Innovation, Sciences et Développement économique Canada
Office de la Propriété Intellectuelle du Canada

Innovation, Science and Economic Development Canada
Canadian Intellectual Property Office

CA 3028103 C 2021/07/13

(11)(21) **3 028 103**

(12) **BREVET CANADIEN**
CANADIAN PATENT

(13) **C**

(22) Date de dépôt/Filing Date: 2018/12/19

(41) Mise à la disp. pub./Open to Public Insp.: 2019/06/20

(45) Date de délivrance/Issue Date: 2021/07/13

(30) Priorité/Priority: 2017/12/20 (US62/608,172)

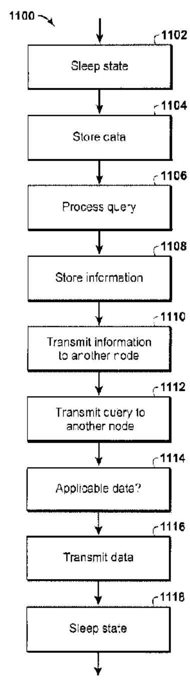
(51) Cl.Int./Int.Cl. *H04W 4/38* (2018.01), *E21B 47/13* (2012.01)

(72) Inventeurs/Inventors:
CLAWSON, SCOTT W., US;
DISKO, MARK M., US;
WALKER, KATIE M., US

(73) Propriétaire/Owner:
EXXONMOBIL UPSTREAM RESEARCH COMPANY, US

(74) Agent: BORDEN LADNER GERVAIS LLP

(54) Titre : METHODE ECOENERGETIQUE D'EXTRACTION DE DONNEES DE CAPTEUR EN RESEAU SANS FIL
(54) Title: ENERGY EFFICIENT METHOD OF RETRIEVING WIRELESS NETWORKED SENSOR DATA



(57) Abrégé/Abstract:
A method of communicating in a wireless network. Devices are positioned such that each device communicates with one or more other devices. Some of the devices include one or more sensors. Each device is a node in the wireless network. At one of the devices, values are recorded from the sensors associated therewith. At least some of the devices, one or more recorded values from the sensors associated with said each device, and/or a sensor associated with at least one other device, are processed in accordance with a variable instruction set, to thereby generate a processed dataset. At each device, at least one of recorded values, a processed dataset associated with another device, or a revision to the variable instruction set are received from another device. At least one of the one or more recorded values, and one or more processed datasets, are transmitted at each device to another device.

ABSTRACT

A method of communicating in a wireless network. Devices are positioned such that each device communicates with one or more other devices. Some of the devices include one or more sensors. Each device is a node in the wireless network. At one of the devices, values are recorded from the sensors associated therewith. At least some of the devices, one or more recorded values from the sensors associated with said each device, and/or a sensor associated with at least one other device, are processed in accordance with a variable instruction set, to thereby generate a processed dataset. At each device, at least one of recorded values, a processed dataset associated with another device, or a revision to the variable instruction set are received from another device. At least one of the one or more recorded values, and one or more processed datasets, are transmitted at each device to another device.

ENERGY EFFICIENT METHOD OF RETRIEVING WIRELESS NETWORKED SENSOR DATA

[0001] <<This paragraph has been intentionally left blank.>>

[0002] <<This paragraph has been intentionally left blank.>>

FIELD

[0003] The present disclosure relates generally to the field of data transmission along a tubular body, such as a steel pipe. More specifically, the present disclosure relates to the transmission of data along a pipe within a wellbore or along a pipeline, whether at the surface, underground, or in a body of water.

BACKGROUND

[0004] In the oil and gas industry, it is desirable to obtain data from a wellbore. Several real time data systems have been proposed. One involves the use of a physical cable such as an electrical conductor or a fiber optic cable that is secured to the tubular body. The cable may be secured to either the inner or the outer diameter of the pipe. The cable provides a hard wire connection that allows for real-time transmission of data and the immediate evaluation of subsurface conditions.

CA 3028103 2020-01-07

Further, these cables allow for high data transmission rates and the delivery of electrical power directly to downhole sensors. However, use of physical cables may be difficult as the cables have to be unspooled and attached to the pipe sections disposed within a wellbore. Accordingly, the pipes being installed into the well may not be rotated because of the attached cables, which may be broken through such installations. This limitation may be problematic for installations into horizontal wells, which typically involve rotating the pipes. These passages for the cables provide potential locations for leakage of fluids, which may be more problematic for configurations that involve high pressure fluids. In addition, the leakage of down-hole fluids may increase the risk of cement seal failures. Further, the use of cables in a well completion requires installing a specially-designed well head that includes through-openings for the wires.

[0005] Various wireless technologies have been proposed or developed for downhole communications. Such technologies are referred to in the industry as telemetry. Several examples exist where the installation of wires may be either technically difficult or economically impractical. The use of radio transmission may also be impractical or unavailable in cases where radio-activated blasting is occurring, or where the attenuation of radio waves near the tubular body is significant.

[0006] The use of acoustic telemetry has also been suggested. Acoustic telemetry utilizes an acoustic wireless network to wirelessly transmit an acoustic signal, such as a vibration, via a tone transmission medium. The tone transmission medium may comprise one or more of a pipe, fluid in the pipe, a tubular element inside or outside the pipe, or the geologic formation surrounding the pipe. In general, a given tone transmission medium may only permit communication within a certain frequency range; and, in some systems, this frequency range may be relatively small. Such systems may be referred to herein as spectrum-constrained systems. An example of a spectrum-constrained system is a well, such as a hydrocarbon well, that includes a plurality of communication nodes spaced-apart along a length thereof. Transmitted acoustic signals are detected by a receiver and converted to electrical signals for analysis.

[0007] Advancements in semiconductor manufacturing and wireless networking have made possible a proliferation of sensor devices that target a variety of industrial applications, including the oil and gas industry in general and downhole wells (hydrocarbon and injection) specifically. The availability of a rich assortment of real time (or nearly so) sensor information enables advanced analytics that in turn can offer efficiencies in installation, stimulation, and production of these assets. Given its high potential value, the trend toward sensor proliferation will continue.

[0008] Sensors typically need to be present in remote locations such as within or near a reservoir deep underground or beneath a body of water (which may both be considered "downhole" for the purposes of this disclosure). Because the sensor is likely irretrievable once installed, it must incorporate its own power supply, usually a battery and less commonly some form of energy harvesting. State-of-the-art sensor devices address these requirements by minimizing power consumption, in part by existing mostly in a low power sleep state, waking occasionally just long enough to take a reading and transmit in a minimally-sufficient format to a nearby listener. The lower the rate of power consumption, the longer the operational life downhole.

[0009] Acoustic wireless data transmission is also costly from an energy consumption standpoint, and network deployment on a practical scale exacerbates this. A typical network might include 100+ sensors distributed along a 6,000+ foot vertical or horizontal tubular. Latency, data rate, acoustic channel capacity, and network complexity (which is proportional to the number of sensor devices) collectively work to limit both quantity and type of retrievable data, constraining the analytical value of the network. Any attempt to retrieve enough downhole sensor data to increase analytical value will significantly decrease network scalability and reduce operational life. This therefore serves as an impediment to realizing the full return on investment of instrumenting a downhole asset with sensors. One might work around this by means of larger batteries as a way of forcing a higher analytical value dataset through the network while maintaining operational life. However, a larger battery would increase the physical size of each sensor device, each of which includes its own power source, and preclude use in space-constrained locations, which in turn would reduce the network's value. This is particularly true in that batteries compatible with the extreme temperatures and pressures common downhole tend to offer lower volumetric capacity.

[0010] Another alternative is to run wiring to each downhole sensor device for power and fast data transfer, but this would also be problematic because each wire creates a continuous path through cement to the surface, increasing the risk of a blowout or other unsafe event from a leak path around the wire or in weakened cement. Additionally, the voltage drop over a long wire would be excessive and get rapidly worse as current flow increases. A wire would be a single point of failure for data transfer, increasing risk of a severed network. Lastly, installing downhole wiring is particularly labor intensive and would increase the risk of a failed installation.

[0011] The above considerations leave an undesirable choice: lose most of the benefits of state-of-the-art downhole sensors, forego instrumentation in space-constrained downhole locations, or accept a short operational life for the sensors. Accordingly, a need exists for a wireless communication network having extended operational life. Additionally, a need exists for a wireless communication network that is suitable for use in a downhole environment.

SUMMARY

[0012] In one aspect, a method is provided for communication in a wireless network having a plurality of nodes including a first node. Each of the plurality of nodes is maintained in a sleep state, which may include a low-power state. If a trigger event occurs at the first node, data relevant to the trigger event may be sensed and/or stored and/or indexed at the first node. If a query applicable to the first node is received by the first node, the query is processed at the first node to produce query-based information. The query-based information is stored at the first node until the processing of the query is complete. The query-based information is transmitted to another node in the network. If the query may have applicability to a node other than the first node, the query is transmitted to another node in the network. If data is received by the first node, it is determined whether the data is needed to process a query applicable to the first node. If the data is not needed to process the query, the data may be transmitted to another of the plurality of nodes. The first node is returned to the sleep state when the query-based information or the data is transmitted.

[0013] In another aspect, a communications network is provided. The network includes a plurality of devices positioned to communicate with one or more other of the plurality of devices. At least some of the devices include one or more sensors and a means to record values from the one or more sensors. At least some of the devices include a processor configured to process one or more recorded values from (i) the one or more sensors associated with said each device, and/or (ii) a sensor associated with at least one other device, in accordance with a variable instruction set, to thereby generate a processed dataset. Each device includes a receiver configured to receive, from another of the plurality of devices, at least one of recorded values, a processed dataset associated with another of the plurality of devices, or a revision to the variable instruction set. Each device includes a transmitter configured to transmit at least one of the one or more recorded values, and one or more processed datasets, to another of the plurality of devices. Each device is maintained in a sleep state unless instructions are received to record values, process the recorded values, and/or transmit to another device, and each device returns to the sleep state when the instructions are fulfilled.

[0014] In yet another aspect, a method of communicating in a wireless network is provided. A plurality of devices are positioned such that each device communicates with one or more other

devices. At least some of the devices include one or more sensors. At one or more of the devices, values from the one or more sensors associated therewith are recorded. At least some of the devices, one or more recorded values from the one or more sensors associated with said each device, and/or a sensor associated with at least one other device, are processed in accordance with a variable instruction set, to thereby generate a processed dataset. At each device, at least one of recorded values, a processed dataset associated with another of the devices, or a revision to the variable instruction set is received from another of the devices. At each device, at least one of the one or more recorded values, and one or more processed datasets, is transmitted to another of the devices. Each device is maintained in a sleep state unless instructions are received to record values, process the recorded values, and/or transmit to another device, and each device returns to the sleep state when the instructions are fulfilled.

DESCRIPTION OF THE DRAWINGS

[0015] The present disclosure is susceptible to various modifications and alternative forms, specific exemplary implementations thereof have been shown in the drawings and are herein described in detail. It should be understood, however, that the description herein of specific exemplary implementations is not intended to limit the disclosure to the particular forms disclosed herein. This disclosure is to cover all modifications and equivalents as defined by the appended claims. It should also be understood that the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating principles of exemplary embodiments of the present invention. Moreover, certain dimensions may be exaggerated to help visually convey such principles. Further where considered appropriate, reference numerals may be repeated among the drawings to indicate corresponding or analogous elements. Moreover, two or more blocks or elements depicted as distinct or separate in the drawings may be combined into a single functional block or element. Similarly, a single block or element illustrated in the drawings may be implemented as multiple steps or by multiple elements in cooperation. The forms disclosed herein are illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings and in which like reference numerals refer to similar elements and in which:

[0016] Figure 1 presents a side, cross-sectional view of an illustrative, nonexclusive example of a wellbore. The wellbore is being formed using a derrick, a drill string and a bottom hole assembly. A series of communications nodes is placed along the drill string as part of a telemetry system, according to the present disclosure.

[0017] Figure 2 presents a cross-sectional view of an illustrative, nonexclusive example of a wellbore having been completed. The illustrative wellbore has been completed as a cased hole completion. A series of communications nodes is placed along the casing string as part of a telemetry system, according to the present disclosure.

[0018] Figure 3 presents a perspective view of an illustrative tubular section of a downhole wireless telemetry system, in accordance with an embodiment of the disclosure. An intermediate communications node in accordance herewith, is shown in exploded form away from the tubular section.

[0019] Figure 4 presents a cross-sectional view of the intermediate communications node of Figure 3. The view is taken along the longitudinal axis of the intermediate communications node.

[0020] Figure 5 is a cross-sectional view of an illustrative embodiment of a sensor communications node having a sensor positioned within the sensor communications node. The view is taken along the longitudinal axis of the sensor communications node.

[0021] Figure 6 is another cross-sectional view of an illustrative embodiment of a sensor communications node having a sensor positioned along the wellbore external to the sensor communications node. The view is again taken along the longitudinal axis of the sensor communications node.

[0022] Figure 7A is a schematic view of a transmitter having multiple-disks for use in an intermediate communications node, according to the present disclosure.

[0023] Figure 7B is a schematic view of a receiver having multiple-disks for use in an intermediate communications node, according to the present disclosure.

[0024] Figure 8 is a schematic diagram showing a state diagram usable with a node in a wireless communication network according to disclosed aspects.

[0025] Figure 9 is a printout showing non-limiting examples of a trigger and two queries, according to disclosed aspects.

[0026] Figure 10 is a flowchart of an exemplary method of communication in a linear downhole acoustic wireless network, according to disclosed aspects.

[0027] Figure 11 is a flowchart of a method according to disclosed aspects.

[0028] Figure 12 is a flowchart of a method according to disclosed aspects.

DETAILED DESCRIPTION

Terminology

[0029] The words and phrases used herein should be understood and interpreted to have a meaning consistent with the understanding of those words and phrases by those skilled in the relevant art. No special definition of a term or phrase, i.e., a definition that is different from the ordinary and customary meaning as understood by those skilled in the art, is intended to be implied by consistent usage of the term or phrase herein. To the extent that a term or phrase is intended to have a special meaning, i.e., a meaning other than the broadest meaning understood by skilled artisans, such a special or clarifying definition will be expressly set forth in the specification in a definitional manner that provides the special or clarifying definition for the term or phrase.

[0030] For example, the following discussion contains a non-exhaustive list of definitions of several specific terms used in this disclosure (other terms may be defined or clarified in a definitional manner elsewhere herein). These definitions are intended to clarify the meanings of the terms used herein. It is believed that the terms are used in a manner consistent with their ordinary meaning, but the definitions are nonetheless specified here for clarity.

[0031] A/an: The articles "a" and "an" as used herein mean one or more when applied to any feature in embodiments and implementations of the present invention described in the specification and claims. The use of "a" and "an" does not limit the meaning to a single feature unless such a limit is specifically stated. The term "a" or "an" entity refers to one or more of that entity. As such, the terms "a" (or "an"), "one or more" and "at least one" can be used interchangeably herein.

[0032] About: As used herein, "about" refers to a degree of deviation based on experimental error typical for the particular property identified. The latitude provided the term "about" will depend on the specific context and particular property and can be readily discerned by those skilled in the art. The term "about" is not intended to either expand or limit the degree of equivalents which may otherwise be afforded a particular value. Further, unless otherwise stated, the term "about" shall expressly include "exactly," consistent with the discussion below regarding ranges and numerical data.

[0033] Above/below: In the following description of the representative embodiments of the invention, directional terms, such as "above", "below", "upper", "lower", etc., are used for

CA 3028103 2018-12-19

convenience in referring to the accompanying drawings. In general, "above", "upper", "upward" and similar terms refer to a direction toward the earth's surface along a wellbore, and "below", "lower", "downward" and similar terms refer to a direction away from the earth's surface along the wellbore. Continuing with the example of relative directions in a wellbore, "upper" and "lower" may also refer to relative positions along the longitudinal dimension of a wellbore rather than relative to the surface, such as in describing both vertical and horizontal wells.

[0034] And/or: The term "and/or" placed between a first entity and a second entity means one of (1) the first entity, (2) the second entity, and (3) the first entity and the second entity. Multiple elements listed with "and/or" should be construed in the same fashion, i.e., "one or more" of the elements so conjoined. Other elements may optionally be present other than the elements specifically identified by the "and/or" clause, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, a reference to "A and/or B", when used in conjunction with open-ended language such as "comprising" can refer, in one embodiment, to A only (optionally including elements other than B); in another embodiment, to B only (optionally including elements other than A); in yet another embodiment, to both A and B (optionally including other elements). As used herein in the specification and in the claims, "or" should be understood to have the same meaning as "and/or" as defined above. For example, when separating items in a list, "or" or "and/or" shall be interpreted as being inclusive, i.e., the inclusion of at least one, but also including more than one, of a number or list of elements, and, optionally, additional unlisted items. Only terms clearly indicated to the contrary, such as "only one of" or "exactly one of," or, when used in the claims, "consisting of," will refer to the inclusion of exactly one element of a number or list of elements. In general, the term "or" as used herein shall only be interpreted as indicating exclusive alternatives (i.e., "one or the other but not both") when preceded by terms of exclusivity, such as "either," "one of," "only one of," or "exactly one of".

[0035] Any: The adjective "any" means one, some, or all indiscriminately of whatever quantity.

[0036] At least: As used herein in the specification and in the claims, the phrase "at least one," in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to

CA 3028103 2018-12-19

which the phrase "at least one" refers, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, "at least one of A and B" (or, equivalently, "at least one of A or B," or, equivalently "at least one of A and/or B") can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements). The phrases "at least one", "one or more", and "and/or" are open-ended expressions that are both conjunctive and disjunctive in operation. For example, each of the expressions "at least one of A, B and C", "at least one of A, B, or C", "one or more of A, B, and C", "one or more of A, B, or C" and "A, B, and/or C" means A alone, B alone, C alone, A and B together, A and C together, B and C together, or A, B and C together.

[0037] Based on: "Based on" does not mean "based only on", unless expressly specified otherwise. In other words, the phrase "based on" describes both "based only on," "based at least on," and "based at least in part on."

[0038] Comprising: In the claims, as well as in the specification, all transitional phrases such as "comprising," "including," "carrying," "having," "containing," "involving," "holding," "composed of," and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases "consisting of" and "consisting essentially of" shall be closed or semi-closed transitional phrases, respectively, as set forth in the United States Patent Office Manual of Patent Examining Procedures, Section 2111.03.

[0039] Couple: Any use of any form of the terms "connect", "engage", "couple", "attach", or any other term describing an interaction between elements is not meant to limit the interaction to direct interaction between the elements and may also include indirect interaction between the elements described.

[0040] Determining: "Determining" encompasses a wide variety of actions and therefore "determining" can include calculating, computing, processing, deriving, investigating, looking up (e.g., looking up in a table, a database or another data structure), ascertaining and the like. Also, "determining" can include receiving (e.g., receiving information), accessing (e.g., accessing data in a memory) and the like. Also, "determining" can include resolving, selecting, choosing, establishing and the like.

[0041] Embodiments: Reference throughout the specification to "one embodiment," "an embodiment," "some embodiments," "one aspect," "an aspect," "some aspects," "some implementations," "one implementation," "an implementation," or similar construction means that a particular component, feature, structure, method, or characteristic described in connection with the embodiment, aspect, or implementation is included in at least one embodiment and/or implementation of the claimed subject matter. Thus, the appearance of the phrases "in one embodiment" or "in an embodiment" or "in some embodiments" (or "aspects" or "implementations") in various places throughout the specification are not necessarily all referring to the same embodiment and/or implementation. Furthermore, the particular features, structures, methods, or characteristics may be combined in any suitable manner in one or more embodiments or implementations.

[0042] Exemplary: "Exemplary" is used exclusively herein to mean "serving as an example, instance, or illustration." Any embodiment described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments.

[0043] Flow diagram: Exemplary methods may be better appreciated with reference to flow diagrams or flow charts. While for purposes of simplicity of explanation, the illustrated methods are shown and described as a series of blocks, it is to be appreciated that the methods are not limited by the order of the blocks, as in different embodiments some blocks may occur in different orders and/or concurrently with other blocks from that shown and described. Moreover, less than all the illustrated blocks may be required to implement an exemplary method. In some examples, blocks may be combined, may be separated into multiple components, may employ additional blocks, and so on. In some examples, blocks may be implemented in logic. In other examples, processing blocks may represent functions and/or actions performed by functionally equivalent circuits (e.g., an analog circuit, a digital signal processor circuit, an application specific integrated circuit (ASIC)), or other logic device. Blocks may represent executable instructions that cause a computer, processor, and/or logic device to respond, to perform an action(s), to change states, and/or to make decisions. While the figures illustrate various actions occurring in serial, it is to be appreciated that in some examples various actions could occur concurrently, substantially in series, and/or at substantially different points in time. In some examples, methods may be implemented as processor executable instructions. Thus, a machine-readable medium may store processor executable instructions that if executed by a machine (e.g., processor) cause the machine to perform a method.

[0044] May: Note that the word "may" is used throughout this application in a permissive sense (i.e., having the potential to, being able to), not a mandatory sense (i.e., must).

[0045] Operatively connected and/or coupled: Operatively connected and/or coupled means directly or indirectly connected for transmitting or conducting information, force, energy, or matter.

[0046] Optimizing: The terms "optimal," "optimizing," "optimize," "optimality," "optimization" (as well as derivatives and other forms of those terms and linguistically related words and phrases), as used herein, are not intended to be limiting in the sense of requiring the present invention to find the best solution or to make the best decision. Although a mathematically optimal solution may in fact arrive at the best of all mathematically available possibilities, real-world embodiments of optimization routines, methods, models, and processes may work towards such a goal without ever actually achieving perfection. Accordingly, one of ordinary skill in the art having benefit of the present disclosure will appreciate that these terms, in the context of the scope of the present invention, are more general. The terms may describe one or more of: 1) working towards a solution which may be the best available solution, a preferred solution, or a solution that offers a specific benefit within a range of constraints; 2) continually improving; 3) refining; 4) searching for a high point or a maximum for an objective; 5) processing to reduce a penalty function; 6) seeking to maximize one or more factors in light of competing and/or cooperative interests in maximizing, minimizing, or otherwise controlling one or more other factors, etc.

[0047] Order of steps: It should also be understood that, unless clearly indicated to the contrary, in any methods claimed herein that include more than one step or act, the order of the steps or acts of the method is not necessarily limited to the order in which the steps or acts of the method are recited.

[0048] Ranges: Concentrations, dimensions, amounts, and other numerical data may be presented herein in a range format. It is to be understood that such range format is used merely for convenience and brevity and should be interpreted flexibly to include not only the numerical values explicitly recited as the limits of the range, but also to include all the individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly recited. For example, a range of about 1 to about 200 should be interpreted to include not only the explicitly recited limits of 1 and about 200, but also to include individual sizes such as 2, 3, 4, etc. and sub-ranges such as 10 to 50, 20 to 100, etc. Similarly, it should be understood that when numerical ranges are provided, such ranges are to be construed as providing literal support for claim limitations that only recite the lower value of the range as well as claims limitation that only recite the upper value of the range. For example, a disclosed numerical range of 10 to 100 provides literal support for a claim reciting "greater than 10" (with no upper bounds) and a claim reciting "less than 100" (with no lower bounds).

[0049] As used herein, the term "formation" refers to any definable subsurface region. The formation may contain one or more hydrocarbon-containing layers, one or more non-hydrocarbon containing layers, an overburden, and/or an underburden of any geologic formation.

[0050] As used herein, the term "hydrocarbon" refers to an organic compound that includes primarily, if not exclusively, the elements hydrogen and carbon. Examples of hydrocarbons include any form of natural gas, oil, coal, and bitumen that can be used as a fuel or upgraded into a fuel.

[0051] As used herein, the term "hydrocarbon fluids" refers to a hydrocarbon or mixtures of hydrocarbons that are gases or liquids. For example, hydrocarbon fluids may include a hydrocarbon or mixtures of hydrocarbons that are gases or liquids at formation conditions, at processing conditions, or at ambient conditions (20 °C. and 1 atm pressure). Hydrocarbon fluids may include, for example, oil, natural gas, gas condensates, coal bed methane, shale oil, shale gas, and other hydrocarbons that are in a gaseous or liquid state.

[0052] As used herein, the term “potting” refers to the encapsulation of electrical components with epoxy, elastomeric, silicone, or asphaltic or similar compounds for the purpose of excluding moisture or vapors. Potted components may or may not be hermetically sealed.

[0053] As used herein, the term “sealing material” refers to any material that can seal a cover of a housing to a body of a housing sufficient to withstand one or more downhole conditions including but not limited to, for example, temperature, humidity, soil composition, corrosive elements, pH, and pressure.

[0054] As used herein, the term "sensor" includes any electrical sensing device or gauge. The sensor may be capable of monitoring or detecting pressure, temperature, fluid flow, vibration, resistivity, or other formation data. Alternatively, the sensor may be a position sensor.

[0055] As used herein, the term "subsurface" refers to geologic strata occurring below the earth's surface.

[0056] The terms "tubular member" or "tubular body" refer to any pipe, such as a joint of casing,

CA 3028103 2018-12-19

a portion of a liner, a drill string, a production tubing, an injection tubing, a pup joint, a buried pipeline, underwater piping, or above-ground piping, solid lines therein, and any suitable number of such structures and/or features may be omitted from a given embodiment without departing from the scope of the present disclosure.

[0057] As used herein, the term "wellbore" refers to a hole in the subsurface made by drilling or insertion of a conduit into the subsurface. A wellbore may have a substantially circular cross section, or other cross-sectional shape. As used herein, the term "well," when referring to an opening in the formation, may be used interchangeably with the term "wellbore."

[0058] The terms "zone" or "zone of interest" refer to a portion of a subsurface formation containing hydrocarbons. The term "hydrocarbon-bearing formation" may alternatively be used.

Description

[0059] Specific forms will now be described further by way of example. While the following examples demonstrate certain forms of the subject matter disclosed herein, they are not to be interpreted as limiting the scope thereof, but rather as contributing to a complete description.

[0060] Figure 1 is a side, cross-sectional view of an illustrative well site **100**. The well site **100** includes a derrick **120** at an earth surface **101**. The well site **100** also includes a wellbore **150** extending from the earth surface **101** and down into an earth subsurface **155**. The wellbore **150** is being formed using the derrick **120**, a drill string **160** below the derrick **120**, and a bottom hole assembly **170** at a lower end of the drill string **160**.

[0061] Referring first to the derrick **120**, the derrick **120** includes a frame structure **121** that extends up from the earth surface **101**. The derrick **120** supports drilling equipment including a traveling block **122**, a crown block **123** and a swivel **124**. A so-called kelly **125** is attached to the swivel **124**. The kelly **125** has a longitudinally extending bore (not shown) in fluid communication with a kelly hose **126**. The kelly hose **126**, also known as a mud hose, is a flexible, steel-reinforced, high-pressure hose that delivers drilling fluid through the bore of the kelly **125** and down into the drill string **160**.

[0062] The kelly **125** includes a drive section **127**. The drive section **127** is non-circular in cross-section and conforms to an opening **128** longitudinally extending through a kelly drive bushing **129**. The kelly drive bushing **129** is part of a rotary table. The rotary table is a mechanically driven device that provides clockwise (as viewed from above) rotational force to the kelly **125** and connected drill string **160** to facilitate the process of drilling a borehole **105**. Both linear and rotational movement may thus be imparted from the kelly **125** to the drill string **160**.

[0063] A platform **102** is provided for the derrick 120. The platform **102** extends above the earth surface **101**. The platform **102** generally supports rig hands along with various components of drilling equipment such as pumps, motors, gauges, a dope bucket, tongs, pipe lifting equipment and control equipment. The platform **102** also supports the rotary table.

[0064] It is understood that the platform **102** shown in Figure 1 is somewhat schematic. It is also understood that the platform **102** is merely illustrative and that many designs for drilling rigs and platforms, both for onshore and for offshore operations, exist. These include, for example, top drive drilling systems. The claims provided herein are not limited by the configuration and features of the drilling rig unless expressly stated in the claims.

[0065] Placed below the platform **102** and the kelly drive section **127** but above the earth surface **101** is a blowout preventer, or BOP **130**. The BOP **130** is a large, specialized valve or set of valves used to control pressures during the drilling of oil and gas wells. Specifically, blowout preventers control the fluctuating pressures emanating from subterranean formations during a drilling process. The BOP **130** may include upper **132** and lower **134** rams used to isolate flow on the back side of the drill string **160**. Blowout preventers **130** also prevent the pipe joints making up the drill string **160** and the drilling fluid from being blown out of the wellbore **150** in the event of a sudden pressure kick.

[0066] As shown in Figure 1, the wellbore **150** is being formed down into the subsurface formation **155**. In addition, the wellbore **150** is being shown as a deviated wellbore. Of course, this is merely illustrative as the wellbore **150** may be a vertical well or even a horizontal well, as shown later in Figure 2.

[0067] In drilling the wellbore **150**, a first string of casing **110** is placed down from the surface **101**. This is known as surface casing **110** or, in some instances (particularly offshore), conductor pipe. The surface casing **110** is secured within the formation **155** by a cement sheath **112**. The cement sheath **112** resides within an annular region **115** between the surface casing **110** and the surrounding formation **155**.

[0068] During the process of drilling and completing the wellbore **150**, additional strings of casing (not shown) will be provided. These may include intermediate casing strings and a final production casing string. For an intermediate case string or the final production casing, a liner may be employed, that is, a string of casing that is not tied back to the surface **101**.

[0069] As noted, the wellbore **150** is formed by using a bottom hole assembly **170**. The bottom hole assembly **170** allows the operator to control or "steer" the direction or orientation of the wellbore **150** as it is formed. In this instance, the bottom hole assembly **170** is known as a rotary steerable drilling system, or RSS.

[0070] The bottom hole assembly **170** will include a drill bit **172**. The drill bit **172** may be turned by rotating the drill string **160** from the platform **102**. Alternatively, the drill bit **172** may be turned by using so-called mud motors **174**. The mud motors **174** are mechanically coupled to and turn the nearby drill bit **172**. The mud motors **174** are used with stabilizers or bent subs **176** to impart an angular deviation to the drill bit **172**. This, in turn, deviates the well from its previous path in the desired azimuth and inclination.

[0071] There are several advantages to directional drilling. These primarily include the ability to complete a wellbore along a substantially horizontal axis of a subsurface formation, thereby exposing a greater formation face. These also include the ability to penetrate into subsurface formations that are not located directly below the wellhead. This is particularly beneficial where an oil reservoir is located under an urban area or under a large body of water. Another benefit of directional drilling is the ability to group multiple wellheads on a single platform, such as for offshore drilling. Finally, directional drilling enables multiple laterals and/or sidetracks to be drilled from a single wellbore in order to maximize reservoir exposure and recovery of hydrocarbons.

[0072] The illustrative well site **100** also includes a sensor **178**. In some embodiments, the sensor **178** is part of the bottom hole assembly **170**. The sensor **178** may be, for example, a set of position sensors that is part of the electronics for an RSS. Alternatively or in addition, the sensor **178** may be a temperature sensor, a pressure sensor, or other sensor for detecting a downhole condition during drilling. Alternatively still, the sensor may be an induction log or gamma ray log or other log that detects fluid and/or geology downhole.

[0073] The sensor **178** may be part of a MWD or a LWD assembly. It is observed that the sensor **178** is located above the mud motors **174**. This is a common practice for MWD assemblies. This allows the electronic components of the sensor **178** to be spaced apart from the high vibration and centrifugal forces acting on the bit **172**.

CA 3028103 2018-12-19

[0074] Where the sensor **178** is a set of position sensors, the sensors may include three inclinometer sensors and three environmental acceleration sensors. Ideally, a temperature sensor and a wear sensor will also be placed in the drill bit **172**. These signals are input into a multiplexer and transmitted.

[0075] As the wellbore **150** is being formed, the operator may wish to evaluate the integrity of the cement sheath **112** placed around the surface casing **110** (or other casing string). To do this, the industry has relied upon so-called cement bond logs. As discussed above, a cement bond log (or CBL), uses an acoustic signal that is transmitted by a logging tool at the end of a wireline. The logging tool includes a transmitter, and one or more receivers that "listen" for sound waves generated by the transmitter through the surrounding casing string. The logging tool includes a signal processor that takes a continuous measurement of the amplitude of sound pulses from the transmitter to the receiver. Alternately, the attenuation of the sonic signal may be measured.

[0076] In some instances, a bond log will measure acoustic impedance of the material in the annulus directly behind the casing. This may be done through resonant frequency decay. Such logs include, for example, the USIT log of Schlumberger (of Sugar Land, Texas) and the CAST-V log of Halliburton (of Houston, Texas).

[0077] It is desirable to implement a downhole telemetry system that enables the operator to evaluate cement sheath integrity without need of running a CBL line. This enables the operator to check cement sheath integrity as soon as the cement has set in the annular region **115** or as soon as the wellbore **150** is completed. Additionally or alternatively, one or more sensors (not shown) may be deployed downhole to monitor a wide variety of properties, including, but not limited to, fluid characteristics, temperature, depth, etc., as those skilled in the art will plainly understand.

[0078] To do this, the well site **100** includes a plurality of battery-powered intermediate communications nodes **180**. The battery-powered intermediate communications nodes **180** are placed along the outer surface of the surface casing **110** according to a pre-designated spacing. The battery-powered intermediate communications nodes **180** are configured to receive and then relay acoustic signals along the length of the wellbore **150** in node-to-node arrangement up to the topside communications node **182**. The topside communications node **182** is placed closest to the surface **101**. The topside communications node **182** is configured to receive acoustic signals and convert them to electrical or optical signals. The topside communications node **182** may be above grade or below grade.

CA 3028103 2018-12-19

[0079] The nodes may also include a sensor communications node **184**. The sensor communications node is placed closest to the sensor **178**. The sensor communications node **184** is configured to communicate with the downhole sensor **178**, and then send a wireless signal using an acoustic wave.

[0080] The well site **100** of Figure 1 also shows a receiver **190**. The receiver **190** comprises a processor **192** that receives signals sent from the topside communications node **182**. The signals may be received through a wire (not shown) such as a co-axial cable, a fiber optic cable, a USB cable, or other electrical or optical communications wire. Alternatively, the receiver **190** may receive the final signals from the topside communications node **182** wirelessly through a modem, a transceiver or other wireless communications link such as Bluetooth or Wi-Fi. The receiver **190** preferably receives electrical signals via a so-called Class I, Division I conduit, that is, a housing for wiring that is considered acceptably safe in an explosive environment. In some applications, radio, infrared or microwave signals may be utilized.

[0081] The processor **192** may include discrete logic, any of various integrated circuit logic types, or a microprocessor. In any event, the processor **192** may be incorporated into a computer having a screen. The computer may have a separate keyboard **194**, as is typical for a desk-top computer, or an integral keyboard as is typical for a laptop or a personal digital assistant. In one aspect, the processor **192** is part of a multi-purpose "smart phone" having specific "apps" and wireless connectivity.

[0082] As indicated, the intermediate communications nodes **180** of the downhole telemetry system are powered by batteries and, as such, system energy limitations can be encountered. While the useful life of the network can be extended by placing the nodes into a “sleep” mode when data collection and communication are not needed; heretofore, there have been no methods available to awaken the intermediate communications nodes **180** when data acquisition is required. Thus, prior to the systems and methods of the present disclosure, the downhole telemetry system was always in the active state; consequently, the life of the network was limited to months, not years.

[0083] As has been described hereinabove, Figure 1 illustrates the use of a wireless data telemetry system during a drilling operation. As may be appreciated, the wireless telemetry system may also be employed after a well is completed. In any event, the wireless data telemetry system shown in the Figures and described herein may be described as having a substantially linear network topology because it generally follows the linear path of a drill string, casing string, wellbore, pipeline, or the like. Such a substantially linear network topology may include multiple drill strings, wellbores, or pipelines, or portions thereof (such as deviations or lateral sections of a wellbore) operationally connected at one or more points.

[0084] Figure 2 is a cross-sectional view of an illustrative well site **200**. The well site **200** includes a wellbore **250** that penetrates into a subsurface formation **255**. The wellbore **250** has been completed as a cased-hole completion for producing hydrocarbon fluids. The well site **200** also includes a well head **260**. The well head **260** is positioned at an earth surface **201** to control and direct the flow of formation fluids from the subsurface formation **255** to the surface **201**.

[0085] Referring first to the well head **260**, the well head **260** may be any arrangement of pipes or valves that receive reservoir fluids at the top of the well. In the arrangement of Figure 2, the well head **260** represents a so-called Christmas tree. A Christmas tree is typically used when the subsurface formation **255** has enough in situ pressure to drive production fluids from the formation **255**, up the wellbore **250**, and to the surface **201**. The illustrative well head **260** includes a top valve **262** and a bottom valve **264**.

[0086] It is understood that rather than using a Christmas tree, the well head **260** may alternatively include a motor (or prime mover) at the surface **201** that drives a pump. The pump, in turn, reciprocates a set of sucker rods and a connected positive displacement pump (not shown) downhole. The pump may be, for example, a rocking beam unit or a hydraulic piston pumping unit. Alternatively still, the well head **260** may be configured to support a string of production tubing having a downhole electric submersible pump, a gas lift valve, or other means of artificial lift (not shown). The present inventions are not limited by the configuration of operating equipment at the surface unless expressly noted in the claims.

[0087] Referring next to the wellbore **250**, the wellbore **250** has been completed with a series of pipe strings referred to as casing. First, a string of surface casing **210** has been cemented into the formation. Cement is shown in an annular bore **215** of the wellbore **250** around the casing **210**. The cement is in the form of an annular sheath **212**. The surface casing **210** has an upper end in sealed connection with the lower valve **264**.

[0088] Next, at least one intermediate string of casing **220** is cemented into the wellbore **250**. The intermediate string of casing **220** is in sealed fluid communication with the upper master valve **262**. A cement sheath **212** is again shown in a bore **215** of the wellbore **250**. The combination of the casing **210/220** and the cement sheath **212** in the bore **215** strengthens the wellbore **250** and facilitates the isolation of formations behind the casing **210/220**.

[0089] It is understood that a wellbore **250** may, and typically will, include more than one string of intermediate casing. In some instances, an intermediate string of casing may be a liner.

[0090] Finally, a production string **230** is provided. The production string **230** is hung from the intermediate casing string **230** using a liner hanger **231**. The production string **230** is a liner that is not tied back to the surface **201**. In the arrangement of Figure 2, a cement sheath **232** is provided around the liner **230**.

[0091] The production liner **230** has a lower end **234** that extends to an end **254** of the wellbore **250**. For this reason, the wellbore **250** is said to be completed as a cased-hole well. Those of ordinary skill in the art will understand that for production purposes, the liner **230** may be perforated after cementing to create fluid communication between a bore **235** of the liner **230** and the surrounding rock matrix making up the subsurface formation **255**. In one aspect, the production string **230** is not a liner but is a casing string that extends back to the surface.

[0092] As an alternative, end **254** of the wellbore **250** may include joints of sand screen (not shown). The use of sand screens with gravel packs allows for greater fluid communication between the bore **235** of the liner **230** and the surrounding rock matrix while still providing support for the wellbore **250**. In this instance, the wellbore **250** would include a slotted base pipe as part of the sand screen joints. Of course, the sand screen joints would not be cemented into place and would not include subsurface communications nodes.

[0093] The wellbore **250** optionally also includes a string of production tubing **240**. The production tubing **240** extends from the well head **260** down to the subsurface formation **255**. In the arrangement of Figure 2, the production tubing **240** terminates proximate an upper end of the subsurface formation **255**. A production packer **241** is provided at a lower end of the production tubing **240** to seal off an annular region **245** between the tubing **240** and the surrounding production liner **230**. However, the production tubing **240** may extend closer to the end **234** of the liner **230**.

[0094] In some completions a production tubing **240** is not employed. This may occur, for example, when a monobore is in place.

[0095] It is also noted that the bottom end **234** of the production string **230** is completed substantially horizontally within the subsurface formation **255**. This is a common orientation for

CA 3028103 2018-12-19

wells that are completed in so-called "tight" or "unconventional" formations. Horizontal completions not only dramatically increase exposure of the wellbore to the producing rock face, but also enables the operator to create fractures that are substantially transverse to the direction of the wellbore. Those of ordinary skill in the art may understand that a rock matrix will generally "part" in a direction that is perpendicular to the direction of least principal stress. For deeper wells, that direction is typically substantially vertical. However, the present inventions have equal utility in vertically completed wells or in multi-lateral deviated wells.

[0096] As with the well site **100** of Figure 1, the well site **200** of Figure 2 includes a telemetry system that utilizes a series of novel communications nodes. This again may be for the purpose of evaluating the integrity of the cement sheath **212, 232**. The communications nodes are placed along the outer diameter of the casing strings **210**, **220**, **230**. These nodes allow for the high speed transmission of wireless signals based on the in situ generation of acoustic waves.

[0097] The nodes first include a topside communications node **282**. The topside communications node **282** is placed closest to the surface **201**. The topside node **282** is configured to receive acoustic signals.

[0098] In some embodiments, the nodes may also include a sensor communications node **284**. The sensor communications node **284** may be placed near one or more sensors **290**. The sensor communications node **284** is configured to communicate with the one or more downhole sensors **290**, and then send a wireless signal using acoustic waves.

[0099] The sensors **290** may be, for example, pressure sensors, flow meters, or temperature sensors. A pressure sensor may be, for example, a sapphire gauge or a quartz gauge. Sapphire gauges can be used as they are considered more rugged for the high-temperature downhole environment. Alternatively, the sensors may be microphones for detecting ambient noise, or geophones (such as a tri-axial geophone) for detecting the presence of micro-seismic activity. Alternatively still, the sensors may be fluid flow measurement devices such as a spinners, or fluid composition sensors.

[0100] In addition, the nodes include a plurality of subsurface battery-powered intermediate communications nodes **280**. Each of the subsurface battery-powered intermediate communications nodes **280** is configured to receive and then relay acoustic signals along essentially the length of the wellbore **250**. For example, the subsurface battery-powered intermediate communications nodes **280** can utilize two-way electro-acoustic transducers to receive and relay mechanical waves.

[0101] The subsurface battery-powered intermediate communications nodes **280** transmit signals as acoustic waves. The acoustic waves can be at a frequency of, for example, between about 50 kHz and 1 MHz. The signals are delivered up to the topside communications node **282** so that signals indicative of cement integrity are sent from node-to-node. A last subsurface battery-powered intermediate communications node **280** transmits the signals acoustically to the topside communications node **282**. Communication may be between adjacent nodes or may skip nodes depending on node spacing or communication range. Preferably, communication is routed around nodes which are not functioning properly.

[0102] The well site **200** of Figure 2 shows a receiver **270**. The receiver **270** can comprise a processor **272** that receives signals sent from the topside communications node **282**. The processor **272** may include discrete logic, any of various integrated circuit logic types, or a microprocessor. The receiver **270** may include a screen and a keyboard **274** (either as a keypad or as part of a touch screen). The receiver **270** may also be an embedded controller with neither a screen nor a keyboard which communicates with a remote computer such as via wireless, cellular modem, or telephone lines.

[0103] The signals may be received by the processor **272** through a wire (not shown) such as a co-axial cable, a fiber optic cable, a USB cable, or other electrical or optical communications wire. Alternatively, the receiver **270** may receive the final signals from the topside node **282** wirelessly through a modem or transceiver. The receiver **270** can receive electrical signals via a so-called Class I, Div. 1 conduit, that is, a wiring system or circuitry that is considered acceptably safe in an explosive environment.

[0104] Figures 1 and 2 present illustrative wellbores **150**, **250** that may receive a downhole telemetry system using acoustic transducers. In each of Figures 1 and 2, the top of the drawing page is intended to be toward the surface and the bottom of the drawing page toward the well bottom. While wells commonly are completed in substantially vertical orientation, it is understood that wells may also be inclined and even horizontally completed. When the descriptive terms "up" and "down"

CA 3028103 2018-12-19

or "upper" and "lower" or similar terms are used in reference to a drawing, they are intended to indicate location on the drawing page, and not necessarily orientation in the ground, as the present inventions have utility no matter how the wellbore is orientated.

[0105] In each of Figures 1 and 2, the battery-powered intermediate communications nodes **180**, **280** are specially designed to withstand the same corrosive and environmental conditions (for example, high temperature, high pressure) of a wellbore **150** or **250**, as the casing strings, drill string, or production tubing. To do so, it is preferred that the battery-powered intermediate communications nodes **180**, **280** include sealed steel housings for holding the electronics. In one aspect, the steel material is a corrosion resistant alloy.

[0106] Referring now to Figure 3, an enlarged perspective view of an illustrative tubular section **310** of a tubular body, along with an illustrative intermediate communications node **380** is shown. The illustrative intermediate communications node **380** is shown exploded away from the tubular section **310**. The tubular section **310** has an elongated wall **314** defining an internal bore **316**. The tubular section **310** has a box end **318** having internal threads **320**, and a pin end **322** having external threads **324**.

[0107] As noted, the illustrative intermediate communications node **380** is shown exploded away from the tubular section **310**. The intermediate communications node **380** is structured and arranged to attach to the wall **314** of the tubular section **310** at a selected location. In one aspect, selected tubular sections **310** will each have an intermediate communications node **380** between the box end **318** and the pin end **322**. In one arrangement, the intermediate communications node **380** is placed immediately adjacent the box end **318** or, alternatively, immediately adjacent the pin end **322** of every tubular section **310**. In another arrangement, the intermediate communications node **380** is placed at a selected location along every second or every third tubular section **310**. In other aspects, more or less than one intermediate communications node **380** may be placed per tubular section **310**.

[0108] In some embodiments, the intermediate communications node **380** shown in Figure 3 is designed to be pre-welded onto the wall **314** of the tubular section **310**. In some embodiments, intermediate communications node **380** is configured to be selectively attachable to/detachable from an intermediate by mechanical means at a well **100**, **200** (see Figures 1-2). This may be done, for example, through the use of clamps (not shown). Alternatively, an epoxy or other suitable acoustic couplant may be used for chemical bonding. In any instance, the intermediate communications node **380** is an independent wireless communications device that is designed to be attached to an external surface of a tubular.

[0109] There are benefits to the use of an externally-placed communications node that uses acoustic waves. For example, such a node will not interfere with the flow of fluids within the internal bore **316** of the tubular section **310**. Further, installation and mechanical attachment can be readily assessed or adjusted, as necessary.

[0110] As shown in Figure 3, the intermediate communications node **380** includes a housing **386**. The housing **386** supports a power source residing within the housing **386**, which may be one or more batteries, as shown schematically at **390**. The housing **386** also supports a first electro-acoustic transducer, configured to serve as a receiver of acoustic signals and shown schematically at **388**, a second electro-acoustic transducer, configured to serve as a transmitter of acoustic signals and shown schematically at **336**.

[0111] The intermediate communications node **380** is intended to represent the plurality of intermediate communications nodes **180** of Figure 1, in one embodiment, and the plurality of intermediate communications nodes **280** of Figure 2, in another embodiment. The first and second electro-acoustic transducers **388** and **336** in each intermediate communications node **380** allow acoustic signals to be sent from node-to-node, either up the wellbore or down the wellbore. Where the tubular section **310** is formed of carbon steel, such as a casing or liner, the housing **386** may be fabricated from carbon steel. This metallurgical match avoids galvanic corrosion at the coupling.

[0112] Figure 4 provides a cross-sectional view of the intermediate communications node **380** of Figure 3. The view is taken along the longitudinal axis of the intermediate communications node **380**. The housing **386** is dimensioned to be strong enough to protect internal components and other electronics disposed within the interior region. In one aspect, the housing **386** has an outer wall **330** that may be about 0.2 inches (0.51 cm) in thickness. A cavity **332** houses the electronics, including, by way of example and not of limitation, a power source **390** such as a battery, a power harvesting device, or the like, a power supply wire **334**, a first electro-acoustic transducer **388**, a second electro-acoustic transducer **336**, and a circuit board **338**. The circuit board **338** will preferably include a micro-processor or electronics module that processes acoustic signals. The first electro-acoustic transducer **388**, and the second electro-acoustic transducer **336** are provided to convert acoustical energy to electrical energy (or vice-versa) and are coupled with outer wall **330** on the side attached to the tubular body.

CA 3028103 2018-12-19

[0113] In some embodiments, the second electro-acoustic transducer **336**, configured to serve as a transmitter, of intermediate communications nodes **380** may also produce acoustic telemetry signals. In some embodiments, an electrical signal is delivered to the second electro-acoustic transducer **336**, such as through a driver circuit. In some embodiments, the acoustic waves represent asynchronous packets of information comprising a plurality of separate tones.

[0114] In some embodiments, the acoustic telemetry data transfer is accomplished using multiple frequency shift keying (MFSK). Any extraneous noise in the signal is moderated by using well-known analog and/or digital signal processing methods. This noise removal and signal enhancement may involve conveying the acoustic signal through a signal conditioning circuit using, for example, a band pass filter.

[0115] The signal generated by the second electro-acoustic transducer **336** then passes through the housing **386** to the tubular body **310**, and propagates along the tubular body **310** to other intermediate communications nodes **380**. In one aspect, the acoustic signal is generated (first electro-acoustic transducer **388**) and/or received (second electro-acoustic transducer **336**) by a magnetostrictive transducer comprising a coil wrapped around a core. In another aspect, the acoustic signal is generated and/or received by a piezoelectric ceramic transducer. In either case, the electrically encoded data are transformed into a sonic wave that is carried through the wall **314** of the tubular body **310** in the wellbore. In certain configurations, a single transducer may serve as both the transmitter and receiver.

[0116] In some embodiments, the internals of intermediate communications nodes **380** may also be provided with a protective layer **340**. The protective layer **340** resides internal to the wall **330** and provides an additional thin layer of protection for the electronics. This protective layer provides additional mechanical durability and moisture isolation. The intermediate communications nodes **380** may also be fluid sealed with the housing **386** to protect the internal electronics. One form of protection for the internal electronics is available using a potting material.

[0117] In some embodiments, the intermediate communications nodes **380** may also optionally include a shoe **342**. More specifically, the intermediate communications nodes **380** may include a pair of shoes **342** disposed at opposing ends of the wall **330**. Each of the shoes **342** provides a beveled face that helps prevent the node **380** from hanging up on an external tubular body or the surrounding earth formation, as the case may be, during run-in or pull-out.

[0118] Figure 5 provides a cross-sectional view of a sensor communications node **484**. The sensor communications node **484** is intended to represent the sensor communications node **184** of Figure 1, in one embodiment, and the sensor communications nodes **284** of Figure 2, in another embodiment. The view is taken along the longitudinal axis of the sensor communications node **484**. The sensor communications node **484** includes a housing **402**. The housing **402** is structured and arranged to be attached to an outer wall of a tubular section, such as the tubular section **310** of Figure 3. Where the tubular section is formed of a carbon steel, such as a casing or liner, the housing **402** is preferably fabricated from carbon steel. This metallurgical match avoids galvanic corrosion at the coupling.

[0119] The housing **402** is dimensioned to be strong enough to protect internal components and other electronics disposed within the interior region. In one aspect, the housing **402** has an outer wall **404** that may be about 0.2 inches (0.51 cm) in thickness. An optional pair of shoes **422** may be disposed at opposing ends of the wall **404**. Each of the shoes **422** may be shaped to provide a beveled face to help prevent the sensor communications node **484** from hanging up on an external tubular body or the surrounding earth formation, as the case may be, during run-in or pull-out. A cavity **406** houses the electronics, including, by way of example and not of limitation, a power source **408**, a power supply wire **410**, and a circuit board **414**. The circuit board **414** will preferably include a micro-processor or electronics module that processes acoustic signals. A first electro-acoustic transducer **416** and a second electro-acoustic transducer **412** are provided to convert acoustical energy to electrical energy (or vice-versa) and are coupled with outer wall **404** on the side attached to the tubular body. The first electro-acoustic transducer **416** is in electrical communication with at least one sensor **418**, possibly through a shared connection to a micro-processor on circuit board **414**, which may be the at least one sensor **178** of Figure 1, in one embodiment. It is noted that in Figure 5, at least one sensor **418** resides within the housing **402** of the sensor communications node **484**. In certain configurations, a single transducer may serve as both the transmitter and receiver. A protective layer **420** resides internal to the wall **404** and provides an additional thin layer of protection for the electronics. This protective layer provides additional mechanical durability and moisture isolation.

[0120] Referring now to Figure 6, an alternate embodiment is presented wherein an at least one sensor **518** is shown to reside external to a sensor communications node **584**, such as above or below the sensor communications node **584** along the wellbore. In Figure 6, the sensor communications

CA 3028103 2018-12-19

node **584** is also intended to represent the sensor communications node **184** of Figure 1, in one embodiment, and the sensor communications nodes **284** of Figure 2, in another embodiment. The sensor communications node **584** includes a housing **502**, which is structured and arranged to be attached to an outer wall of a tubular section, such as the tubular section **310** of Figure 3.

[0121] In one aspect, the housing **502** has an outer wall **504** that may be about 0.2 inches (0.51 cm) in thickness. An optional pair of beveled shoes **522** may be disposed at opposing ends of the wall **504** as described in previous embodiments. A cavity **506**, lined with a protective layer **520**, houses the electronics, including, by way of example and not of limitation, a power source **508**, a power supply wire **510**, and a circuit board **514**. The circuit board **514** will preferably include a micro-processor or electronics module that processes acoustic signals. A first electro-acoustic transducer **516** and a second electro-acoustic transducer **512** are provided to convert acoustical energy to electrical energy (or vice-versa) and are coupled with outer wall **504** on the side attached to the tubular body. The electro-acoustic transducer **516** is in electrical communication with at least one sensor **518**. A dashed line is provided showing an extended connection between the at least one sensor **518** and the electro-acoustic transducer **516**. In certain configurations, a single transducer may serve as both the transmitter and receiver.

[0122] In operation, the sensor communications node **584** is in electrical communication with the (one or more) sensors. This may be by means of a wire, or by means of wireless communication such as infrared or radio waves. The sensor communications node **584** is configured to receive signals from the sensors.

[0123] The sensor communications node **584** transmits signals from the sensors as acoustic waves. The acoustic waves can be at a frequency band of about 50 kHz and 1 MHz, from about 50 kHz to about 500 kHz, from about 60 kHz to about 200 kHz, from about 65 kHz to about 175 kHz, from about 70 kHz to about 300 kHz, from about 75 kHz to about 150 kHz, from about 80 kHz to about 140 kHz, from about 85 kHz to about 135 kHz, from about 90 kHz to about 130 kHz, or from about 100 kHz to about 125 kHz, or about 100 kHz. The signals are received by an intermediate communications node, such as intermediate communications node **380** of Figure 4. That intermediate communications node **380**, in turn, will relay the signal on to another intermediate communications node so that acoustic waves indicative of the downhole condition are sent from node-to-node. A last intermediate communications node **380** transmits the signals to the topside node, such as topside node **182** of Figure 1, or topside node **282** of Figure 2.

[0124] As indicated above, one embodiment of the intermediate communications nodes described herein is of a novel dual transducer design. The design consists of two transducers: one serving as a transmitter and another serving as a receiver. Though a single electronic board is used to operate the transmitter and receiver, separate electronic circuits are employed to optimize the performance of transmission and receiving respectively. The dual transducer design provides optimal overall performance as an intermediate communication node and offers extended range.

[0125] In addition to improved communication performance, the dual transducer design may provide such advanced benefits as: a) the receiver may be designed and used as an energy harvesting device to harvest the vibration from the transmitter when transmitting; b) the transmitter and receiver may be designed and used as a pair of active sensing devices for measurement of physical parameters of interest, such as material surrounding the node, flow velocity, casing corrosion, or the like; c) the transmitter and receiver pair may be designed and used to provide advanced diagnostic information.

[0126] Referring now to Figure 7A, the transmitter **600** may be designed to have multiple disks, **602**, **604**, ..., with electrodes connected in parallel, as shown. A single voltage may be applied equally to all disks **602**, **604**, ... via MFSK signal generator **610**. Based on piezo transducer theory, the mechanical vibration output of such a multi disk stack is given by summation of the output of each disk, **602**, **604**, ... The amplitude of vibration displacement of each disk is approximately given by:

$$Y_{disk} = d_p V_{t0}$$

where d_p is the piezo charge constant. The total amplitude of the displacement of parallel multi-disk stack is approximately:

$$Y_{total} = nY_{disk} = n\, d_p V_{t0}$$

where n is the number of disks. Clearly, the mechanical output of the piezo stack can be increased by increasing the number of disks while applying the same voltage. For the same output required, more disks allow using a lower driving voltage.

[0127] Referring now to Figure 7B, the receiver **700** is designed to have multiple-disks **702**, **704**, ..., with electrodes connected in series or a single thicker disk. The voltage output to MFSK receiver electronics **710** of a single disk of thickness h, when subjected to a vibration force with an amplitude, F_0, is given approximately by the following relation:

$$V_{disk} = g_p\, h\, F_0/A$$

where g_p is the piezo voltage constant, and A is the disk surface area. The overall voltage output of a series of multiple disks is approximately:

$$V_{r0} = m\, V_{disk} = m\, g_p\, h\, F_0/A$$

where m is the number of disks. In theory, a thick disk with thickness of $L = m\, h$ will perform equally well as multiple disks in series. Therefore, we could increase the thickness of a single disk or number of disks of the same thickness to boost the receiver voltage output. With higher voltage output at a given vibration signal, the receiver sensitivity increases, which will improve detection accuracy or increase the communication range.

[0128] In the preferred embodiment, the piezo transmit and receive stacks will be fitted with an end mass **606** and **706**, respectively, to enhance transmission output or receiver sensitivity. The end mass provides properly timed reflections to improve the piezo performance. With separate transmit and receive transducers, the end mass lengths can be individually selected to optimize overall acoustic performance. Additional performance customization can be achieved with combined collective adjustments to both the electrical impedance matching circuits and the end mass adjustments. With separate transmit and receive transducers, four independent adjustments are available compared to two with a single transmit/receive transducer. Performance parameters such as power consumption, signal to noise ratio, and bandwidth can be adjusted to improve telemetry and battery life.

[0129] In some embodiments, the electronic circuit for the transmitter **600** and for the receiver **700** could be configured as separate entities to optimize their performance. For example, different amount of inductance could be used for transmitter **600** and receiver **700**. Cross-talk and receiver noise may also be reduced. Laboratory data has shown significant improvement with the dual transducer designs disclosed herein over a single transducer design, the benefits being as much as 20 dB or better. This improvement is based on comparing the dual transducer design with the transducer shown in Figure 7A used as the sole transducer. Most of the improvement is attributable to flexibility using separate receive and transmit circuitry.

[0130] The disclosed aspects include a method by which sensor devices accessible via an acoustic wireless network can provide data equivalent in analytical value to a substantially larger and more comprehensive dataset, while simultaneously operating within a low energy envelope conducive to long operational life using small, limited capacity power sources compatible with placement in space-constrained downhole locations subject to extreme temperature and pressure.

[0131] Some research has occurred in recent years with respect to efficient querying of distributed sensor networks, but such research generally assumes a 2- or 3-dimensional network in which each node can communicate with any other within spherical range and there are multiple distinct paths between any two such nodes. The research also assumes the existence of always-available (or nearly so) radio communication and focuses on responding to ad hoc queries from a particular client. In contrast, a downhole acoustic wireless network installed on a tubular (such as a hydrocarbon well or an injection well) generally offers only one-dimensional networking and a single path between any two nodes. Because the nodes exist in an unresponsive sleep state most of the time, each ad hoc query from a receiver (such as receiver **190**) or a topside node (such as topside communications node **182**) has a high probability of failing by not reaching the necessary downhole node in a timely manner (if at all).

[0132] Figure 8 shows a state transition diagram **800** for a device comprising a node in a wireless network according to one possible aspect addressing the above issues. The device usually sleeps, as shown by sleep state **802**, but the device wakes periodically to check for incoming communication (state change line **804**) and wakes in response to "trigger" conditions (state change line **806**) that cause it to take sensor readings (state **808**). Non-limiting examples of triggers might include: a sensor value exceeding or falling below a particular range or a threshold value; a sensor value staying within a particular range for a period of time; and/or a one-time or recurring timed interval. The specific triggers active in a device will determine which sensor values the device will acquire, and under what circumstances it will acquire them. As used herein, a "sleep state" may include a device state in which a device is not operating (i.e., consuming no power), and/or device states in which a device is operating at a very low power level compared to a normal operating state. Such very low power level may be calculated based on instantaneous power usage or a time-based average power usage. A very low power level may be less than 10%, or less than 5%, or less than 2%, or less than 1%, or less than 0.1%, or less than 0.01% of the power level of a normal operating state.

[0133] Once sensor data is acquired **808**, the device will assemble query results if possible (state **826**) and either return (via state change line **822**) to the sleep state **802** if query results are still incomplete, or proceed (state change line **828**) to "push" query results closer to topside (state **818**) if query results are complete (in other words, one or more queries is fully satisfied). If an incoming communication is received by the device (state **810**), it is determined whether the communication is a query specification (or query spec), a data packet, a trigger specification (or trigger spec), or some other communication that may not be relevant to the device but may be relevant to a different device.

[0134] To retrieve sensor data, a receiver or topside device ("client") issues one or more queries to the downhole network. A given device receives the query spec (state change line **812**), stores each relevant query spec and, at state **814**, assembles (but not yet transmitting) corresponding data until the query is fully satisfied. The data may be manipulated, filtered, transformed, summarized, tagged with node-specific identifier, or otherwise processed (collectively, "processed"), to thereby generate a processed dataset. The data and/or the processed dataset is buffered and stored at state **816**. This allows the device to sleep and otherwise conserve energy while servicing the query spec. In some cases, data and/or processed datasets received from other devices may be combined with local data and/or processed datasets to be further processed at state **836**. In other words, the local processing of data according to the disclosed aspects may incorporate data already relayed from other devices. As a non-limiting example, several sensing devices could contribute to a result set already on its way to the surface. The query could, in such a case, specify something that may naturally come from a group of devices, such as temperatures from a range of depths. In any event, the device may apply data filtering, transformations such as moving average, summarizations, or other processing locally, thereby displacing a portion of analysis from topside to the sensor devices themselves in lieu of the usual practice of returning all necessary raw data to the client for processing. This downhole analysis yields a substantially smaller result set in most cases and saves energy due to a reduced number of transmissions.

[0135] In various aspects of the disclosure, the data is processed at a device according to instructions provided in one or more trigger specs and/or query specs. Such instructions are considered a "variable instruction set" because of the ability to change how the data is processed by varying instructions in a trigger spec and/or query spec.

[0136] To determine the sensor data available for a query spec, a receiver or topside device ("client") issues one or more trigger specs to the downhole network. A given sensor device receives the trigger spec (state change line **832**) and, at state **834**, stores each relevant trigger spec and updates the "trigger" conditions that cause the sensor device to take sensor readings. As non-limiting examples: the trigger specs may depend solely on sensor values from the local sensor device; or the trigger specs may depend at least in part on sensor data from at least one other sensor device; or the trigger specs may not depend on sensor data from any sensor device.

[0137] Since downhole sensor devices may have intermittent availability (due to sleep, acoustic channel saturation, production noise, and many other causes), each device "pushes" query results closer to topside (at state **818**) as available peers exist to do so. Data received from other devices (via state change line **820**) is preprocessed as necessary (at state **836**) then stored at state **816** and relayed at state **818**, similar to received queries. In some cases, communications received from other devices may be immediately (via state change line **830**) relayed at state **818** while bypassing the typical processing and/or storage. Once sensor data is relayed at state **818**, the device will return (via state change line **824**) to the sleep state **802**. This behavior contrasts with the ad hoc approach of "pulling" sensor data in response to the immediate query, and likewise contrasts with the conventional "polling" approach in which the client checks the status of one or more devices on a scheduled basis or on an ad hoc basis. Note that pushing query spec results also allows for positioning of results near the top of the downhole network even if no topside device is present (a "headless" network) to make later retrieval of results faster and more energy efficient, and to reduce the possibility that results become irretrievable due to device and/or network failure.

[0138] Figure 9 shows examples of a hypothetical trigger spec **902** and first and second hypothetical query specs **904**, **906**. Note that all are device independent, identifying target devices via functional aspects of the network (such as downhole depth) rather than specific device IDs or addresses. This simplifies operation and allows for consistent queries across an entire field of downhole network installations regardless of the specific sensor device configuration in each well. Hypothetical trigger spec **902** instructs all devices at 600-1,200 foot depths downhole to save a temperature reading in their log every ten minutes. First hypothetical query spec **904** requests temperatures from all devices at 600-1,200 foot depths downhole. Each device should return the ten-point moving average of every twelfth temperature from the 96th through the 600th temperature in the log. Second hypothetical query spec **906** requests temperatures from all devices at 600-1,200 foot depths downhole. Each device should return the ten-point moving average of every twelfth temperature from the log, but only when it exceeds the previous moving average value by more than twenty percent. Other types of inputs, such as pressure, acoustic energies, and the like, may be recorded at one or more devices and processed as disclosed herein.

[0139] In one embodiment, a topside receiver can synchronize the sensor devices in multiple downhole networks such that a single trigger spec or query spec can result in temporal data from all networks that corresponds to the same moments in time across all networks.

[0140] In other embodiments, sensor devices can compress query spec results to save additional energy as compared to transmitting the same query spec results in uncompressed form. In one such embodiment, two or more sensor devices provide portions of the query spec results such that each sensor device compresses its contribution to the query spec results but does so with the benefit of a compression dictionary, sensor value deltas, or other metadata from at least one other sensor device. In this form of collaborative compression, no single device has the entire result set, but the devices share metadata (i.e., information about the nature of the data each device is holding) to improve the quality of the overall compressed result set. As a non-limiting example: if the sensed temperatures across a group of devices were between 82 °C and 85 °C, the devices could return the temperatures themselves, with each value requiring eight bits of data to transmit; however, according to the disclosed embodiments, the first value in the result set could be 82 °C, which would establish a result set baseline, and all subsequent transmitted values would be 0-3 depending on how much each measured temperature exceeds the baseline. These subsequent transmitted values of 0-3 require only two bits of data to transmit, which is roughly 75% smaller than simply returning the actual temperatures. The devices can only achieve such compression if some degree of metadata is shared between the devices prior to each device compressing its own data.

[0141] The disclosed aspects provide a communications network and a method of communicating over such a communications network. Such a communications network may include a plurality of devices, which may comprise the nodes in a wireless communications network as disclosed herein. These devices are positioned to communicate with other devices in the network and may include a receiver and a transmitter. The devices are arranged to form a substantially linear network topology as previously discussed. Some, if not all, of the devices include one or more sensors such as a pressure sensor, a flow meter, a fluid flow measurement device, a temperature sensor, a chemical composition or pH sensor, a formation density sensor, a fluid identification sensor, a strain gauge, a pressure sensor, a resistivity sensor, a vibration sensor, a microphone, or a geo-phone. Devices with sensors include some means of recording inputs from the respective sensors as well as information received from other devices. Each device has a processor that processes, according to a variable instruction set residing in the device, recorded values from the sensors associated with the respective device and/or other devices. The variable instruction set may be changed by commands from other devices, or from a transmitter external to the network, such as a topside transceiver. For example, patterns in the sensor data from one or more devices may be recognized or detected (such as a regular cycling of temperatures or flow rates, or temperature gradient greater than a predetermined amount), and based on such pattern detection the variable instruction set for one or more devices may be modified. The modifications to the variable instruction set(s) may include executing other data requests from any device in the network, instructing one or more devices to relay or to not relay recorded information or secondary data to other devices, and/or take other local or remote actions. In this manner, secondary or tertiary measurement data or other derived quantities may be generated and transmitted through the network. Such secondary data or derived quantities may include a ratio, calculated metric, or some sort of a derivative or integrated value (such as mass flow rate, temperature change over time, etc.) obtained from sensor data, such as mass flow rate. The local combining of this data results in less power required to transmit necessary information along the network. As an example, data received at a given device in a wellbore may look at its local temperature and the 5 temperatures lower in well that have been passed to the given device. Temperature data would only be relayed up-well if it matches a certain gradient, or if a continuity occurs, or if there is a single high temperature (indicating high flow or a leak). In this way, network bandwidth is saved, data containing more information is relayed, and thus data compression ratios can be extremely high, in an effective compression fashion.

[0142] Devices without sensors may also be included. These sensor-less devices may be specifically dedicated to processing (e.g., performing calculations on) sensor data or processed data from other devices. The sensor-less devices may be interspersed on the network such that multiple sensor data or processed data from sensor-included devices only need to be transmitted a short distance along the network before being recorded and processed to a single data message at the sensor-less device. Additionally, devices (with or without sensors) may be programmed to complete at least one sleep cycle (or other low-power cycle) between recording a sensor value and combining the sensor value with a sensor value recorded by another device. The devices may also be programmed to complete at least one sleep cycle between recording a sensor value and transmitting that sensor value to another device in the network.

[0143] The disclosed combination of small, low power sensor devices capable of placement in space-constrained locations and operation in extreme temperature and pressure, with long operational life, while supplying sensor data and/or processed data equivalent in analytical value to a substantially larger and more comprehensive data set, provides many advantages over known wireless communication techniques, especially in the context of downhole acoustic wireless networks or guided wave telemetry. For example, device-independent queries allow use across and/or throughout a production field regardless of configuration specifics for each well. The disclosed aspects support the autonomous push of query results for unattended or headless network operation. The disclosed aspects can query sensor devices despite intermittent availability. The disclosed aspects can synchronize temporal sensor data across multiple downhole networks. The disclosed aspects permit energy-efficient use of a linear network. Furthermore, the disclosed aspects provide longer sensor device operational life, ability to instrument space-constrained locations (therefore a greater proportion of the downhole environment), increased analytical value of retrieved sensor data, significantly reduced operational expense due to unattended or headless operation, and more reliable indication of anomalous downhole condition (via push strategy proactively moving query results to topside), among others.

[0144] Aspects of the disclosure provide a method of communicating using a downhole wireless network using a plurality of sensors. It is within the scope of the disclosure to employ the wireless network in other environments. For example, a pipeline may also exhibit similar acoustic aspects as a wellbore, and a sensor network as disclosed herein may be particularly effective to transmit data bi-directionally along the pipeline. Additionally, aspects of the disclosure may be implemented with types of wireless networks other than acoustic networks. Lastly, aspects of the disclosure are described as being used advantageously for downhole or pipeline sensor data collection, processing, and transmission, but may also be used to communicate with and control pipeline tools and other well control functions.

[0145] Figure 10 is a flowchart showing a method **1000** of communicating in a wireless network according to disclosed aspects. The wireless network may have a substantially linear topology. At block **1002** data from one or more sensors associated with a communications node or device is collected and either processed locally at the node (block **1004**) or combined with sensor data from at least one other node and processed locally at the first node (block **1006**). Locally processed data may then be sent to another node in the wireless network for further processing, or may be directed toward an end of the network (block **1008**). Alternatively, data collected in block **1002** may be sent to a local processing node or sensor-less device as previously described herein (block **1010**), where data from multiple nodes may be combined and processed as described with respect to block **1006**. Each node or device is maintained in a sleep state unless instructions are received to record values, process the recorded values, and/or transmit to another node or device, and each node or device returns to the sleep state when the instructions are fulfilled.

[0146] Figure 11 is a flowchart showing a method **1100** of communication in a wireless network having a plurality of nodes including a first node, according to one possible aspect of the disclosure. At block **1102**, each of the plurality of nodes is maintained in a sleep state. At block **1104**, if a trigger event occurs at the first node, data relevant to the trigger event is sensed and/or stored and/or indexed at the first node. At block **1106**, if a query applicable to the first node is received by the first node, the query at the first node is processed to produce query-based information. At block **1108**, the query-based information is stored at the first node until the processing of the query is complete. At block **1110**, the query-based information is transmitted to another node in the network. At block **1112**, if the query may have applicability to a node other than the first node, the query is transmitted to another node in the network. At block **1114**, if data is received by the first node, it is determined whether the data is needed to process a query applicable to the first node. At block **1116**, if the data is not needed to process the query the data may be transmitted to another of the plurality of nodes. At block **1118**, the first node is turned to the sleep state when the query-based information or the data is transmitted.

[0147] Figure 12 is a flowchart showing a method **1200** of communicating in a wireless network according to another possible aspect of the disclosure. At block **1202** a plurality of devices are positioned such that each of the plurality of devices communicates with one or more other of the plurality of devices. At least some of the plurality of devices include one or more sensors. At block **1204**, at one of the devices, values are recorded from the one or more sensors associated therewith. At block **1206**, at least some of the devices, one or more recorded values from the one or more sensors associated with said each device, and/or a sensor associated with at least one other device, are processed in accordance with a variable instruction set, to thereby generate a processed dataset. At block **1208**, at each device, at least one of recorded values, a processed dataset associated with another of the devices, or a revision to the variable instruction set receiving, are received from another of the devices. At block **1210**, at each device, at least one of the one or more recorded values, and one or more processed datasets, are transmitted to another of the plurality of devices. At block **1212**, each device is maintained in a sleep state unless instructions are received to record values, process the recorded values, and/or transmit to another device, and each device returns to the sleep state when the instructions are fulfilled.

[0148] As may be appreciated, the blocks of Figures 10-12 may be omitted, repeated, performed in a different order, or augmented with additional steps not shown. Some steps may be performed sequentially, while others may be executed simultaneously or concurrently in parallel. In addition, the methods described in any of Figures 10-12 may be used within a wellbore or along one or more tubular members, such as along a subsea conduit and/or along a pipeline, to enhance associated operations. As a specific example, the wireless network may be used along midstream pipelines and storage tanks, and/or downstream refinery and distribution operations.

[0149] The disclosed communications network provides an advantage over wired downhole communications systems in that it is robust. Each network element is configured to possess temporal, spatial, and chemical pattern recognition, thereby reducing the possibility of a single point failure (such as the break of a communications wire). Such pattern recognition, due to the distributed processors at each device or node and the ability to modify the variable instruction set at each device, permits the disclosed communications network to provide and support high quality, reliable operational decisions. Wired systems may not need distributed, or local, computational power at the node level as disclosed herein. The local computational power is most advantageous for wireless networks because more energy is saved (via transmissions) than it costs.

Industrial Applicability

[0150] The apparatus and methods disclosed herein are applicable to the oil and gas industry.

[0151] It is believed that the disclosure set forth above encompasses multiple distinct inventions with independent utility. While each of these inventions has been disclosed in its preferred form, the specific embodiments thereof as disclosed and illustrated herein are not to be considered in a limiting sense as numerous variations are possible. The subject matter of the inventions includes all novel and non-obvious combinations and subcombinations of the various elements, features, functions and/or properties disclosed herein. Similarly, where the claims recite "a" or "a first" element or the equivalent thereof, such claims should be understood to include incorporation of one or more such elements, neither requiring nor excluding two or more such elements.

[0152] It is believed that the following claims particularly point out certain combinations and subcombinations that are directed to one of the disclosed inventions and are novel and non-obvious. Inventions embodied in other combinations and subcombinations of features, functions, elements and/or properties may be claimed through amendment of the present claims or presentation of new claims in this or a related application. Such amended or new claims, whether they are directed to a different invention or directed to the same invention, whether different, broader, narrower, or equal in scope to the original claims, are also regarded as included within the subject matter of the inventions of the present disclosure.

[0153] While the present invention has been described and illustrated by reference to particular embodiments, those of ordinary skill in the art will appreciate that the invention lends itself to variations not necessarily illustrated herein. For this reason, reference should be made solely to the appended claims for purposes of determining the true scope of the invention.

CLAIMS:

1. A method of communication in a wireless network having a plurality of nodes including a first node and a second node, the method comprising:

maintaining each of the plurality of nodes in a sleep state;

when a trigger event occurs at the first node, performing at least one of: sensing, storing, and indexing data associated with the trigger event at the first node;

when a query applicable to the first node is received by the first node:

processing the query at the first node to produce first node query-based data; and

storing the first node query-based data at the first node until the processing of the query is complete;

wherein the second node has second node query-based data stored thereat, the method further comprising:

compressing the first node query-based data in accordance with a collaborative compression based on the first node query-based data and the second node query-based data, to obtain compressed first node data;

compressing the second node query-based data in accordance with the collaborative compression based on the second node query-based data and the first node query-based data, to obtain compressed second node data;

transmitting the compressed first node data and the compressed second node data to another node of the plurality of nodes;

wherein:

when the query is applicable to a node other than the first node, transmitting the query to another node in the wireless network;

when additional data is received by the first node, determining whether the additional data is needed to process a query applicable to the first node; and

when the additional data is not needed to process the query, transmitting the additional data to another of the plurality of nodes;

and

returning the first node to the sleep state subsequent the compressed first node data being transmitted.

Date Reçue/Date Received 2020-10-09

2. The method of claim 1, wherein the first node includes at least one sensor, and wherein the sensor is one of a pressure sensor, a flow meter, a fluid flow measurement device, a temperature sensor, a chemical composition or pH sensor, a formation density sensor, a fluid identification sensor, a strain gauge, a pressure sensor, a resistivity sensor, a vibration sensor, a microphone, and a geo-phone.

3. The method of claim 1, wherein a topology of the wireless network is substantially linear, and wherein the first node is a sensor communications node placed along a tubular body and affixed to a wall of the tubular body, the sensor communications node being in electrical communication with at least one sensor and configured to receive signals therefrom.

4. The method of claim 1, wherein the first node enters at least one sleep state between sensing and/or storing and/or indexing data relevant to a trigger event, and transmitting the compressed first node data.

5. The method of claim 1, further comprising: transmitting the compressed first node data toward a surface end of the wireless network.

6. The method of claim 1, wherein the first node is an electro-acoustic communications node, and wherein the electro-acoustic communications node is one of a plurality of electro-acoustic communications nodes spaced along a tubular body and attached to a wall of the tubular body, each electro-acoustic communications node comprising:

a housing having a mounting face for mounting to a surface of the tubular body;

one or more piezoelectric elements positioned within the housing and structured and arranged to collectively receive acoustic waves that propagate through the tubular body and transmit acoustic waves through the tubular member; and

a power source positioned within the housing;

the method further comprising transmitting, using the electro-acoustic communications nodes, signals received from at least one sensor communications node to a topside communications node in a substantially node-to-node arrangement.

7. The method of claim 6, further comprising:

at the topside communications node, storing signals transmitted from the at least one sensor

Date Reçue/Date Received 2020-10-09

communications node thereto; and

transmitting the stored signals to a receiver that is separate from the wireless network, when a transmit command is transmitted from the receiver and received by the topside communications node.

8. The method of claim 6, wherein, in the sleep state, the first node is incapable of transmitting information to other nodes in the wireless network.

9. The method of claim 1, wherein the wireless network is installed in or on one of a drill string, wellbore, or a pipeline.

10. The method of claim 1, wherein the steps of:

compressing the first node query-based data in accordance with a collaborative compression based on the first node query-based data and the second node query-based data, to obtain compressed first node data; and

compressing the second node query-based data in accordance with the collaborative compression based on the second node query-based data and the first node query-based data, to obtain compressed second node data;

are carried out as a function of metadata associated with the first node query-based data and of metadata associated with the second node query-based data.

Date Reçue/Date Received 2020-10-09

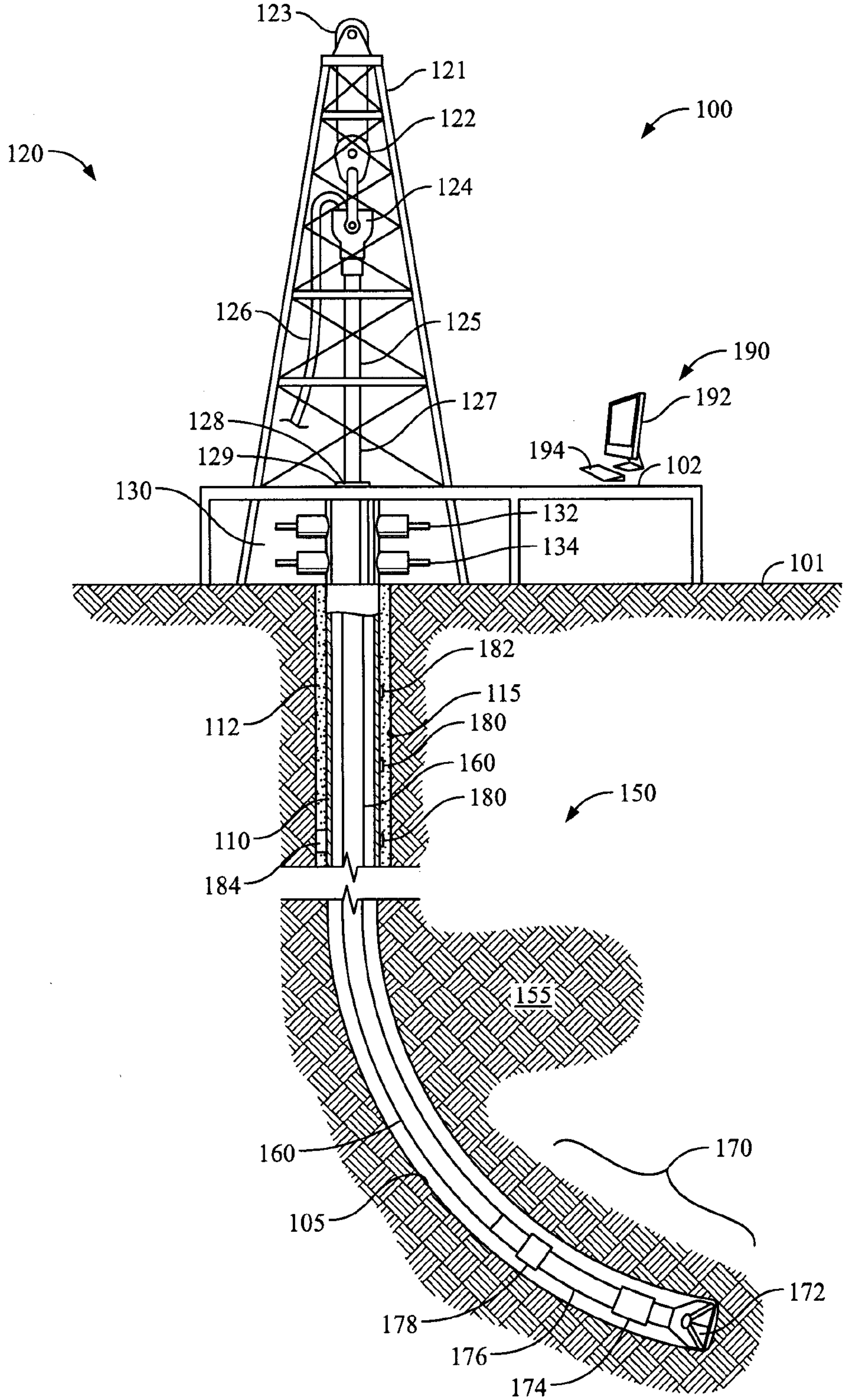

123
121
122
100
120
124
126
125
190
127
192
128
194
129
102
130
132
134
101
182
115
112
180
160
150
180
110
184
155
170
160
105
172
178
176
174

FIG. 1

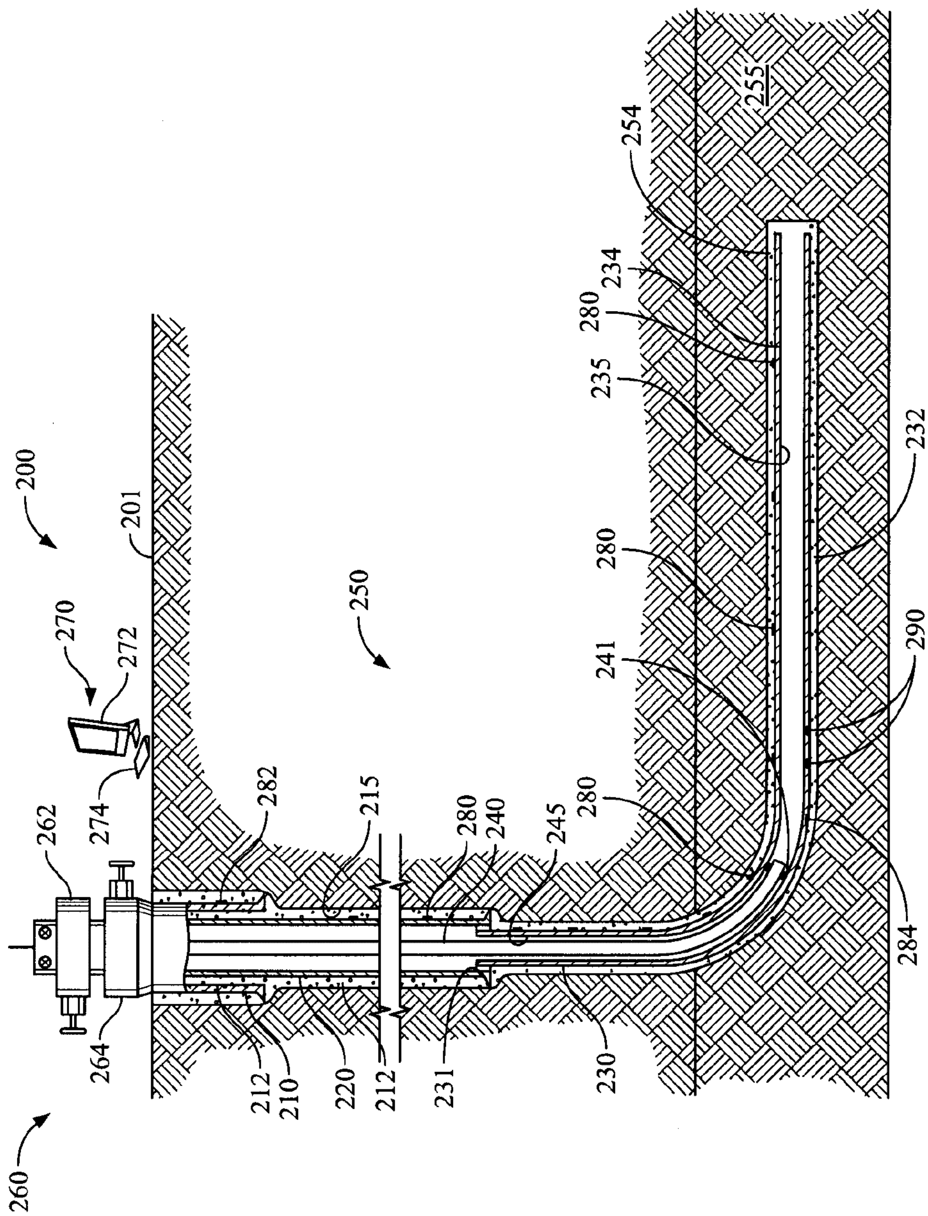

200
201
250
260
262
264
270
272
274
282
215
280
240
245
212
210
220
212
231
230
280
241
280
235
280
234
254
255
232
290
284

FIG. 2

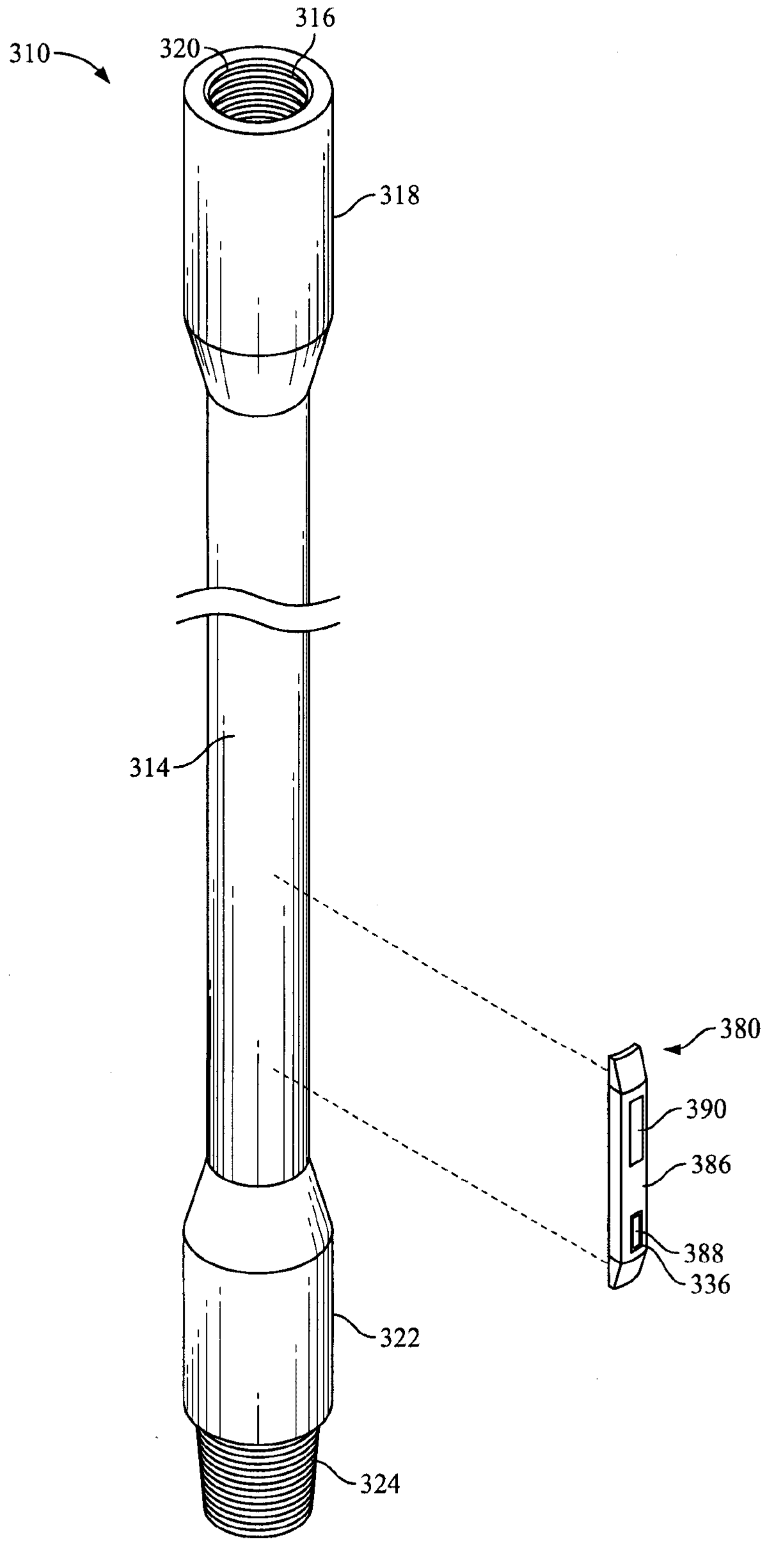


FIG. 3

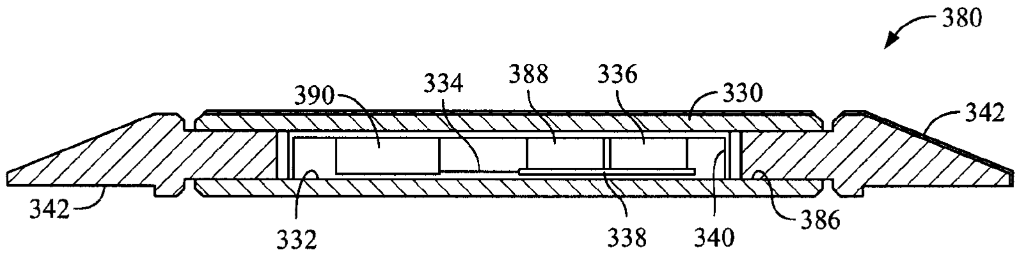


FIG. 4

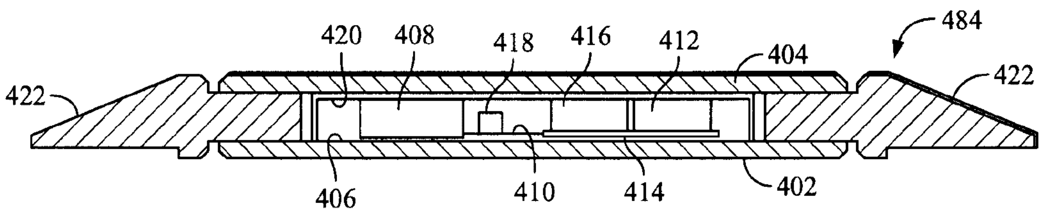


FIG. 5

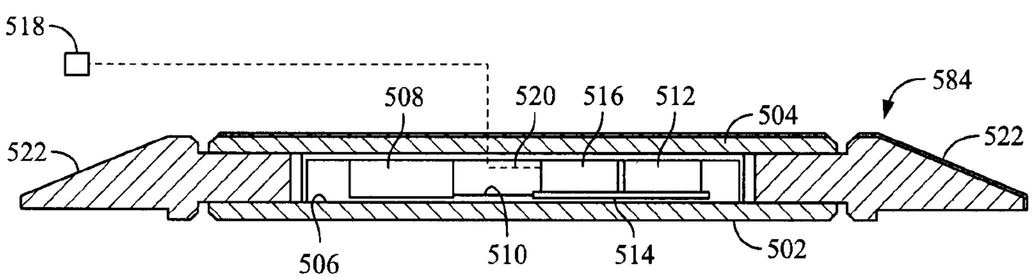


FIG. 6

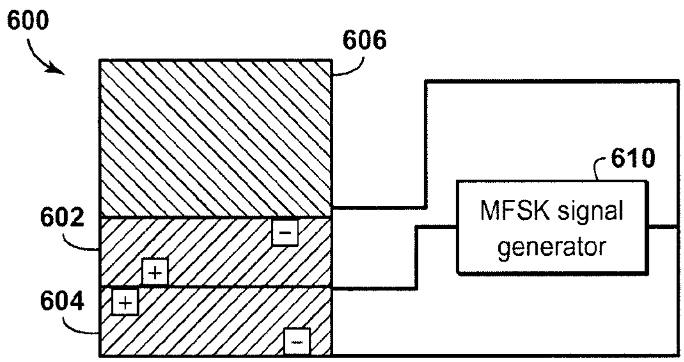

600
606
610
MFSK signal generator
602
604
+
−

FIG. 7A

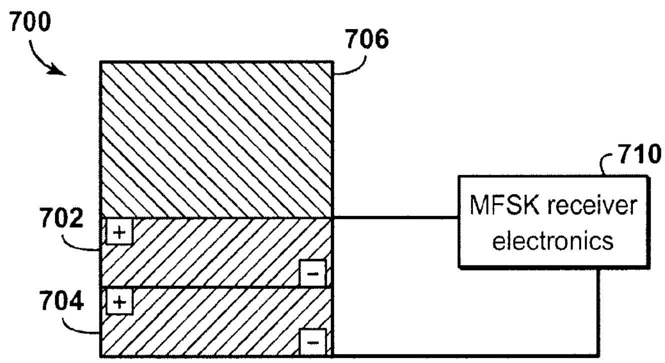
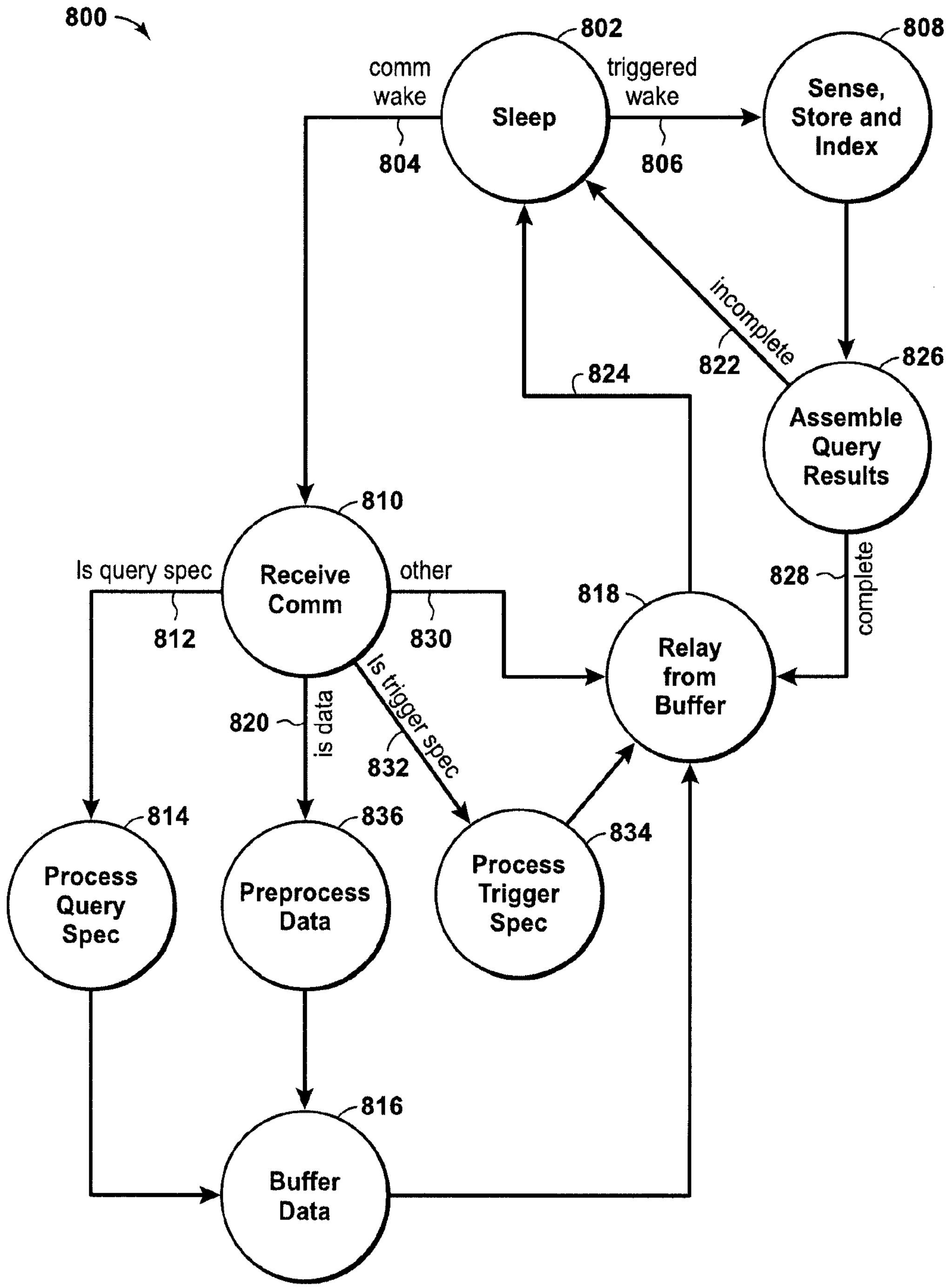

700
706
710
MFSK receiver electronics
702
704
+
−

FIG. 7B



800
802
Sleep
comm
wake
804
triggered
wake
806
808
Sense,
Store and
Index
incomplete
822
824
826
Assemble
Query
Results
828
complete
810
Receive
Comm
Is query spec
812
other
830
818
Relay
from
Buffer
820
is data
Is trigger spec
832
814
Process
Query
Spec
836
Preprocess
Data
834
Process
Trigger
Spec
816
Buffer
Data

FIG. 8

```
// Example trigger instructing that all sensor devices
// at 600-1200 foot depth downhole should save a
// temperature reading in their log every 10 minutes

trigger TEMPERATURE
  where DEPTH in (600..1200ft)
    and SAMPLE @ 10min
```

902

```
// Example query requesting temperatures from all
// sensor devices at 600-1200 foot depth downhole:
// each sensor device should return the 10-point
// moving average of every 12th temperature from
// 95th through 600th temperature in the log

select ma10(TEMPERATURE)
  where DEPTH in (600..1200ft)
    and SAMPLE in (96..600)
    and SAMPLE % 12 == 0
```

904

```
// Example query requesting temperatures from all
// sensor devices at 600-1200 foot depth downhole:
// each sensor device should return the 10-point
// moving average of every 12th temperature from
// the log, but only when it exceeds the previous
// moving average value by more than 20%

select ma10(TEMPERATURE)
  where DEPTH in (600..1200ft)
    and SAMPLE % 12 == 0
   when VALUE[0]  / VALUE[-1] > 1.20
```

906

FIG. 9

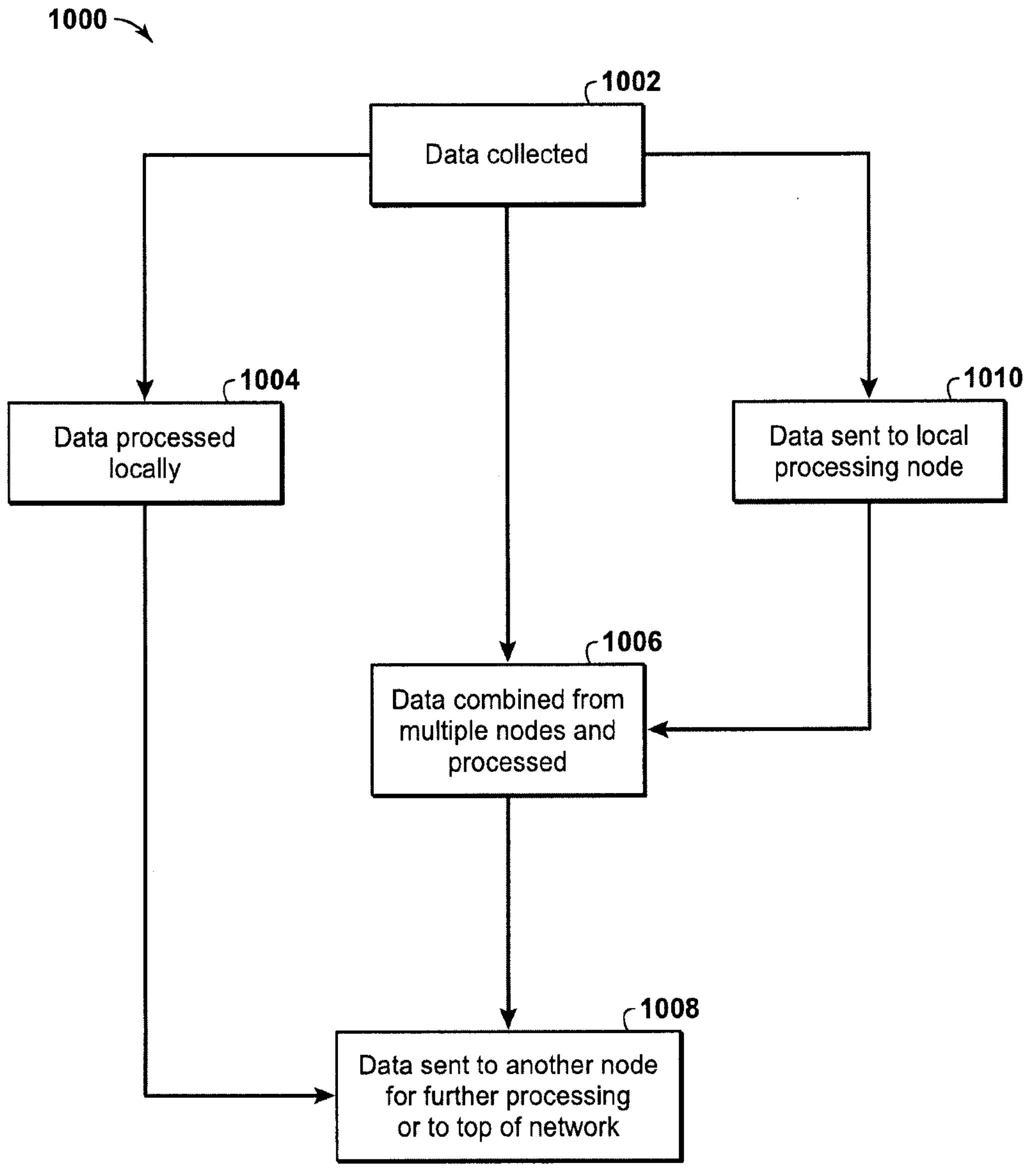

1000
1002
Data collected
1004
Data processed locally
1010
Data sent to local processing node
1006
Data combined from multiple nodes and processed
1008
Data sent to another node for further processing or to top of network

FIG. 10

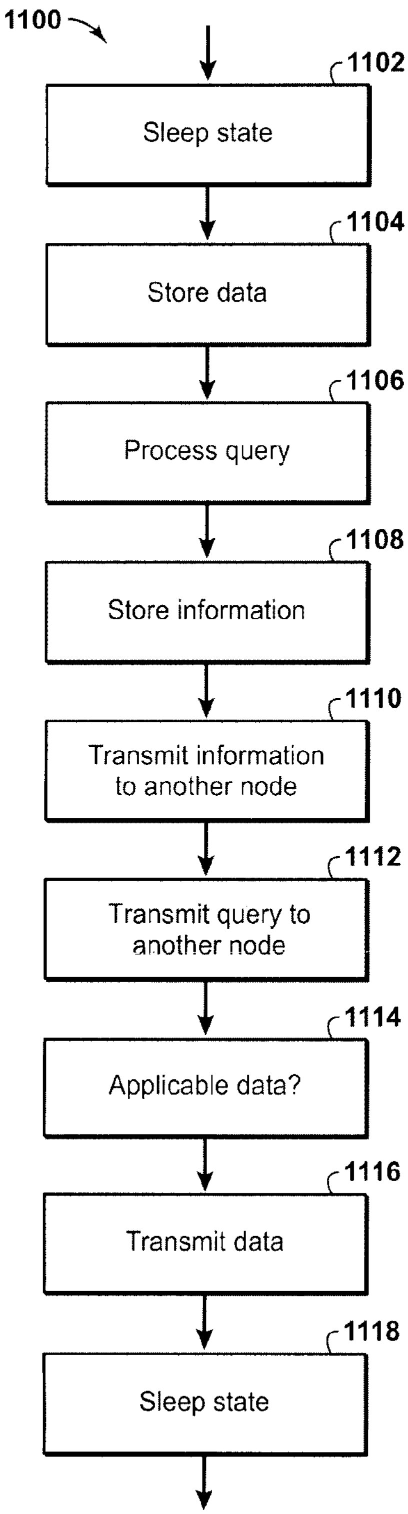

1100
1102
Sleep state
1104
Store data
1106
Process query
1108
Store information
1110
Transmit information to another node
1112
Transmit query to another node
1114
Applicable data?
1116
Transmit data
1118
Sleep state

FIG. 11

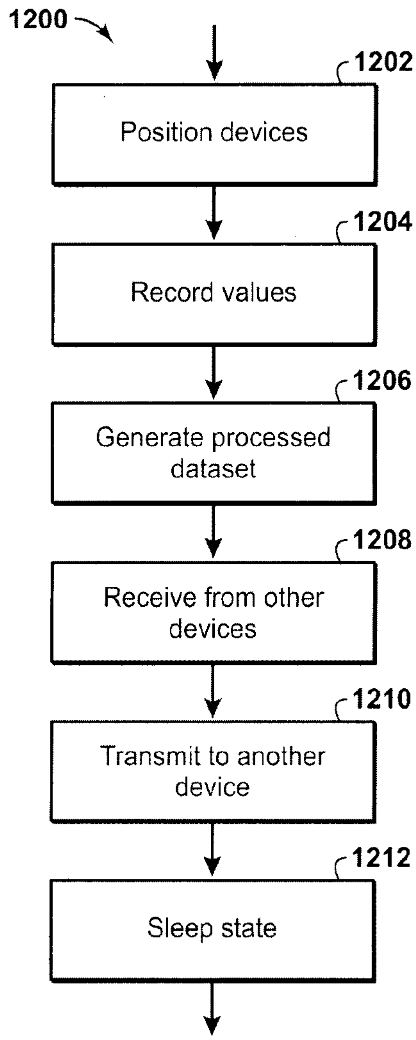
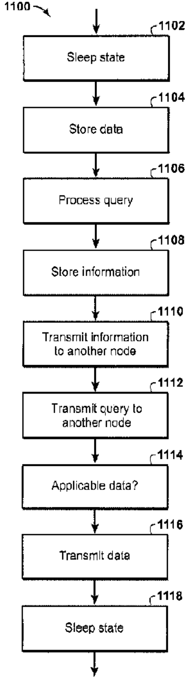

1200
1202
Position devices
1204
Record values
1206
Generate processed dataset
1208
Receive from other devices
1210
Transmit to another device
1212
Sleep state

FIG. 12



1100
1102
Sleep state
1104
Store data
1106
Process query
1108
Store information
1110
Transmit information to another node
1112
Transmit query to another node
1114
Applicable data?
1116
Transmit data
1118
Sleep state