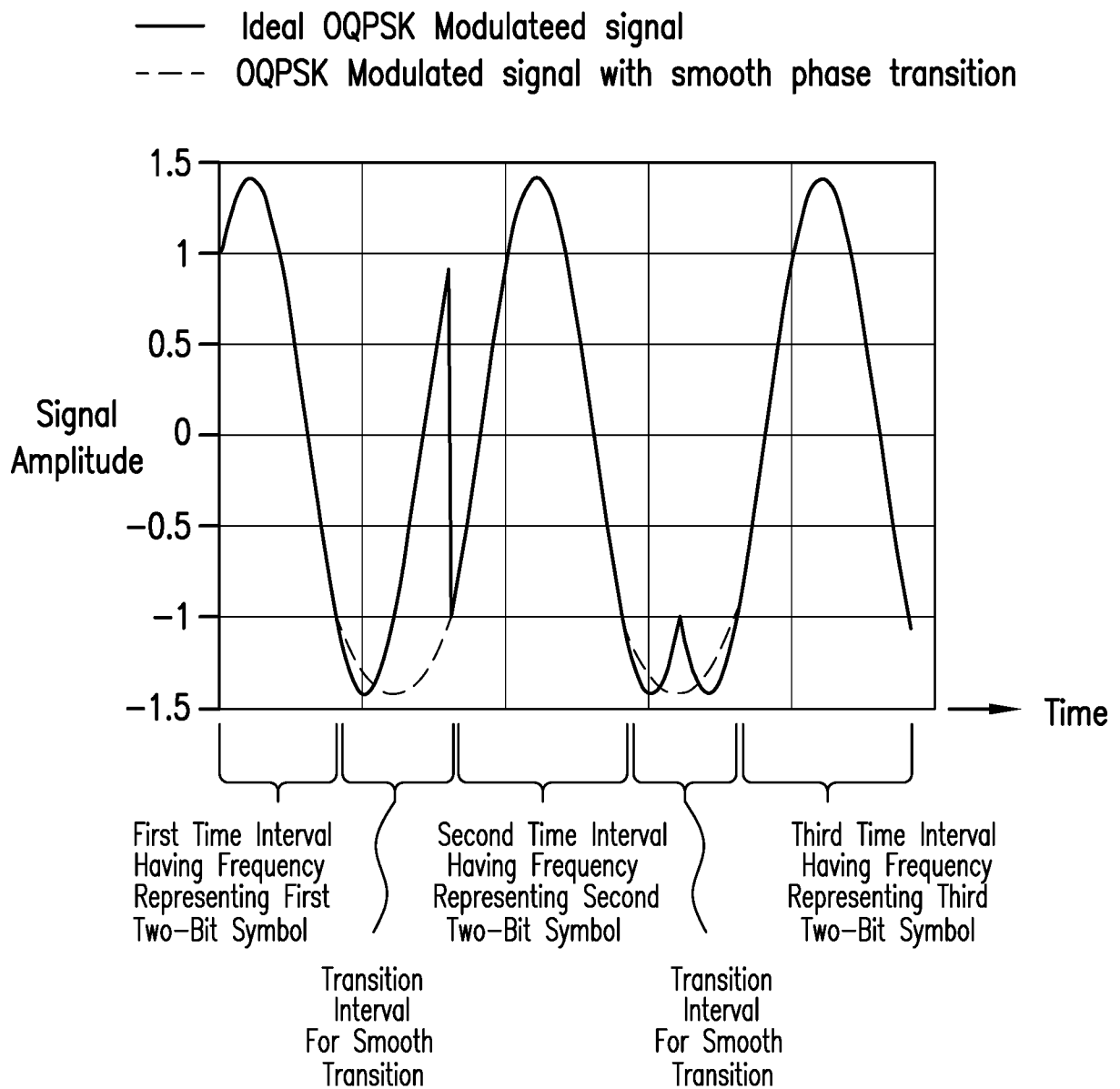


FIG.5B

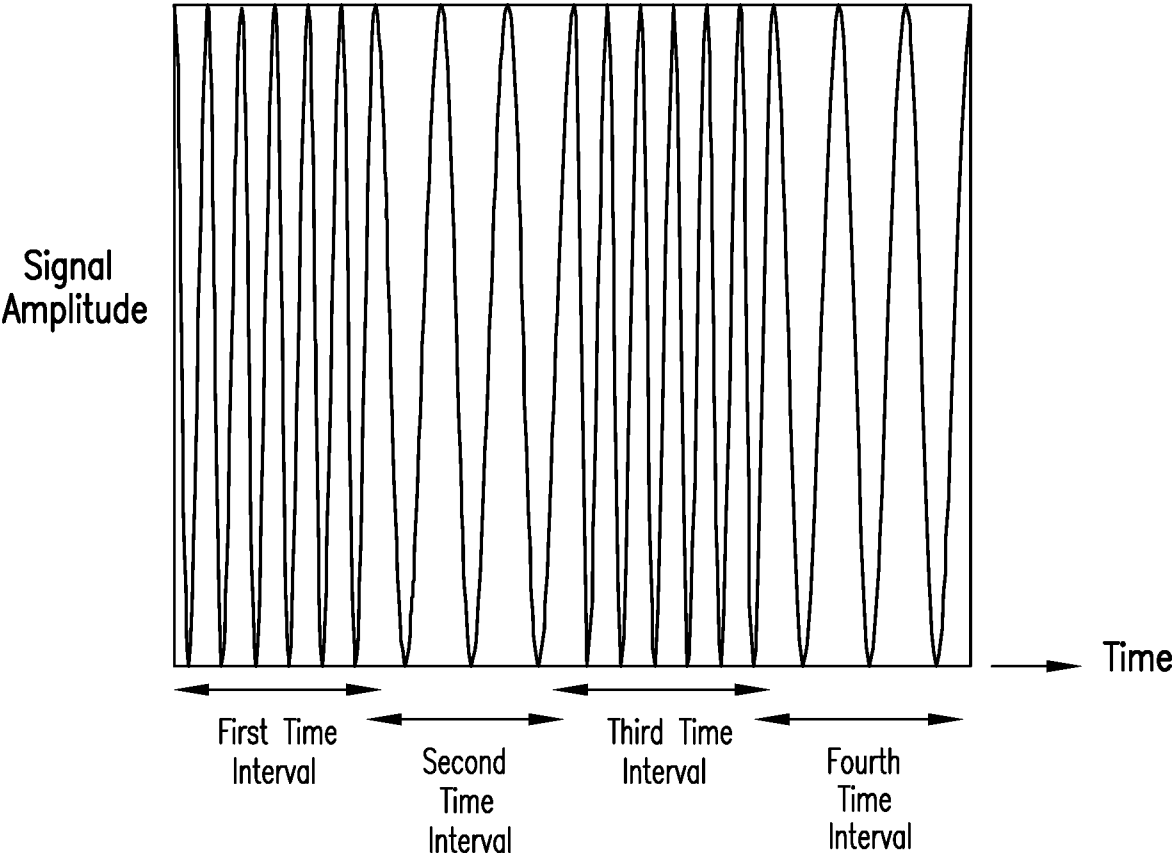


FIG.6

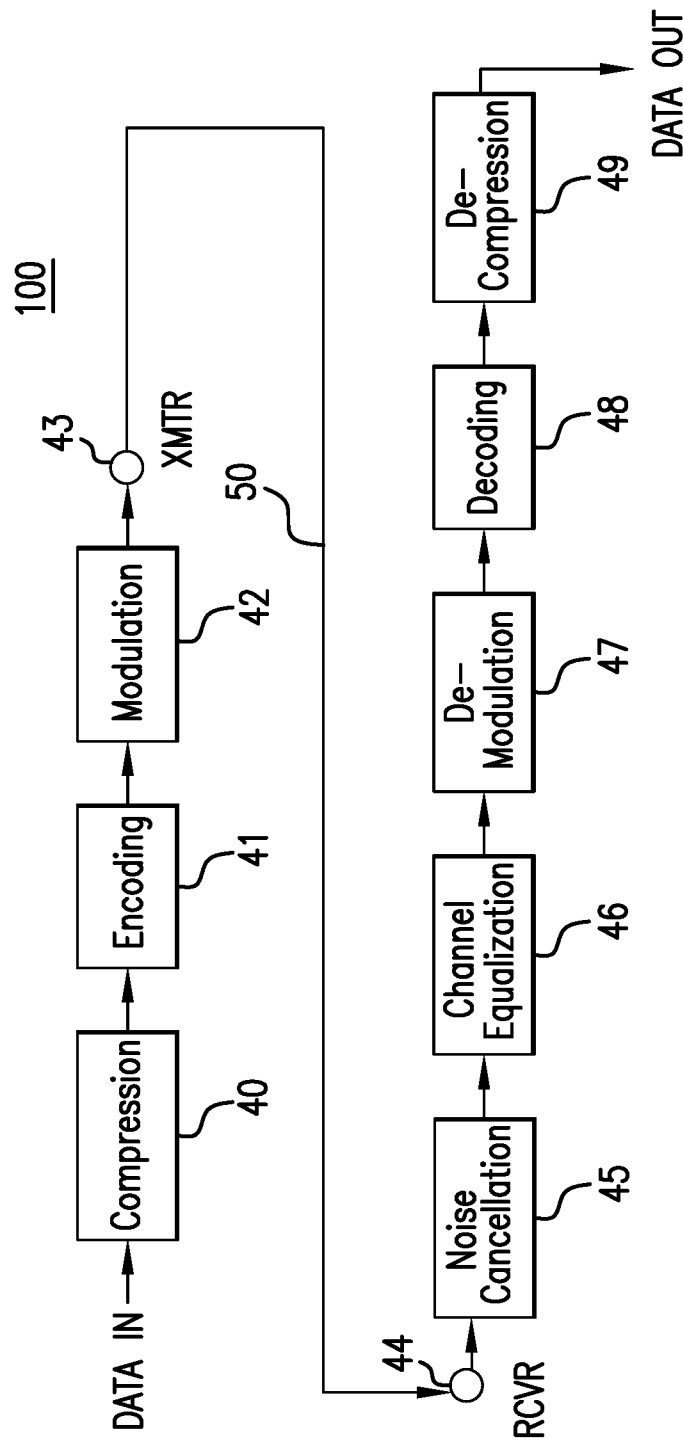


FIG. 7

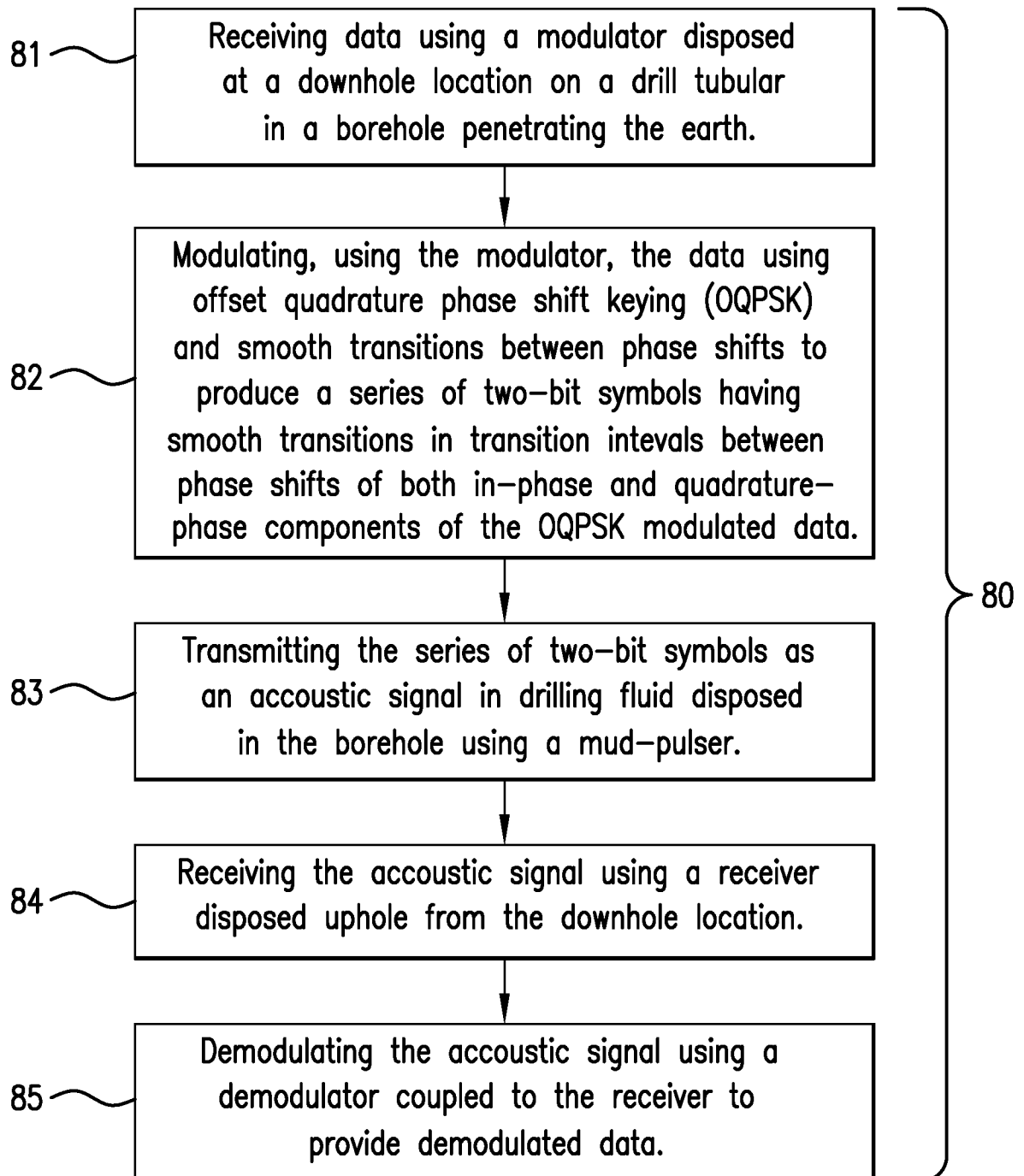


FIG.8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/018464**A. CLASSIFICATION OF SUBJECT MATTER****E21B 47/12(2006.01)i, E21B 47/18(2006.01)i, E21B 47/20(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; H04H 9/00; E21B 47/00; G01V 3/00; E21B 47/06; E21B 47/18; E21B 47/20

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: mud, pulse, offset quadrature phase shift keying (OQPSK), smooth, transition, error

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2010-0245121 A1 (REED et al.) 30 September 2010 See paragraphs [0006], [0008], [0022]-[0028], [0032]; and figure 1.	1-15
Y	US 2010-0195442 A1 (REYES et al.) 05 August 2010 See paragraphs [0025]-[0029], [0033]-[0038]; and figures 1, 3, 6.	1-15
A	US 5375098 A (MALONE et al.) 20 December 1994 See column 4, line 46 - column 5, line 16; column 7, line 43 - column 8, line 10; column 13, line 58 - column 14, line 49; and figures 1, 7e-7f.	1-15
A	WO 2014-094160 A1 (EVOLUTION ENGINEERING INC.) 26 June 2014 See page 12, line 24 - page 15, line 16; and figures 1-2.	1-15
A	US 2007-0056771 A1 (GOPALAN et al.) 15 March 2007 See paragraphs [0050]-[0055], [0100]-[0108]; and figures 1-3.	1-15



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

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

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Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/018464

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