Energy-Efficient Protocols for Wireless Communication in Biosensor Networks

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Abstract—**Advances in semiconductor technology have made it possible to build miniature but reliable biosensors. A network of such biosensors can be implanted in humans for health monitoring and prosthesis. However, such networks are fundamentally different from other wireless networks. They have a continuous but very small source of power. This energy constraint necessitates the use of highly energy-efficient communications protocols. We present two such protocols in the context of a biomedical application we are working on, namely, retinal prosthesis. Our first approach is a cluster-based protocol in which only a small fraction of the nodes make expensive long distance transmits to the external base station. Our second approach is a tree-based protocol. We also analyse the energy efficiency of these protocols while varying parameters such as number of nodes in the system and distance between nodes. Our analysis shows that the cluster-based protocol has better energy performance.**

Keywords: network protocols, energy efficiency, wireless LAN, embedded sensors, biomedical applications

I. INTRODUCTION

A significant number of people have poor or no vision because the rods and cones in their retinas have degenerated. However, the ganglions in the eye may still be alive and may be excited artificially to create a sensation of sight [1]. We intend to stimulate these nerve endings by using a network of biosensors. These biosensors receive commands from an external processor regarding the timing and intensity of the stimulation. The processor itself makes decisions after processing images it receives from a camera placed on the patient's goggles (Figure 1). The biosensors also have the added responsibility of sensing conditions in the retina and transmitting a feedback to the external processor.

A wired network is not suitable for placement in the human body. Laying the wires and connecting the nodes entails extensive incisions, a potentially hazardous and time-consuming task. On the other hand, a wireless network is easier to put in place. Hence we rely on wireless communications between the external processor and the sensors, and amongst the sensors themselves. It is also desirable to have a wireless source of power. In our work, we have an IR beam supply a small but constant power to the biosensors. It is however important to keep the power supplied by this beam as low as possible for two important reasons: the power dissipated by the IR beam will warm up the surrounding tissue, and the IR beam itself is powered by a portable battery pack carried by the user. It is therefore imperative that we develop a communication protocol that consumes minimal energy.

In this paper, we present, analyse and compare two communications protocols that are designed to reduce energy consumption. In our cluster-based protocol, we work on the idea that energy consumption can be reduced by stipulating that only a small fraction of the nodes are allowed to communicate with the base station. These nodes are called leaders and each leader is in charge of data from a cluster of nodes around it. Each leader collects data from nodes in its cluster, compresses the data to eliminate redundancy and transmits the compressed data to the base station. This method is similar to the LEACH protocol proposed by Heinzelmann et al [6]. In their study, the authors had assumed that the system had a limited and non-renewable source of energy, and in which nodes died as the energy level fell. Their motive was to increase system lifetime and this was achieved by dynamic clustering of nodes. However, this is not an issue for biosensor networks as they will be provided with a continuous source of energy. Hence our sole concern is that of reducing energy consumption. Our static clustering approach has two major advantages:

- Data is compressed at the source and hence only relevant data is transmitted to the external processor; and
- Only a small subset of the nodes make a long distance transmission and hence energy is conserved.

In our tree-based approach, energy is conserved as no expensive long distance transmits are done to the base station. Instead, all data is passed along a tree structure that is familiar to wired networks. Here again, data compression can be done at several layers.

We observe that energy can be conserved by reducing or eliminating medium access contention. An interesting fact about our biosensor network is that the communications pattern is deterministic and periodic. Each node has to transmit its data once in 250ms. This leads us to adopting a fixed TDMA method at the MAC sub-layer. A TDMA scheme has the added advantage that nodes can sleep when they are not sending/receiving data. This leads to less power usage and extended battery life. Here we have adapted a generic version of the Multilevel-Multiaccess channel reservation protocol. This protocol is used for both subscription to a cluster and for scheduling TDMA slots to individual nodes.

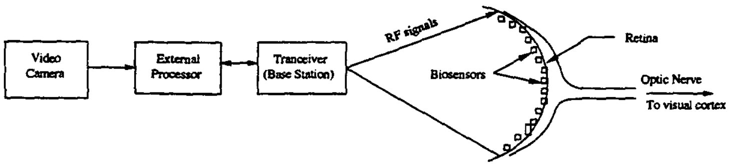

Fig. 1. **System Model.**

In the next section we give a brief overview of related work. In section III we describe our system model and the underlying assumptions. We also describe the energy model that we have used in our analysis. In section IV we describe the two energy efficient protocols and provide the algorithms. We then analyse these protocols in section V. We present the results of our performance analysis in section VI.

II. RELATED WORK

Biosensor networks are fundamentally different from other sensor network applications [2]. There are several issues involved here including low power availability, limited computation, continuous operation, robustness and scalability.

A number of research groups have been studying sensor networks. Although these sensor networks do not match the requirements for biomedical sensor networks, a brief review of some of this work is included for completeness.

Byers and Nasser [3] have proposed dividing the sensors into different types to reduce power usage. Some sensors are used for communication and others for the sensor application. Heinzelman et al. [6] have proposed using clusters of sensors and rotating the cluster head to equalize power usage among sensors and extend sensor life. Bhagwat et al. [5] propose emphasizing battery lifetime and cost over maximizing wireless bandwidth efficiency. None of these models are directly applicable to biomedical sensors applications as described in this paper.

Some recent work [7], [8], [9] has also examined improving power efficiency through topology control. In these papers, however, the authors have focused on adjusting the transmission range, and hence the topology, for a mobile network.

Another interesting research effort on creating extremely small and low-power sensors is the Smart Dust project. This work is not directly applicable to biomedical sensors, however, because optical transceivers are used for communication. Optical transceivers require a line-of-sight path between transmitter and receiver and hence are usable in implanted devices.

Estrin et al. have proposed a communication model called directed diffusion for scalable co-ordination in sensor networks [4]. This paper motivates the need for tightly integrating the routing functions with the application. Such approaches would also be useful for biomedical applications.

Some of the issues involved in designing communication protocols for wireless communication within human body are addressed in Personal Area Networks (PANs) research. A PAN enables data communication between electronic devices on and near human body by capacitively coupling picoamp currents through the body [10].

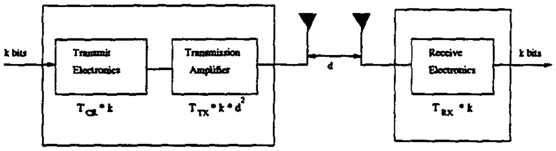

Fig. 2. **Radio Model.**

III. SYSTEM MODEL

Our system consists of an array of biosensors implanted behind the retina. Each biosensor (henceforth called *node*) not only has the function of stimulating the ganglions, but also to gather data and provide feedback to the external processor via the external transceiver (henceforth called the *base station*). Since the placement of nodes in the body is predetermined and fixed, we assume that the base station is aware of the positioning. All communication is wireless. TDMA is used for media access and we assume that all nodes are perfectly synchronized and are aware of the beginning of each slot. We have a system with N nodes. Each node collects and transmits data R times a second.

The body is mostly composed of water and water absorbs much of the radiation. However, since the nodes are very close to each other, we adopt an r^2 energy loss model. We have assumed that for an acceptable signal-to-noise ratio, the transmitter requires 100 pJ/bit/m^2. Further, the transmit and receive circuitry dissipates another 50 nJ/bit. Thus we have the following:

- Reception circuitry cost per bit, T_{RX} = 50 nJ/bit
- Transmit amplification cost per bit per square meter, T_{TX} = 100 pJ/bit/m^2
- Transmission circuitry cost per bit, T_{CR} = 50 nJ/bit

The radio model is shown in figure 2.

IV. PROTOCOLS

In this section we present two protocols, the cluster-based and a tree-based. Both protocols rely on a TDMA MAC sublayer.

A. Cluster Based Approach

In our first approach, we work on the idea that energy consumption can be reduced by stipulating that only a small fraction of the nodes are allowed to communicate with the base station. These nodes are called *leaders* and each leader is in charge of data from a cluster of nodes around it. As shown in figure IV-A, each leader collects data from nodes in its cluster, compresses the data to eliminate redundancy and transmits the compressed data to the base station.

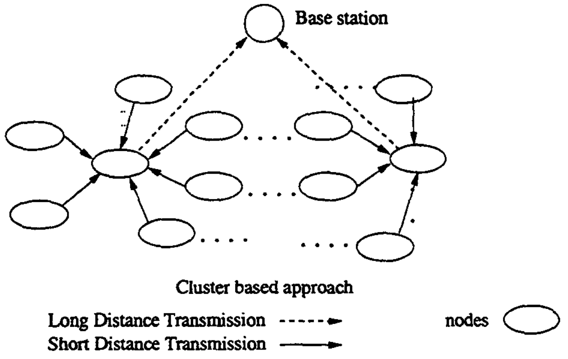

Fig. 3. **Cluster Based Approach.**

There are several issues involved here. First, we must have some way of deciding which nodes should be leaders. Second, the remaining nodes should join a cluster. How does a node decide which cluster to join?

It is our opinion that since the location of the sensors are predetermined and fixed, and only the base station has global knowledge about the system, it is best for the base station to nominate the leaders. If we allowed leaders to be elected probabilistically, there is a good chance that an elected leader may not be the best choice. For example, the leaders may not be evenly distributed throughout the network and several of them may be from the edge of the network. On the other hand, the base station has global knowledge of the system and is in a better position to nominate leaders. For example, while deciding leaders, the base station can take into consideration the node concentrations and allocate more leaders in denser areas and less in sparser areas. It can also take into account various other factors such as cost of communications etc. and improve overall system performance by choosing an optimal number of leaders with optimal positioning.

Once the leaders have been nominated, each node in the system has to decide on which cluster to join. In our scheme, all leaders transmit a signal concurrently but at different frequencies. The frequencies can be allocated by the base station. Every non-leader node in the system scans all the frequencies and identifies the one frequency that offers it the best signal-to-noise ratio. The node then joins the cluster represented by that frequency.

To join a cluster, the node has to inform the leader of the cluster about its intent. But there is a possibility that several nodes send their join requests at about the same time. This will cause a collision. To avoid such collisions, we adapt the Multilevel-Multiaccess protocol that was originally developed for channel reservation. In this scheme, nodes transmit a binary one in slots corresponding to their address. The added advantage of this scheme is that all nodes in that cluster will know which other nodes have joined and in what order.

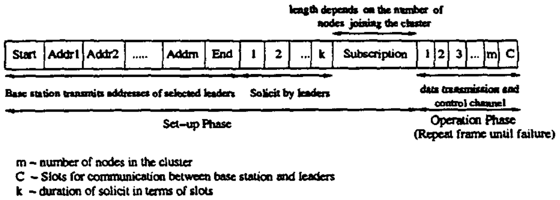

Fig. 4. **TDMA scheme for cluster-based protocol.**

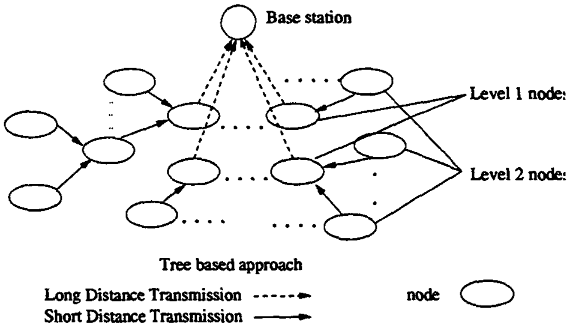

Fig. 5. **Tree Based Model.**

After clusters have been formed, nodes in each cluster will have to send data to the leader of that cluster. Here again, there is possibility of collisions if the media is not regulated. To avoid this problem, we propose to use TDMA. Each node in the cluster will be allocated a slot in a frame. The allocation need not be explicitly done as we can simply follow the order in which the nodes joined the cluster. As we stated earlier, each node is aware of who joins the cluster and when, and hence each node is aware of its position in the frame. Once the leader collects data from all the nodes in its cluster, it can compress the data and transmit it to the base station. The TDMA frame structure for the cluster-based approach is shown in figure 4.

B. Tree-based Approach

In our second approach, we reduce the number of long distance transmissions by having nodes send their data to the base station along a tree structure that has the base station at the root (figure 5. The base station selects one or more nodes to be its children based on factors such as their proximity to itself, and node densities across the system. Each of these selected nodes then makes a low intensity transmit, each node at a different frequency. Nodes that can receive this transmit at a predetermined minimum signal-to-noise ratio can then request the transmitting node to be its parent. To make this request, the prospective children will have to use the subscribing protocol we mentioned earlier. Once the children have selected their parents, it is their turn to solicit children. This continues until all nodes in the system are covered.

By following the above method, we will obtain a spanning tree for the network. When a node wants to send data, it will send it to its parent node by a low-energy transmission. The parent will collect data from all its children, compress the data if required and in turn transmit it to its parent. Only the children of the root node (base station) will be required to make the high energy transmit to the base station. The TDMA frame structure for the scheme is given in figure 6.

V. ANALYSIS OF THE PROTOCOLS

In this section we will analyse the energy requirements for these protocols. Let us assume that the network has N nodes

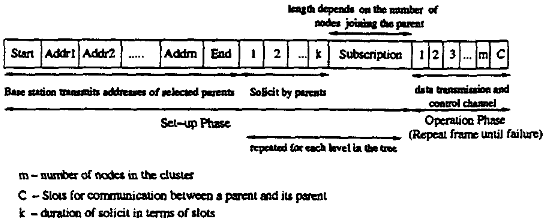

Fig. 6. **TDMA scheme for tree-base protocol.**

of which the base station chooses n nodes to be leaders. There will be n clusters. To simplify the analysis, we assume that the nodes are evenly divided amongst the n clusters. Therefore each cluster will have N/n nodes.

A. *Cluster-based Protocol*

1) Network Setup Phase: In this section we analyse the power requirements during the system setup phase. First, the base station has to transmit a list of leaders and during this period, all nodes will have to switch their receivers on. This transmission will be of length n+1 slots as n slots will be required to transmit the addresses of the n leaders and 1 slot will be required to indicate the end of transmission. Hence the cost of selecting the leaders, per node, will be $T_{RX}(n+1)b$, where b is the number of bits in a slot.

Next, the nodes have to subscribe to the clusters. Here, the leaders will have to make an initial transmission, say of k slots, so that nodes can monitor all frequencies and decide which offers the strongest signal. Once each node has identified its channel, it will have to subscribe to the corresponding cluster. From the subscription scheme mentioned above, we observe that the total number of slots required for all nodes in a cluster to subscribe is dependent on the total number of nodes in the system, the spacing in the addresses and on the radix of the scheme itself. In our initial study, we assume the best case in which all the addresses are closely packed. For such a case, the total number of slots required for x nodes to join a cluster is given by:

$$r(d-p) + \sum_{i=1}^{p-1} r^i + \lceil \frac{x}{r} \rceil r \qquad (1)$$

where r is the radix, d is the number of digits in the address and p is the number of digits in the address that vary.

In our study, we took the total number of nodes as 1000 (000-999) and assumed a radix of 10 for the scheme. If there are N nodes in the network and n clusters, x in equation 1 will be $\frac{N}{n}$. Further, we made the assumption that the addresses of nodes within a cluster did not vary in more than two digits i.e $p = 2$. Therefore the total number of slots is $20 + \frac{N}{n}$. The amount of energy expended per leader will be:

$$P_{Leader} = kb(T_{TX} + T_{CR}) + (20 + \frac{N}{n})bT_{RX} \qquad (2)$$

Each node has 3 digits in its address and hence will transmit 3 times. It will however have to receive for the entire duration of the subscription phase. The energy expended by a non-leader will be:

$$P_{nonleader} = kbT_{RX} + 3b(T_{TX} + T_{CR}) + (20 + \frac{N}{n})bT_{RX} \qquad (3)$$

In the above equation, the number of bits per slot, b, can be set to 1 as each node needs to transmit only 1 bit during a slot. k is the number of slots a node takes to scan all the available frequencies in order to identify the cluster head offering the best signal-to-noise ratio.

2) Network Operation Phase: In the normal operation mode, each node in the cluster makes a transmission to the leader during its slot. Each frame will have $\frac{N}{n}$ slots for this purpose. Further, there will be one slot for the control messages. If the frames are repeated R times a second, we have:

$$N_{RX} = \text{number of receives per second} = (\frac{N}{n} + 1)R \qquad (4)$$

$$N_{TX} = \text{number of transmits per second} = R \qquad (5)$$

The power consumed by the leader for transmission and reception will be:

$$P_{RX_{Leader}} = N_{RX}T_{RX}b \qquad (6)$$

$$P_{TX_{Leader}} = (N_{TX}b(\frac{N}{n} + 1)\alpha)(T_{TX}T_{CR}) \qquad (7)$$

where α is the data compression ratio.

The total power consumed by the leader will be:

$$P_{Leader} = P_{RX_{Leader}} + P_{TX_{Leader}} \qquad (8)$$

Each non-leader node will transmit during its slot and receive during the control slot. This will be repeated R times a second.

$$P_{nonleader} = (T_{TX} + T_{CR} + T_{RX})bR \qquad (9)$$

The total power spent by the network will be:

$$P_{Total} = P_{Leader}n + P_{nonleader}(N - n) \qquad (10)$$

B. *Tree-based Approach*

Here again we assume that there are N nodes in the system. Let the number of levels in the tree be L.

1) Network Setup Phase: After the base station selects its children, those children in turn select their children. Each of the parents will have to make a transmit to solicit children. All nodes will then have to keep their receivers on during the subscription. Lets assume that the solicit transmission takes k slots. After this, subscription starts. Here, we assume that the number of nodes subscribing is very small and hence we suggest binary radix for the subscription protocol, We can calculate the number of slots required from eq 1 given in section V-A.1. Thus, the energy required by each parent is,

$$kb(T_{TX} + T_{CR}) + T_{RX}b(2(d-p) + \sum_{i=1}^{p-1} 2^i + \lceil \frac{x}{2} \rceil * 2) \qquad (11)$$

where x is the number of prospective children. Energy required by the children is,

$$T_{RX}kb + 2(d-p) + \sum_{i=1}^{p-1} 2^i + 2\lceil \frac{x}{2} \rceil + T_{TX}b \qquad (12)$$

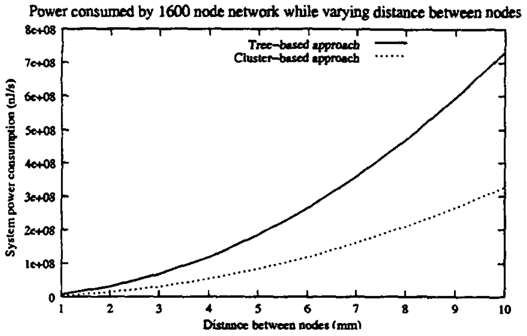

Fig. 7. **Power Consumption vs distance between nodes.**

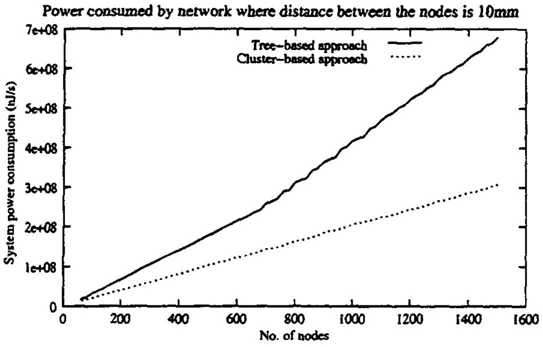

Fig. 8. **Power consumption vs. number of nodes in the network.**

2) Network Operation Phase: Once the tree structure has been set up, the nodes can start sending data. Let us consider the case of a node having x children. The node will have to receive data from all x children, compress the data and transmit it to its parent R times a second. Let α_i be the data compression ratio at level i of the tree. Then we have the power consumed for a node on level i as:

$$P_{node} = (T_{RX}xD + (T_{TX} + T_{CR})\alpha_i xD)R \qquad (13)$$

where D is the number of data bits each child transmits. Here we should note that the the value of D will increase as we move up the tree. This is because the amount of data routed through a node is directly proportional to the number of nodes downstream. The total energy consumed by the network will be the sum of energy consumed by the individual nodes.

VI. RELATIVE COMPARISON

We wrote simple C programs to estimate the power consumptions of the two protocols. We observed that the power consumption depended on (a) Number of nodes,(b) Percent of clusters, (c) Loss factor, and (d) distance between nodes. The value of parameters used is shown in Table 1.

TABLE I

Parameters and their values used in the performance analysis.

Parameter	Value	Parameter	Value
T_{TX}	100 pJ/bit/m^2	α	0.5 - 1
T_{RX}	50 nJ/bit	N	50-1600
T_{CR}	50 nJ/bit		

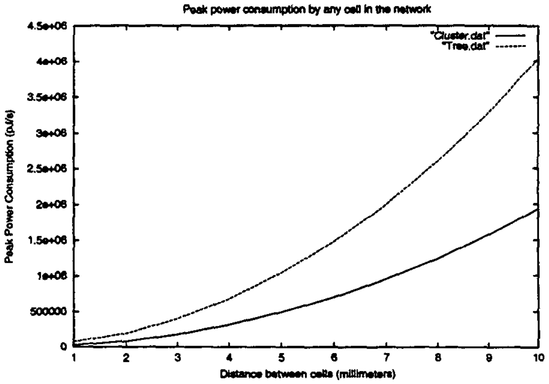

Fig. 9. **Peak Power Consumption vs distance between nodes.**

From figures 7,8 and 9, it is apparent that the cluster-based scheme is more energy-efficient than the tree-based scheme. We attribute this to the fact that in the tree-based scheme each data packet passes via several levels of the tree and transmission/reception costs are incurred at each level. The cost of such multihop routing then becomes greater than the cost of single-hop routing that is present in the cluster-based scheme.

VII. CONCLUSIONS

We have seen that energy efficiency is of utmost importance in biosensor networks. In this paper we presented two energy efficient communications protocols and analysed their performances. On comparison, we found that the cluster-based approach offered better energy efficiency. We now intend to simulate the two protocols using *ns*-2 to obtain a more accurate comparision. We also intend to study the effect of applying these protocols in an hierarchical manner.

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