International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:2, No:12, 2008

Practical Applications and Connectivity Algorithms in Future Wireless Sensor Networks

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Abstract**—**Like any sentient organism, a smart environment relies first and foremost on sensory data captured from the real world. The sensory data come from sensor nodes of different modalities deployed on different locations forming a Wireless Sensor Network (WSN). Embedding smart sensors in humans has been a research challenge due to the limitations imposed by these sensors from computational capabilities to limited power. In this paper, we first propose a practical WSN application that will enable blind people to see what their neighboring partners can see. The challenge is that the actual mapping between the input images to brain pattern is too complex and not well understood. We also study the connectivity problem in 3D/2D wireless sensor networks and propose distributed efficient algorithms to accomplish the required connectivity of the system. We provide a new connectivity algorithm *CDCA* to connect disconnected parts of a network using cooperative diversity. Through simulations, we analyze the connectivity gains and energy savings provided by this novel form of cooperative diversity in WSNs.

Keywords**—**Wireless Sensor Networks, Pervasive Computing, Eye Vision Application, 3D Connectivity, Clusters, Energy Efficient, Cooperative diversity.

I. INTRODUCTION

PERVASIVE computing will change the computing landscape enabling the implementation of new applications that were never imagined. As the population of the USA ages, vision loss is becoming an increasingly serious public health problem. Already, approximately 3.3 million Americans over the age of 40, or one person in 28, are either blind or have low vision [7] (vision so poor that it significantly interferes with everyday life and can't be corrected, even with eyeglasses). That number is expected to reach 5.5 million by 2020. The financial burden to United States taxpayers is also immense. According to a joint report by Prevent Blindness America and the National Eye Institute (NEI), blindness and vision loss cost the federal government more than $4 billion annually in benefits and lost income. Two major causes of blindness, age-related macular degeneration (AMD) and retinitis pigmentosa (RP), damage the photoreceptor cells in the light-sensitive membrane in the eye (retina) but leave the nerve connections to the brain intact. Patients eventually lose their vision. Scientists funded by the U.S. Department of Energy (DOE) Biological and Environmental Research (BER) program are developing a prototype artificial retina that could help provide a solution for this growing challenge. Ultimately, the goal is to restore useful vision for patients blinded by AMD and RP. This work builds upon a first-generation device containing a 16-electrode array on a miniature disc that can be implanted in the back of the eye to replace a damaged retina. After years of research and laboratory prototypes, artificial vision is being tested in humans for the first time. Artificial vision researchers take inspiration for another device, the cochlear implant, which has successfully restored hearing to thousands of deaf people. But the human vision system is far more complicated that the hearing system. The eye perceives millions of distinct points of light. Light entering through the pupil, is converted to electrical signals anatomical rods and cons, the light sensitive cells in the retina. Those electrical pulses are carried through the optic nerve to the brain, where they yield images to the world.

In this paper, we consider another approach to artificial eye vision using wireless sensor networks. To the best of our knowledge, our proposed idea of using wireless sensor networks for improving sight has never been approached yet. Because the sensor devices are placed in the human body, the research problems differ from traditional wireless sensor networks. Most work concerning artificial vision has included a digital camera transmitting wireless data to a micro-chip in the eye [8]. The challenge is that the actual mapping between the input images to brain pattern is too complex and not well understood. Since the sensors are irreplaceable and incase of emergency, we need to report to the central computer, we require that our network to be connected at all time if some sensor nodes were deployed on near by objects to form a connected network. We also provide algorithms for achieving connectivity of a system in a three dimensional space. In wireless networks, signal fading arising from multipath propagation is a particularly severe channel impairment that can be mitigated through the use of diversity [11-14]. Space, or multi-antenna, diversity techniques are particularly attractive as they can be readily combined with other forms of diversity, *e.g.*, time and frequency diversity, and still offer dramatic performance gains when other forms of diversity are unavailable. In contrast to the more conventional forms of space diversity with physical arrays, our work examines the problem of creating and exploiting space diversity using a collection of distributed sensor nodes cooperating in order to

Manuscript received February 6, 2007.
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achieve maximum connectivity with minimum energy consumption.

The rest of the paper is organized as follows. Related work in WSNs is presented in section 2. In section 3, we propose the new approach to artificial eye vision using wireless sensor networks and the challenges that will arise. In section 4, we provide algorithms for achieving connectivity of the sensor network when the initial deployment resulted in a disconnected network. Simulation results that validate out proposed algorithms are presented in section 5. The paper is concluded in section 6.

II. Related Work

Wireless sensor networks (WSNs) have been under development for many years and are about to gain widespread use as technology improves, prices drop, and new applications are developed. "Microelectromechanical Systems (MEMS)" technology [1] made it possible to fit sensors into a smaller volume with more power and with less production costs. Smart disposable micro sensors can be deployed on the ground, in the air, under water, on bodies, in vehicles, and inside buildings. Sensor networks are playing an important role in bridging the gap between the physical world and the virtual information world [2]. Wireless sensor networks can be an integral part of military command, control, communications, computing, intelligence, surveillance, reconnaissance and targeting systems. The rapid deployment, self-organization and fault tolerance characteristics of sensor networks make them a very promising sensing technique for military. Wireless sensor networks applications include tracking the movements of birds, small animals, and insects; monitoring environmental conditions that affect crops and livestock; macro instruments for large-scale Earth monitoring and planetary exploration; chemical/biological detection; precision agriculture; biological, Earth, and environmental monitoring in marine, soil, and atmospheric contexts; forest fire detection; meteorological or geophysical research; flood detection; bio-complexity mapping of the environment; and pollution study [3,4]. Some of the health applications for sensor networks are providing interfaces for the disabled; integrated patient monitoring; diagnostics; drug administration in hospitals; monitoring the movements and internal processes of insects or other small animals; monitoring of human physiological data; and tracking and monitoring doctors and patients inside a hospital [5]. As technology advances, smart sensor nodes and actuators can be buried in appliances, such as vacuum cleaners, micro-wave ovens, refrigerators, and VCRs [6]. They allow end users to manage home devices locally and remotely more easily.

Although the technology of biomedical sensors is relatively new, a number of interesting applications are already out there. A glucose level monitor is one application that had emerged recently. Another application is cancer detectors. Wireless sensors have also been proposed for use as implanted general health monitors. Swallowing a pill containing smart sensors enables wireless transmission of information about contractions of intestinal muscles or intestinal acidity that will help doctors diagnose the disease.

An important issue in WSNs is connectivity. In general, a multi-hop network tries to find a route between a source and a destination to forward the information. As a theoretical minimum, at least one route must exist to perform data transport. If two nodes in this route are not able to communicate to each other because they are too far away to send/receive RF-signals the network is segmented. A network is connected if any active node can communicate with any other active node, possibly using intermediate nodes as relays. Once the sensors are deployed, they organize into a network that must be connected so that the information collected by sensor nodes can be relayed back to data sinks or controllers. An important frequently addressed objective is to determine a minimal number of working sensors required to maintain the initial coverage area as well as connectivity. Selecting a minimal set of working nodes reduces power consumption and prolongs network lifetime. An important, but intuitive result was proved by Zhang and Hou [9], which states that if the communication range, is at least twice the sensing range, a complete coverage of a convex area implies connectivity of the working nodes. If the communication range is set up too large, radio communication may be subject to excessive interference. Therefore, if the communication range can be adjusted, a good approach to assure connectivity is to set transmission range as twice the sensing range. Wang et al [10] generalized the result in [9] by showing that, when the communication range is at least twice the sensing range, a k-covered network will result in a k-connected network. A k-connected network has the property that removing any k-1 nodes will still maintain the network connectivity. The work in [10] introduces coverage configuration protocol (CCP) that can dynamically configure the network to provide different coverage degrees requested by applications.

Our connectivity technique is based on some other interested works in the field of cooperative diversity. Cooperative diversity utilizes intermediate transmitters as repeaters to extend the range of transmission of a source. The advantage of cooperation is the accumulation of power from all relays, which is a source of diversity, and also of signal to noise ratio improvement ([11-14]). In [15] the authors understand cooperative transmission in the sense that several sensor nodes transmit symbols simultaneously to achieve a power gain. The broadcast-coverage of a system using cooperative transmission is analyzed. Their results simplify the modeling and leads to closed-form solutions and formulations.

III. Proposed Vision

Before we present our approach, let us identify some of the challenges of using wireless sensor networks for this particular kind of application:

1- *Limited Power and Computation:* Small physical size of the sensor and also the absence of wires make them

International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:2, No:12, 2008

have very limited power supply and thus limited computational capabilities.

2- *Shape, Size and Material*: Since the sensors will be implanted inside the human body, restrictions are made on the shape, size and the material used for the sensors.
3- *Energy Constraints*: Once a sensor is implanted in the human body, it is required to operate for years without interruption.
4- *Distributed Network*: A failure of one node should not affect the entire network of sensors.
5- *Fault tolerance*: Device redundancy and consequently information redundancy can be utilized to ensure a level of fault tolerance in individual sensors.
6- *Dynamic sensor scheduling:* Dynamic reaction to network conditions and the optimization of network performance through sensor scheduling.
7- *Moral issues*: People suffering from the disease under experiment are likely to volunteer to advance science in this area. Safe tests that are harmless to patients should be the only kind of tests that are performed.

In its simplest form, vision is produced when light entering the eye is turned into electrical signals that are carried by the optic nerve to the brains visual cortex. When the circuit is broken, blindness results. The idea is to replace the broken circuit with electronics. The goal of this proposed approach is to allow people with no vision or with low vision to see what their neighboring partners can see. Unlike some other artificial vision proposals, this approach is applicable to virtually all causes of blindness. Our device may also help some legally blind low vision patients because the cortex of sighted people responds to stimulation similarly to the cortex of blind people. A lot of work has been done to try to imitate the functionality of the human eye and artificial vision techniques have been proposed. The challenge is that the actual mapping between the input images to brain pattern is too complex and not well understood. In our case, we do not need to understand that complex mapping pattern since human brains function in a similar way and the input to one brain (sent from another human with normal vision) could well be analyzed in the same way as if it was originated from the blind man's brain.

The sensor implants are inside both the eye of the blind man's eye and a normal man's (or dog's) eye (Figure 1).Vision is established using the following steps:

A. Light entering through the pupil, is converted to electrical signals. Those electrical pulses are converted to data and are stored in the retinal implant of the normal eye.
B. The data is then transmitted using the wireless transceiver to the blind mans eye.
C. The signal travels along a tiny wire to the retinal implant.
D. The back side of the retina is simulated electrically by the sensors on the chip.
E. These electrical signals are converted to chemical signals by tissue structures and the response is carried via the optic nerve to the brain.

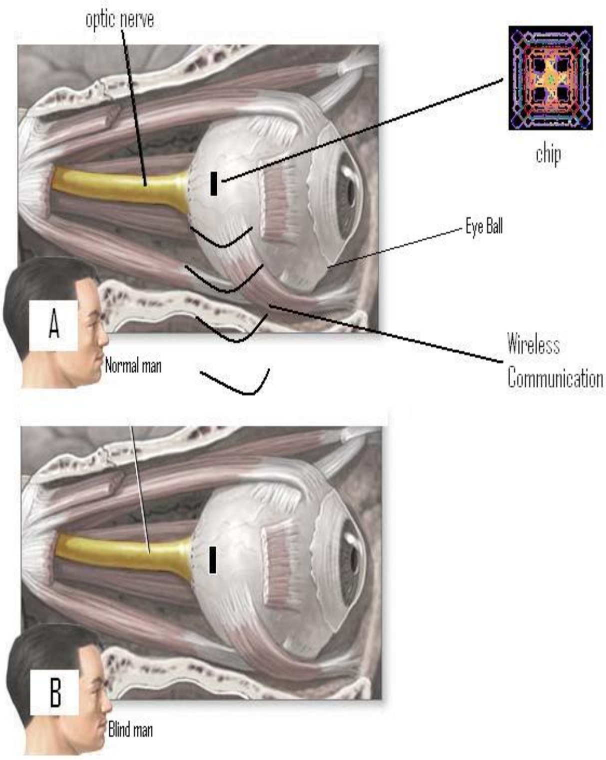


Fig. 1 Our proposed approach for eye vision.

The unique difference between our approach and any other is that by using the data from one man's eye we do not need to understand the complex mapping of an image from the retina to the brain via the optic nerve. This application might be very useful in scenarios where the blind person and his partner are focusing their attention on a static phenomenon (e.g. watching a movie, attending a lecture...).

IV. CONNECTIVITY IN WIRELESS SENSOR NETWORKS

In some other envisioned scenarios where a sensor network would be deployed on near by objects and will fuse the data and send them to the sensor node on the blind man's eye we provide a greedy solution to establish a connected network between the sensor nodes and a given sink. In a typical WSN deployment, it is usually assumed that the entire sensor network is connected. This may not always be true, especially when sensors have limited communication range, and are distributed randomly. The main problem is that, while individual sensors over a large area can be queried directly the sensors can only respond and hence, be detected by the user through the network. In case of an emergency the bio sensors need to report to a central computer. To do that the network need to be connected at all time.

4.1 Problem Formulation

International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:2, No:12, 2008

Consider a sensor network comprising of n sensors: S_1, S_2….S_n each with a sensing radius R_s and communication radius R_c respectively. Let A_{is} and A_{ic} be the sensing and communication regions of sensor S_i respectively. Let O_i be the output of a sensor S_i that is capable of sensing a phenomenon P_i. Let $\overline{C} = \bigcup_{i=1}^{i=m} A_{is}$ and $\overline{\overline{C}} = \bigcup_{i=1}^{i=m} A_{ic}$ be the sensing space and communication space of a set of sensor nodes $C = \{S_1, S_2, \ldots S_m\}$ respectively.

Definition 1: The phenomenon P_i located at $y \in R^3$ is said to be **detected** by sensor s_i located at $X_i \in R^3$ if and only if there exists a threshold δ such that:

$$O_i(y) \begin{cases} \geq \delta & \textit{if the phenomenon } P_i \textit{ is present,} \\ = 0 & \textit{otherwise.} \end{cases}$$

Definition 2: The **sensing region** of sensor S_i located at $X_i \in R^3$ is defined as $A_i = \{ y \in R^3 \mid \|y - X_i\| < R_s \}$, where $\|.\|$ is the Euclidean distance between y and X_i.

Definition 3: A set of sensors $C_i = \{S_{a1}, S_{a2}, \ldots S_{am}\}$ is said to **cover** the region R_i if and only if $R_i \subseteq \overline{C_i}$.

Definition 4: A set of sensors $C_i = \{S_{a1}, S_{a2}, \ldots S_{am}\}$ is said to be **connected** if $\forall$ a, b $\in \overline{\overline{C_i}}$, $\exists$ a continuous function f : [0,1] → $\overline{\overline{C_i}}$ such that : f(0)=a , f(1)=b, $a \leq t \leq b$, $f(t) \in \overline{\overline{C_i}}$

C_i *is connected then* $\forall$ $S_a, S_b \in C_i$

$\Leftrightarrow \exists$ *a path 'P' from* S_a *to* S_b.

A path exists from X_{eye} and $X_{computer}$ respectively (Figure 3.) if there is a sequence of sensor nodes $S_1, S_2, \ldots, S_k$ at locations $X_1, X_2, \ldots, X_k$ such that:

$P_1 : \|X_a - X_{eye}\| \leq R_s$ (eye *can be sensed*);

$P_2 : \|X_i - X_{i-1}\| \leq R_c$ *for* $i = 1 \ldots K$ (*event transmitted*);

$P_3 : \|X_k - X_{Computer}\| \leq R_c$ (S_k *can transmit to station*).

Definition 5: A node S_i is said to be a **neighbor** of node S_j if and only if $d(X_i, X_j) \leq 2R_c$, where R_c is the communication radius of sensor nodes S_i, S_j.

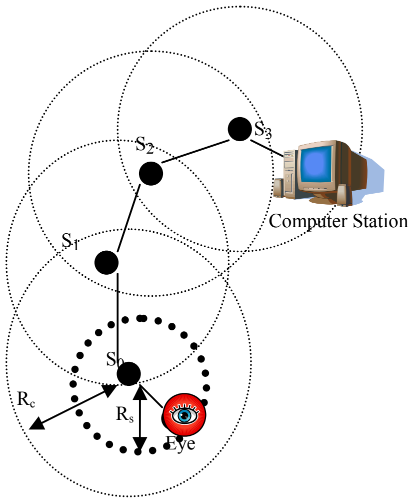


Fig. 2 An example of a path from the eye to the emergency computer station using sensors S_1,S_2 and S_3.

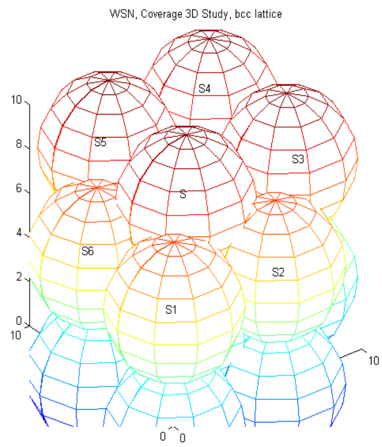


Fig. 3 An example where 3D coverage doesn't necessary mean connectivity

Definition 6: The **neighbor set** $N(i)$ of sensor node S_i is the set of all the neighbors of node S_i and is defined as $N(S_i) = \{S_j \in C \mid d(X_i, X_j) \leq 2R_c\}$.

4.2 Three Dimensional Coverage and Connectivity

Connectivity requires that the location of any active node be within the communication range of one or more active nodes such that all the active nodes form a connected communication backbone, while coverage requires all locations in the coverage region be within the sensing range of at least one active node. Obviously, the relationship between coverage and connectivity depends on the ratio of sensing radius to communication radius. We are more interested with wireless sensor networks in three dimensions where the sensing region is modeled by balls rather than circles. In Figure 3, consider the spheres S, S1, S2, S3, S4, S5, and S6 with sensing radius R_s and communication radius R_c respectively. Connectivity requires that the center of any sphere be within the communication range of one or more spheres such that all the nodes form a connected backbone. The centers of S and S1 are $2R_s-\zeta$ apart where $\zeta>0$.If $R_c< 2R_s-\zeta$ then the WSN is not connected. If $\zeta=0$ ($R_c=2R_s$), then the WSN is completely covered and connected. Consider the following lemma whose proof could be derived from the 2D case [9, 10].

Lemma 1: A necessary and sufficient condition to ensure that coverage implies connectivity in 3D is that the radio range should be at least twice of the sensing range.

4.3 Simple Connectivity Algorithm (SCA)

When we don't have complete coverage, we provide an algorithm that will always form a connected path between the origin sensor (e.g. eye sensor) and the sink (e.g. emergency center). This can be established if there is at least one path between the source and the destination i.e. the network is connected. However if the network is disconnected then we provide in the next section a unique approach to form a connected network from a disconnected one using cooperation between the sensor nodes. We designed a greedy algorithm *SCA* to select a Connected Sensor Set CSS of optimal size. In short, the greedy algorithm works by selecting, at each stage, a communication path of sensors that connects an already selected sensor to the origin sensor S_0. The selected path is then added to the already selected sensors at that stage. We classify the messages sent into 2 types:

1. Downstream messages originated from the sink.
2. Upstream messages originated from the origin.

The algorithm terminates when the selected set of sensors is connected to the designated sink S_{sink} i.e. when the upstream path meets the downstream path. A subset of the network of sensors between them will be selected to form a connected path. Let us assume that CSS_0 is the set of sensors already selected for inclusion in the Connected Sensor Set of S_0. Initially, CSS_0 contains only S_0 (origin sensor). At each stage, the greedy algorithm selects a sensor S_1 from the set of neighbors who has a downstream path to the sink otherwise just form an upstream path to the sink. CSS_0 is updated to $CSS_0 = CSS_0 \cup CSS_1$. Thus, at any stage of the algorithm, the communication graph induced by CSS_0 is connected. A formal description of the algorithm is as follows.

The algorithm terminates when S_{sink} is a subset of CSS_0.The computational complexity of the algorithm developed in this section is $\mathrm{O}(N)$ where $N = \left(\max_{i=1}^{n} |N(i)|\right)$ is the maximum number of nodes in the neighbor set of any sensor in the network.

Simple Connectivity Algorithm (*SCA)*

$CSS_0 = \{S_0\} \rightarrow UPstream$

$while\ (CSS_i \rightarrow UPstream)$

$For\ each\ S_i \in N(S_0)$

$CSS_0 = CSS_0 \cup CSS_i$

$end\ while$

$return\ CSS_0$

4.4 Cooperative Diversity Connectivity Algorithm (CDCA)

A problem with *SCA* is that the loss of connectivity of the deployed sensor nodes in the path between the source sensor node and the destination node may lead to partitioning the network. This scenario might happen when the density of deployed sensor nodes is not large enough or due to some environmental conditions leading to higher noise in the channel and thus preventing two neighboring nodes from communicating with each other. Also, a disconnected network might be formed after the some sensor nodes have ran out of energy. The communication range of the nodes is limited and therefore leading to isolated partitions in the network as depicted in Figure 4. Initially (Figure 4), we had one connected network (one big cluster) but the failure of two nodes F1, and F2 lead to dividing the network into four small clusters and preventing the source from establishing a connected path to the destination (Figure 4).

We suggest using cooperative transmission where we introduce redundancy and a group of nodes can combine their transmission power and thus achieve a virtual wider range of communication with their neighbors. The idea is the nodes working as a group transmit identical signals synchronously to superimpose the emitted waves on the physical medium (Figure 5). The destination receives a sum of waves and thus a total higher power. Cooperative diversity is a recent breakthrough at the physical layer, which exploits the broadcast nature of the wireless channel to emulate a Multi Input Single Output system. Nodes participating in a cooperative diversity scheme, broadcast the same packet simultaneously. By providing the receiver with multiple replicas of the same signal, one can achieve the same benefits of an antenna system mounted on a single node. The research at the physical layer has proved the significant potential of cooperative diversity. To the best of out knowledge, the techniques introduced in this paper to establish connectivity in a WSN have never been addressed yet.

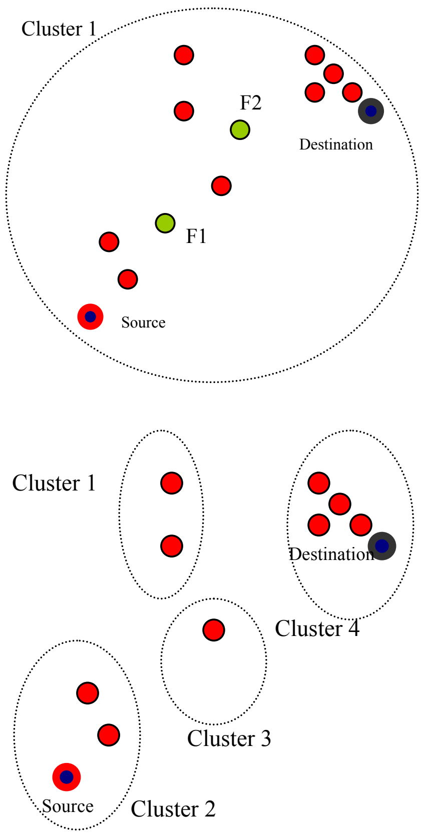


Fig. 4 A connected sensor network with one cluster. A disconnected network with four clusters.

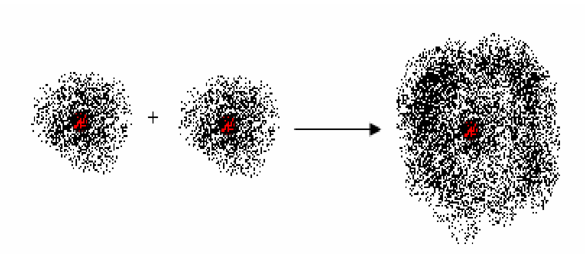


Fig. 5 Increasing the transmission range of each sensor node by summation of radio powers

We are proposing a technique in which we initially classify the network into different connected clusters and then use cooperative diversity techniques to connect neighboring clusters together. Within a cluster, we can use SCA since the nodes within a cluster are connected so we can establish a connected path between any two. To divide the network into clusters of connected nodes, each node will exchange HELLO packets with its neighbors in a distributed fashion. Each HELLO packet will contain an Identification of the sender node and a cluster number. Each receiving node will set their cluster number to the same cluster number as its neighbors until no more updates are needed i.e. $\forall S_i \in N(S_j), CN(S_i) = CN(S_j)$ where $N(S_j)$ is the set of neighboring sensor nodes within the communication range of S_j and $CN(S_i)$ is the cluster number for which S_i belongs to. An initiator (source) starts a transmission session to a destination. If the destination is within the same cluster then we use a simple multi-hop communication strategy to connect to the destination. However, if the network is not connected i.e. the destination belongs to a different cluster then the nodes who hear the packet within the same cluster decode and retransmit. The retransmissions are done simultaneously, even though they may not be synchronized. The retransmissions continue until every node who can hear the others retransmits once. Due to simultaneous transmissions, the reception power is enhanced, and packets can reach farther distances. The nodes decode and retransmit if and only if their received signal-to-noise ratio (SNR) exceeds a certain threshold η. The network performance crucially depends on the threshold. One would like to make it as low as possible to maximize the number of nodes who participate in transmission. On the other hand, a low threshold means decreased communication rate, or higher probability of error. Inherently, there exists a trade-off between the transmission rate and the number of participants in each transmission. Next we provide some notations that will be used later to model the system.

$P_{t,i}$: transmission power of a sensor node S_i

$P_{r,i}$: receiving power of a sensor node S_i

$d_{i,j}$: Euclidean distance between two sensor nodes S_i and S_j

η: SNR threshold

Suppose a source S_0 initiates the transmission. Every node S_i will check if $P_{r,i} = \frac{P_{t,0}}{d_{i,0}^{2}} > \eta$. If that is true, it will decode and retransmit the same packet right after reception. The n[th] node will hear the transmission with power $P_{r,n} = \sum_{i=1}^{n} \frac{P_{t,0}}{d_{i,n}^{2}}$. We assumed squared distance path attenuation, but our results could easily be generalized to any path loss model. The noise is assumed to be of unit power. We also assume every node knows its received SNR and if the SNR is high enough, it will decode the packet without any errors.

The performance of the connectivity algorithm over time will also be studied through simulations to determine the benefits of using our algorithm over traditional flooding or simply making all the sensor nodes send the message using cooperative diversity techniques. This is done by assuming that each sensor node has a limited energy supply of 300 Joules and is deactivated when the available energy is used up. The performance is evaluated in terms of *connectivity lifetime.* The *connectivity lifetime* is the continuous operational time of the system before the connectivity drops below a specified threshold (for example 0.9). If the network is connected then its connectivity level is 1. The nodes are assumed to consume 1400mW for each transmission and 1000mW for each reception. Further, the nodes are assumed to consume 830mW, 130mW in the idle and sleep states respectively. The flow chart of the Cooperative diversity connectivity algorithm CDCA is presented in Figure 6.

In Figure 7, the source node first uses SCA, a simple multi hop connectivity algorithm to be connected to its neighbors in the same cluster. After that, all the sensor nodes in the cluster cooperatively transmit the message to reach the neighboring cluster and so on until we form a connected network between the source and the destination.

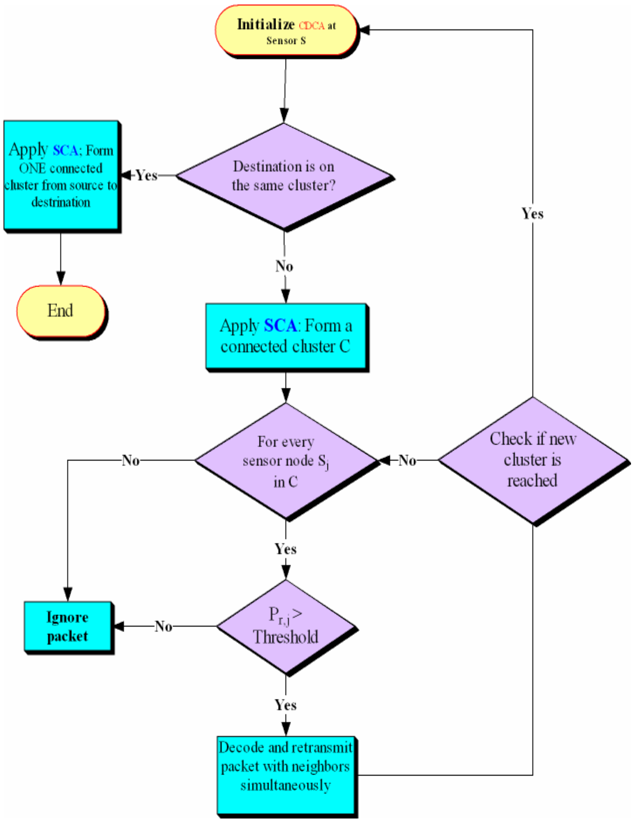


Fig. 6 Cooperative Diversity Connectivity Algorithm *CDCA* implemented at a source sensor node S.

V. Simulation Results and Analysis

The theoretical developments in section 4 are validated through numerical examples in this section. By combining the transmitting power with neighboring nodes, nodes can increase their radio range and thus increase the connectivity of the network. In addition to that, our connectivity algorithm uses SCA to achieve connectivity between nodes belonging to the same cluster.

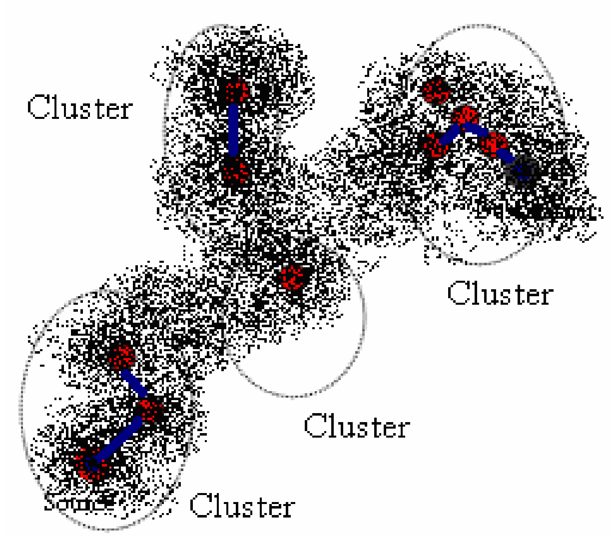


Fig. 7 A snapshot using *CDCA* and clustering. A disconnected network is transformed into a connected one. Within a cluster we use SCA and if the destination is still not reached the whole group of nodes will retransmit simultaneously in order to connect to the neighboring cluster.

Sensor nodes are uniformly deployed over a 2D region of size 1000 units by 1000 units (or a 3D region of size 1000x1000x1000). The communication radius of each sensor node is 20 meters. We compare between four different connectivity strategies: Simple flooding, *SCA*, *CDCA* and Cooperative Communication where each node transmits to its 1-hop neighbors and each neighbor will retransmit along with the initiator until the destination is reached. When nodes use the cooperative transmission, each node will repeat a received message several times. It will do this together with all other nodes who at the same time received the same message. The number of times a sensor node resends the message is a simulation parameter and we vary it from 1, 2 or n where n is the maximum number of times needed to rebroadcast the message until the destination is reached.

We assume that we have a fixed sink in which all the other nodes have to be connected to. It has a very high power directly reaching all nodes in the field. The nodes are low-power devices and cannot reach the sink in a single-hop manner. The information flow is only between the sink and the nodes. Information exchange between nodes in a peer-to-peer manner is only with the intention to relay packets to the sink. A node is considered connected if it can forward or route a message towards the sink node and the whole network is connected if all the nodes in the network are connected and the connectivity measure is equal to one. If there are *n* nodes deployed in the region of interest and there are *m* nodes connected to the sink then the connectivity measure is simply $\frac{m}{n}$. Next, we conducted a series of experimental simulations to analyze and validate some of our results.

Experiment 1 (*Connectivity Measure*)

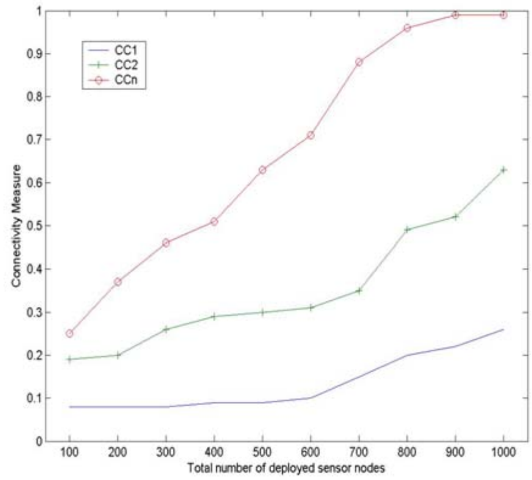
In the first experiment, we are concerned about the connectivity level achieved using different algorithms under different random deployment scenarios. A number of trials were conducted and the resulting connectivity average was calculated. Figures 8.a and 8.b show, as we vary the number of sensor nodes deployed from 100 to 1000, the resulting connectivity measure for six connectivity algorithms: Flooding, *SCA*, *CDCA*, CC1, CC2, CCn where CC1, CC2 and CCn are when each sensor node cooperatively resends the message simultaneously along with its neighbors one time, two times and n times (until the destination is reached). The best results are achieved by the CCn. This behavior is as expected as CCn forces each sensor node to retransmit the message multiple times until the destination is reached. This behavior will however lead to a great increase in the energy usage as will be depicted in the next experiment. As for *CDCA*, it outperforms all the other connectivity algorithms as it maximizes the connectivity of the nodes with the destination while minimizing the energy consumption over time (or multiple queries)

In Figure 8.b, the advantages that *CDCA* can contribute are highlighted as it increases the connectivity gain in sparse settings. When approximately 700 nodes are present using simple flooding (or *SCA*), the connectivity measure is 0.5 i.e. only 50% of the nodes are connected to the sink; However, using SDCA, the connectivity measure is 0.83 which means 33% more nodes are connected to the sink.

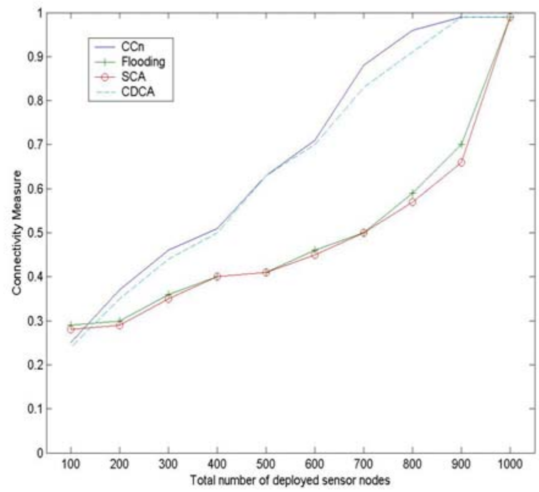
Experiment 2 (*Energy Usage and System Lifetime)*

The performance of the system over time was also studied to determine the benefits of using a reduced cover. This is done by assuming that each sensor node has a limited energy supply of 300 Joules and is deactivated when the available energy is used up. The performance is evaluated in terms of energy usage or *connectivity lifetime.* Figure 9 show the overall connectivity obtained over time as the WSN processes a series of queries. An initial deployment of 1000 sensor nodes is simulated. It can be seen that the overall connectivity drops over time as the available energy is used in processing the queries and establishing a connection to the sink. Using *CDCA*, it is seen that the resultant connectivity over time is significantly better that all the others since it maximizes the connectivity while minimizing the energy usage. When the system is all connected the connectivity using SCA or simple flooding will be better but as soon as the network would be portioned then some nodes away from the destination will lose connectivity and the overall connectivity measure will drop significantly. CDCA performs better since each node in the network uses multi-hop connectivity *SCA* when possible and when there is no other choice it will use cooperative diversity to establish a connection to neighboring nodes resulting in more efficient communications and less energy expenditure per query.

This improvement in the connectivity lifetime comes at a cost. *CDCA* requires the communication between a node and its neighbors and as a result, a portion of energy is used up during the initialization stage of the network which justifies *SCA* performing better at starting stages but over time when the nodes start wasting their energy and deactivating the resulting network will be disconnected and all the nodes away from the sink won't be able to reply to a query resulting in a big drop in the connectivity measure using *SCA* (or flooding). Using Multi-Level cooperative communication where each node sends a message and together with its neighbors sends it again and so on until the destination is reached has the worst connectivity lifetime since a lot of energy is wasted due to unnecessary communications.



(a)



(b)

Fig. 8 (a) The connectivity measure of 3 algorithms CC1, CC2, and CCn as the number of deployed nodes vary. (b) The connectivity measure of 4 algorithms CCn, Flooding, SCA and CDCA as the number of deployed nodes vary.

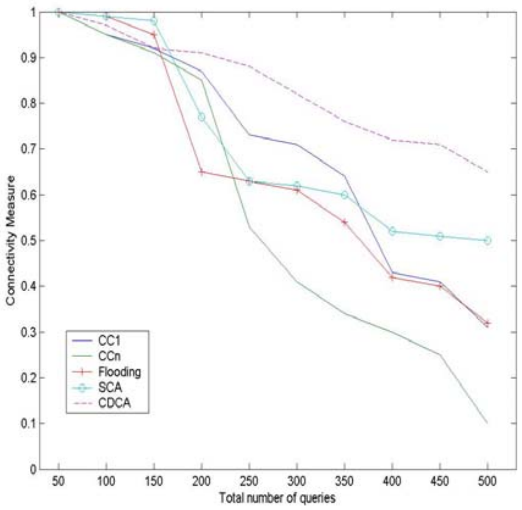


Fig. 9 The connectivity lifetime (*Energy Usage*) of the network as the number of queries is increased.

Experiment 3 (*Minimum Number of Nodes*)

In our previous work [16 and 17], the coverage problems in both 2D and 3D regions were rigorously analyzed. It was shown that the Hexagonal Lattice Deployment always results in the least number of sensor nodes in 2D (bcc lattice in 3D). In this paper, if nodes are randomly distributed over a certain area, our goal is not how many nodes cover that area however our goal is if the connection of a certain number of nodes must be guaranteed, then what is the minimum necessary number of nodes that need to be deployed. In this experiment (Figure 10), we analyze the minimum number of nodes needed to guarantee connectivity. The maximum line connectivity (the 1st bisector) is shown in the figure in order to visualize where the total number of deployed nodes would be enough to guarantee connectivity. As can be seen in Figure 10, when the total number of deployed nodes is about 800 nodes then CDCA and CCn will result in almost 100% connectivity. This number is useful since it puts a lower bound on the number of nodes needed to be deployed in a region of interest to guarantee connectivity.

VI. CONCLUSIONS AND POSSIBLE EXTENSTIONS

Billions of dollars are being committed to the research and development of sensor networks in order to address the many technical challenges and wide range of immediate applications. In the first part of this paper, we have described our initial approach to a wireless sensor network implant in a human eye, which will be refined further as testing and developments continue. We bypass the brain complexity challenge by proposing a different approach from any other before. Hopefully that will offer a ray of hope for all blind people all over the world. We explain the challenges of human embedded sensor networks.

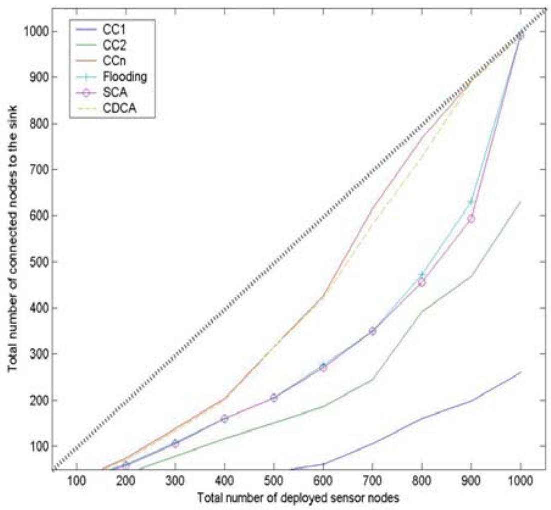


Fig. 10 The total number of deployed sensor nodes that are connected to the sink as we vary the number of deployed sensor nodes.

In the second part of this paper, we provided algorithms to achieve connectivity in a sensor network. We first provided a simple multi hop connectivity algorithm and then when the network is disconnected, we provided cooperative transmission techniques which can support especially topologies of clustered and partitioned networks that contain separated groups of nodes. This new communication principle can overcome connectivity problems in sparse settings or heavily partitioned topologies. Through simulations, we validated our results and show how our algorithms could increase the connectivity of a network while minimizing the energy consumption.

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