Self-Organizing Distributed Sensor Networks

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ABSTRACT

Advances in CMOS IC and micro electrical-mechanical systems (MEMS) technology are enabling construction of low-cost building blocks each of which incorporates sensing, signal processing, and wireless communications. Collections of these integrated microsensor nodes may be formed into sensor networks in a wide variety of ways, with characteristics that depend on the specific application – the total number of nodes, the spatial density, the geometric configuration (e.g., linear vs. areal), topographic aspects (e.g., smooth vs. rough terrain), and proximity and proportion of user/sink points. The power of these distributed sensor networks will be unleashed by means of their ability to self-organize, i.e., to bootstrap and dynamically maintain organizational structure befitting the purpose and situation that is presented without the need for human assistance. A prototype sensor system and networking protocols are being developed under the DARPA/TTO AWAIRS Program and are described. The current system is capable of self-organizing the communications among nodes so as to bring the initial system on-line via discovery mechanisms, establish needed end-to-end circuits that provide information to and commands from end users, allow new nodes to be added and reconfigure when existing nodes fail, and to quickly evolve so as to achieve these functions via low power operation. Improved network protocols have been designed and simulated that are expected to enhance performance in bootstrap and routing, and these will be integrated into the existing modular system architecture. Self-organizing procedures for cooperative signal processing and resource management are also being incorporated into the AWAIRS microsensor network system.

Keywords: self-organization, wireless, sensors, networks, protocols

1. INTRODUCTION

Rapid technological advances are being made toward developing self-organizing distributed microsensor networks. The essential purpose of such systems is to sense the environment and inform users.[1-5] Use of *distributed* sensor nodes, organized into a system, offers (1) expanded spatial coverage of the environment, (2) fusion opportunities, combining different perspectives, (3) high aggregate intelligence via parallel processing, (4) robust, adaptable and scalable performance via decentralized control, and (5) a dispersed, fault tolerant information base embodied in the nodes, consisting of target detection histories, sensor network system configuration and performance logs, environment characterization (e.g., sensor signal propagation), and user histories. Potentially, users may also be able to interact with the system by establishing a local connection with any node anywhere in the distributed sensor network.

The communications network infrastructure is fundamental to enabling the interaction among sensor nodes to yield improved environment perception and system efficiency, as well as providing information to and disseminating queries and commands from users. The applicability of a distributed sensor network is vastly expanded if a wireless communications medium is used, as this facilitates rapid deployments and reconfiguration in largely unconstrained arrangements. In our research, we have focused on radio-based linkages among the sensor nodes, and this aspect is reflected in the subsequent discussions in this paper. Closely coupled with this is the presumption that each sensor node is self-contained, and in particular carries its own means for power, such as batteries.

The advanced capabilities of a distributed sensor network are achieved by organized behavior among the nodes. Organizational structure is established to enable and/or enhance (1) basic sensing, such as alerting neighboring nodes to awaken due to a new environmental stimulus, (2) cooperative signal processing in which data is exchanged and fused into refined information and decisions, (3) communications network operations in support of both internode and sensor system/user interaction, and (4) resource management, especially the collective energy of the aggregate, in order to maximize the sensor system lifetime. As part of the ongoing research under the AWAIRS DARPA/TTO Program, we are investigating and designing the appropriate organizational form for these various functions, and how these structures must mutually relate to realize a consistent whole. In this paper, we concentrate on the communications networking aspects; however, we do emphasize that integration with these other functions will significantly influence the network architecture and operation.

Self-organization refers to the ability of the system to achieve the necessary organizational structures without requiring human intervention, particularly by specially trained installers and operators. Self-organization is a critical attribute needed to achieve the wide use and applicability of distributed sensor networks. It is also the essence of building the building block; the nucleus that enables an individual node to cooperate with others in order to bootstrap a vital, functional collective. A sensor network, in our vision, will consist of many dynamically interacting entities that give rise to a complex adaptive system. This complex behavior is in fact desirable, providing agility to accommodate unforeseeable situations, and to perceive a complex environment. A conventionally designed system would attempt to suppress such complex behavior (e.g., through centralized organization) so that a human operator could micromanage the system without suffering "information overload." Instead, we envision an architecture that utilizes the proper balance of autonomy within individual nodes, among small collections of nodes (say those prosecuting a particular target), and harmonious compliance to societal protocols of the overall sensor system. Borrowing a phrase from military science, the goal is to imbue the "commander's intent" into the system. In particular, the user should not be burdened with demanding setup, operations and maintenance tasks. However, the network would indicate problems beyond its direct control to completely mitigate, such as weaknesses in sensor or radio coverage or depleted energy reserves, which might require the user to deploy replenishment nodes.

In the remainder of this paper, we describe self-organization procedures associated with the communications network. As was identified in an earlier paper[2], although the sensor system will have wide applicability (e.g., battlespace situational awareness, industrial process control monitoring, condition-based maintenance of equipment), the communications requirements are constrained. For example, while there will be many generators of communications traffic (the sensor nodes), there will be relatively few (perhaps only one) users in the system. Furthermore, when messages are exchanged among sensor nodes such as for cooperative signal processing and synchronization, they will generally be very localized. Thus source-destination patterns (the "traffic topology") will be highly restricted. Also, the latency requirements on the different traffic types will be largely known, as are the expected volumes. While there will be considerable randomness in the sensor network traffic (caused, e.g., by unpredictable environmental events), it will be much more structured than the offered traffic supported by a typical common carrier network (e.g., public switched telephone network or the Internet). This can be used to advantage by organizing the communications network accordingly. The protocols described in the next sections are designed to achieve this organization.

2. SENSOR NETWORK SELF-ORGANIZATION

Several particular aspects influence the organization of the networking that supports the distributed sensor system. One that was already discussed was the constrained set of traffic requirements (source-destination patterns, latency, volume). Also indicated was that a wireless (radio) medium is presumed. This implies that a broadcast/multiaccess medium is used which may be utilized for efficient transport of multicast messages such as fusion or synchronization with neighboring nodes. The range of each radio will be much less than the entire network, so that a multihop (hypergraph) topology will result.

Another aspect is that the sensor nodes are generally assumed to be nonmobile. Robotic or other mobile extensions notwithstanding, our focus is on applications such as a security perimeter or surveillance of a particular choke point. Remote reconnaissance needs might be supported by a sensor array having one or a small number of ports to long range radio relays; in this case the "user" (the long range relay node), from the perspective of the sensor network, is stationary. In some scenarios, the user may be intermittent. A user may reappear at different places (i.e., connect to different nodes). A more demanding case is where users may be itinerant, moving among sensor nodes that hand off the interconnection with the user. Generally, the networking needs for the nonmobile nodes may be quite different from those of mobile users. The procedures described below apply to the sensor node internetworking; the user/network interconnection impact for nomadic users is the subject of active research.

A further critical aspect of the distributed sensor network is that each node will contain its own power source. Typically, this will take the form of batteries; however, energy harvesting methods such as use of solar cells are also possible. In any event, the energy supply to the nodes will be finite and precious, requiring very efficient power management. In fact, we expect that the primary performance measure of the communications system will relate to power efficiency, as opposed to the conventional metric of bandwidth utilization.

The ability for each node and the network as a whole to self-organize will be essential to the success of the microsensor network. Because of the nonmobile nature of the sensor nodes, as well as the finite energy resources (and therefore lifetime) of the nodes, there will be a distinct bootup phase. While radio resources are somewhat "overprovisioned" so that bandwidth is secondary to energy as a design metric, bandwidth is nevertheless not free. Therefore, it is worthwhile to expend energy on a one-time effort to establish a communications link structure among the nodes, supporting long-term circuits. This will optimize spatial reuse, enabling greater network throughput and reduced latency. This aspect significantly alters the problem from that of earlier packet radio research[7-9]. The large attenuation of signal power with distance means that frequencies and time slots can be re-used at relatively short ranges compared to the mean distance between nodes. This fact is what permits a distributed protocol to also be scalable. While node additions and deletions must be accommodated (including "overseeding" the system with new nodes), these events are expected to be relatively infrequent and tolerant of some latency in incorporating the changes in the network population. In the following we discuss aspects of the network bootup.

The efficiency of this organizational process can be heavily dependent on the particular deployment of the network and the degree and accuracy of information that is preprogrammed into the nodes. For example, if all nodes are powered up simultaneously, their attempts to find one another will be subject to heavy contention. However, if this situation is foreseen, the nodes could be preprogrammed to awaken at slightly different times, one by one, so a much more organized startup process is used. The two extremes of "all at once" versus "one at a time" may be differentiated as "network bootup" versus "node entry," but clearly there will be intermediate cases. Our objective is to design a self-organization protocol that will always converge, even if the preprogrammed information is wrong, but will do so more efficiently with accurate prior knowledge embedded in the nodes.

In our system concept, the network is based upon an underlying time division multiple access (TDMA) structure. This is chosen for two primary reasons: to allow nodes to turn their transceivers off when communications are unneeded, and to provide network time synchronization for use in sensor sampling and signal processing (e.g., coherent beamformation[6]). A simplified representation of a TDMA frame, showing functional elements, is given in Figure 1 below.

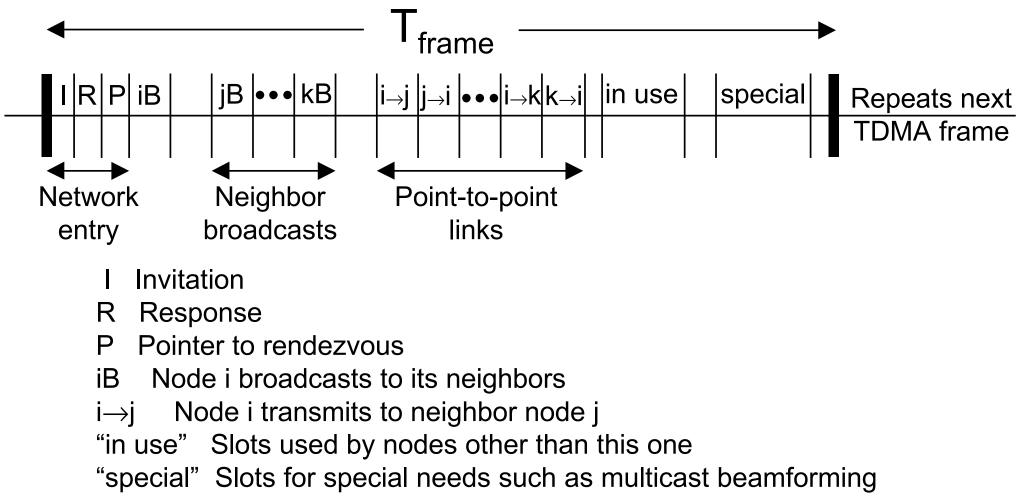

Figure 1. TDMA frame structure (simplified).

Each node has its own view of the world around it, and maintains a database and time base that is its own but is compatible with its community. Figure 1 is the perspective for a particular node, node *i*. There are several general types of time slots that are assigned. These are (1) the network entry/access slots, (2) the node's own broadcast-to-its-neighbors slot, (3) slots for this node's neighbors to broadcast to their neighbors, (4) slots for point-to-point communication between this node and its neighbors (both directions), (5) slots that are assigned for other purposes that do not involve this node but cannot be used by this node (i.e., they are too close for spatial reuse), (6) specially assigned slots for temporary high bandwidth needs, such as beamforming, and (7) all of the rest of the bandwidth, which is currently unassigned and therefore free to be seized for new purposes as they arise.

The basic structure of TDMA is a repeating pattern, as shown in Figure 1. However, the diagram has been simplified as though the different types of slots have the same frequency requirements (reflected by the occurrence of one slot per frame); in fact, they generally will differ. One may generalize the figure by considering a repeating "superframe" within which frames recur at different rates; however, even this can be generalized further. The important thing is that the node knows when and which transmissions and receptions will take place, and whenever new allocations are made, they must be compatible with the existing TDMA structure. The Network Entry slots consist of invitation, invitation response, and pointer (to a rendezvous time for further negotiation) slots. The Broadcast slots are used for several functions, including network synchronization maintenance, announcement of new bandwidth allocation needs, and neighbor query regarding cooperation on a detected target. Similarly, the point-to-point links serve multiple purposes, including specific responses to queries and relaying of traffic. "Special" slot allocations may be created to support multicast groups, i.e., a strict subset of the whole neighborhood but more than one receiver. This latter type will require sophisticated design and implementation, and will not be further discussed in this paper. In general, when a node encounters a slot assigned to it for reception, the node will only keep its receiver on as long as it detects data is present, and not necessarily for the entire slot interval.

A top-level design has been developed for a generic node that specifies the procedural (software) flow from initial power-up through normal network operation. This provides the architectural basis describing the major components and their interfaces. The network self-organization is composed of initialization routines, network discovery, network access, node type announcement, program/command injection/exchange, topology learning and position determination, neighborhood TDMA scheduling, subnetwork merging, traffic determination, routing, network TDMA scheduling, network time distribution, and dynamic circuit establishment/disestablishment. Brief descriptions of these components follow.

- *Power-up node initialization.* Upon power-up, a node will execute a number of initialization routines, such as internal node self-test and health status determination, and built-in calibration. It will also launch any procedures that have been preprogrammed to reflect specific mission requirements and expectations (e.g., begin sampling a particular sensor).

- *Network discovery.* The node then determines whether it can hear an already-operational microsensor network, by listening for invitations to join and possibly "overhearing" other ongoing communications. Normal network operations will provide radio broadcasts of such invitations to discover the network within a bounded time (preprogrammed for this mission), so that if a new node does not hear anything within a prescribed time, it knows the network does not yet exist (i.e., it is the first node, unless it powered up at exactly the same time as another/others). Note that the ability to hear these "discovery" messages may require acquisition of a spread spectrum code. If the node does not hear anything within the network discovery time-out, it will assume that it is the first node, and begin to issue invitations for other nodes to join it. The network bootup latency specification determines the frequency of invitations, which in turn bounds the discovery time-out. Procedures must account for the possibility of multiple nodes entering this state at the same instant, so that they "desynchronize" and find one another. A lone node issuing occasional invitations will only listen for responses in a small fraction of the frame, so that it will deplete its energy resource waiting for newcomers at a low rate. If the lone node doesn't receive a response after a prescribed number of attempts, it reverts again to network discovery mode, possibly after sleeping for some duration.

- *Network entry access.* Once a node hears an invitation to join the network, it transmits a response. It is possible that multiple nodes will hear the same invitation and therefore the responses will randomly access the response time slot or slots. The protocol will incorporate a contention resolution method for this situation. We envision that the frequency of issuing invitations as well as the number of response slots will vary according to the evolution of the network, viz., when the network is at a young age, contention among newly entering nodes will be more likely so that more invitations and response slots will be allocated. Again, this will be mission dependent, based upon requirements on the tolerable latency for the network to bootup and new nodes to be added.

- *Node-type announcement.* Upon hearing the new node's response, the inviting node will establish a TDMA circuit slot within the TDMA frame for further negotiations to take place with the new node. The inviting node will nominally assume responsibility for incorporating the new node into the network, although it is possible that if the inviting node is a bottleneck or its energy reserve is low then it will attempt to offload this task to a neighbor. The invited node is able to determine whether a user, long-range radio or other similar device is attached. The invited node will indicate whether it is a user node or a sensor node. If it is a user node, the process for establishing network-wide communications will be hastened so that time-critical information and commands may be exchanged with minimum delay; if the new node is a typical sensor node, a more resource-efficient but slower process will be used.

- *Program exchange.* If the new node has a message/command/program for the network (e.g., a new signal processing algorithm) then the new information is downloaded/sent and disseminated throughout the network. Similarly, if there is an existing desired state or program for the new node, the inviting node uploads it for execution on the new node. Also, a new sensor node may have a preprogrammed message or program that requires rapid dissemination (such as a command that is sent as a "message in a bottle" rather than directly over the radio).

- *Topology learning and position location.* The new node must next determine its topological relationship in the radio network. A well-known technique for learning the network topology is to allocate a block of **N** slots, where **N** is the maximum total number of nodes, and preassign a slot for each node. The node uses this slot to transmit its understanding of what other nodes it can hear, so that all nodes quickly (within **2N** slots) determine the total topology. There are a number of disadvantages with this approach, including the a priori need to know the upper bound **N**, the need to assign unique ID numbers to all nodes, and the inefficiency of allocating **N** slots since no spatial reuse is possible. While this technique is commonly used in networks having mobile nodes and therefore continuously changing topologies, it is not necessarily appropriate for our situation (since our nodes are spatially stationary). However, in the case where the entire network is being booted up simultaneously, use of this technique may be effective, both for speeding the process and reducing overhead transmissions. Once the network topology is determined for a high proportion of nodes, the topology learning process may subsequently proceed one by one. This corresponds to differentiating between network bootup versus new node entry.

The mechanism for learning the topological impact of a single new entry can fruitfully be interleaved with the position location process for greater efficiency. By incrementally determining position information, the size of the potential radio neighborhood is constricted at each step due to the known range limitations on the radio. Thus certain nodes are known to be outside the region of radio contact/conflict with the new node. This allows the TDMA slots being used for the new node to be freed up for spatial reuse by other nodes, and limits the number of nodes that must participate in connectivity determination. Specific topological linkage is found by exchanging probing messages among the nodes whose connectivity is in doubt. Our nodes will be able to transmit at different power levels; the ability to transmit and receive directionally may also be possible. Clearly the topology is impacted, and the procedures above must be extended to accommodate this.

- *Neighbor TDMA scheduling.* Once the topology surrounding the new node is known, circuits must be established with their neighbors, to exchange periodic information (e.g., synchronization) and to allow rapid coordination on cooperative signal processing and command relaying. TDMA schedules that satisfy these needs are therefore determined. Scheduling for the node to broadcast to all its 1-hop neighbors is expected to be the primary requirement here, as opposed to scheduling point-to-point slots for pairwise links.

- *Subnetwork merging.* The situation can arise where the new node bridges two subnetworks that were previously unaware of each other's existence, and probably operating asynchronously to each other. The new node will join the first subnetwork to issue an invitation, hopefully not significantly disrupting the other subnetwork's operation in the process. After being incorporated into the first subnetwork, the new node will continue to listen for invitations from any such additional subnetworks. If it hears an additional invitation, it will attempt to join that subnetwork as well. Once this occurs, the new node will be responsible for merging the subnetworks; in particular, their timing must be coordinated. Two such subnetworks may not be disjoint; for example, the new node may complete a ring topology where previously the two ends of the network were many hops apart and therefore had significantly different clock phases.

- *Traffic determination and routing.* The new node must inform the rest of the network of its traffic needs. For example, if it is a user node then it will become a destination for many traffic sources. Coupling this information with the existing traffic demands, the radio topology and the resources available in the network (including most importantly the finite energy supply), the routing algorithm will select the appropriate paths through the network. This then translates into link demands. Note that the asymmetry of sources versus destinations causes demand on the links close to a user node to be much heavier than the load on links farther from a user node. Thus there is a critical need for the routing to balance traffic particularly near the sink nodes, using energy as the primary performance metric.

- *Network TDMA scheduling.* The link demand information (including relaying requirements) is then used to form TDMA schedules that support the end-to-end information transport needs of the network. The resulting schedules, as in the neighborhood scheduling case, will provide dedicated "channels" that will be used only as necessary, based on the receive-only-if-something-is-heard protocol. Unlike the neighbor scheduling case, link scheduling (where a node transmits to a single neighbor) is expected to be more appropriate for relaying end-to-end traffic. We intend to perform the routing and TDMA scheduling in two steps. While there may be some gain in attempting to derive an integrated routing and link scheduling solution, we expect that the increase in performance will be offset by the overhead in deriving the solution; the complexity of the problem is formidable even when these processes are decoupled. Again, this is driven by the engineering principle that energy conservation is the primary metric, and operating with a somewhat reduced level of bandwidth utilization is acceptable as long as the radios are "off" when no communications are needed.

- *Normal operation.* At this point in the process, the new node has been integrated into the rest of the network. However, to be a full-fledged citizen, it must also perform maintenance operations (e.g., network time distribution, issue invitations for more new nodes) and must be able to accommodate dynamic communications establishment/disestablishment.

3. RESEARCH STATUS

Prototype Network. A prototype microsensor network has been developed in parallel with our research efforts. The sensor node platform used, together with associated user interfaces and development aids that can support research activities and field experiments, is described in the companion paper in this proceedings[10]. Briefly, the prototype node, called AWAIRS 1, is based on an open, modular design using widely available COTS technology and allows incorporation of a range of sensors. The AWAIRS 1 node consists of a stack of base circuits comprising the processor, radio and power supply, which are coupled with the desired sensors. Board interconnection is provided by two 40-pin mini-connectors that form a system bus that provides power and control lines to the sensor boards, and supports multiple open interfaces such as RS232, SPI and USB. The circuit boards are built from predominantly surface mount components and packaged in a $2\frac{7}{8}$ x $2\frac{7}{8}$ x $3\frac{1}{2}$ enclosure. The software environment consists of the monitor/Hardware Abstraction Layer, the real-time operating system, system applications, and user interface applications. The HAL hides many of the hardware dependencies yet allows access to low level functions such as power control. A real-time, preemptive, multi-tasking kernel has been ported to the processor module that is based on the open source kernel MicroC/OS[11], and designed to run on top of the HAL. Applications such as signal processing algorithms are written in a high level language such as C.

Multiple communications protocols have been implemented on the AWAIRS 1 prototype nodes to support various end user applications. For example, a multi-channel, bandwidth-efficient protocol with selective repeat ARQ has been developed for the explicit purpose of collecting streaming raw sensor data, which is needed for developing cooperative signal processing algorithms. The network protocol of interest here, however, is intended to support the operational sensor network, in which processed decisions (which require low bandwidth) comprise the primary traffic. The protocol is carefully partitioned between the 6502C processor on-board the radio module and the StrongARM microprocessor on the processor board. The radio board processor implements a basic carrier sense random access scheme. It also provides the software control interface to enable the StrongARM to control the transition between states of the radio. In particular, the radio can be placed in idle mode (neither receiving nor transmitting) in order to save energy. The transmission power level can also be adjusted via the StrongARM.

The StrongARM processor, in addition to performing such functions as signal processing and decision-making, performs higher level networking functions. A time-hop code division multiple access capability that effectively allows the network to boot up using asynchronous random access has been implemented. Each node transmits according to a prescribed sequence of time intervals, which it repeats cyclically. This transient condition temporarily consumes relatively high energy because each node is always receiving when not transmitting. Also, packet "collisions" may occur, although bounded latency in access is guaranteed by assigning a unique M-sequence or Gold code to each node. As nodes learn of each other's existence and the time slots they've selected, the active nodes can begin to turn their receivers off when no reception is anticipated. In addition, the nodes can learn to avoid imminent collisions with neighboring nodes. Thus the system evolves to a TDMA network schedule.

A blackboard-based transport/routing protocol layer is also executed by the StrongARM processor. This allows multihop networking, in which messages are relayed through intermediate nodes. The current implementation provides a broadcast capability, i.e., although the physical radio network topology is arbitrary, every node receives all sensor detection information. This is useful for certain cases, such as when users, which use radios with the same protocol, are roaming the network and nevertheless have continuous access to information. In fact, all nodes are allowed to be mobile with this protocol. The protocol uses a two-phase process, in which nodes initially exchange counters that indicate the time of the most recent message (state change). If a node determines that another node's information is older than that represented by the associated counter field, then (and only then) transmission of the data is performed in the second phase. Therefore, if no activity causes sensor information to be generated, transmissions are limited to periodic short counter exchanges, thus conserving energy. Broadcasting of information is generally inefficient for sensor networks, since source-destination patterns are much more restricted, so that most data transmitted ends up being filtered out at the receiver. Protocol extensions that achieve specific routing without extraneous communications are being developed.

In addition to prototype implementations, we have developed more advanced network protocols that have been analyzed by simulations. Two such research activities are briefly described next: a network bootstrap medium access control protocol, and a routing technique designed for low-energy operation.

Network Bootstrap Protocol. An improved low power, distributed, and scalable self-organization protocol has been designed that results in the rapid formation of a connected network, starting from a condition of no knowledge of either the connectivity or timing. The algorithm uses multiple frequency channels and yields joint formation of a time schedule similar to TDMA for bootstrap functions and assignment of channels for pairwise links. A TDMA superframe is defined in which some frames will be allocated for expected network operations, and some to allow for new nodes to join or reconfigurations to take place, with most of the resources available for assignment on demand. The situation in which channel resources are not scarce permits local decisions to be made, with a small likelihood of conflict with decisions being independently made by neighboring nodes. Thus, conflict resolution will be rarely needed, allowing simple distributed algorithms to be devised for managing the traffic.

These same factors enable distributed bootup to take place. As we are not particularly concerned with efficient bandwidth allocation, but may not pass a large number of (energy-consuming) messages to perform bootup, both the topology discovery and primary time/frequency assignment tasks are performed simultaneously using a distributed method. Since no global timing is available, at the beginning, each node spends all its time in random access mode. In this mode it listens for other nodes on a fixed channel. When the first node is found, a two-node network is formed. The network organization starts with the formation of these two-node networks across the field of nodes. We call these initial networks sub-nets. These sub-nets continue to grow as they find new unattached nodes, or merge with other sub-nets. Based on this view, we divide the network organization procedure in three stages: node/node, node/sub-net, and sub-net/sub-net attachment.

Each of these procedures has been implemented in detail in a simulation. We have simulated bootup for networks of sizes ranging from 18 to 150 nodes, with varying degrees of network size compared to radio range. With superframe lengths of 40 slots (each with 10 different frequencies), bootup in all cases was achieved in fewer than 5 superframes, with radios being turned on less than 30% of the time during bootup. That is, within 5 superframes, the network reached its terminal state of connectivity. Moreover, the time to bootup only weakly depended on the size, indicating the potential scalability of the algorithm. An interesting result is that bootup is slowed down when the radio range extends to a large fraction of the network. Use of power control, where we begin at transmitter power levels below the maximum, can actually improve convergence speed in these situations. This is also desirable from the point of view of reducing the probability of intercept by hostile observers during network bootup. We are presently investigating additional scenarios, and working towards implementation on the AWAIRS 1 nodes.

Network Routing. Sensor networks that operate from batteries are different from conventional networks in several ways. They are characterized by a life-cycle proceeding from bootup to maturity to a degraded phase, and finally to network failure and death. Every message that is passed hastens the end of the network. As there will ordinarily be little opportunity for repairing the network beyond deployment of new nodes, the routing protocol is designed to extend the useful life of the network for as long as possible.

In a situation where there are a few long-range radios and a large number of sensor nodes, a primary concern in devising a routing protocol is to enable access (connectivity) to these longer-range nodes to continue for as long as possible, for as large a fraction of the network as possible. The situation is complicated by the fact that management of the routing also consumes energy, and thus there is a trade-off between the frequency of updates of the routing tables (to promote efficiency and provide some fairness in energy use), versus the energy consumed in performing such an update.

We have examined a variety of algorithms via simulation modeling. The most suitable approach from the point of view of robustness and limited upkeep requirements is based on partially overlapping spanning trees. Traffic is routed according to a split-traffic algorithm, which makes choices based on an additive metric related to the energy consumption on the route, and the energy reserves along the different paths to the destination. A fairly low update rate is required, and given the variety of paths to the end destination, time is available to build alternative routes in response to node failures.

We are presently investigating low-energy approaches to forming ad hoc networks for exchange of information for such purposes as data fusion and distributed beamforming. In contrast to the global problem outlined above, information will be exchanged only among a relatively small number of nodes geographically proximate, and for a limited duration in time. However, the quantity of traffic may be quite large. We must trade the resources required to set up the sub-network against the efficiency of data transfer.

4. CONCLUSION

Wireless distributed sensor network technology will provide a bridge between the physical world and the exponentially growing information infrastructure. An essential enabler for these systems to be capable of facile deployment, commissioning and operation with no or limited human assistance. We have described general properties of self-organization as applied to communications, signal processing, and resource (e.g., energy) management in distributed sensor networks. The paper focused on self-organization as applied to the communications network. A collection of procedures for network creation has been described, including network discovery, network access, topology learning, TDMA scheduling, subnetwork merging, traffic determination, and routing. A prototype distributed sensor network has been developed and implements many of the self-organizing protocols that were described. Additional ongoing research in design of low power network protocols and their performance analysis via simulation was also presented.

Wireless distributed sensor networks are ideal examples of complex adaptive systems in which emergent behavior is expected. For example, the ability for a large collection of nodes to track a moving target involves intelligence far greater than that of an individual node. While individual nodes are constructed with relatively simple hardware and behave according to relatively simple rules, the synergy from their interaction promises to yield higher levels of sensor system functionality. These types of network systems will eventually be capable of evolving and adapting to many varied scenarios as the underlying software technology is advanced. New distributed software services are needed to implement embedded algorithms and to allow users to easily access and task the sensor network. Designing and verifying that the distributed system will achieve desirable organizational structures will require sophisticated systems analysis methods.

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