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(54) **UNDERWATER MULTI-HOP COMMUNICATIONS NETWORK**

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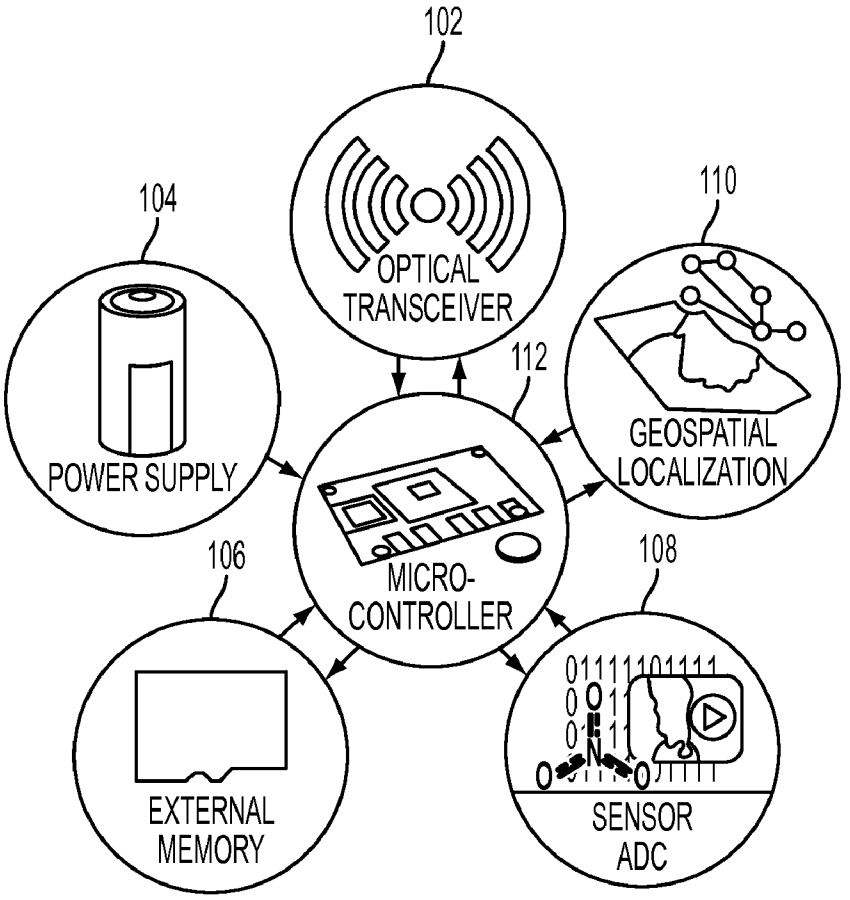
(57) **ABSTRACT**

A multi-hop ad hoc communications network may allow optical communications between underwater nodes. Each node may be fitted with environmental sensors. Each node may collect data from the sensors and transmit the data to other nodes in the network according to a time division multiple access (TDMA) scheme. The data may propagate through a series of child and parent nodes to reach a master node. The master node may have a wired connection for power and data transfer.



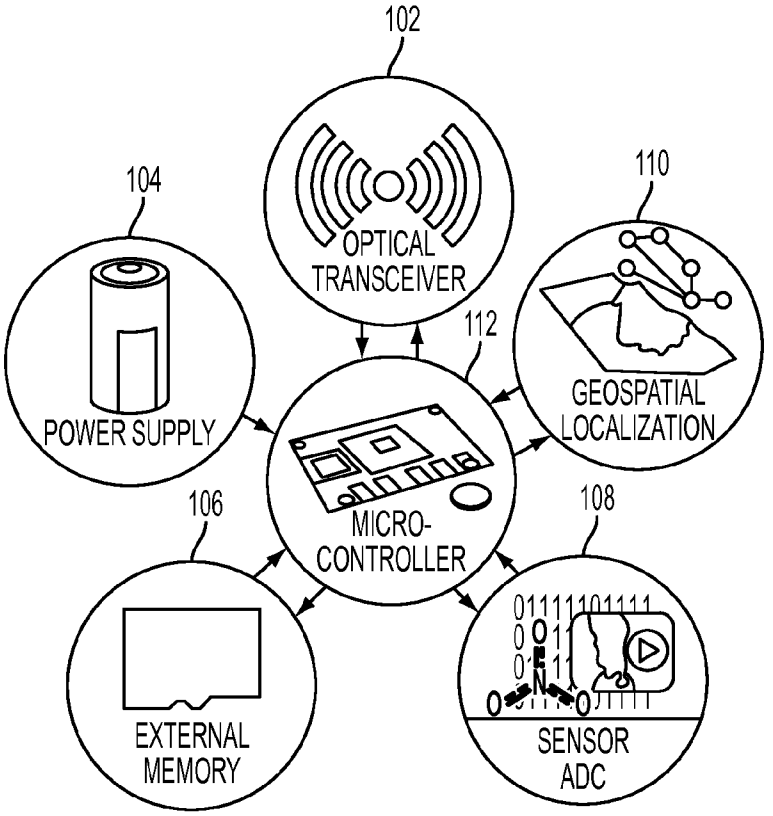

102
OPTICAL TRANSCEIVER
104
POWER SUPPLY
110
GEOSPATIAL LOCALIZATION
112
MICRO-CONTROLLER
106
EXTERNAL MEMORY
108
SENSOR ADC

FIG. 1

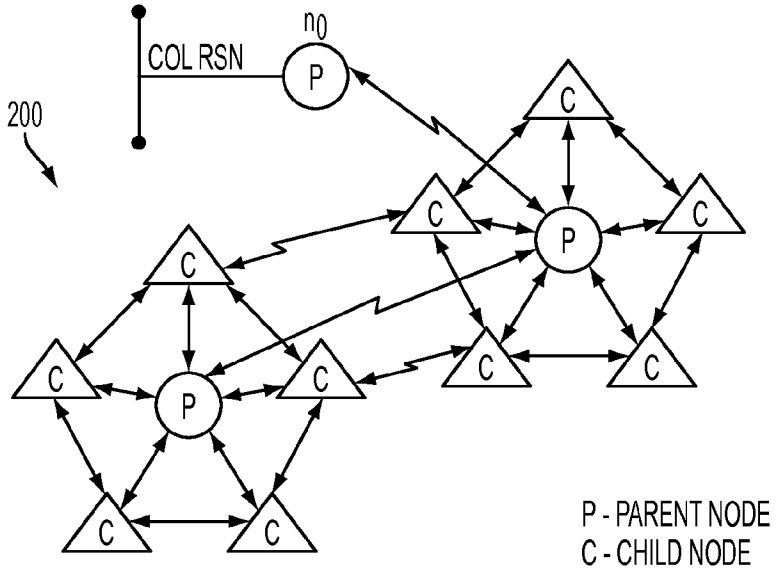

200
COL RSN
n0
P
C
P - PARENT NODE
C - CHILD NODE

FIG. 2

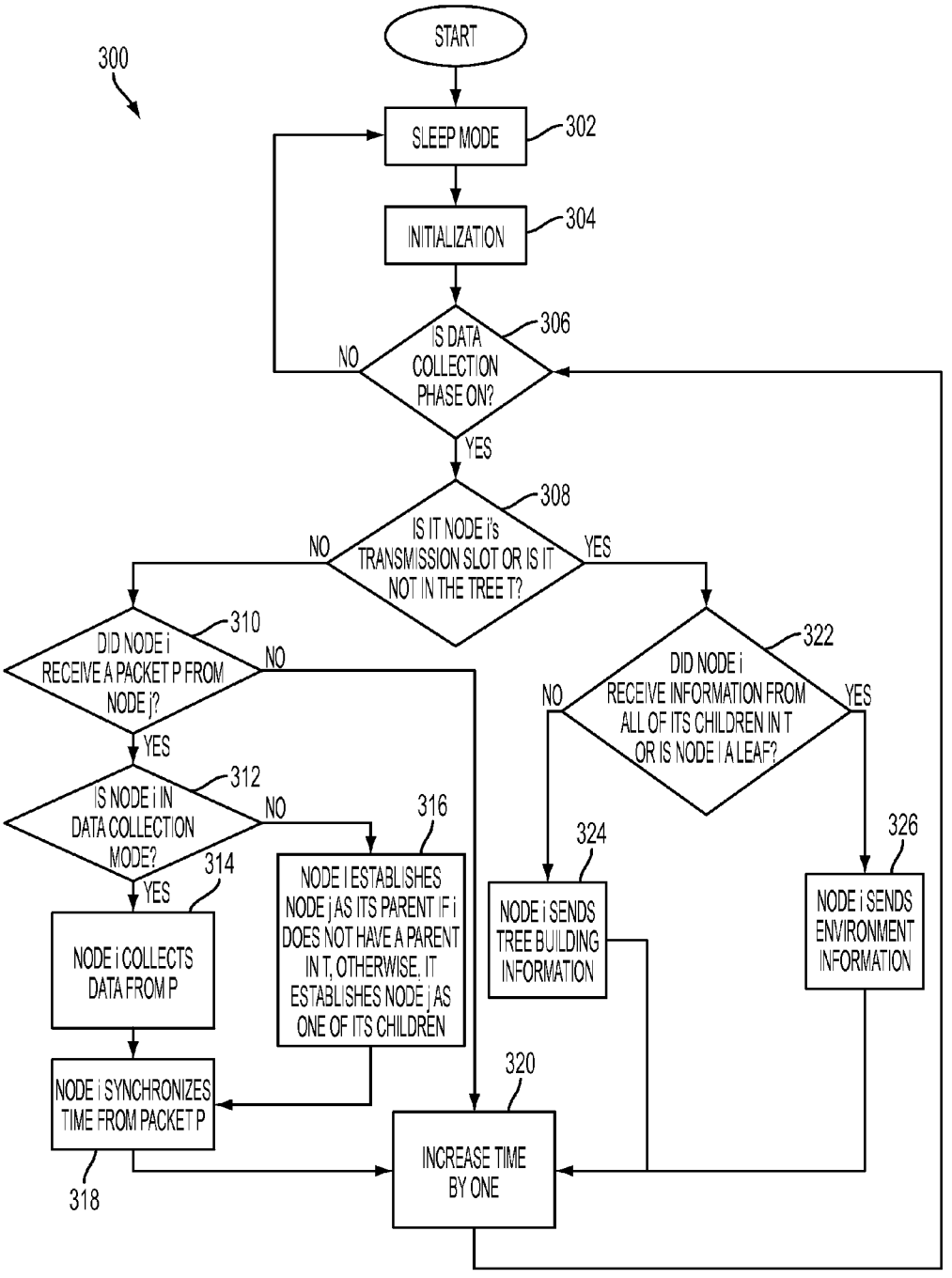

300
START
SLEEP MODE
302
INITIALIZATION
304
IS DATA COLLECTION PHASE ON?
306
NO
YES
IS IT NODE i's TRANSMISSION SLOT OR IS IT NOT IN THE TREE T?
308
NO
YES
DID NODE i RECEIVE A PACKET P FROM NODE j?
310
NO
YES
IS NODE i IN DATA COLLECTION MODE?
312
NO
YES
NODE i COLLECTS DATA FROM P
314
NODE i ESTABLISHES NODE j AS ITS PARENT IF i DOES NOT HAVE A PARENT IN T, OTHERWISE, IT ESTABLISHES NODE j AS ONE OF ITS CHILDREN
316
NODE i SYNCHRONIZES TIME FROM PACKET P
318
DID NODE i RECEIVE INFORMATION FROM ALL OF ITS CHILDREN IN T OR IS NODE i A LEAF?
322
NO
YES
NODE i SENDS TREE BUILDING INFORMATION
324
NODE i SENDS ENVIRONMENT INFORMATION
326
INCREASE TIME BY ONE
320

FIG. 3

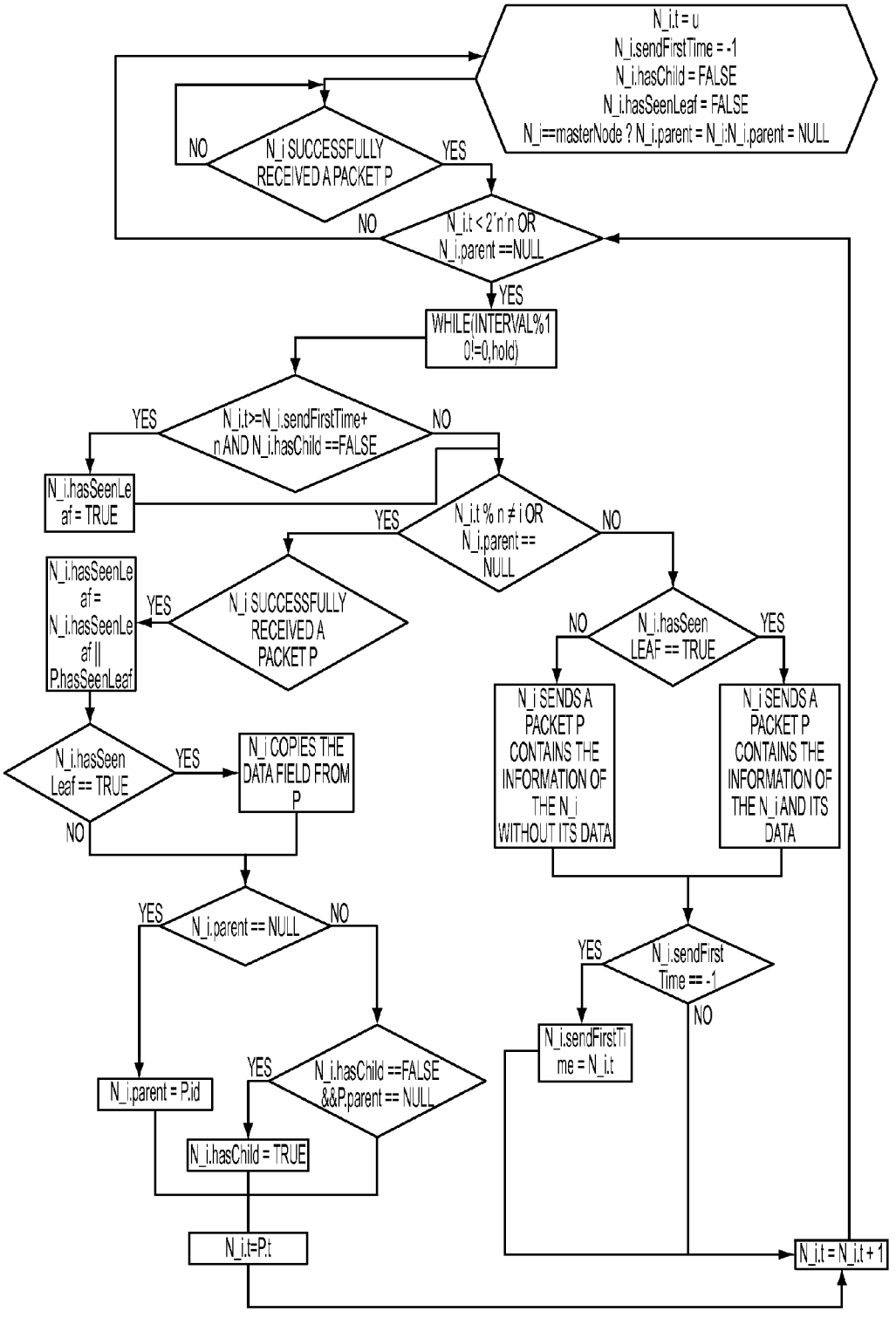

N_i.t = u
N_i.sendFirstTime = -1
N_i.hasChild = FALSE
N_i.hasSeenLeaf = FALSE
N_i==masterNode ? N_i.parent = N_i:N_i.parent = NULL
N_i SUCCESSFULLY RECEIVED A PACKET P
NO
YES
N_i.t < 2^n^n OR N_i.parent ==NULL
NO
YES
WHILE(INTERVAL%10!=0,hold)
N_i.t>=N_i.sendFirstTime+n AND N_i.hasChild ==FALSE
YES
NO
N_i.hasSeenLeaf = TRUE
N_i.t % n ≠ i OR N_i.parent == NULL
YES
NO
N_i.hasSeenLeaf = N_i.hasSeenLeaf || P.hasSeenLeaf
N_i SUCCESSFULLY RECEIVED A PACKET P
YES
N_i.hasSeen Leaf == TRUE
YES
NO
N_i COPIES THE DATA FIELD FROM P
N_i.hasSeen LEAF == TRUE
NO
YES
N_i SENDS A PACKET P CONTAINS THE INFORMATION OF THE N_i WITHOUT ITS DATA
N_i SENDS A PACKET P CONTAINS THE INFORMATION OF THE N_i AND ITS DATA
N_i.parent == NULL
YES
NO
N_i.sendFirst Time == -1
YES
NO
N_i.sendFirstTime = N_i.t
N_i.parent = P.id
N_i.hasChild ==FALSE &&P.parent == NULL
YES
N_i.hasChild = TRUE
N_i.t=P.t
N_i.t = N_i.t + 1

FIG. 4

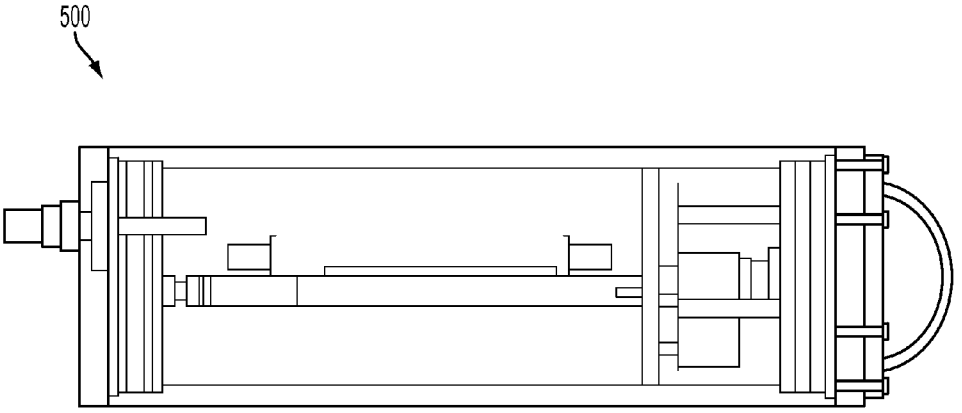


FIG. 5A

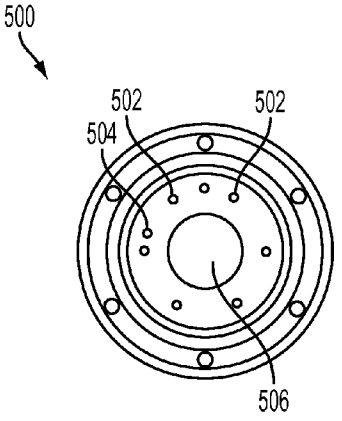


FIG. 5B

UNDERWATER MULTI-HOP COMMUNICATIONS NETWORK

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority of U.S. Provisional Patent Application No. 61/835,392 to Youngbull et al. entitled "Underwater Multi-Hop Communications Network" and filed on Jun. 14, 2013, which is hereby incorporated by reference.

GOVERNMENT LICENSE RIGHTS

[0002] This invention was made with government support under contract 1213070 awarded by the National Science Foundation and under contract number 1116368 awarded by the National Science Foundation. The government has certain rights in the invention.

FIELD OF THE DISCLOSURE

[0003] This disclosure relates to methods and apparatuses for communicating information, and more particularly relates to communicating information underwater.

BACKGROUND

[0004] Acoustic transmission is one method of underwater communications. Commercial off-the-shelf acoustic modems are available. However, many underwater communications applications require non-acoustic transmission, such as applications with operational constraints on sonar interference, security constraints of being overheard, and technical interests in signal speed, bandwidth, device scale and power. Even as acoustic technologies mature, the physical principles of optical signal propagation and scattering in water are fundamentally faster (1500 meters per second for acoustic signal propagation underwater compared to 10^8 meters per second for electromagnetics) and more rapidly modulated (up to of 100 kilobaud for acoustics compared to many Gigabaud for electromagnetics).

BRIEF SUMMARY

[0005] Optical communications may be implemented for an underwater network. Optical communications provide higher bandwidths and lower energy cost per transferred bit. In certain embodiments, optical transmission may be carried out with smaller transducers than acoustic communications systems. For example, a light emitting diode may be used as the optical transducer, which measures less than a few cubic millimeters.

[0006] A TDMA-based MAC protocol, called OPT-ADHOC, may be implemented in nodes of an optical communication underwater network. The protocol may be applied in one embodiment to an ad-hoc multi-hop underwater optical sensor network. The network may include optical sensor nodes. The network may be configured such that one node acts as a master node and is directly wired to a cable with power and/or network access. Other nodes may communicate with each other through wireless optical waves.

[0007] The OPT-ADHOC algorithm is an ad-hoc multi-hop wireless sensor network protocol, which may be used in underwater networks. A cross-layer local protocol design of the algorithm combines a TDMA (Time Division Multiple Access) approach for lightwave contention resolution (MAC layer) integrated with an ad-hoc spanning tree building mechanism on a set of n nodes.

[0008] In one embodiment, nodes of the network may have sensors for collecting environmental data. The spanning tree may be used for coordinating the flow of environmental data collected by the nodes to the master node, which may then transmit this information to a computer on the surface via the wired cable. The spanning tree algorithm may also wake up certain nodes at the start of each data collection cycle. In one embodiment, each collection cycle of data is 12 minutes. Each node may go to sleep after transmitting data to a parent node on the spanning tree.

[0009] The spanning tree construction and data collection procedure may be completed without global clock synchronization. As each node wakes up at the start of each data collection cycle and establishes a link to a parent node, the node may receive the current time according to the parent node. Drifts introduced by the link traversal times may be compensated for by setting the TDMA slot to be long enough to ensure that, even if the receiver and transmitter clocks differ slightly, they will both have a long enough overlap of their respective TDMA slots to allow communication.

[0010] In one embodiment, the protocol may implement a spanning tree backbone construction for the data aggregation phase. For example, a node may wait until information from all of its children in the tree has arrived before forwarding the collected data to a parent node on the tree. Redundancy in the network may be configured such that, if a node v overhears a data transmission destined to some other parent node in the tree (given the TDMA schedule, all transmissions are collision-free), it stores that data and sends it to its parent node together with the data collected from its children nodes in the tree, provided the data arrives at v before the data v is waiting for from its children nodes. In certain embodiments, timing of the TDMA network may be configured such that v waits long enough to receive data from all the nodes within its reception range.

[0011] In one embodiment, the spanning tree may be built from scratch at the start of each data collection phase allowing the protocol to adapt to any changes, such as node/link failures and/or changes in communication ranges due to environment, in the network topology.

[0012] In one embodiment, nodes may enter into a sleep mode between data collection cycles, except when a node is sensing the environment, and may be awake only during the time when data is being transmitted to another node. The sleep mode allows long-term operation of underwater nodes without changing power sources. For example, the nodes may monitor environment conditions with a lifetime of months to years, depending on the data collection schedule, without the need of human intervention for battery recharges or replacements.

[0013] The foregoing has outlined rather broadly the features and technical advantages of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described hereinafter that form the subject of the claims of the invention. It should be appreciated by those skilled in the art that the conception and specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the

invention as set forth in the appended claims. The novel features that are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages will be better understood from the following description when considered in connection with the accompanying figures. It is to be expressly understood, however, that each of the figures is provided for the purpose of illustration and description only and is not intended as a definition of the limits of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The following drawings form part of the present specification and are included to further demonstrate certain aspects of the present disclosure. The disclosure may be better understood by reference to one or more of these drawings in combination with the detailed description of specific embodiments.

[0015] FIG. **1** is a block diagram illustrating a remote node according to one embodiment of the disclosure.

[0016] FIG. **2** is a block diagram illustrating a network of remote nodes communicating with a master node according to one embodiment of the disclosure.

[0017] FIG. **3** is a flow chart for a communications algorithm according to one embodiment of the disclosure.

[0018] FIG. **4** is a flow chart illustrating a communications algorithm according to one embodiment of the disclosure.

[0019] FIG. **5**A is an illustration showing a master node according to one embodiment of the disclosure.

[0020] FIG. **5**B is an illustration showing a master node from another viewpoint according to one embodiment of the disclosure.

DETAILED DESCRIPTION

[0021] FIG. **1** is a block diagram illustrating a remote node according to one embodiment of the disclosure. A remote node may include an optical transceiver **102**, a power supply **104**, a memory **106**, a sensor **108**, a localization system **110**, and/or a micro-controller **112**. The optical transceiver **102** may be, for example, a light-emitting diode (LED), one or more 473 nm blue LED, Silicon photodiodes, incandescent bulbs, or the like. The optical transceiver **102** may include both an optical transmitter and an optical receiver. The optical receiver may include a photodiode, phototransistor, photomultiplier, charge-coupled device (CCD), complimentary metal-oxide-semiconductor (CMOS) circuits, or the like. The wavelength of the optical transceiver **102** may be configured corresponding to the characteristics of the water in which the node is placed. In one embodiment, multiple, wide-emission LEDs may be used to diffuse radiation patterns for a nearly uniform radiation pattern over 4π solid-angle allowing the node to have uniform transmission over a large range of angles.

[0022] According to one embodiment, the optical transceiver **102** may be the surface of the node configured to modulate its reflectance using lower power modulation of an absorption filter. By placing these modulated absorbance filters in-line with an onboard retroreflector, an optical signal originating from a distant location may be returned to that location with encoded data. The originating light source may be a laser with minimal dispersion and maximum penetration in the underwater environment.

[0023] The power supply **104** may be, for example, a battery, such as a Lithium Ion (Li-Ion) battery, a Nickel Cadmium (NiCd) battery, and/or a fuel cell. The memory **106** may be, for example, a secure digital (SD) memory card, a NAND flash memory device, eMMC memory, a hard drive, magnetic random access memory (MRAM), and the like.

[0024] The sensor **106** may be, for example, Oxygen, conductivity, temperature, depth, optical backscatter sensors, autofluorescence sensors, accelerometers, conductivity sensors, and/or pressure sensors. The sensor **106** may include other sensors that transduce a measurement into an electrical signal for processing by circuitry on the node. In one embodiment, two types of each sensor may be included in the node to provide redundancy against faults. Furthermore, when the nodes are positively buoyant and tethered by a short (e.g., approximately 1 meter) line to the seafloor, knowing the node's angle of orientation may allow calculation of the direction and strength of the local ocean current. Additionally, nodes may carry microphones, cameras, and/or video cameras.

[0025] According to one embodiment, the sensor **106** may be a transbulkhead absorber. Transbulkhead absorption spectrometry may allow analyte detection through absorption in the water column. Light may be allowed to pass through the exterior water by means of a mirrored surface on a far side of a water channel as shown in FIG. **3**. The reflected LED light may then be collected inside the node by, for example, a spectrometer or a translated variable-notch filter fixed onto a single-point detector.

[0026] According to another embodiment, sensors on the outside of the node may operate by measuring changes in the response to optical excitation of fluorescent/phosphorescent thin films in the presence of target analytes. The thin film sensors may be fixed to the outside of the node and may be optically excited and detected through the bulkhead of the node, such as a transparent housing or window in the node hull. On the interior of the housing may be an excitation light source, a sensor response detector, and/or a receiver. The excitation source may include a low-power ultraviolet LED, and the receiver may be a reverse-biased photodiode. The transbulkhead emission spectrometer may measure an analog intensity change detected in the sensor thin film. The analog sensor response may calibrated in the laboratory with known controls.

[0027] One or more sensors **106** may be integrated into the node or placed on an exterior of the hull of the node. In one embodiment, a thin-film sensor may be molecularly bound to a transparent sheet, from which sensor "buttons" may be stamped out and then chemically welded to flat locations on the node bulkhead.

[0028] The localization system **110** may include internal rotational sensors used to identify mote orientation. The neighborhood of network nodes near a node may be determined from packet exchange and neighbor position may be determined by relative intensity measurements of adjacent photodiodes. The combined knowledge of network neighborhood and angular position may achieve partial or complete network localization.

[0029] The micro-controller **112** may couple to each of the optical transceiver **102**, the power supply **104**, the memory **106**, the sensor **106**, and/or the localization system **110**. In certain embodiments, some components may be integrated with the micro-controller **112** in a single package, such as when the memory **106** is integrated with a micro-controller in a package-on-package (PoP) configuration.

[0030] Networks of nodes illustrated in FIG. **1** may be placed in static positions using a Remotely Operated Vehicle (ROV) or deployed as an array on a frame. The nodes may then be observed from a single remote location using an imaging detector. The spatial separation of the nodes may reduce overlap of signals so their signals may be transmitted asynchronously.

[0031] A node may be configured to operate in several modes. In standby mode, a node may hibernate and conserve power. In this mode, the node may operate at minimum power levels, such as by not transmit or gathering data. The frequency at which each node enters this mode may be controlled by parameters, such as a period between maintenance or intervention, the duration of data acquisition, and/or how often data will be transmitted. In a sensing mode, each node may gather data from the environment. To save power, this mode may be entered at a predetermined frequency determined, for example, by expected environmental conditions such as tides, cyclic biological blooms, or regular chemical efflux. A higher-data acquisition frequency may be triggered if an interesting pattern is observed in the data profile. In a communication mode, a node may transmit acquired environmental and proprioceptive data. During this mode, the node power consumption may reach a maximum level. Thus, this mode may be the shortest of the three operation modes and may require a highly efficient communication scheme.

[0032] Nodes, such as those described with reference to FIG. **1**, may be configured for short-range communications, such as by creating an intelligent link between nodes, to extend the coverage of the node network over long distances, such as through multi-hop networking. With multi-hop capability, a network of nodes may be distributed with sufficient spatial density (with up to 50 meters separation) to carry sensor data over large areas (up to and exceeding several square kilometers). The sensor data may be carried back to a central observation point that is either periodically recovered or continuously monitored through a cabled connection to land. In one embodiment, multi-hop nodes communicate data redundantly to every node in the underwater network.

[0033] FIG. **2** is a block diagram illustrating a network of remote nodes communicating with a master node according to one embodiment of the disclosure. A network **200** may include n nodes, denoted as $N=\{n_i|i=0 \ldots n-1\}$. A master node may be the n_0 node. The master node may be wired to the cable. Other nodes may be wireless nodes, communicating through optical transceivers. The other nodes may be organized into parent nodes, P, and child nodes C. Communications may occur from child node to parent node, child node to another child node, and/or parent node to another parent node. The communications path allows multi-hop transmission between nodes to reach the master node, n_0. In one embodiment, a node may transmit to all nodes within range, and each other node may relay data to the master node.

[0034] A method for communicating within the network **200** may include constructing a tree T with n_0 as the root node. Each node, n_i, may acquire information regarding parent and children nodes in the network **200**. Then, starting from leaf nodes, data, including sensor data, may be propagated back up to the root node, such that the master node has the entire information about the network. Then, another pass of data may propagate information in a top-down fashion from the root node to other nodes.

[0035] Nodes may maintain level information ($n_{i,level}$), which is defined with respect to its distance from the master node, calculated as the number of communication hops from n_0 to the node. Additionally, each node may track assigned parent and children nodes, such as $n_{i,parent}$ and $n_{i,child}$, where $n_{i,child}$ is a linked list of n_i's children.

[0036] According to one embodiment, the protocol may be TDMA-based, such that each time frame is divided into n time slots, and in each time slot i, only n_i may transmit. Risk of a collision between nodes is reduced or eliminated through this transmission scheme. In one embodiment, a size of a packet for transmission may be 256 bits, the transmission range of the sensors may be up to 50 m, the speed of transmission may be between 5 kHz and 300 kHz, and the data collection cycle may be 12 minutes. Sensors of the nodes may take measurements at any time, regardless of the data collection cycle period. In certain embodiments, nodes may broadcast clock time, starting from the master node, and/or an error correction code, such as a cyclic redundancy code (CRC) may be applied to transmissions. The network **200** may support a contention resolution optical wireless protocol as described herein.

[0037] The network **200** may integrate a Time Division Multiple Access (TDMA) approach for lightwave contention resolution (at the media access control (MAC) layer) with an ad-hoc spanning tree building mechanism on a set of n nodes. A spanning tree may be used for coordinating the flow of environmental data collected by the nodes to the master node, which may then transmit this information to a computer on the surface via the wired cable. The spanning tree may also wake up nodes at the start of each data collection cycle. Each node may go to sleep after it has transmitted its data to its parent node on the tree. This network provides both robustness and energy efficiency.

[0038] FIG. **3** is a flow chart for a communications algorithm according to one embodiment of the disclosure. A method **300** begins at block **302** with entering a sleep mode. At block **304**, the node initializes and determines, at node **306**, whether the data collection phase is on. If not, the node returns to sleep mode ad block **302**. If data collection is enabled, then the method **300** continues to block **308** with determining if it is node i's transmission slot or if it is not in the tree T. If the determination at block **308** is yes then the method **300** proceeds to block **322**. If the determination at block **308** is no then the method **300** proceeds to block **310**.

[0039] At block **310**, it is determined whether node i received a packet P from node j. If not, then the method **300** proceeds to block **320** to increase a time counter by one and then return to block **306**. If the determination at block **310** is yes, then the method **300** determines at block **312** if node i is in data collection mode. If yes, then node i collects data from packet P at block **314**. If no, then, at block **316**, node i establishes node j as its parent if node i does not have a parent in tree T, and otherwise establishes node j as one of its children. After either of block **314** or **316** is performed, the method **300** proceeds to block **318** for node i to synchronize time from packet P and to block **320** to increase a time counter by one. After block **320**, the method **300** returns to block **306**.

[0040] If the determination at block **308** is yes, then the method **300** proceeds to block **322**. At block **322** it is determined whether node i received information from all of its children in tree T or if node i is a leaf. If no, then, at block **324**, node i sends tree building information. If yes, then, at block **326** node i sends environment information. After either of block **324** or block **326**, the method **300** continues to block **320** to increase a time counter by one and return to block **306**.

[0041] FIG. **4** is a flow chart illustrating a communications algorithm according to one embodiment of the disclosure. One embodiment of the method shown in FIG. **4** is implemented in the following pseudo-code for an underwater communication protocol:

```
n_i.t <- 0
n_i.sendFirstTime <- -1
if (n_i == masterNode or successfully received a packet P then)
    while n_i.t < 2n^2 or n_i.parent == null do
        while interval % 10 != 0 do
        hold
    end while
    if (n_i.t % n != i or n_i.parent == null) then
        if n_i successfully received a packet P then
            if n_i.parent == null then
                n_i.parent <- P.src
                n_i.t <- P.t
            else if P.src == n_i.botId then
                n_i.child <- P.botId
            end if
            n_i.t = P.t
        end if
    else
        if n_i.parent != null then
            n_i sends a packet P (= P.n_i, P.src, n_i.t,
                timestamp(hh,mm,ss),"I'm alive") containing the
                information of the n_i.{ID, timestamp, level, "I'm
                alive"}
            if n_i.sendFirstTime == -1 then
                n_i.sendFirstTime <- n_i.t
            end if
        end if
    end if
    if (n_i.t == n_i.sendFirstTime + n and n_i.child == 0) then
        n_i.isLeaf <- true
    end if
    // Entering data transmission phase.
    if ( (n_i.isLeaf == true or n_i.hasReceivedFromAllChildren == true) and
        n_i.t % n == i) then
        n_i sends a data packet P containing all the data gathered by n_i and
            its children, i.e., n_i.DATA[j] for all n_i' child n_j
    else
        if n_i successfully received a packet P then
            n_i.DATA[P.src] <- P.DATA
                if n_i has successfully received all packets from
                all children then
                    n_i.hasReceivedFromAllChildren <- true
                end if
            end if
        end if
        n_i.t <- n_i.t + 1
    end while
end if
```

[0042] Generically, an algorithm for operating the nodes, such as the specific embodiments described above and in FIG. **4**, includes constructing a tree with n_0 as a root in a level-by-level, as well as TDMA fashion. Each of the nodes may acquire its parent and children information. Then, starting from the leaf nodes, the data may be propagated back up to the root node, such that the master node has all information about the network. Optionally, to improve the robustness of the network, each node may be provided with a copy of the entire network data, through a top-down pass of information from the root node to propagate information to each of the nodes in the tree.

[0043] In some embodiments, in addition to an identifier (ID), the nodes may also maintain level information (as n_i.level), which is defined with respect to the node's distance from the master node as, for example, how many communications hops are between the root node n_0 to the node itself. Further, each node may track its parent and children nodes (as n_i.parent and n_i.child, where n_i.child is a linked list of n_i's children). For these communications, each time frame may be divided into n time slots, and, in each time slot i, n_i may be assigned to transmit data.

[0044] Data transmission through the nodes may be in, for example, 256 bit packets through distances between approximately less than 2 meters to up to and beyond 50 meters, at transmission rates of approximately 1 kHz up to and exceeding 300 kHz (where 10 Hz means 10 bits/second). Data collection by the nodes may be set, for example, to occur at periodic intervals of approximately five to sixty minutes. When transmitted by the nodes, the data may be transmitted along with error correction codes, such as a cyclic redundancy check (CRC) codes, to improve robustness of the network.

[0045] FIG. **5**A is an illustration showing a master node according to one embodiment of the disclosure. A node **500** may include a cabled underwater housing to contain a principle photomultiplier (PMT). The cabled PMT may be a terminal receiver link connecting the most proximal parent node(s), and through the proximal parent node(s) of other child nodes, to the network. This PMT housing may allow submerging of the node in water. The high sensitivity photomultiplier system of the PMT may allow to monitoring of communications from the multi-hop network.

[0046] FIG. **5**B is an illustration showing a master node from another viewpoint according to one embodiment of the disclosure. The node **500** may include light emitting diodes (LEDs) **502**, photo integrated circuit (IC) sensors **504**, and photocell **506**.

[0047] The nodes, which may be light and small, may move unintentionally, such as in dynamic underwater currents. Communication between these devices can be disrupted for several reasons, including: (a) obstacles (e.g., fish, descending flocculant, or algal blooms) that block communication between lightwave underwater sensor nodes for long and unpredictable periods of time, (b) mobility or orientation changes, (c) different forms of background noise in the environment (such as turbidity, day versus night ambient light, or visiting ROVs), and (d) interference problems due to "stray" transmissions from wireless network nodes (including due to back scattering from the node itself).

[0048] Once the node network is deployed, human intervention to deployed nodes may not be available until the end of the deployment, when the sensor nodes are retrieved. The protocols described here are robust against changes in the network topology (such as node and link failures and node joins/leaves) or changes in the data traffic demand (the data flow from the nodes may not be uniform at all times). They nodes are also self-stabilizing, by converging back to a valid state, in a localized fashion, with minimal or no human intervention.

[0049] According to one embodiment, the nodes may operate in MIMO (Multiple-Input-Multiple-Output) mode. That is, if a node is simultaneously transmitting through two optical transceivers, the node may compensate for the interference generated between its two simultaneous transmissions in advance at the physical (PHY) layer, which will in turn have an impact on how the media access control (MAC) layer protocols operate.

[0050] If implemented in firmware and/or software, the functions described above, such as with reference to FIG. **3** and FIG. **4**, may be stored as one or more instructions or code on a computer-readable medium. Examples include non-tran-

sitory computer-readable media encoded with a data structure and computer-readable media encoded with a computer program. Computer-readable media includes physical computer storage media. A storage medium may be any available medium that can be accessed by a computer. By way of example, and not limitation, such computer-readable media can comprise RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to store desired program code in the form of instructions or data structures and that can be accessed by a computer. Disk and disc includes compact discs (CD), laser discs, optical discs, digital versatile discs (DVD), floppy disks and blu-ray discs. Generally, disks reproduce data magnetically, and discs reproduce data optically. Combinations of the above should also be included within the scope of computer-readable media.

[0051] In addition to storage on computer readable medium, instructions and/or data may be provided as signals on transmission media included in a communication apparatus. For example, a communication apparatus may include a transceiver having signals indicative of instructions and data. The instructions and data are configured to cause one or more processors to implement the functions outlined in the claims.

[0052] Although the present disclosure and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the disclosure as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the present invention, disclosure, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present disclosure. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

What is claimed is:

1. An apparatus, comprising:

a master node; and

an ad hoc network comprising at least one remote node, each remote node comprising:

a power source;

a transmitter comprising a light source;

a receiver;

a sensor; and

a processor,

wherein the processor is configured to:

identify a communications path to the master node through at least one other remote node of the ad hoc network;

obtain data from the sensor;

receive, through the receiver, other sensor data from at least one other remote node of the ad hoc network;

relay, through the transmitter, the sensor data and the other sensor data to the master node according to a time division multiple access (TDMA) scheme along the communications path; and

dynamically reconfigure the communications path when the ad hoc network changes.

2. The apparatus of claim **1**, in which the transmitter is a wireless transmitter.

3. The apparatus of claim **1**, in which the communications path comprises a path to the master node through at least two neighboring remote nodes of the ad hoc network, and in which the processor is configured to relay the sensor data to the at least two neighboring remote nodes according to a point-to-multipoint scheme.

4. The apparatus of claim **1**, in which the receiver comprises at least one of a photodiode, a phototransistor, a photomultiplier, a charge-coupled device (CCD), and a complimentary metal-oxide-semiconductor (CMOS) circuits.

5. The apparatus of claim **1**, in which the processor of each of the plurality of remote nodes is further configured to receive a clock time at a start of a data collection cycle in the TDMA scheme.

6. The apparatus of claim **5**, in which the processor of each of the plurality of remote nodes is further configured to activate a sleep mode at the end of the data collection cycle in the TDMA scheme.

7. The apparatus of claim **1**, in which the master node is wired to a communications network and is wired to a power supply.

8. The apparatus of claim **1**, in which the sensor comprises at least one of a temperature sensor, a pH sensor, a dissolved O_2 sensor, a backscatter sensor, a camera, an ambient light sensor, an autofluorescence sensor, an accelerometer, a conductivity sensor, and a pressure sensor.

9. The apparatus of claim **1**, in which the light source comprises a 473-nanometer blue light emitting diode (LED).

10. The apparatus of claim **1**, in which the master node comprises a photo-multiplier tube (PMT) configured to amplify light signals received from the light source of the at least one remote node.

11. A method, comprising:

receiving, by a processor of a remote node of an ad hoc network, data from a sensor;

identifying, by a processor, a communications path to a master node through at least one other remote node of the ad hoc network;

receiving, by the processor, other sensor data from at least one other node of the ad hoc network;

transmitting, through a transmitter of the remote node by the processor, the sensor data and the other sensor data through the communications path according to a time division multiple access (TDMA) scheme; and

dynamically reconfiguring, by the processor, the communications path when the ad hoc network changes.

12. The method of claim **11**, in which the step of transmitting comprises wirelessly transmitting through an optical interface.

13. The method of claim **11**, in which the step of transmitting according to the TDMA scheme comprises identifying a time slot in a time frame corresponding to the remote node.

14. The method of claim **11**, further comprising transmitting, through the transmitter, a clock time to at least one other node of the ad hoc network.

15. The method of claim **11**, in which the step of identifying the communications path comprises:

seeding a tree with n_0 as the master node;

populating the tree with n_i nodes between the remote node and the master node; and

tracing the communications path through at least one other node of the ad hoc network to the master node.

16. The method of claim **15**, further comprising storing, at the remote node, information regarding the ad hoc network.

17. The method of claim **16**, further comprising:

receiving, from at least one other remote node of the ad hoc network, the tree comprising information regarding a plurality of remote nodes in the ad hoc network; and

propagating the tree from the remote node to at least one other remote node of the ad hoc network.

18. The method of claim **16**, further comprising storing, at the remote node, level information regarding a number of hops from the remote node to the master node.

19. The method of claim **11**, in which the sensor data comprises at least one of temperature data, pH data, dissolved O_2 data, backscatter data, and ambient light data.

20. The method of claim **11**, further comprising transmitting, through the transmitter of the remote node, the sensor data and the other sensor data to a second at least one other remote node of the ad hoc network according to a point-to-multipoint scheme.

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