Performance Of A Novel Self-Organization Protocol For Wireless Ad-Hoc Sensor Networks

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Abstract- The paper presents an ad-hoc architecture for wireless sensor networks and other wireless systems similar to them. In this class of wireless system the physical resource at premium is energy. Bandwidth available to the system is in excess of system requirements. The approach to solve the problem of ad-hoc network formation here is to use available bandwidth in order to save energy. The method introduced solves the problem of connecting an ad-hoc network. This algorithm gives procedures for the joint formation of a time schedule (similar to a TDMA schedule) and activation of links therein for random network topologies.This self-organization method is energy-sensitive, distributed, scalable, and able to form a connected network rapidly.

I. INTRODUCTION

As a result of advances in MEMS and IC technologies it is possible to combine sensors, radio transceivers, CPUs and signal processors on a single IC. So it is now conceivable to combine remote sensing with remote actuation, and connect the physical world to the existing data networks [1]. In this framework two issues arise. One, that of architectures for the sensor networks themselves, and the other of the problem of linking such networks to the existing data and communications infrastructure. This paper is concerned with the architecture of the wireless sensor network itself. The interesting issue here is that the characteristic system requirements and physical limitations of a wireless sensor network are quite different from those of existing data and communications networks, and therefore call for new systems level solutions [2].

The physical resource at premium in these systems is energy. Bandwidth available to the communication system is in excess of system requirements, therefore it need not be aggressively managed. Our system is real-time, that is, a bound exists on the maximum delay that is tolerable. However, this delay requirement translates to a much smaller bandwidth requirement than is available. This is due to the fact that, instead of raw data, typically we will transport information about the physical world; information that has been extracted from raw data [2].

The most general case of a wireless sensor system includes a number of wireless nodes (anywhere from tens to hundreds of nodes) which are battery operated and are placed randomly in an unknown environment. Since a single radio transceiver exists on each node, it is only able to either transmit or receive at a time. The radio range is small, on the order of a few tens of meters. This topology may have access to one or more gateway type nodes which are also members of an existing high-speed network and may be mobile themselves [2]. These nodes are responsible for connecting the sensor network to the outside world. The sensor nodes in this system are responsible for organizing an ad-hoc multihop wireless network. This task must be performed with a limited energy source and without human supervision. We propose a novel method for self organization of ad-hoc wireless sensor networks. This algorithm gives procedures for the joint formation of a primary conflict free time schedule (similar to a TDMA schedule) and activation of links therein.

The rest of this paper is organized as follows: Section II gives a more precise description of the system architecture and related background information. In section III the network organization algorithm is described in detail. Section IV gives some simulation results about the performance of the self-organization algorithm. Section V concludes the paper.

II. BACKGROUND INFORMATION

In our system, nodes communicate with neighbors intermittently, and their radios, which are a major energy consumer, need not be turned on at all times. This fact leads to TDMA as a natural choice for channel access method.

The nodes in this network must establish links with others in relatively small neighborhoods to perform collaborative signal processing tasks such as beam-forming [2]. In addition they will be used as relays in a multihop network to transport long dis-

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tance data across the entire network. The local networks of which a node is a member change in time, and need to be built and rebuilt on the fly. Therefore the entire bandwidth available to each node must be constantly managed.

Since the system is not a centralized network the notion of network wide synchronization is meaningless and thus a single TDMA schedule does not exist. Nevertheless to describe the bandwidth allocation in this system an abstraction of a "super frame" is introduced. This "super frame" is similar to a TDMA schedule, whose structure could change from epoch to epoch. Figure 1 gives a diagram that describes the vision of bandwidth allocation for our system

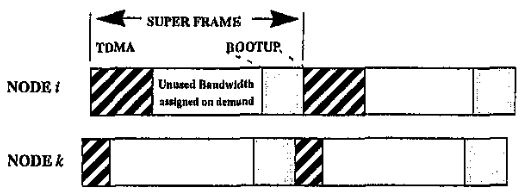

Figure 1. Frame Structure

General Requirements

Our algorithm must be scalable, i.e. the methods must not be limited by the number of nodes. In this respect, our solution will build non-hierarchical network topologies that are as flat as possible. Message passing in this environment is highly costly, therefore few messages must be passed. Hence the algorithm relies only on local, i.e. one-hop away, data. The flat architecture and reliance on local data only, imply highly distributed procedures as well.

Related Work

Self organizing networks have been previously considered in mobile packet radio networks, such as those described in [3-7]. The scope of these solutions are however different from ours. There, multimedia traffic, mobility, high power radios, and possibly separate signalling channels are present. The algorithms investigated generally assume an initial level of organization, in the form of network wide slot synchronization. Given this, the algorithms proceed to assign slots to links, and maintain these assignments as network topology and traffic demands change with node mobility.

Our problem in contrast is concerned with an even earlier condition, which is the formation of this early "skeletal" time reference. We assume, no mobility (sensor nodes do not move), one slot per link per direction and limited node energy.

Resource Allocation

In order to understand any network organization algorithm, it is necessary to clarify the format of the desired organization. To this end, a brief description of the MAC layer issues of this network will be provided in this section. As mentioned earlier, the medium access will be a type of TDMA, where the contents of the "super frame" may vary from epoch to epoch. Various sub-frames, or members of the "super frame" are allocated to different tasks, as shown in Figure 1. In a fully functional network, a node will spend a portion of time in communication with others in a TDMA mode to exchange local control and house keeping data, marked as TDMA in the diagram. There is also a period where nodes engage in a random access mode to search for new nodes to absorb in the network, or rebuild severed links. This is called the BOOTUP period. There will be excess bandwidth available in each "super frame" which is used to build local networks dedicated to specific tasks for short durations of time. The TDMA mode will be used to allocate bandwidth in this period.

Interference Mitigation

Our system will not operate under centralized control. Therefore it is impractical, in terms of the amount of energy needed, to align slot boundaries for all nodes. In addition, the network organization algorithm is greedy in the sense that at the time of formation of each new link, the first time interval during which both nodes are free (neither transmitting or receiving) is assigned. This assignment occurs regardless of the possibility that there may be other links in the vicinity of this link which may conflict with it.

Due to these two conditions, links could experience some interference from other links. To mitigate this self-interference, there will be made available a number of separate channels to the entire system. At the time of establishment each link will choose at random one of these channels. A channel could take the form of a frequency or a spreading code. The success of this approach hinges on the assumption that a large number of such channels are physically available.

Two facts are in favor of this assumption. First is the fact that self interference has local scope. Since radio ranges are not large (after all nodes have limited energy), any given radio will have a relatively small footprint around it as far as radio interference is concerned. Beyond this footprint, the channels which are used by this node will be available for reuse. The second fact is that system bandwidth requirements are less than the actual bandwidth available. This is true because of the nature of observation data (sensor data is distilled locally and only information about the physical world is transported). Also, because of recent advances in RF circuit design, it will be possible to use on our nodes, high bandwidth radios which consume extremely low energy levels.

III. NETWORK ORGANIZATION ALGORITHM

The aim of the self organization protocol is the formation of a multi-hop wireless network in a distributed fashion with little energy usage. In order to do this, a) information about the network topology, and b) some organization in time, frequency, or code space among nodes, must be obtained.

Several methods for formation of ad-hoc wireless communication networks have been investigated, as described in [3][5][7]. In these methods the network discovery phase and resource allocation are performed separately and periodically and all assume an existing slot synchronization. In [4] formation and reformation are done concurrently, but prior network time reference is assumed.

Typically a number of messages are exchanged either locally or throughout the entire network to first determine the topology. Next, bandwidth is assigned to links using distributed or centralized algorithms. Since we do not even have a basic slot synchronization to begin with, the energy cost of network-wide sync establishment, topology discovery and resource allocation in separate stages will not be acceptable. The solution proposed in our algorithm is to combine the "topology discovery" and "primary time/frequency assignment" phases, without centralized synchronization. This approach may result in less than optimum bandwidth allocation. However since bandwidth is not a premium, we will accept this in exchange for energy savings that result from passing very few messages. The other key idea behind our self organization protocol is that the behavior of the node changes with time, and the level of information it acquires about its immediate vicinity.

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 of: node/node, node/*sub-net*, *sub-net*/*sub-net* attachment.

The core of our self organization algorithm is comprised of the definitions of procedures that control node behavior in each stage. A short description of these procedures follow in the next section. Further details of the protocol may be found in [9].

Assumptions and definitions:

The operation of each node is done under various modes, each mode corresponding to one of the "super frame" sub-frames. For now we assume there are only two modes, and focus our attention on the BOOTUP and TDMA modes. In BOOTUP the node operates in a random access fashion and searches for, and attaches to new nodes. In TDMA mode, following its own local schedule, the node goes through a sequence of transmission and reception bursts.

Each node upon power up enters the BOOTUP mode. Then it listens on the radio channel to see if any neighboring nodes are sending an invitation message. If so, the node responds to it, and if it is chosen by the inviter, a simple handshake follows, where nodes exchange their connectivity information and channel use decisions. If the node does not hear an invitation within a certain window, it will then initiate transmission of an invitation and will listen to hear a response. There is a possibility of collisions among incoming responses if more than one node hears the invitation. For this reason the responding nodes choose at random one of K possible time intervals immediately following the invitation to send their responses. The inviter node will repeat this procedure until either it hears a response or another node's invitation.

The content of the handshaking messages, and the behavior of the node in receiving them depends on whether the node is already attached to other nodes or not. After successful attachment between any two nodes, if both were previously unattached, a new TDMA schedule is formed. Otherwise existing schedules will be modified. The nodes will then spend time in both BOOTUP and TDMA modes. Details of BOOTUP and TDMA modes are given in [9]. The state machine describing the protocol behavior is outlined in figure 2.

IV. SIMULATION RESULTS

We are interested to determine the time it takes until a given set of nodes becomes connected and also to determine energy levels used to achieve this.

The latter parameter is dependent on the specific hardware used. However a good measure of the performance of the algorithm, is the average duration of time a node radio is powered up until network is connected.

The algorithm was simulated in PARSEC. PARSEC is a parallel discrete event simulation environment and is derived form MAISIE [8]. Here, the results of the self -organization algorithm for a network of 18 randomly placed nodes are given. The radio range is set to be 2 units of distance. Node separation is at most 8 units of distance. The "super frame" has length of 40 slots, and there are 10 different frequency channels available. The channel search during BOOTUP is done on a frequency band different than these 10 frequencies. Nodes wake up at random times, which are distributed uniformly over [0, $T_{sup}/2$), where T_{sup} is the length of "super frame". Figure 3 gives the network topology for this example. The diagram shows the network at the time when the network has just become connected.

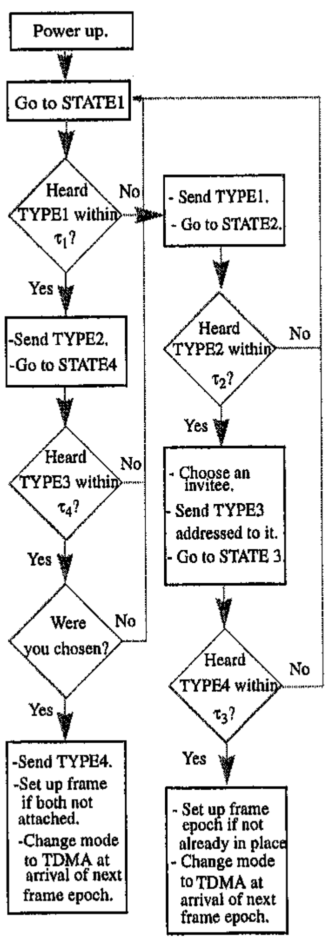

Figure 2. BOOTUP state machine.

The self-organizing algorithm is able to form a connected network in $3.34*T_{sup}$. Node radios, on average, were turned on only during 30% of this time, equivalent to $1.00*T_{sup}$. In Figure 4 the node schedules are given for this example. Here only the contents of the portion of frame structure corresponding to the TDMA period are given. It is interesting to note that nodes in this network have formed themselves into five disjoint sets. Each set corresponds to a different time reference. The frame epochs for these are marked in Figure 4. Also note the excess bandwidth which is still available in the TDMA portion.

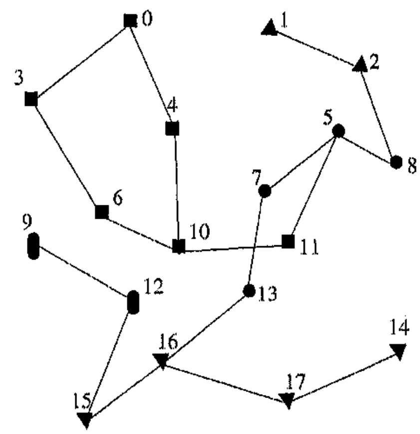

Figure 3. Self organized network with 18 nodes.

As a qualitative comparison, here we give the results for network formation for four different networks. Table I gives these results for four networks of 18, 45,100,150 nodes. Note that the time until network is connected does not vary significantly as numbered nodes is increased. In all these networks, the node density does not change. The results hint at the scalability of the algorithm.

Table I. Time until network is connected

Number of nodes	Time until network is connected (FRAMES)	Average percentage of time radio is powered until network is connected
18	3.34	30.0
45	3.44	13.0
100	3.49	12.9
150	4.52	23.2

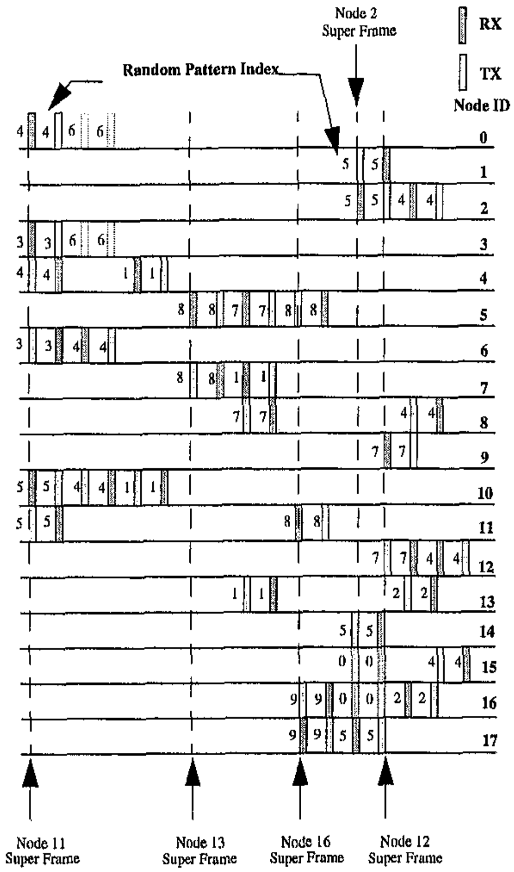

Figure 4. TDMA structure of the 18 node network.

V. CONCLUSIONS

The self-organizing algorithm is described. A simple example illustrated the operation of the algorithm and the type of organization achieved. Based on early simulation results, there is strong indication that under the right conditions the algorithm performs in a scalable fashion. This behavior can be explained intuitively. There is a local neighborhood size associated with each network. The network formation occurs in these local neighborhood in parallel. Once the local neighborhood is connected, the entire network becomes connected.

The size of this neighborhood depends on the total number of channels available to the system and the channel re-use distance.

The results given are preliminary results of a work in progress. The authors are currently investigating the relationship between the size of the available channel space and the time and energy needed to connect the network, by means of simulations.

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