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(19) **United States**(12) **Patent Application Publication****Elson et al.**(10) **Pub. No.: US 2007/0223497 A1**(43) **Pub. Date: Sep. 27, 2007**(54) **LOW-LATENCY MULTI-HOP AD HOC WIRELESS NETWORK****Publication Classification**(51) **Int. Cl.****H04L 12/56** (2006.01)(52) **U.S. Cl.** ..... **370/400**

(57)

**ABSTRACT**

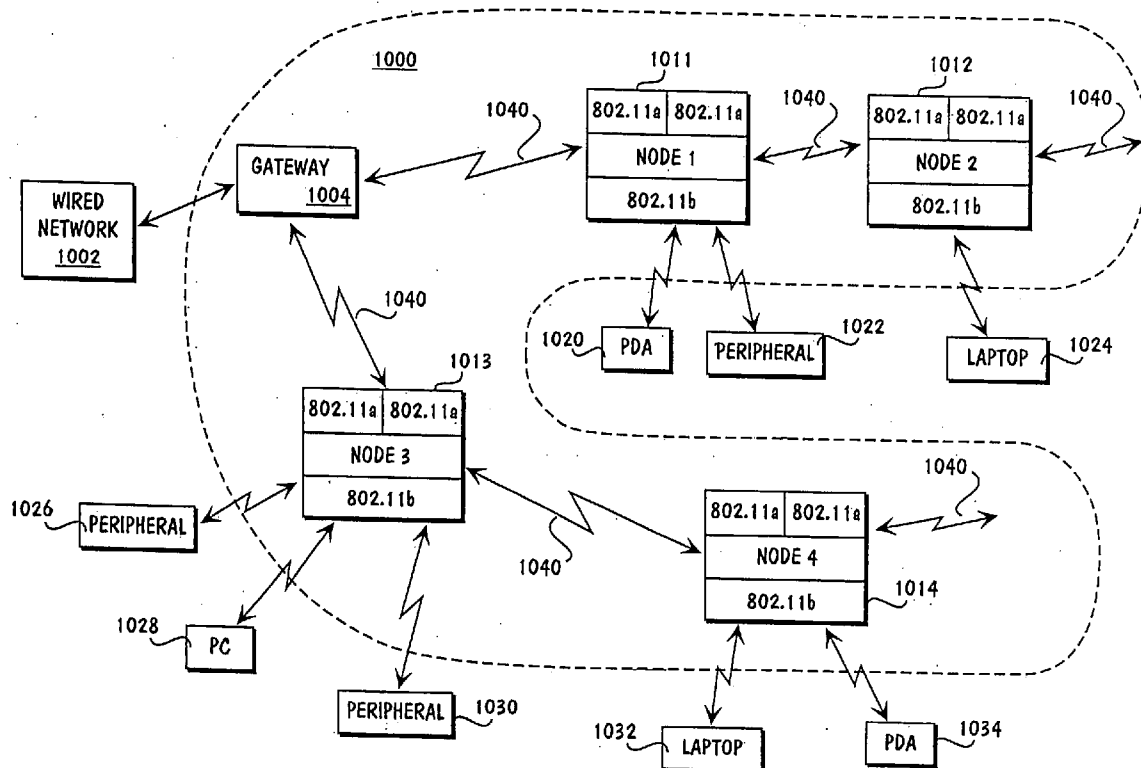
A multi-radio sensor node is provided that includes two or more communication devices. The communication devices include radio frequency (RF) devices like radios. Each communication device supports simultaneous communications among multi-radio sensor nodes of respective independent network clusters. A network structure is provided that includes two or more local network clusters. Each local network cluster includes numerous multi-radio sensor nodes. Each communication device of a multi-radio sensor node supports communication among the multi-radio sensor nodes of a different one of the local network clusters so that simultaneous communications are supported among the multi-radio sensor nodes of the local network clusters. The multi-radio sensor nodes of the local network clusters determine their locations relative to the other multi-radio sensor nodes of the independent network clusters with which they communicate. The location determination includes performing timing synchronization via synchronization signals communicated among the local network clusters, and acoustic signaling.

Correspondence Address:

**COURTNEY STANIFORD & GREGORY LLP**  
**P.O. BOX 9686**  
**SAN JOSE, CA 95157 (US)**(21) Appl. No.: **11/651,224**(22) Filed: **Jan. 8, 2007****Related U.S. Application Data**

(63) Continuation of application No. 10/188,514, filed on Jul. 3, 2002, now Pat. No. 7,161,926.

(60) Provisional application No. 60/302,795, filed on Jul. 3, 2001. Provisional application No. 60/343,312, filed on Dec. 21, 2001.



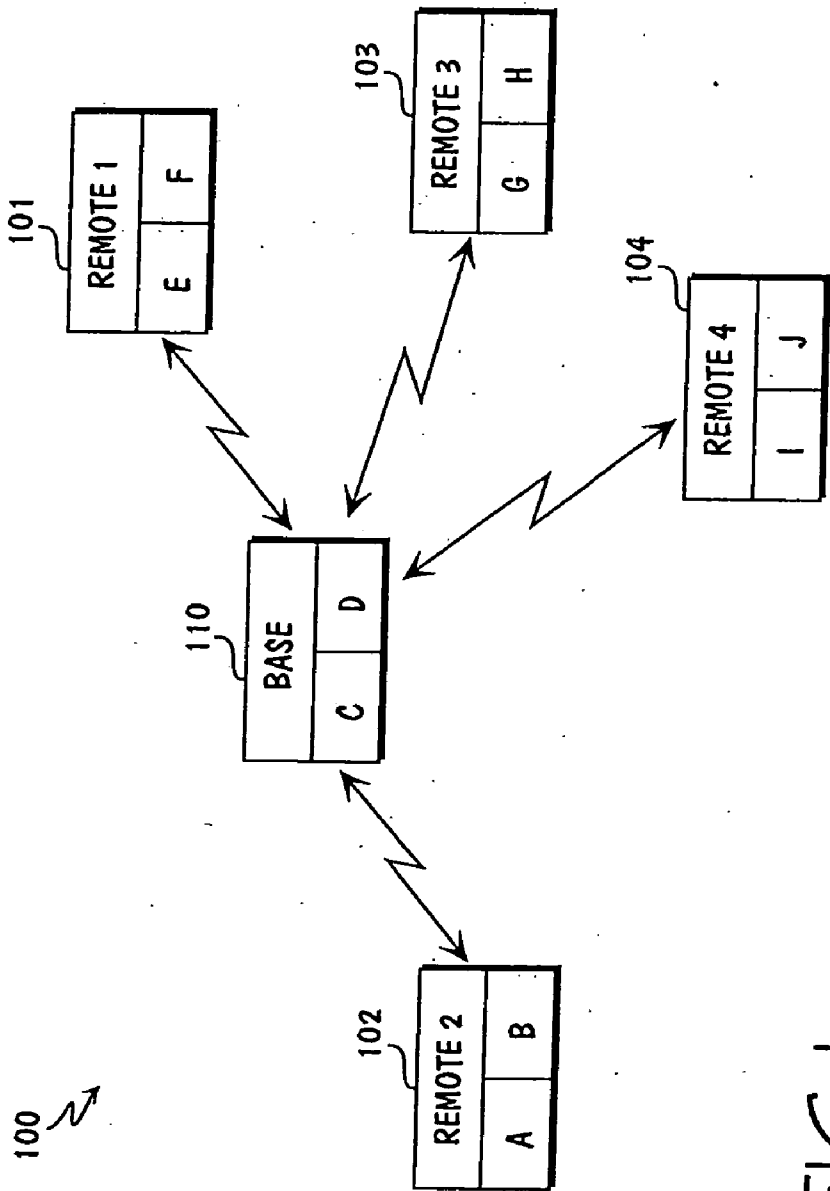


FIG. 1

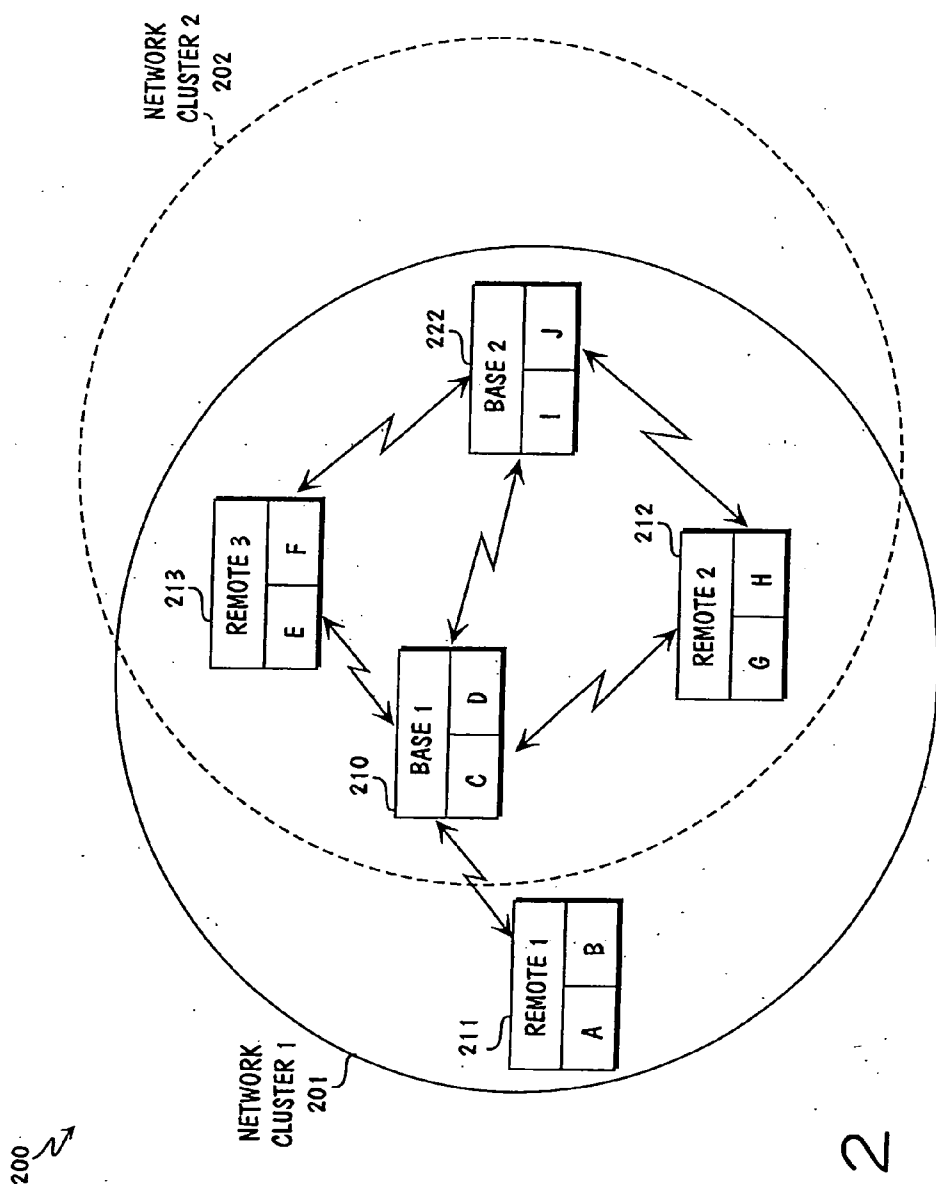


FIG. 2

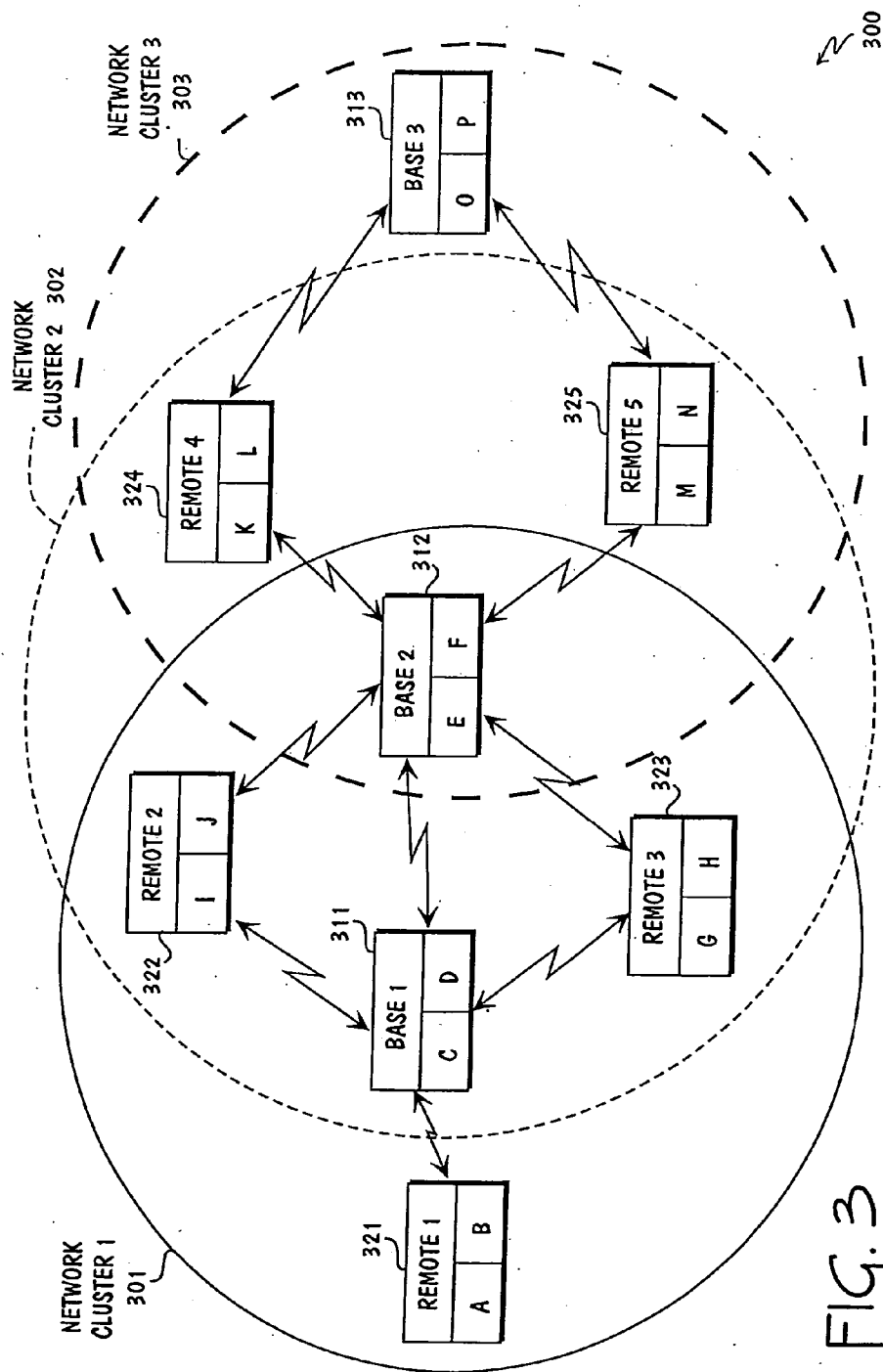


FIG. 3

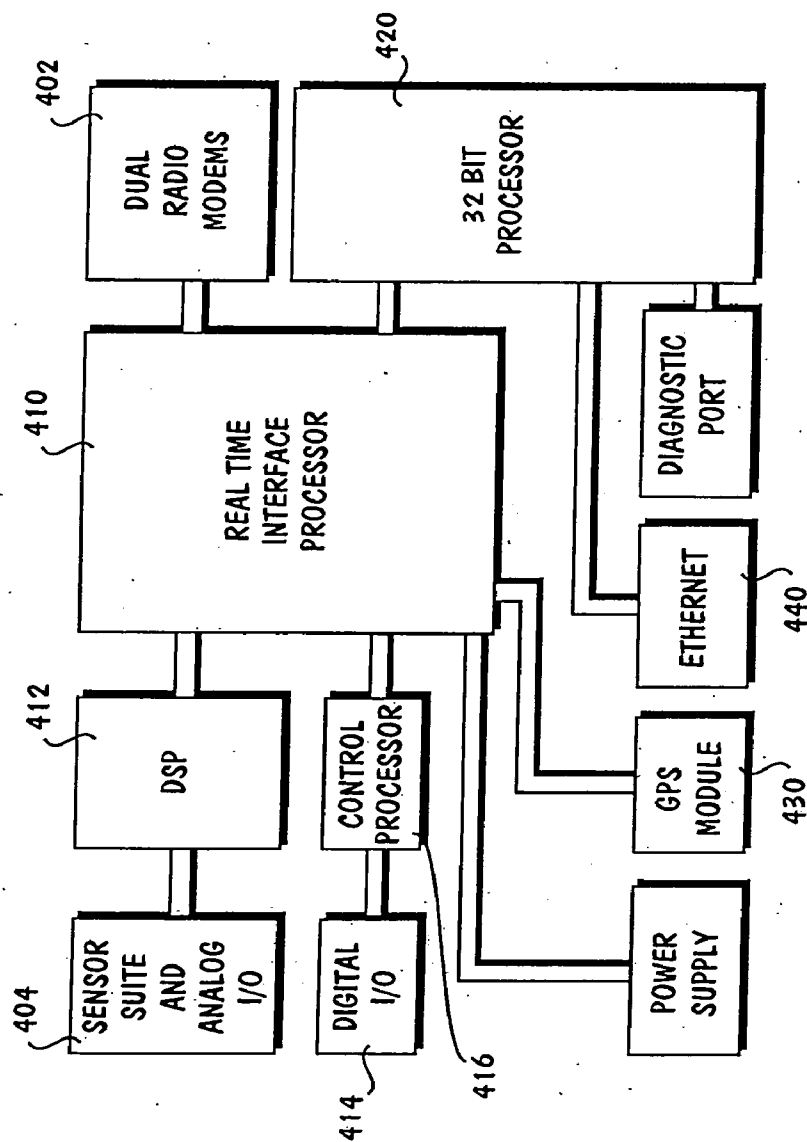


FIG. 4

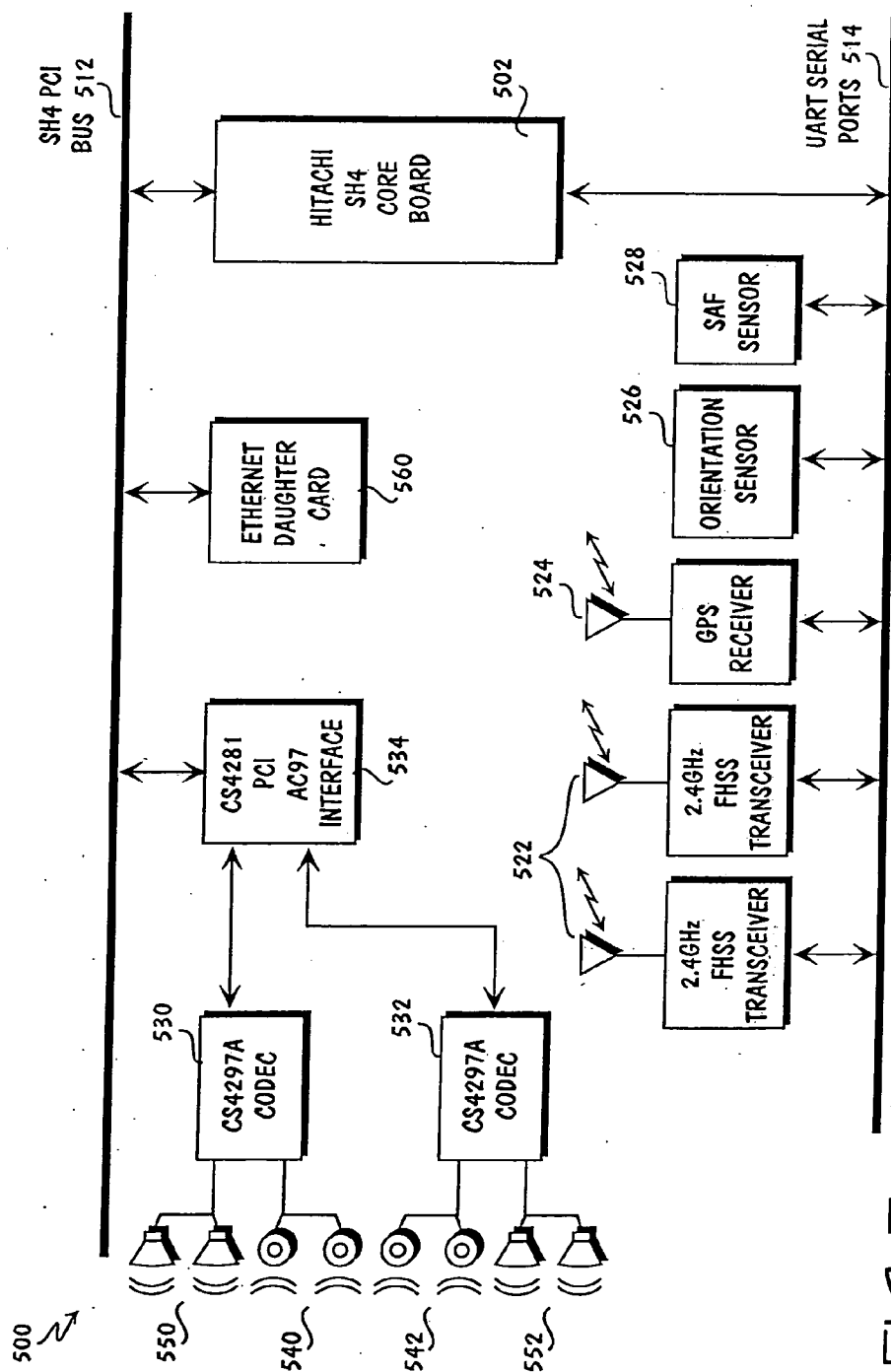


FIG. 5

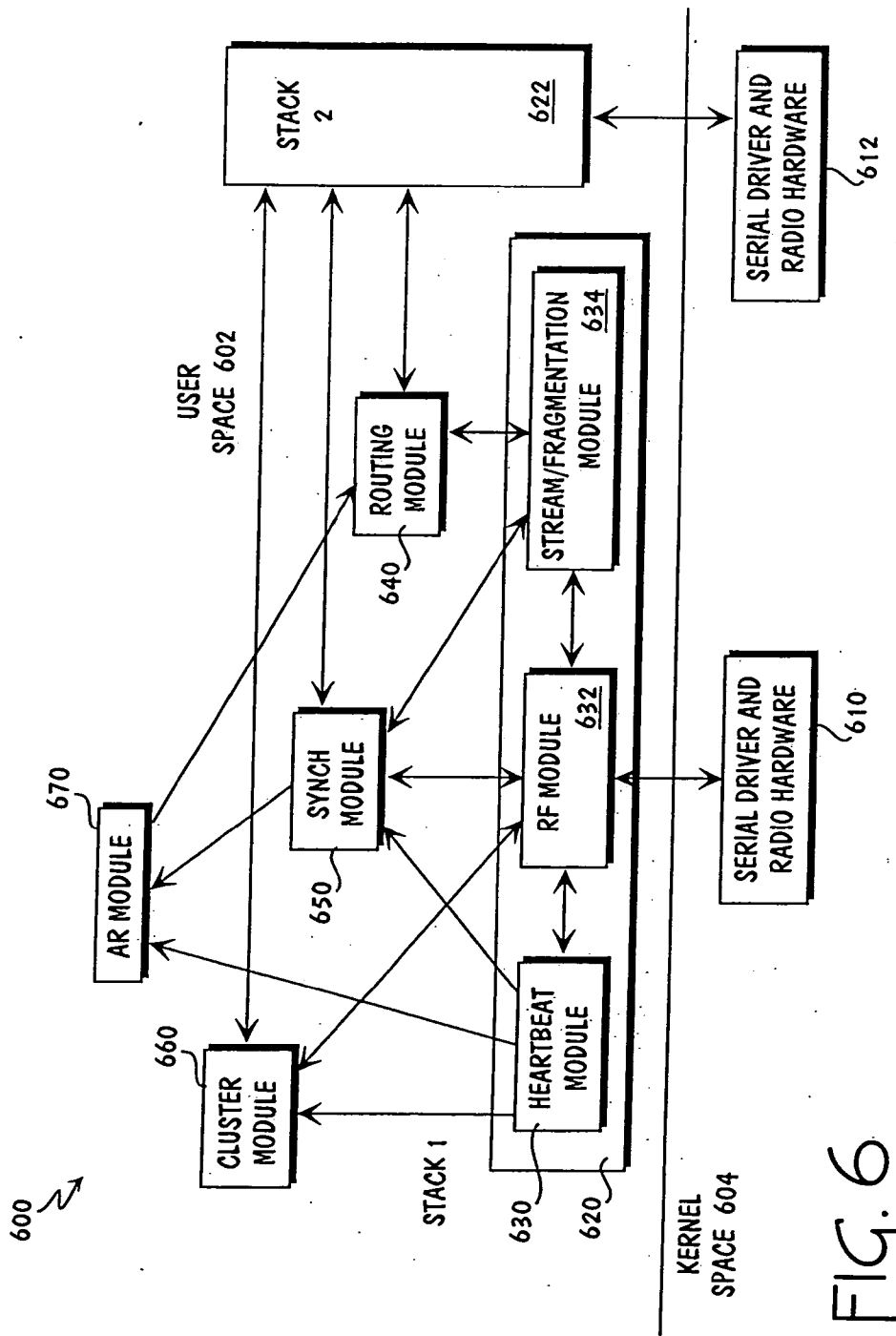


FIG. 6

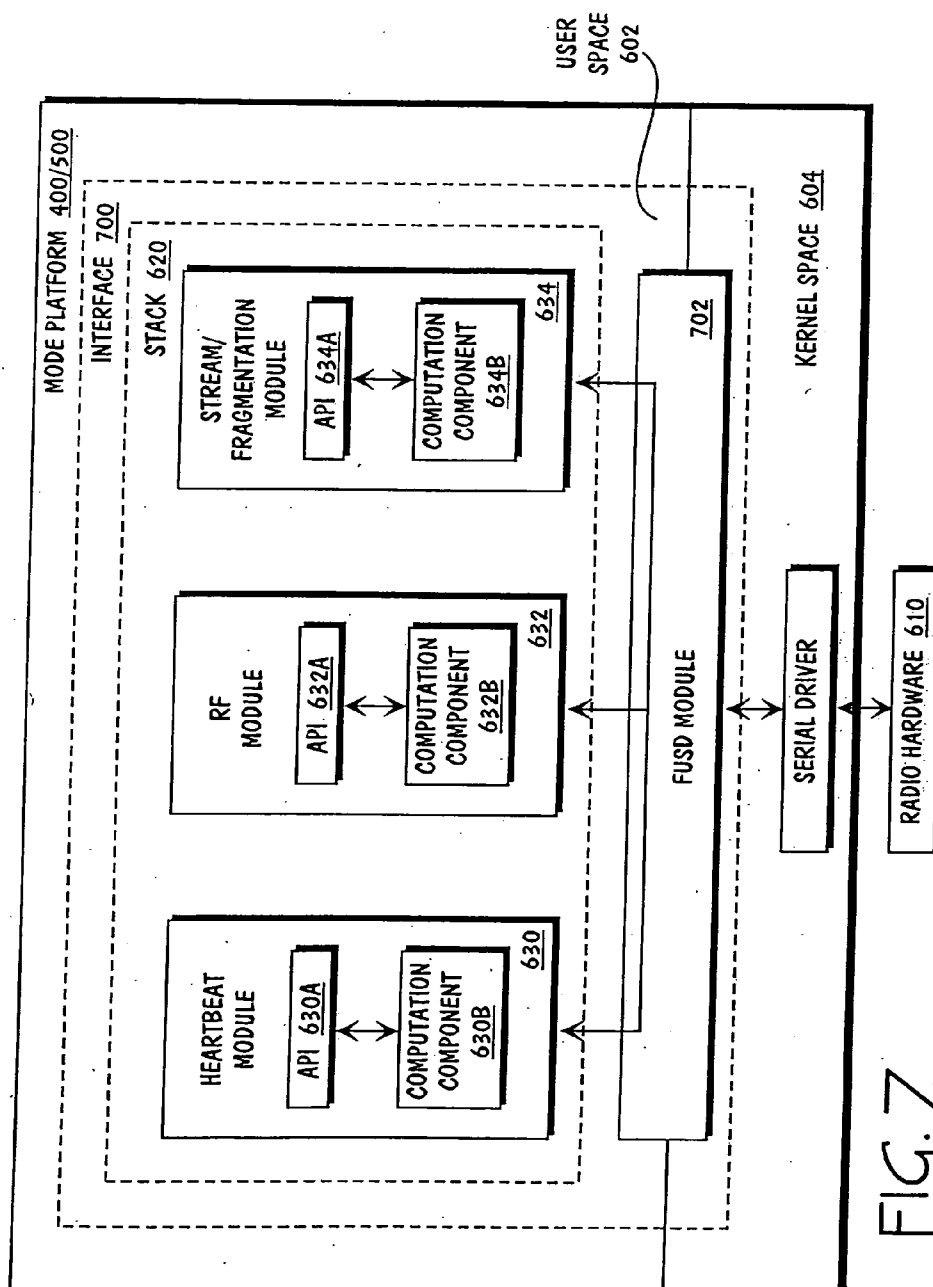


FIG. 7



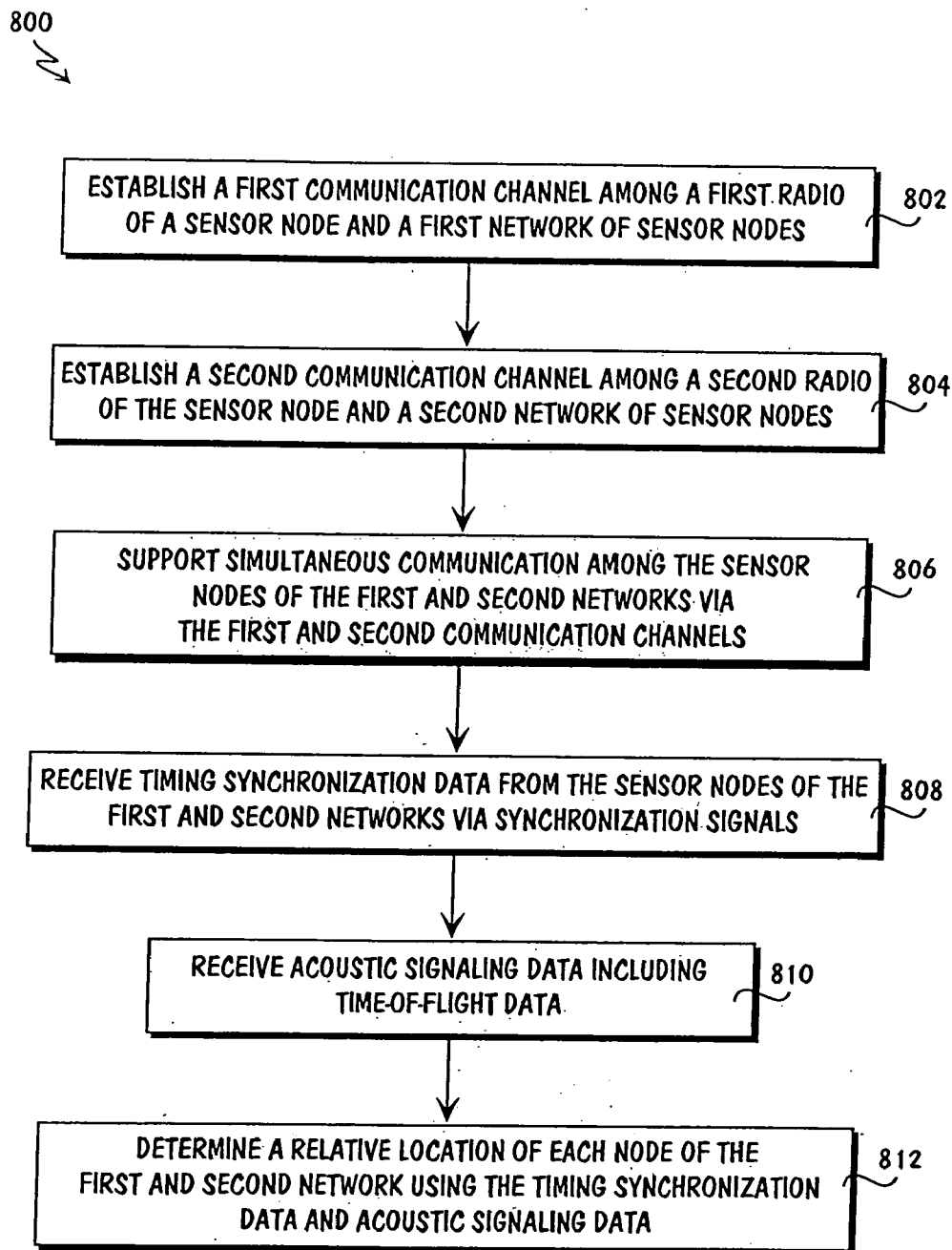


FIG. 8

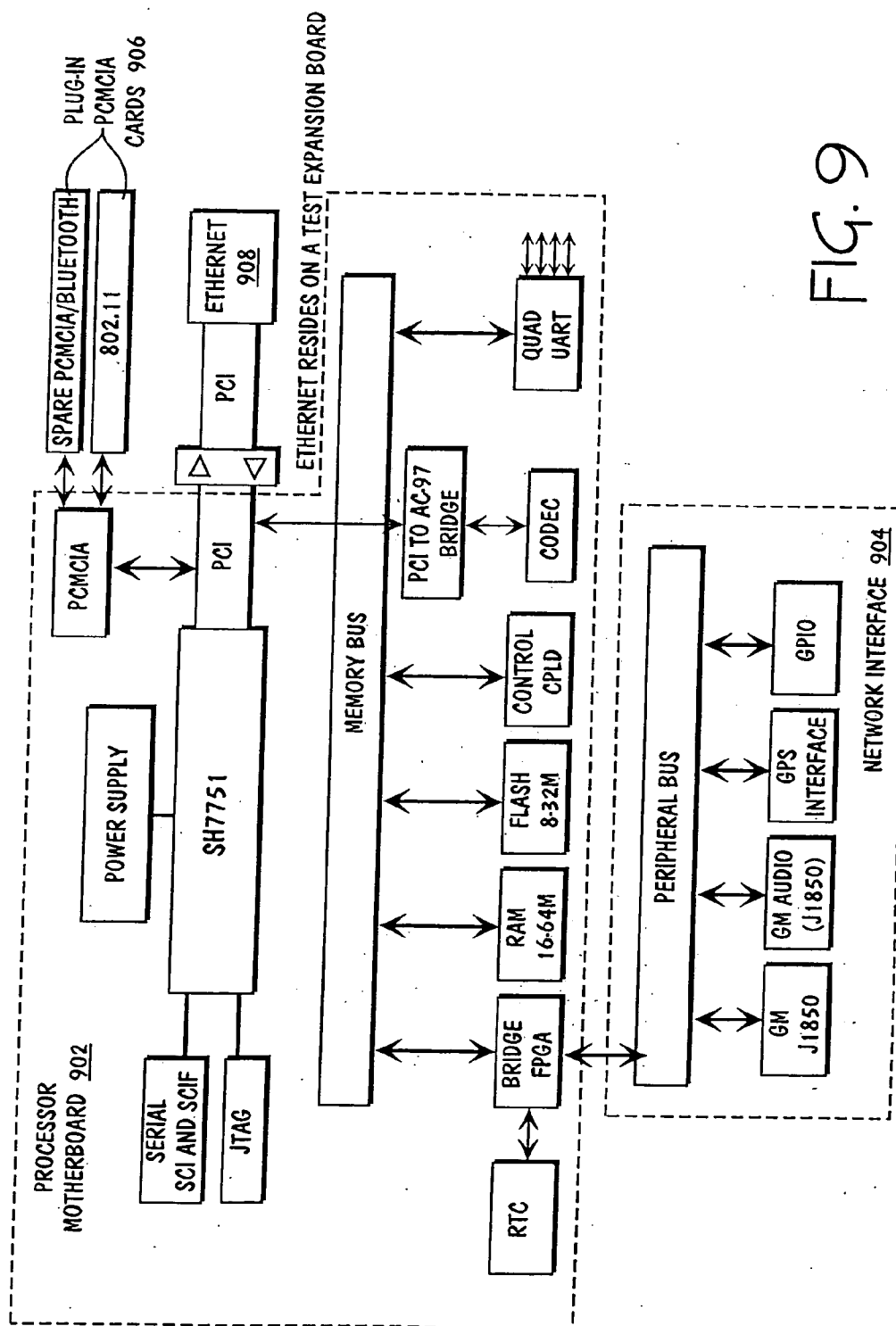


FIG. 9

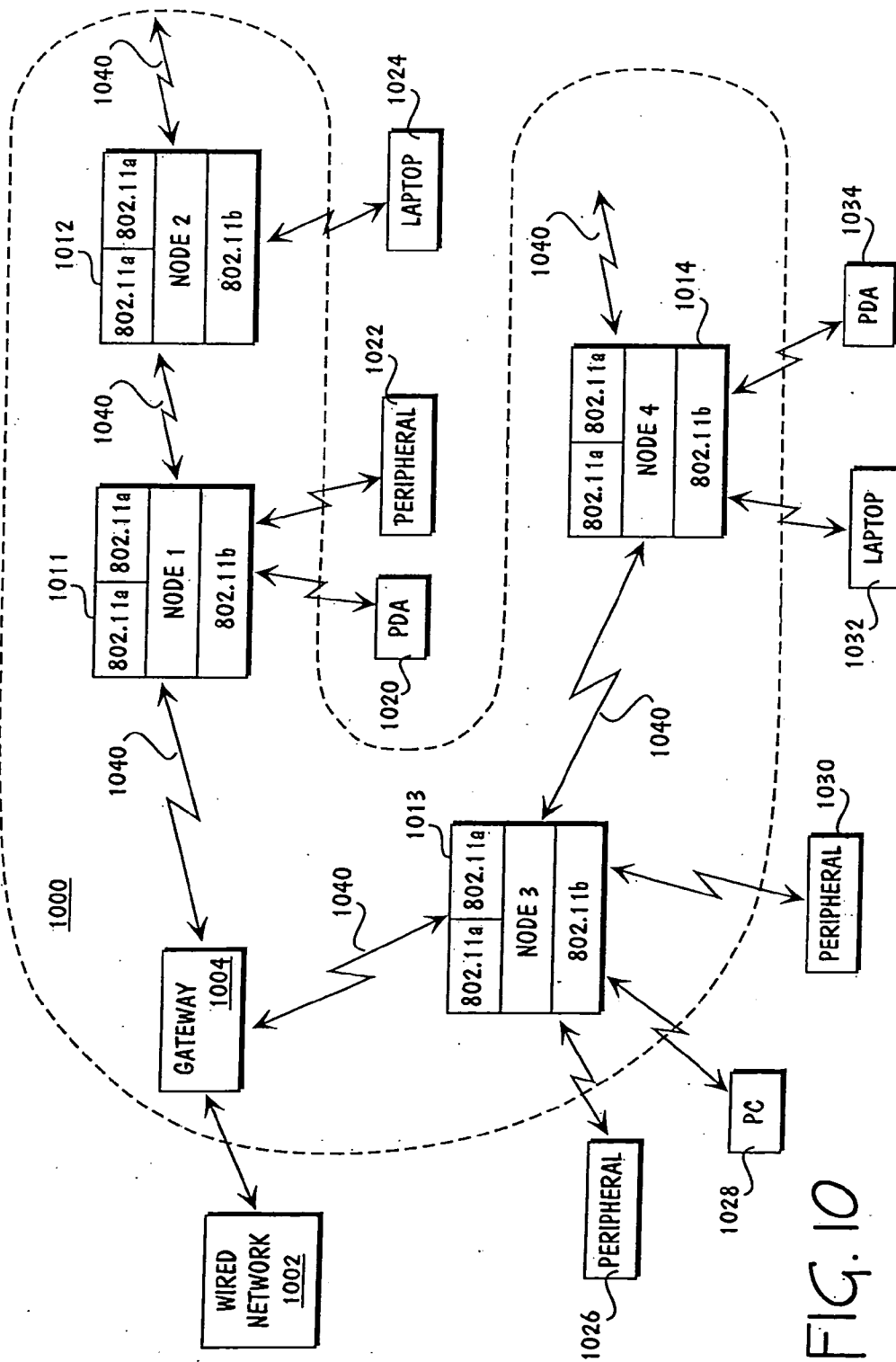


FIG. 10

## LOW-LATENCY MULTI-HOP AD HOC WIRELESS NETWORK

### RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Patent Application Nos. 60/302,795 filed Jul. 3, 2001 and 60/343,312 filed Dec. 21, 2001, both of which are currently pending and incorporated herein by reference in their entirety. This application is related to U.S. patent application Ser. Nos. 09/684,706, 09/684,565, 09/685,020, 09/685,019, 09/684,387, 09/684,490, 09/684,742, 09/680,550, 09/685,018, 09/684,388, 09/684,162, and 09/680,608, all filed Oct. 4, 2000, and 60/311,183 filed Aug. 9, 2001, 60/335,120 filed Oct. 24, 2001, 60/345,198 filed Jan. 2, 2002, 60/366,877 filed Mar. 22, 2002, and the application titled "Open Platform Architecture For Shared Resource Access Management" filed Jun. 28, 2002 (Attorney Docket Number SENS.P034; Application Number to be assigned), all of which are currently pending and incorporated herein by reference in their entirety.

### STATEMENT OF GOVERNMENT INTEREST

[0002] This invention was made with United States government support under Contract Number DAAE30-00-C-1055 awarded by the Defense Advanced Research Projects Agency (DARPA) Advanced Technology Office (ATO) and Contract Number F30602-99-C-0171 awarded by the DARPA Information Exploitation Office (IXO). The United States government may have certain rights in this invention.

### TECHNICAL FIELD

[0003] The disclosed embodiments relate to robust low delay ad hoc wireless networks.

### BACKGROUND

[0004] A basic assumption of ad hoc wireless networks is that there is no pre-existing network infrastructure. This means that the network nodes must establish communication routes among themselves in order to transfer information through the network. Algorithms devised for network self-assembly, clustering, and multi-hop routing include those described by K. Sohrahi, J. Gao, V. Ailawadhi, and G. Pottie in, "A Self-Organizing Sensor Network," Proc. 37<sup>th</sup> Allerton Conf. On Comm., Control, and Computing, Monticello Ill., September 1999. These algorithms can for example enable arbitrarily large networks to self-assemble, and permit multi-hop routing over large geographic areas under varying conditions of node mobility.

[0005] However, commercially available communication radios that enable wireless local area networks typically support only star network configurations. In the star network configuration one node of a cluster is designated as the master node, and the other nodes in the cluster are slave nodes that communicate only with the master node. Examples of typical protocols supporting the star network configuration include the IEEE 802.11 family of protocols including the 802.11a and 802.11b protocol, Hiperlan, and Bluetooth. The 802.11b protocol also includes an "ad hoc" mode, in which there is no single master node, but in which a local network of equal peer nodes is formed; each peer node can communicate directly with all other peer nodes. The advantages of the star network protocols include rela-

tively simple network formation, ease of management of channel access, and ease of establishing and maintaining synchronism. Moreover, the low cost of such radios and the ubiquitous software support for them over many computing platforms make them attractive for a wide variety of applications.

[0006] The typical protocols supporting the star network configuration also have a number of problems. One problem with the star configuration protocols is that they do not easily support efficient multi-hop communication. For example, as described in the Related Applications, a protocol is described in which particular nodes of a network belong to multiple clusters of the network and, as such, communicate with multiple cluster heads. Unfortunately, when using a commercial radio that implements a media access control (MAC) protocol which assumes a star topology, the radios provide communication with multiple cluster heads by time-sharing communications between the cluster heads. The time-share communication significantly reduces the communication throughput of the network.

[0007] Furthermore, and even more detrimental, is that each time a node radio switches communication between different cluster heads, the radio encounters a start-up time delay as if it is being newly joined to the network. Consequently, communication delays are very large across multi-hop networks that rely upon MACs supporting a star configuration. This situation is further aggravated when using the 802.11b ad hoc mode because radios that are too far away for reliable communication with network nodes may still interfere with other links of the network, and there is no mechanism within the protocol for resolving these types of conflicts. Thus, formation of a reliable network is problematic.

[0008] Yet another problem encountered in star network configurations is that it is difficult to maintain a common timing base (synchronism) across cluster boundaries using the star network protocols. This makes it difficult to automatically establish network position or accurately time-stamp data, as may be important in sensor network applications.

### BRIEF DESCRIPTION OF THE FIGURES

[0009] FIG. 1 is a point-to-multipoint wireless network cluster using a base-remote network configuration including multi-radio network nodes, under an embodiment.

[0010] FIG. 2 is a block diagram of a network including two local network clusters with dual-radio network nodes supporting communication among the clusters, under an embodiment.

[0011] FIG. 3 is a block diagram of a network including three local network clusters with dual-radio nodes supporting communication among the clusters, under an embodiment.

[0012] FIG. 4 is a block diagram of a multi-radio sensor node, under an embodiment.

[0013] FIG. 5 is a block diagram of a multi-radio sensor node, under an alternative embodiment.

[0014] FIG. 6 is a block diagram of the software architecture of a multi-radio sensor node incorporating a language-independent user-space driver interface, under an embodiment.

[0015] FIG. 7 is a block diagram of the user space/kernel space (US/KS) interface of a multi-radio node, under an embodiment.

[0016] FIG. 8 is a flow diagram of a method of forming a sensor network of an embodiment.

[0017] FIG. 9 is a block diagram of a multi-radio node, under another alternative embodiment.

[0018] FIG. 10 is a block diagram of an IEEE 802.11 access network including the multi-radio nodes of an embodiment.

[0019] In the drawings, the same reference numbers identify identical or substantially similar elements or acts. To easily identify the discussion of any particular element or act, the most significant digit or digits in a reference number refer to the Figure number in which that element is first introduced (e.g., element 400 is first introduced and discussed with respect to FIG. 4).

[0020] The headings provided herein are for convenience only and do not necessarily affect the scope or meaning of the claimed invention.

#### DETAILED DESCRIPTION

[0021] A multi-radio network node is provided herein that supports a multi-hop wireless network. The multi-radio nodes described below solve the long-standing problem that restricts most commercial spread spectrum modem solutions to local cluster/star networks. Each multi-radio network node, referred to herein as a multi-radio node, includes two or more commercially available communication radios or modems, and each radio supports communications with separate network clusters. The network, therefore, includes overlapped clusters in which nodes may belong to as many clusters as they have radios. This enables the use of standard commercial radios while permitting low-latency multi-hop networking, robustness in the form of alternate routing and ease of network reconfiguration, and ease of synchronization among clusters to facilitate position location and accurate time-stamping of sensor data. The multi-radio concept also enables the efficient use of radios with custom protocols to achieve the robustness and synchronization advantages.

[0022] FIG. 1 is a point-to-multipoint wireless network cluster 100 using a base-remote network configuration including multi-radio network nodes, under an embodiment. The cluster includes a base node 110 and four remote nodes 101-104, all of which include two radios A-J. While the nodes of this example include dual radios, alternative embodiments can include any number of radios. The base-remote, or master-slave, configuration provides for communication among the radios A-J of the nodes 101-110 by fixing the synchronization mechanism dictated by the base node 110 and all associated remotes 101-104. The remote nodes 101-104 communicate with one another via the base node 110. Any combination of radios A-J support communications among the remote nodes 101-104 and the base node 110. For example, a communication path between remote node 101 and remote node 102 may include radios E, D, and B, or alternatively E, D, C, and B.

[0023] The multi-radio nodes of an embodiment support communication among numerous clusters by enabling each node to operate on two or more star networks concurrently

so that packets can be routed quickly between network clusters. In order for a node to communicate with any node outside of the cluster of which it is a member, the node synchronizes to a separate communication link with the outside node. FIG. 2 is a block diagram of a network 200 including two local network clusters 201 and 202 with dual-radio nodes 210-222 supporting communication among the clusters, under an embodiment. FIG. 3 is a block diagram of a network 300 including three local network clusters 301-303 with dual-radio nodes 311-313 and 321-325 supporting communication among the clusters 301-303, under an embodiment.

[0024] With reference to FIG. 2, two local clusters 201 and 202 form the network. Local cluster 201 includes nodes 210-222, while local cluster 202 includes nodes 210, 212, 213, and 222. In this particular configuration, node 210 is the base node of local cluster 201, and node 222 is the base node of local cluster 2. Base node 210 communicates with all nodes of local cluster 201, including nodes 211-222. Base node 222 communicates with all nodes of local cluster 202, including nodes 210, 212, and 213. The remote nodes 211-213 communicate with one another via the base nodes 210 and 222. Numerous combinations of radios A-J support communications among the nodes of the local clusters 201 and 202. For example, a communication path between remote nodes 211 and 212 may include radios B, C, and G, or alternatively radios A, C, and H. A communication path between remote node 211 and base node 222 may include radios A, C, D, and I, or alternatively radios A, C, D, G, H, and J.

[0025] With reference to FIG. 3, three local clusters 301-303 form the network. Base nodes 311, 312, and 313 are the base nodes for local clusters 301-303, respectively. Communication among the nodes and clusters is as described above with reference to FIGS. 1 and 2.

[0026] In order to provide low latency packet transmission the multi-radio node of an embodiment provides multi-cluster access using dedicated hardware rather than by expanding the complexity of each individual modem. This provides a robust, scalable extension of the single network cluster architecture (a cluster corresponding to a synchronized channel between nodes) with the flexibility to support a large variety of networking algorithms. FIG. 4 is a block diagram of a multi-radio node 400, under an embodiment. This multi-radio node includes dual radio modems 402 like, for example, the WINS NG 2.0 network node available from Sensoria Corporation of San Diego, Calif. However, the multi-radio nodes described herein are not limited to two radios, and alternative embodiments of the nodes can include any number of radio modems.

[0027] Referring to FIG. 4, each of the radio modems 402 operates with Frequency Hopped Spread Spectrum (FHSS) signaling with transmission rates up to 56 kbps on each channel. The hopping is distributed over 75 channels within the 2.4 gigahertz (GHz) to 2.4835 GHz worldwide ISM band at a hopping rate of once per 14.375 milliseconds (ms) transmitting at 100 mW or 10 mW. Communication between base and remotes is synchronized within a time division multiple access (TDMA) cycle within each hop. At the beginning of a hop the base transmits first a synchronization signal, then any data in its buffer, followed in TDMA time slots by transmissions from each of the remotes synchro-

nized by that base. The number of remotes dictates the time slot assigned to each remote and hence the packet size sent with the transmission set up to operate efficiently with up to 8 remotes. A larger number of remotes per base can be used. However, communication efficiency drops as the header size occupies increasingly large portions of each packet. While the base and remote channel is TDMA, from the API perspective the radios appear to communicate in full duplex mode as transmitted and received packets at a single modem are interleaved.

[0028] The multi-radio node **400** of an embodiment includes high performance analog sensor sampling **404**, sensor signal processing **412**, wireless network support, a 32-bit application processor **420** and a Portable Operating System Interface (POSIX)-compliant real-time operating system. The node platform architecture includes a Real Time Interface Processor (RTIP) **410** and supports high-speed multi-port sampling integrated with both a high-speed digital signal processor (DSP) **412** and direct digital input/output (I/O) **414**. The RTIP **410** together with the associated DSPs **412** and control processors **416** are the preprocessor of the node **400**.

[0029] The node **400** also includes a 32-bit Application Processor **420** with numerous memory devices including random access memory (RAM), read-only memory (ROM), and flash memory. The Application Processor **420**, for example, the Motorola Power PC MPC 823 Rev A supplemented by 16 MB RAM and 8 MB flash memory, supports the QNX Neutrino POSIX-compliant, microkernel real time operating system (RTOS). Digital I/O **414** and Global Positioning System (GPS) **430** geolocation capability is provided with an attached active antenna.

[0030] The analog sensor interfaces **404** include two sets of interfaces. One set provides sampling rates from 1-25 kHz at 12-bit resolution, and the second set provides sampling from 1.88 to 101.1 Hz at 16-bit resolution, both with selectable gains. This provides support for a wide range of sensors. The sensor front-end high-speed input sample rate is accommodated in a power-efficient approach with a dedicated, programmable DSP **412**, for example the Texas Instruments **5402**. This DSP **412** is supplied with an integrated development environment. The DSP code may be communicated to the node **400** via a developer port or directly via the wireless network. The system also provides wireline interfaces with both 10 Mb ethernet **440** and RS-232 serial port access.

[0031] The multi-radio node **400** includes the software application programming interfaces (APIs), as described below. Node development may be conducted through the node ethernet port **440** or an RS-232 diagnostic port. The node **400** can mount a file structure on a remote machine, and development and file transfer is facilitated by the nodes capability to run telnet, tftp, and other file transfer protocols.

[0032] When a modem is powered on in operation and assigned to a specific network as a base node it acquires any remote nodes within range that are not already synchronized with another base node on the same channel. Similarly any remote nodes that are powered synchronize with any existing bases on their networks. Once every 256 hops each remote node re-registers with the associated base node, so that if a remote node disappears after registering with the network it will be noticed within approximately 4 seconds.

Similarly if a base node disappears after registering with the network, its disappearance is discovered immediately by the associated remote nodes because the base node transmits a synchronization signal each hop. Modems appearing and disappearing on the wireless channel of an embodiment are passed through the API as connect or disconnect packets generated by each internal modem when they are no longer synchronized with a specific base node or remote node.

[0033] Within the modems of an embodiment each packet is sent with an automatic repeat request (ARQ) scheme that initiates retransmission of any lost packets at the physical layer up to 16 times based on a 24-bit checksum. The number of retransmissions is configurable, to modify communication as desired. However, the ARQ is only enabled for point-to-point transmissions. While every transmission from a remote node to the associated base node is point-to-point and hence uses the ARQ if configured, transmissions from a base node to a remote node may be point-to-point (if a specific node is addressed) or broadcast in which no retransmission is implemented. A one-byte checksum is also provided at the driver layer to provide error checking in the case of broadcast transmissions.

[0034] Additional feedback on the channel is provided through the Received Signal Strength Indication (RSSI) option of the radio API. This provides the power level averaged over the last ten frequency hops seen by a remote node. The RSSI value is not defined at a base node because each base node may be communicating with multiple remote nodes, while each remote node only communicates with a single base node. The RSSI value is the ten-hop average of the regular synchronization header transmitted from the base node at the start of each hop. The RSSI value provides a relative reference for that radio and outputs an integer value from 0 to 255.

[0035] The radio API provides access to support setting of the operational status of each modem (base or remote, transmit power, network, etc.); however, a default operational status is also provided based on a deterministic node layout. This initial network configuration facilitates quick use of the multi-hop nature of the network, while enabling overlay of a large variety of self-assembly, reconfiguration and routing protocols.

[0036] Within a dual-radio node of an embodiment two modems operate simultaneously, each on an independent network or cluster. The dual architecture facilitates passing information between clusters and allows messages to be passed between networks. For example, with reference to FIG. 3, the dual modems of each node **311-313** and **321-325** provide multiple paths among the nodes. Additionally, by transferring a message between each modem driver on a node the message can be passed over many hops like, for example, passing signals from remote node **321** to base node **313** of the network **300** via a path including base node **311**, base node **312**, and remote node **324**. This communication path may use radios A, C, D, F, K, L, and O. Independent operation of the dual modems reduce the latency in message passing to that required to route information between each modem driver. The header of each packet passed up through the radio API enables directed routing as well as provides for packets to be passed along in a broadcast mode.

[0037] Since each dual-radio node is operating two independent modems, each node also has two radio frequency

(RF) addresses. At the RF modem API level everything is referred to the RF address. For example, with reference to FIG. 3, rather than labeling the nodes with node numbers 311-313 and 321-325, the associated radios are addressed by the radio addresses A-P. This provides flexibility in building a routing table based on neighboring radio addresses. While the RF modem API returns the identities of all radios connected to a selected radio it does not specify at the API level to which node a radio is attached. The node thus provides the capability to pass messages between individual radios to ascertain which nodes they are associated with in order to build node-driven routing tables.

[0038] Networks including multi-radio nodes have a higher capacity for multi-hop transmissions through the network because the multi-radio nodes have the advantage of being able to conduct simultaneous transmissions through multiple channels. The multiple radio architecture provides a further advantage of increased robustness to degradations such as jamming because the radios may be tuned to independent channels. This architecture also provides a greater number of connection combinations or alternative communication paths between two nodes. Two radios per node is the minimum necessary for low-latency multi-hop communications where conventional MACs are used, but a larger number provides higher inter-cluster capacity.

[0039] FIG. 5 is a block diagram of a multi-radio node 500, under an alternative embodiment. This node 500 includes a Hitachi SH4 core board 502 that includes a preprocessor and processor. The core board 502 is coupled among an SH4 peripheral component interconnect (PCI) bus 512 and universal asynchronous receiver/transmitter (UART) serial ports 514. In a dual-radio configuration, two 2.4 GHz FHSS transceivers 522 are coupled to the UART serial ports 514 along with a GPS receiver 524, orientation sensor 526, and SAF sensor 528. Each of two coder/decoders (CODECs) 530-532 couple to the PCI bus 512 via a PCI AC97 interface 534. Each coder/decoder (CODEC) 530-532 couples to two microphones 540-542 and two speakers 550-552, with the combinations being used for acoustic ranging, as described in detail below. An Ethernet card 560 couples to the PCI bus 512 for use in test and monitoring.

[0040] This node 500 includes a platform hardware configuration and software architecture that provides for shared resource access management. As further described below, and by W. Merrill, K. Sohrabi, L. Girod, J. Elson, F. Newberg, and W. Kaiser in "Open standard development platforms for distributed sensor networks," Aerosense Conference, Orlando, Fla., Apr. 5, 2002, and in the Related Applications, a Framework for User-Space Devices (FUSD) module or redirection module resides in kernel space and receives requests for access to resources from applications in user space. The FUSD module routes signals representative of the received requests to a device driver interface in user space. Components of the device driver interface include resource management modules and device drivers that correspond to available resources. The resource management modules generate queries to the device drivers regarding availability of the requested resources. Upon receipt of resource status information from the device drivers, components of the device driver interface generate schedules for granting access to the requested resources. Further, the device driver interface components control access to the

resources in accordance with the generated schedules including issuing responses to the requesting applications and the device drivers of the requested resources.

[0041] The platform software architecture of the sensor nodes described herein uses the FUSD to program functions as applications together with a special driver or driver interface that acts as a proxy for the application at the device level, as described below and in the Related Applications. In this way the FUSD provides access to all drivers and most system resources, and makes use of the security and communications features already built into or onto a standard operating system such as Linux. In this manner, one or more software-exchange mechanisms can be layered on top of the operating system as the mechanisms become available, without the need for any modifications or extensions to the mechanisms in order to enable access to the devices.

[0042] Moreover, the platform software architecture permits secure distribution of applications and key management software across multiple platforms, enabling convenient upgrades of both hardware and software, management of network access by communications and computer peripherals, and cost-accounted and secure interactions among local networks. For example, the software architecture supports personal and handheld computers and their associate network of peripherals, industrial or home automation, security networks, and vehicular systems, for example.

[0043] The FUSD causes the open interface of the sensor node software architecture of an embodiment to appear to the application developer as if increased functionality is provided at the level of the accessed device drivers. This enables access from applications via the standard POSIX virtual file system (VFS). While actually adding the needed functionality within the system kernel (device driver level), the FUSD architecture provides access to the system drivers and resources. In this manner, one or more software-exchange mechanisms can be layered on top of the operating system without the need for any modifications or extensions to these mechanisms to enable access to the devices.

[0044] In typical device drivers there is a layer of indirection between applications (such as read or write) and devices (such as I/O ports). This layer of indirection is needed because there must be some point of synchronization between processes competing for serial resources. Typically, this is managed with "trusted" (verified, stable) code that runs in kernel space and which has direct access to hardware, memory, and other system resources. Unfortunately, device drivers residing in the kernel cannot access most user-space services such as files, the outside world (e.g., serial ports, network interfaces), or user-space libraries, and are unable to block or run for long periods of time. Moreover, typically it is very difficult to write and debug code that must run in the kernel. The FUSD architecture of an embodiment avoids these difficulties by fusing the kernel and user space.

[0045] The FUSD architecture, including a kernel module and a cooperating user-space library, is a Linux framework for proxying device file callbacks into user-space, allowing device files to be implemented by daemons instead of kernel code. Despite being implemented in user-space, FUSD devices can look and act just like any other file under /dev implemented by kernel callbacks.

[0046] A user-space device driver can do many of the things that kernel drivers can not, such as perform a long-

running computation, block while waiting for an event, or read files from the file system. Unlike kernel drivers, a user-space device driver can use other device drivers—that is, access the network, talk to a serial port, get interactive input from the user, pop-up graphical user interface (GUI) windows, or read from disks, for example. Further, user-space drivers implemented using FUSD can be much easier to debug. Also, it is impossible for user-space drivers to crash the host platform, and they can be killed and restarted without rebooting even if they become corrupted. User-space drivers can also be swapped out, whereas kernel drivers lock physical memory.

[0047] The FUSD drivers are conceptually similar to kernel drivers in that they include a set of callback functions called in response to system calls made on file descriptors by user programs. The FUSDs C library provides a device registration function, similar to the kernel's `devfs_register_chrdev()` function, to create new devices. The `fusd_register()` function accepts the device name and a structure full of pointers. Those pointers are callback functions which are called in response to certain user system calls, for example, when a process tries to open, close, read from, or write to the device file. The callback functions should conform to the standard definitions of POSIX system call behavior. In many ways, the user-space FUSD callback functions are identical to their kernel counterparts.

[0048] The proxying of kernel system calls that makes possible this kind of program is implemented by FUSD, using a combination of a kernel module and cooperating user-space library. The kernel module implements a character device, `/dev/fusd`, which is used as a control channel between the kernel module and the user-space library. The `fusd_register()` function uses this channel to send a message to the FUSD kernel module, telling the name of the device the user wants to register. The kernel module, in turn, registers that device with the kernel proper using `devfs`. The `devfs` and the kernel do not know anything unusual is happening; it appears from their point of view that the registered devices are simply being implemented by the FUSD module.

[0049] When the kernel subsequently makes a callback due to a system call (e.g., when the character device file is opened or read), the FUSD kernel module callback blocks the calling process, marshals the arguments of the callback into a message and sends it to user-space. Once there, the FUSD user-space library unmarshals it and calls whatever user-space callback the FUSD driver passed to the `fusd_register()` function.

[0050] When the user-space callback returns a value, the process happens in reverse, wherein the return value and its side-effects are marshaled by the library and sent to the kernel. The FUSD kernel module unmarshals this message, matches it up with a corresponding outstanding request, and completes the system call. The calling process is completely unaware of this trickery; it simply enters the kernel once, blocks, unblocks, and returns from the system call, just as it would for any other blocking call.

[0051] As a general example of a system call within a sensor node platform using the FUSD architecture, an application in user space reads from a device driver, but now the VFS calls the FUSD module's read callback. The FUSD module, or redirection module, resides in kernel space and

serves mainly to redirect calls to drivers residing in user space, which may for example be written in C, Java, or other standard programming languages. Further, because the driver resides in user space it has access to all the user-space resources. The FUSD module calls the device driver callback, and the response propagates back to the original calling application. The semantics of the return variables under the FUSD architecture are exactly the same as if the device driver were in the kernel space. However, now it is possible to include a much broader set of functions in the driver, which can access user-space resources as well as make calls to other drivers within the kernel space.

[0052] The FUSD enables convenient control of the radios through a set of management tools residing in user space, which the application developer can access via device drivers for each software module. FIG. 6 is a block diagram of the software architecture 600 of a node incorporating a language-independent user-space driver interface, also referred to herein as a driver interface, under an embodiment. The multi-radio nodes 400 (FIG. 4) and 500 (FIG. 5) each host this architecture 600. Access to a hardware subsystem such as the radio hardware may be provided in one embodiment via a kernel-space serial port driver 610-612 on each node. Access to this serial port driver 610-612 is then provided in user space via FUSD so that at the lowest software layer, the RF modem driver 632 interfaces to each specific radio, and is dependent on the radio used. This driver 632 then presents a standard interface so that each higher layer module can operate over alternate radios having a driver in place, allowing only user space software changes to the specific radio driver 632 to use a separate radio over this serial connection. Interfacing above the RF modem driver 610-612 within the user space 602 of the communication network are stacks 620-622, each of which include three modules 630-634. The three modules include, but are not limited to, a heartbeat module 630 or link-monitoring module, an RF module 632, and a stream/fragmentation module 634.

[0053] FIG. 7 is a block diagram of the user space/kernel space (US/KS) interface 700, under an embodiment. The multi-radio nodes 400 (FIG. 4) and 500 (FIG. 5) each host this interface 700. Each of the heartbeat module 630, the RF module 632, and the stream/fragmentation module 634 include two components, an API 630A, 632A, 634A and a computational component 630B, 632B, 634B, coupled via a FUSD module 702. The API component of each module 630A, 632A, 634A resides in the associated stack 620 and 622 in user space 602. Each API component 630A, 632A, 634A couples to the corresponding computational component 630B, 632B, 634B that also resides in user space 602 via the FUSD module 702, thereby providing a language independent interface supporting standard POSIX calls just as a kernel-space device file. Thus, the US/KS interface 700 is expanded by the FUSD module 702 to provide device file access within user space to the serial driver and radio hardware as well as the API components 630A, 632A, 634A and computational components 630B, 632B, 634B of the heartbeat module 630, RF module 632, and stream/fragmentation module 634.

[0054] The components 630-634 of each stack couple to a number of other user-space components including, but not limited to, a cluster module 660 or network discovery and self-assembly module, a synchronization module 650 or



sync module, a routing module **640**, and an acoustic ranging (AR) module **670**. The heartbeat module **630** of each stack couples to the cluster module **660**, the sync module **650**, and the AR module **670**. The RF module **632** of each stack couples to the cluster module **660** and the sync module **650**. The stream/fragmentation module **634** of each stack couples to the sync module **650** and the routing module **640**. The sync module **650** and routing module **640** also couple to the AR module **670**. Each of these modules is described in further detail below. FIG. **8** is a flow diagram of a method of forming a sensor network under and embodiment, as described below.

[**0055**] Referring to FIGS. **6** and **7**, the RF modem driver **610** and RF module **632** provide capabilities for multiple upper layer software modules **640-670** to send data over the node radios (via user space access through a FUSD device file) and for different systems to configure the radios through the standard API provided by the radio-specific RF driver **632**. Radio-specific protocols are built into the RF modem driver **632** in order to provide a radio-independent API **700** to the upper layer software modules **640-670** of the node, with general configuration commands abstracted from the radio physical layer connection properties. The serial port driver **610** and RF driver **632** are flexible in allowing independent communication to as many radios as are on the node by running multiple versions of the driver for each device file (e.g., a serial port) connected to a modem. The RF module API **632A** provides a language-independent API for higher layer software to use supporting standard POSIX-compliant system calls. The RF module API **632A** also provides a useful debugging interface through command line-queriable device files reporting radio specific status information.

[**0056**] The node platform architecture of the embodiments described herein is consistent with the FUSD architecture described in the Related Applications in that multiple users (or multiple software modules) can access, monitor, and write to each software system, through a protected language independent device file. This allows for easy evaluation of module status, or radio status in the case of the radio driver.

[**0057**] In addition to enabling configuration of the radios, software operating at the highest layer of the RF modem driver **632** also parses large packets to utilize the maximum amount of data put into each packet as limited by the radio physical layer. This allows higher layer applications to send data as needed without being dependent on characteristics of individual radios. Alternatively, in order to ensure that a message including multiple packets gets through, the upper layer of the RF modem driver tracks the packet order and monitors the transfer of all message packets, for example the stream/fragmentation module **634**.

[**0058**] Returning to FIGS. **6** and **7**, the cluster module **660**, or network discovery and self-assembly module, operates through the RF module **632** to configure the radios and set up the communication network autonomously. In operation, the cluster module **660** sets parameters of each RF modem driver **632** to form each local network cluster in order to ensure communication is possible across the network. The network nodes may for example operate in a TDMA cycle controlled by a base node, communicating to a number of remotes units. The network nodes of various alternative embodiments also support other communication protocols,

including but not limited to, frequency division multiple access (FDMA), code division multiple access (CDMA), and orthogonal frequency division multiplexing (OFDM). This base/remote command is abstracted by the RF modem driver **632** to the role of one modem providing cluster synchronization while the other modems are adherents to that synchronization.

[**0059**] The cluster module **660** autonomously determines which modem **610-612** should act as the cluster synchronizer, based on the modems with which the cluster module **660** can directly communicate. In so doing, the cluster module **660** sets the role of each modem **610-612** of a node **400/500** by first assigning each modem of a node as a passive listener within each cluster (to determine if another node is synchronizing the network). Then, based on a schedule of which modems can be heard by the listening modems, the cluster module **660** either (1) offers to synchronize each modem with any other modem that the listening modem can hear, or (2) allows the listening modem to be synchronized by a node that the listening modem finds. The clustering algorithm of the cluster module **660** listens for a random period of time for other radios before attempting synchronization. The cluster algorithm also cycles between listening and attempting synchronization until each cluster stabilizes. Regarding synchronization, the cluster algorithm uses a minimum of other available nodes to synchronize (minimum number or remotes synchronized by each base with the current radios).

[**0060**] Once the cluster module **660** has assembled the individual clusters, the heartbeat module **630**, or radio link-monitoring module, actively transmits a heartbeat signal over each connection of the cluster. The heartbeat signal transmits periodically, which in an embodiment is every N seconds (where N is easily configurable), plus or minus 30%, where the heartbeat time is randomized between each pulse. However, alternative embodiments may transmit heartbeat signals with a different periodicity and random dither. The heartbeat signals or packets are transmitted both ways through the cluster to ensure two-way communication.

[**0061**] Embedded within each heartbeat signal is a bit map that corresponds to the processes operating on each node of a cluster. The bit map allows nodes receiving the bit map to determine the operational status of neighboring nodes in addition to the operational status of the RF link. By actively testing the physical layer link within the heartbeat module **630**, both the over-the-air connectivity and the interface to the radio are tested. For example, the heartbeat module **630** uses the same interface via the RF driver module **632** as any other software module of a node to communicate with the radio **610** (i.e., uses the device driver provided by the RF driver **632A**), so that the heartbeat module **630** is continuously testing the communication channel exactly as seen on the node. This supports troubleshooting where, for example, the modem communicates fine over the air, but the radio firmware or even the radio driver is experiencing problems buffering data prior to sending it resulting in lost data.

[**0062**] Leveraging the heartbeat module **630** is the RF synchronization module **650**, or sync module, which provides microsecond level accuracy between nodes. The sync module **650** is built independently of the heartbeat module **630** to easily allow the use of alternate broadcast messages for synchronization, and the integration of alternate syn-

chronization modules. The synchronization operates above the heartbeat software but leverages the fact that each heartbeat packet is broadcast from the cluster module **660** and hence received by all the synchronized radios of a cluster at the same time, as described by J. Elson, L. Girod, and D. Estrin in "Fine-Grained Network Time Synchronization using Reference Broadcasts", submitted to SIGCOMM 2002. Thus each modem that receives the broadcast packet has a consistent time reference with all the other nodes synchronized in the same cluster.

[0063] The base or synchronizing radio does not have a reference time point based on its own broadcast "heartbeat", but since each node participates in two clusters, it has a reference time from the other cluster in which it participates. Since "heartbeat" packets are sent periodically, each node also conditions for drift in its own clock (based on temperature variations for example) with respect to its neighbors to ensure that once synchronized the nodes stay synchronized for as long as possible, even if no synchronization packets are received for a long period. In addition, with every node participating in two clusters, substantial cluster overlap occurs enabling multiple clusters to be synchronized.

[0064] The nodes **400/500** of an embodiment include any number of routing modules **640**. The routing modules **640** operate over the clusters assigned by the cluster module **660** and over the links tested by the heartbeat module **630**.

[0065] The nodes **400/500** of an embodiment use the AR module **670** to determine their relative locations to other local nodes with which they communicate. The AR module **670** determines the range and angle between local clusters of nodes and, from this range and angle data, builds a local coordinate system for these nodes using a multilateration module (not shown). Components of the AR module **670** including a merging algorithm that merges multiple local coordinate systems to create a field table. The field table includes the coordinates of many nodes. As an example, the field table may include coordinates for approximately fifty nodes, but is not so limited.

[0066] The AR module **670** leverages the inter-cluster synchronization provided by the heartbeat module **630** through its associated FUSD device driver. The heartbeat provides synchronization over RF, which can be abstracted beyond the local RF cluster. With this synchronization data each node can determine the range to other nodes based on a one-way acoustic time of flight. Each node that includes a modem operating as an RF base synchronizes all acoustic signaling within a local area. This coordination is abstracted from the topology dictated by the network cluster. Determination of the ranges to a sufficient number of neighbors is considerably enhanced by having clusters with a large degree of overlap, as is made convenient with nodes that employ two or more independent radios or modems.

[0067] Referring to FIG. 5, the AR modules **670** of an embodiment transmit a different coded acoustic chaotic sequence out of each of four speakers **550-552** of the host node **500**. The transmission of these acoustic chaotic sequences is scheduled by the base node of each network cluster. As such, each node within a network cluster attempts to get the range and angle to every other node in the cluster.

[0068] The transmitted acoustic chaotic signals are received by the microphones **540-542** of each of the nodes

that expect a signal, and correlated for each of the expected chaotic sequences. In the performance of the correlation, the sampled data on each of the four microphones **540-542** is also correlated with an alternate chaotic sequence to determine a representative noise level. Then, based on the correlated signal level, a signal-to-noise ratio (SNR) is assigned to each of the sixteen combinations of microphone/speaker pairs.

[0069] The assigned SNRs are used to determine whether or not to use the sampled data, as follows. To begin, signals from the various transmitting speakers are compared, and the speaker associated with the signal having the highest SNR values is chosen as the signal source for use in all processing (giving an indication that this speaker is pointed towards the receiving node). Signals from the four microphones sampling the signal received from the source speaker are then compared (if they have a large enough SNR) in order to provide both a range between nodes and an angle between nodes. The range between nodes is provided in the form of a weighted average, and the angle between nodes is determined from the weighted time of flight differences between each microphone pair.

[0070] The base node of each network cluster collects the range and angle data calculated between each pair of nodes between which it coordinated ranging. The base node generates a range table using this range and angle data. The range table is then used as input to a local multilateration module to determine a relative coordinate system for the list of nodes in the range table. An algorithm of the multilateration module should use a range and angle combination between these groups of nodes that is adequate to provide an initial guess for the location of nodes, from which an iterative least squares approach is used to generate a multilateration table.

[0071] In expanding the multilateration table to include location information of the nearest fifty or so neighbor nodes, the multilateration data from each base node is intelligently passed to approximately fifty of the nearest neighbor nodes. The AR module transmits the multilateration data using the routing module.

[0072] Upon receipt of the multilateration data, each node contains a collection of multilateration tables that are merged to provide a field table. Each node independently executes the merging in order to provide a field table having the local node as the table origin. Further, in order to minimize the error nearest each node, the merging is accomplished by starting with the largest multilateration table that contains the local node and then merging in each of the other multilateration tables based on the largest common node set. In this manner the nodes propagate field tables including very accurate node position information throughout their associate network.

[0073] The AR modules **670** update the field table by transmitting updates to the multilateration tables. The multilateration update tables are then merged into the field tables of each node. These updates include a number of status flags to signify the current state of each node, for example if it has been moved (tampered) but is still participating in the network or if it has disappeared from the network. In this manner the disappearance or appearance of a node from the network is passed via updates to the multilateration table within the network. These multilateration table updates also

provide a mechanism by which a new node integrates into the network, and provide a soft state approach to system operation by providing information redundantly to each node.

[0074] Note from the above discussion that in the absence of RF synchronization the acoustic ranging would be difficult as the time of flight measurements are subject to unacceptable error. For successful position location many nodes have to determine their relative location. The connectedness of the multilateration tables is greatly improved when nodes may belong to multiple clusters. The multi-radio nodes described herein allow the required level of synchronization to be easily achieved and thus serve more than the single purpose of coordination of communications among nodes of a cluster.

[0075] Similarly, in pursuing applications such as acoustic or seismic beamforming, coherent data is needed as these applications share many of the properties of position location applications. Coherent data uses timing that is accurate to within a small fraction of one wave oscillation. Achieving such a level of synchronization across RF cluster boundaries would be difficult in the absence of overlapped cluster membership of nodes.

[0076] The overlapped cluster architecture provides not only low-latency connectivity, but also provides for improved robustness, capacity, and power efficiency compared to typical networking schemes. For example, in a typical pure hierarchical network configuration the cluster heads may be the only nodes with multiple radios and thus the only nodes capable of inter-cluster communication. This limits the number of routes and, due to propagation losses that are typically on the order of the fourth power of distance for ground-to-ground links, leads to increased power consumption.

[0077] By contrast, where other nodes of the cluster can serve as relays there are more paths available for getting around obstacles (such as structures and surface relief), and each link is shorter thereby reducing the total transmitted power along the path. This architecture also provides the secondary benefit of decreased probability of interception of communications and improved resistance to jamming. Additionally, since two radios are active, overall network capacity is increased.

[0078] FIG. 9 is a block diagram of a multi-radio node 900, under another alternative embodiment. This node 900 includes a processor motherboard 902 and a network interface 904. The motherboard 902 of an embodiment accepts at least two plug-in Personal Computer Memory Card International Association (PCMCIA) cards 906 and an Ethernet card 908. The motherboard 902 supports operation as a multi-radio node when configured with an 802.11b radio port in the Ethernet port 908 and two 802.11a radio ports in the PCMCIA ports 906.

[0079] The processor motherboard 902 includes the power supply, PCMCIA slots and interfaces, SH7751, PCI, Serial SCI and SCIF, JTAG, Memory Bus, RTC, bridge field programmable gate array (FPGA), random access memory (RAM) 16-64M, flash memory 8-32M, control complex programmable logic device (CPLD), PCI to AC-97 Bridge, CODEC, and quad universal asynchronous receiver transmitter (UART). The network interface includes a peripheral

bus, GM J1850 (audio) bus (vehicle applications), GPS interface, and general purpose input/output (GPIO), but alternative embodiments support numerous different interface options. The test expansion board is shown with an Ethernet board, but also supports an IEEE 802.11 radio port. Plug-in PCMCIA cards include IEEE 802.11 radio ports, and a spare, which might be used for Bluetooth.

[0080] With the configuration depicted, the SH7751 is the host for the node software architecture described above. The use of multiple additional processors enables many critical real-time management functions to be offloaded from the main processor, allowing determinism without requiring a special operating system. As described in the Related Applications, with respect to vehicle gateways with both a main processor and logic comprising a real-time interface processor (RTIP), systems with this general architecture enable convenient hosting of applications while also assuring real-time operation.

[0081] The processor of an embodiment is a Hitachi HD6417751F167, but is not so limited. The SH7751 can be programmed via a 14-pin JTAG header on the core board. This header is accessible when the board stack is removed from the nodes enclosure. The SH7751 has two native serial ports. The SCI port is used to communicate with the PCI, which controls the power state of the system. This port is used in a SPI mode where the SH7751 acts as a slave. The SCIF port on the SH7751 exits the gateway via the main connector at RS232 levels with full flow control.

[0082] The RAM on the board is scalable from 16 megabytes (M) to 64M in 16M increments. This is implemented by chip selection and the choice of the number of chips populated. The chips are populated in pairs. Using two chips that are 16 bits wide allows a 32-bit write which is twice as fast as two 16-bit writes.

[0083] The flash memory on the board is scalable from 8M to 32M in 8M increments. This is implemented by chip selection and the choice of the number of chips populated. The chips are populated in pairs. Using two chips that are 16 bits wide allows a 32-bit write which is twice as fast as two 16-bit writes.

[0084] The FPGA is responsible for aiding the SH7751 in controlling several devices on the core board. The address bus, data bus, chip selects, and IRQs of the SH7751 are routed to the FPGA so that they may be decoded before interfacing with other devices. The FPGA interfaces with the quad UART, the network interface 904, and the CODEC and generates GPIOs, which are used for debugging. The FPGA can be programmed either through the SH7751 or a 5-pin JTAG header on the core board.

[0085] The node architecture of an embodiment further supports nodes including radios supporting different protocols. The use of different protocols on the same platform is found in hierarchical networks, for example, where base nodes have improved power supplies, antenna elevation, or simply more powerful radios. The separation of functions among the local networking and the longer range multi-hop network can simplify operations in hierarchical networks.

[0086] FIG. 10 is a block diagram of an IEEE 802.11 access network 1000 application including the multi-radio nodes of an embodiment. The installation of an 802.11 access network 1000 in a hospital, airport, mall, or other

structures in which stringing new communications cable to the access points is costly and difficult in the absence of the multi-radio nodes. Further, use of portable wireless devices alone to actually perform the multi-hop routing is complicated, unreliable (due to their motion), and would demand operating their protocols in an irregular mode. However, the multi-radio nodes of an embodiment facilitate provision of a wireless access network as described below.

[0087] With reference to FIG. 10, the access network 1000 presents a network access point to the end-user that appears to be the same as that of a wired network. The nodes 1011-1014 that support this access network 1000 under an alternative embodiment include at least three radios, and more radios can be included to support alternative network configurations. The three radios include two 802.11a radios that establish a high-speed low-latency multi-hop backbone. The third radio of the node is an 802.11b radio that provides local access for portable electronic devices 1020-1034 like laptop computers and other portable devices equipped with wireless capability. The network access nodes 1011-1014 support the provision of multiple paths 1040 between any given access point 1011-1014 and the gateway 1004 to the wired network 1002, thereby providing reliable network access under failures of any given element. The overlapping cluster algorithms described above can then be applied to the formation of the multi-hop access radio wireless backbone.

[0088] Alternative embodiments of the access network 1000 may include nodes 1011-1014 with three 802.11a radios, nodes 1011-1014 with three 802.11b radios, and/or nodes 1011-1014 with various other combinations of 802.11a/802.11b radios. Additionally, alternative embodiments of the access network 1000 may include nodes 1011-1014 that support various other communication protocols or wireless local area network (LAN) standards.

[0089] The multi-radio node hardware and software described herein and in the Related Applications provides a convenient means of implementing these access networks. The capability for local control over resources such as radio ports supports provision of differentiated quality of service and security without the need for large back-end servers in each installation. The local control over resources further enables remote upgrade of this software. The enterprise-level software provides the capabilities for multiple Internet service providers to be supported, giving economies of scale in the user population.

[0090] The multi-radio nodes of an embodiment are also useful in combination with multi-hop systems known in the art. For example, consider deployment of sensor networks in a security application wherein certain critical locations require coverage by a field of sensors, with a large gap between the critical locations and a command post that receives the sensor information. In this case, there is a need for longer range radios to overcome the gaps in the network. Use of the multi-radio nodes across the gap provides multi-hop coverage over these long-range links while requiring less power than when attempting to bridge the link in one hop. Use of multiple radios for each long-range relay also provides low latency across the link. The overlapping cluster algorithms described above may be used at each level of this network hierarchy.

[0091] The multi-radio nodes described above are not limited to use in local networks of a star architecture, as they

may be used with numerous other network protocols to establish both network clusters and/or flat networks. Even with other network protocols, use of the multi-radio nodes enables higher communication throughput (in not having to time share as much on connections) and simplifies synchronization and channel assignment.

[0092] The use of multiple radios on nodes within a sensor or wireless access network provides for efficient leveraging of single cluster protocols to provide low latency multi-hop networks. Multiple radios also facilitate node self-location and coherent combination of data, while providing a more densely connected and more robust network. Numerous embodiments have been described above, and it will be apparent to those skilled in the art that many more alternative embodiments are possible.

[0093] Aspects of the embodiments described herein may be implemented as functionality programmed into any of a variety of circuitry, including programmable logic devices (PLDs), such as field programmable gate arrays (FPGAs), programmable array logic (PAL) devices, electrically programmable logic and memory devices and standard cell-based devices, as well as application specific integrated circuits (ASICs). Some other possibilities for implementing aspects of the embodiments include: microcontrollers with memory (such as electronically erasable programmable read only memory (EEPROM)), embedded microprocessors, firmware, software, etc. Furthermore, aspects of the embodiments herein may be embodied in microprocessors having software-based circuit emulation, discrete logic (sequential and combinatorial), custom devices, fuzzy (neural) logic, quantum devices, and hybrids of any of the above device types. Of course the underlying device technologies may be provided in a variety of component types, e.g., metal-oxide semiconductor field-effect transistor (MOSFET) technologies like complementary metal-oxide semiconductor (CMOS), bipolar technologies like emitter-coupled logic (ECL), polymer technologies (e.g., silicon-conjugated polymer and metal-conjugated polymer-metal structures), mixed analog and digital, etc.

[0094] Unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise," "comprising," and the like are to be construed in an inclusive sense as opposed to an exclusive or exhaustive sense; that is to say, in a sense of "including, but not limited to." Words using the singular or plural number also include the plural or singular number respectively. Additionally, the words "herein," "hereunder," and words of similar import, when used in this application, shall refer to this application as a whole and not to any particular portions of this application.

[0095] The above description of illustrated embodiments of the invention is not intended to be exhaustive or to limit the invention to the precise form disclosed. While specific embodiments of, and examples for, the invention are described herein for illustrative purposes, various equivalent modifications are possible within the scope of the invention, as those skilled in the relevant art will recognize. The teachings of the invention provided herein can be applied to other network systems, not only for the network systems described above.

[0096] The elements and acts of the various embodiments described above can be combined to provide further embodi-

ments. All of the above references and Related Applications are incorporated herein by reference. Aspects of the invention can be modified, if necessary, to employ the systems, functions and concepts of the various references and applications described above to provide yet further embodiments of the invention.

[0097] These and other changes can be made to the invention in light of the above detailed description. In general, the terms used in the following claims should not be construed to limit the invention to the specific embodiments disclosed in the specification and the claims, but should be construed to include all network systems that operate under the claims. Accordingly, the invention is not limited by the disclosure, but instead the scope of the invention is to be determined entirely by the claims.

[0098] While certain aspects of the invention are presented below in certain claim forms, the inventors contemplate the various aspects of the invention in any number of claim forms. Accordingly, the inventors reserve the right to add additional claims after filing the application to pursue such additional claim forms for other aspects of the invention.

1. A network comprising a plurality of local network clusters, wherein each local network cluster includes a plurality of nodes, wherein each of the nodes includes a plurality of communication radios, wherein each of the communication radios supports communication among the nodes of one of the local network clusters so that simultaneous communications are supported among the sensor nodes of the local network clusters, wherein each of the nodes include at least one network discovery and self-assembly module that automatically forms the local network clusters via the plurality of communication radios, wherein the network discovery and self-assembly module determines with which other nodes of the plurality of local network clusters it can communicate.

2. The network of claim 1, wherein each of the nodes further comprise:

at least one time synchronization subsystem that collects timing synchronization information from the plurality of nodes of the local network clusters via synchronization signals communicated among the plurality of nodes of the network clusters; and

at least one acoustic ranging subsystem including two or more microphones and two or more speakers, wherein the acoustic ranging subsystem collects data of acoustic signaling including time-of-flight data to determine a relative location of each node among local network clusters with which the node communicates.

3. The network of claim 1, wherein each of the nodes further comprise a subsystem for providing shared resource access management among two or more applications, wherein the resources include the communication radios, comprising:

a routing module that fuses user space and kernel space of the node; and

a radio driver interface residing in user space of the node, wherein the radio driver interface comprises components including at least one application programming interface and at least one computation component corresponding to each of the communication devices;

wherein the routing module receives radio access requests from the applications and generates and routes calls representative of the received requests to the radio driver interface;

wherein the radio driver interface, upon receipt of the calls, determines radio availability using resource status information received in response to queries transferred among the components;

wherein the radio driver interface generates schedules for granting access to the requested resources in accordance with the status information, and controls access to the radios by the applications in accordance with the generated schedules.

4. The network of claim 1, wherein a first communication radio of a remote node of a first local network cluster communicates among other nodes of the first local network cluster via a first independent channel, and wherein a second communication radio of the remote node communicates among nodes of a second local network cluster via a second independent channel, wherein a link is established among the first and second local network clusters by transferring communication packets between the first and second communication radios, wherein the first and second communication radios support low-latency multi-hop communications among nodes of the first and second local network clusters.

5. The network of claim 1, wherein the communication radios include at least one communication device selected from among radio frequency (RF) devices and radio modems, wherein each communication radio has an assigned radio frequency (RF) address.

6. (canceled)

7. A node comprising two or more communication devices, wherein each communication device supports simultaneous communications among nodes of two or more respective independent network clusters, wherein the communication devices include radio frequency (RF) devices, wherein the node includes at least one network discovery and self-assembly module coupled to the two or more communication devices, the network discovery and self-assembly module configured to automatically form the network clusters via the two or more communication devices and determine with which other nodes of the network clusters it can communicate.

8. The node of claim 7, further comprising a node interface that provides shared access among communication device drivers of the communication devices, the node interface comprising:

a routing module that fuses kernel space and user space of the node; and

a communication device driver interface that couples to the routing module, wherein the communication device driver interface resides in user space of the node, wherein the communication device driver interface comprises at least one application programming interface and at least one computation component corresponding to each of the communication devices.

9. The node of claim 8, wherein the communication device driver interface:

receives calls representative of communication device requests from the routing module, wherein the routing

module generates the calls in response to communication device access requests from applications of the node;

generates queries to determine availability of the requested communication devices;

receives status information in response to the queries;

generates schedules for granting access to the requested communication devices in accordance with the status information; and

provides requesting applications with shared direct access among the requested communication devices in accordance with the generated schedules.

**10.** The node of claim 7, wherein the node includes an Institute of Electrical and Electronics Engineers (IEEE) 802.11 media access control (MAC) sublayer.

**11.** The sensor node of claim 7, further comprising at least one ranging component that determines a location of the node relative to nodes of the independent network clusters with which the node communicates.

**12.** The node of claim 11, wherein the location determination comprises:

receiving timing synchronization information from the nodes of the independent network clusters via synchronization signals communicated among the nodes of the network clusters; and

generating range and angle information to the nodes of the network clusters from time of flight information of acoustic signaling.

**13.** The node of claim 7, further comprising an acoustic ranging subsystem that uses data of acoustic signaling to determine a location of the node relative to nodes of the independent network clusters with which the node communicates.

**14.** The node of claim 13, wherein the acoustic ranging subsystem includes two or more microphones and two or more speakers.

**15.** A method of forming a network, comprising:

establishing a first communication channel among a first radio of a node and a first network of nodes, wherein the first network includes the node;

establishing a second communication channel among a second radio of the node and a second network of nodes;

supporting simultaneous communication among the nodes of the first and second networks via the first and second communication channels, wherein each node of the first and second network automatically determines with which other nodes of the first and second networks the node can communicate;

receiving timing synchronization data from the nodes of the first and second networks via synchronization signals communicated among the plurality of nodes of the network clusters using the first and second communication channels;

receiving acoustic signaling data including time-of-flight data to determine a relative location of each node of the first and second networks; and

determining a relative location of each node of the first and second network using the timing synchronization data and acoustic signaling data.

**16.** The method of claim 15, further comprising designating one node of the first network and one node of the second network as base nodes, wherein each of the base nodes:

collects the timing synchronization data and acoustic data of the nodes for which the base coordinated timing synchronization and acoustic ranging;

generates a relative coordinate table for the nodes for which the base node coordinated timing synchronization and acoustic ranging using the collected data; and

transmits the relative coordinate table to a plurality of neighbor nodes.

**17.** The method of claim 16, wherein each of the nodes of the first and second networks:

receive relative coordinate tables from base nodes with which the nodes communicate;

merge the received relative coordinate tables to form a position table including position information of neighboring nodes.

**18.** A network comprising at least one wired network coupled to a plurality of local network clusters via at least one gateway, wherein each local network cluster includes a plurality of nodes, wherein each of the nodes includes at least two communication radios operating under a first wireless communication protocol that supports communications between the nodes and the gateway and supports communications among the nodes of one of the local network clusters so that simultaneous communications are supported among the nodes of the local network clusters, wherein each of the nodes includes at least one communication radio operating under a second wireless communication protocol that supports communications among the nodes and a plurality of portable wireless devices, wherein each of the nodes includes at least one network discovery and self-assembly module that automatically forms the local network clusters via the communication radios, wherein the network discovery and self-assembly module determines with which other nodes of the plurality of local network clusters it can communicate.

**19.** The network of claim 18, wherein one or more of the first wireless communication protocol and the second wireless communication protocol is an Institute of Electrical and Electronics Engineers (IEEE) 802.11 protocol.

**20.** (canceled)

**21.** A method of forming a network, comprising:

providing a plurality of nodes that each include a plurality of communication radios;

transferring communication signals among at least one set of the plurality of nodes using each of the communication radios so that simultaneous communications are supported among the nodes of the at least one set;

automatically forming a plurality of local network clusters, the forming including each node determining with which other nodes of the plurality of local network clusters it can communicate.