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A Cluster-Based Protocol for Self-Organizing UWB Wireless Ad hoc Sensor Networks

Hai H. Hoang
Department of Electrical & Computer Engineering
Florida State University
Tallahassee, FL 32310, U.S.
hoanghu@eng.fsu.edu

Bing W. Kwan
Department of Electrical & Computer Engineering
Florida State University
Tallahassee, FL 32310, U.S.
kwan@eng.fsu.edu

***Abstract*— Ultra wideband (UWB) technology with features of low cost, low power and high time resolution has potentially important applications in wireless ad hoc sensor networks. This paper proposes a cluster-based protocol for a class of UWB wireless ad hoc sensor networks. We consider a network of a large number of virtually identical but stationary sensor nodes that are energy-constrained with limited computing capabilities. This protocol fully exploits the features of impulse-radio-based UWB technology and orthogonal signaling to allow sensor nodes self-organizing and becoming aware of their locations without the need to use ID numbers. The entire network is divided into clusters. Each cluster is uniquely identified by a gradient index and a sector index. Any detected information is transmitted via a multi-hop path characterized by steep descent in the gradient index. The proposed protocol combines the advantages of both flat-based and hierarchical-based routing protocols. In this protocol, the key issues of the physical layer and the medium access control tasks of the data link layer can be jointly handled by the appropriate use of multiple access techniques. Computer modeling demonstrates that the proposed protocol performs well with different network scenarios.**

***Keywords*— Clustering, Self-organization, UWB Wireless Sensor Network, Cross-layer design**

I. INTRODUCTION

UWB technology has recently been given much consideration in the application of wireless ad hoc sensor networks because of low complexity, high reliability, good time resolution, and efficient multiple access features [1], [2]. We consider a network of very large number of identical sensor nodes with limited processing capability, memory, and power supply. In addition to the usual sensor modules, actuator modules, and a microcontroller, the key components of a sensor node include an UWB transceiver, a random number generator, and a bank of orthogonal pseudorandom (PR) codes. Such a sensor network can be deployed in harsh environment for the detection of chemical, biological, or nuclear agents. Once detection is made, the information will be routed to a data-collecting sink node. This paper proposes a gradient cluster-based protocol to allow the sensor network perform self-organization as well as information routing along a steep-descent path to the sink node. The main idea of the protocol is to combine the use of gradient information with multiple access technique in an intricate manner such that the network organizes itself into clusters. As a consequence, each cluster becomes identifiable with a pair of parameters taking the form of a gradient index and a sector index.

The idea of encoding gradient information has been proposed in the directed diffusion paradigm [3], which is a flat routing protocol. However, each sensor node is required to remember all the nodes in both the backward and forward paths while propagating the *interest* message. Another requirement of the paradigm is to evaluate and reinforce the best paths so as to prevent extensive flooding [4]. These features increase the energy consumption and hence decrease the network lifetime, especially when the number of sensor nodes is very large. A hierarchical or cluster-based routing method, such as LEACH (an acronym for Low Energy Adaptive Clustering Hierarchy) [5], is able to increase the network lifetime. However, LEACH assumes that all sensor nodes can provide enough power to reach the sink if needed [4]. Further, the well-known LEACH and its extensions [11], [12] require to maintain the sensor node ID numbers in data routing. This requirement may be impractical in a network of a large number of sensor nodes. The protocol proposed here combines the attractive features of flat routing and cluster-based routing to determine the route of steep descent without using the ID numbers. In addition, the sink node can locate the cluster from which the information originates. An address-free clustering protocol utilizing orthogonal codes [6] is a first attempt on exploiting gradient information to acquire self-organization ability. However, the sink node is assumed to be powerful and well-equipped, including the use of a directional antenna.

The paper is organized as follows. Section II describes a typical UWB wireless ad hoc sensor network. In particular, UWB signal, multiple access techniques, and architecture of a sensor node are discussed. Section III presents the self-organization procedure for cluster formation. Section IV shows a routing scheme according to the proposed protocol. Computer simulation results are provided in Section V. Finally, concluding remarks of this study are made in Section VI.

II. ULTRA WIDEBAND WIRELESS SENSOR NETWORKS

A. *Ultra Wideband Technology*

The key feature of UWB is to use short duration pulses instead of using carrier waves to transmit and receive information. UWB systems may be divided into impulse radio (IR) and multiband (MB) systems. While MB-UWB systems

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have the advantage of efficient spectrum utilization, IR-UWB systems have the significant advantages of simplicity and spectrum randomization support. Transmission of pico second to nano second pulses results in wide communication bandwidth of more than 500 MHz as well as excellent resolution in time domain. UWB pulse transmission not only requires much lower power than narrowband signal transmission but also reduces the complexity of the receiver. Moreover, high time resolution provides high performance for wireless communications over multipath fading channels [7]. Therefore, IR-UWB technology has potential applications in wireless sensor networks. The data modulation schemes most often used in IR-UWB systems are on-off keying (OOK), pulse position modulation (PPM) and pulse amplitude modulation (PAM).

B. Impulse Radio Ultra Wideband Signal

Since continuous pulse transmission results in strong lines in the spectrum of the transmitted signal, a randomizing technique is applied to make the spectrum of the IR-UWB transmission more noise-like [2]. The interferences between communication links of groups of sensor nodes can be eliminated by introducing randomization to the transmitted signal. Sensor nodes in each group use a unique PR code to communicate to the others in the same group. There are two typical modulation techniques used in UWB systems namely time hoping (TH) and direct sequence (DS). A TH technique randomizes the positions of transmitted UWB pulses in time domain, while a DS technique employs spread spectrum approach to produce a sequence of pulses with pseudorandom inversions [7]. The TH-based technique can be employed in PPM data modulation since the information is given by the position of the pulse. On the other hand, the DS approach is suitable for PAM and OOK data modulation schemes. Since the TH technique is more sensitive to time synchronization that increases the complexity of the receiver, the DS technique is selected in the applications of wireless sensor networks. Here, the pulse waveform takes the role of chips in a spread spectrum system. The transmitted DS-UWB signal using PAM data modulation of the uth group is given by [7]:

$$s^{(u)}(t) = \sum_{k=-\infty}^{\infty} \sum_{j=1}^{N_s} w(t - kT_d - jT_{ch})(c_p)_j^{(u)} d_k^{(u)} \qquad (1)$$

where d_k is the kth data bit, $(c_p)_j$ is the jth chip of the PR code, $w(t)$ is the pulse waveform, T_{ch} is the chip length, and N_s is the number of pulses per data bit. The PR sequence has value $\{-1,+1\}$ and the bit length is $T_d = N_s T_{ch}$. At the receiver, the PR code $c_p^{(u)}$ is correlated with the received signal to demodulate the data $d^{(u)}$. Since the PR codes are orthogonal, only sensor nodes in the group uth can demodulate the transmitted signal $s^{(u)}(t)$.

C. Ultra Wideband Sensor Node

The basic architecture of a UWB sensor node is shown in Fig. 1. Each sensor node has the following modules: power management, sensor and actuator, PR code bank, random generator, microcontroller, UWB transceiver. Recent FPGA technology allows integrating all of these modules into a single device [9]. The sensor module has a capability of sensing different agents of chemical, biological, or nuclear origin. The random generator module returns a uniform random variable by the requirement from the microcontroller. The random variable is important when an equilibrium situation happens. The PR code bank contains orthogonal PR codes for direct sequence UWB modulation.

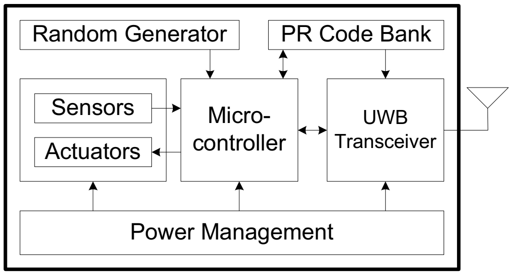

Figure 1. Architecture of a UWB sensor node

Each sensor node is characterized by the following parameters:

$$Node(g, s, c, m, r)$$

where the gradient index g indicates roughly how far the sensor node is from the sink; the sector index s shows the relative position of a sensor node to the others in the same annulus; the sensor nodes that belong to a cluster have the same particular cluster index c; in additional, the cluster head has the member index m equal to zero, while the other members have the m indices of ones; finally, the random index r obtained from the random generator is used to active the internal clock to set the priority in a competition situation.

D. Orthogonal Pseudorandom Code

The PR code bank consists of a set of orthogonal codes $\{C_{ab}\}$ with $0 \le a < N_G$ and $0 \le b \le N_S$. Here, N_G and N_S are the maximum number of annuluses and the maximum number of clusters in an annulus, respectively. The code bank is organized as follows:

$$\left.\begin{array}{ccccc} C_{10} & C_{11} & C_{12} & \cdots & C_{1N_S} \\ C_{20} & C_{21} & C_{22} & \cdots & C_{2N_S} \\ \vdots & \vdots & & \ddots & \vdots \\ \underbrace{C_{N_G0}}_{\textit{Codes for intra-annulus}} & \multicolumn{4}{c}{\underbrace{\cdots \quad \cdots \qquad C_{N_GN_S}}_{\textit{Codes for clusters}}} \end{array}\right\} \textit{Codes for annuluses}$$

At the beginning, the code C_{00} is employed to explore the network. The codes C_{a0} in the first column are then used for communications inside annulus a before the cluster formation, while the other codes C_{ab} are used for communications in cluster b of annulus a after the cluster formation.

Walsh-Hadamard basis functions are used to generate the orthogonal PR codes. The orthogonal Walsh-Hadamard basis functions of dimension N_{PR}, where $N_{PR} = 2^n$, $n = 1, 2, 3, \ldots$, come from the row vector of an $N_{PR} \times N_{PR}$ matrix $\mathbf{H}_n$, which can be generated using the recursive relation [8]:

$$\mathbf{H}_n = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathbf{H}_{n-1} & \mathbf{H}_{n-1} \\ \mathbf{H}_{n-1} & -\mathbf{H}_{n-1} \end{pmatrix} \text{ with } \mathbf{H}_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \quad (2)$$

It is important to recognize that the factor $1/\sqrt{N_{PR}}$ can be ignored in the generation of the orthogonal codes. A set of PR codes $\{C_{ab}\}$ now can be obtained from the row vectors of the matrix $\mathbf{H}_n$.

III. SELF-ORGANIZATION

We consider a situation of N UWB sensor nodes are employed in a field $\Re$. In the self-organization, the sensor nodes are grouped into clusters in which each is labeled by a pair of gradient and sector indices. The self-organization process will be started by the sink node. First, the *interest* message is propagated through the sensor nodes to setup the annuluses. All nodes in the same annulus have a particular gradient index. In the second stage, each annulus forms clusters in parallel. Finally, the sector index is assigned to individual clusters in each annulus. Let T_G, T_C, and T_S are the time intervals for each *interest* message propagation, cluster formation, and sector index increment, respectively. The time line for the self-organization has been shown in Fig. 2.

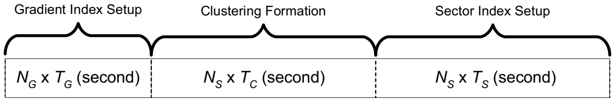

Figure 2. Time line for self-orgnization

For convenience, the rest of the paper uses the following notations: $Nodetype.parameter_{node\ index}^{annulus\ index}$ denotes the parameter of a certain sensor node in a particular annulus, if available; and $Function\{PR\ code, message, information\}$ indicates the PR code used to transmit or receive a message and information enclosure.

A. Gradient Index Setup

All the sensor nodes have gradient index zero from the manufacturer. When a sink node needs to collect information, it starts broadcasting the *interest* message and its gradient index $Sink.g_0$. The *interest* message propagation and gradient index setup at node *k* are handled following the rules:

```
If Receive $\{C_{00}, interest, Node.g_i\}$
        If { $Node.g_k = 0$ } then
                $Node.g_k = Node.g_i + 1$
        Else
                $Node.g_k = Node.g_k$
        End If
    Wait for $T_G$ second
    Transmit $\{C_{00}, interest, Node.g_k\}$
End If
```

A sensor node only updates the gradient index when it receives the *interest* message and it has the initial gradient index zero. After T_G second, the sensor node transmits the *interest* message along with its gradient index for further exploration. All sensor nodes have the same gradient index form an annulus. After the gradient index setup, the entire network is partitioned in several annuluses in which the one closer to the sink has lower gradient index. The code used in each annulus is decided by the gradient index of the sensor nodes in the annulus.

B. Cluster Formation

After the gradient-based annuluses have been formed, the sink node sends a synchronization signal to the sensor nodes in each annulus to start electing the cluster heads (CH). Let $NodeA^a$ be a set of sensor nodes in the annulus *a*:

$$NodeA^a = \{Node \mid Node.g_i = a\} \quad 0 \le a < N_G \qquad (3)$$

Each node activates the random generator to obtain a random index:

$$NodeA.r_j^a = \alpha * rand \quad 0 < j \le N^a \qquad (4)$$

where α is a constant to rescale the random number, and N^a is the number of nodes in annulus *a*. Without loss of generality, let A^a be a set of sensor nodes in annulus *a* in which:

$$A^a = \{NodeA^a \mid NodeA.r_{j-1}^a \ge NodeA.r_j^a\} \qquad (5)$$

The internal clock allows the sensor nodes that have higher random indices to transmit the *claim* message first using the code C_{a0}. The sensor node chosen to broadcast the *claim* message disables the other CH candidates around by setting their member indices to one. In addition, each sensor node records the time-of-arrival (TOA) corresponding to each CH. Again, the IR-UWB technology with high resolution in time domain allows sensor nodes using TOA to roughly determine the distances to the CHs. The CH election is implemented as follows:

```
For $NodeA_j^a$ in $A^a$
        Wait for internal clock
        If $NodeA.r_j^a \ne 0$
                $NodeA.m_j^a = 0$
                Transmit $\{C_{a0}, claim, NodeA.r_j^a\}$
        End If
End For
```

```
If Receive $\{C_{a0}, claim, NodeA.r_j^a\}$
        $NodeA.r_k^a = 0$
        $NodeA.m_k^a = 1$
        Save $TOA_j^a$
End If
```

After the CHs are selected, the member nodes start registering to claim their membership to the CH associated with the smallest TOA. Because the TOA estimation has certain sensitivity [10], if more than one CH have the same smallest TOA, the random generator is used to decide which cluster the member node belongs to. The member nodes that can hear from more than one CH are called the gateway (GW) nodes. The CH creates a time-division multiplexing schedule and sends the confirmation message to the member nodes. The CH elections and cluster formation in all annuluses can be performed in parallel since each annulus uses a particular orthogonal code.

C. *Sector Index Setup*

Each cluster now has been formed by a CH and a set of member nodes. The main purpose of sector index setup is to allow a CH to use a particular code to communicate with the member nodes and to know the codes used in the adjacent clusters. In the set A^a of annulus *a*, the first sensor node that is also a CH starts sending a *hello* message to the other CHs. This CH called the Anchor CH has the sector index zero, $AnchorCH.s^a = 0$. A GW node could play a role as a relay node to transfer the *hello* message to a CH. At the beginning of sector index setup stage, all sensor nodes are in the listening mode. When receiving the *hello* message, a CH becomes the active CH and follows a set of rules to find an external GW node in the other clusters and propagate the sector index:

1. The active CH notifies the member nodes its sector index, and sets them in sleeping mode.
2. The active CH looks for the external GW nodes using the code C_{a0}.
3. If the active CH cannot find an external GW node, the internal GW nodes are sequentially activated to find the external GW nodes using the code C_{a0}.
4. The external GW node having the shortest TOA is assigned to be the relay node.
5. The relay node notifies its CH to increase the sector index by 1. The CH of the cluster containing the relay node now becomes the active CH.

A flowchart of the sector index setup is shown in Fig. 3.

To make sure that the sector index is propagated in both directions in an annulus, the Anchor CH activates the members waiting for the *hello* message after time of a few propagations. If the Anchor CH receives the *hello* message, annulus *a* is complete and each cluster has a particular sector index in a set of consecutive indices. Here, two adjacent clusters are assigned two successive indices. If the Anchor CH does not hear the *hello* message, the dead end situation happens, in which both the active CH and the internal GW nodes cannot find the external GW nodes. In this case, the Anchor CH takes the role of the active CH and searches for a relay node among the remaining external GW nodes.

Finally, the end CHs send their sector indices to the Anchor CH to scale the sector indices to positive values starting from 1.

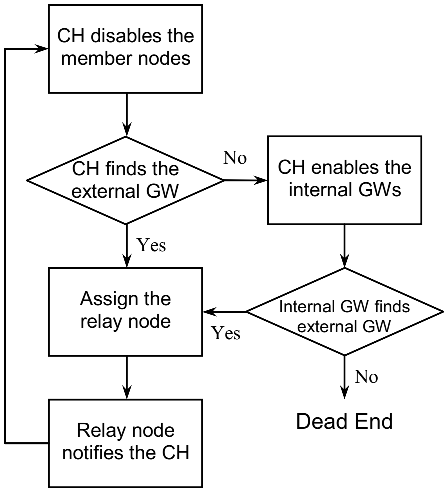

Figure 3. Flowchart of sector index setup

Based on the combination of gradient index *g* and sector index *s*, each cluster uses a PR code C_{gs} for intra-cluster communication, with $1 \le g \le N_G$ and $1 \le s \le N_S$. The cluster using code C_{gs} may be logically labeled as Z_{gs}. Since the sector indices in each annulus are assigned by continuous integers, a CH is able to know the codes used in the nearby clusters. This feature allows the sink to be aware of the location of the cluster that has the information. In addition, a CH can forward information to the neighbor clusters if the current cluster cannot communicate with any cluster at the lower annulus.

IV. STEEP DECENT ROUTING

After self-organization stage, all the sensor nodes are set in the sensing mode. When a sensor node detects an agent, the information including of the agent type and the cluster label is forwarded to the CH. To avoid collisions, the CH requests detection reporting according to a certain time-division multiplexing scheme. Such a scheme typically depends on the sensor platform and the number of agents to be detected.

In the routing stage, a CH makes use of the codes $C_{(a-1)0}$ to communicate with a CH in the lower annulus, and the code C_{gs} to talk to the member nodes in the order of priority. Here, a member node uses the codes $C_{(a-1)0}$ to find a CH in the lower annulus, and the codes $C_{g(s-1)}$ and $C_{g(s+1)}$ to notify CHs in the adjacent clusters in the same annulus following the order from its CH.

Now consider a single incidence of sensor detection for simplicity. Assume that a certain agent is detected by a sensor node in cluster Z_{jk}. This means Z_{jk} is located in the annulus with gradient index *j* lying within sector *k*, and the PR code for the cluster is C_{jk}. The information is transmitted to the sink along the steep decent path as follows:

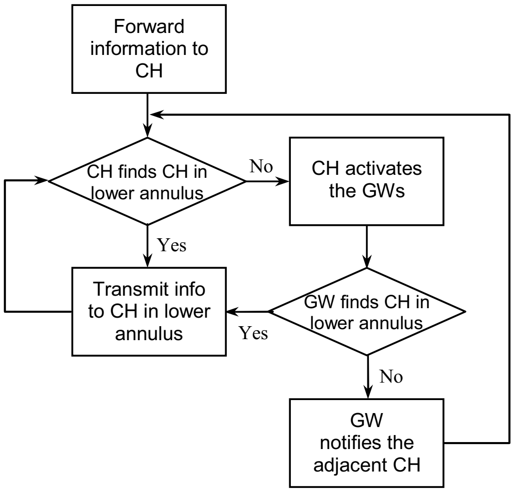

Figure 4. Flowchart of steep decent routing

1. If the agent is detected by a member node, the information is forwarded to the CH using the code C_{jk} .
2. The active CH finds a CH in the lower annulus using the code $C_{(j-1)0}$. If no CH is found that means no direct link between CHs, the CH activates the GWs to search for a CH in the lower annulus by code C_{jk} .
3. In the case of both active CH and GWs cannot transfer information to the lower annulus, the active GW notifies the CHs in the adjacent clusters using the codes $C_{j(k\pm1)}$.
4. The CH that receives the information from the upper annulus now becomes the active CH.

The flowchart of steep decent routing is shown in Fig. 4.

V. SIMULATIONS AND DISCUSSIONS

To demonstrate the feasibility and the effectiveness of the proposed protocol, computer simulations are performed using Matlab. The statistics are based on 1000 simulation runs for each network topology. The relevant network operating parameters and model data are specified as follows: (a) The sensor field is a 50m × 50m square area. (b) The number of sensor nodes is N = 500, corresponding to a medium dense network. (c) The range of the UWB sensor node is 10m that is proposed for low data rate UWB systems with low power of less than 10mW [7]. (d) The PR code bank contains $N_G \times (N_S + 1) + 1$ orthogonal Wash-Hadamard codes, where $N_G = 5$ and $N_S = 12$. That means the PR code bank in each sensor node can support a network having maximum 5 annuluses and 12 clusters in each annulus. Since each annulus only needs to recognize the upper and the lower annulus, the PR codes used for annuluses can be reused. In this case $N_G = 3$, and the total number of codes is $3N_S + 4$. The size as well as the orthogonal codes of the PR bank can be loaded in all sensor nodes before employing them in the field. The PR code bank size is depended on the node range and the field dimension.

Three network scenarios corresponding to 3 locations of the sink node (25, 25), (36, 14), and (46, 4) are considered respectively. Fig. 5 shows the formation of clusters in a network in which the location of the sink is (36, 14). The routing path from an arbitrary node in the outer annulus to the sink is also shown in Fig. 5. After numerous simulation runs, it is quite evident that the information always flow along a steep path of descending gradient index. The statistics of cluster formation and data routing for all the scenarios are presented in Table I and Table II, respectively.

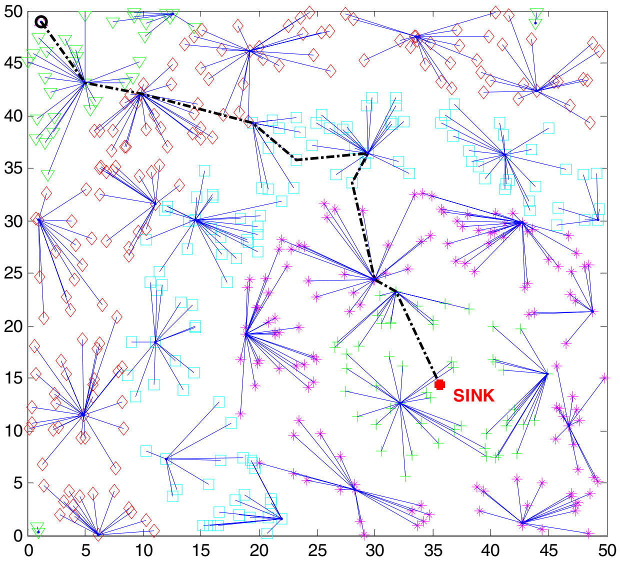

Figure 5. A data routing path and cluster formation in a sensor network of 500 nodes with Scenario II - The sink locates at (36, 14)

TABLE I. STATISTICS OF CLUSTER FORMATION

	Scenario I	**Scenario II**	**Scenario III**
% of CHs	5.81%	6.01%	5.99%
Average cluster size	18.20	17.64	17.82
Std. dev. of cluster size	7.94	8.35	8.27
% of non-single clusters	96.24%	94.23%	95.47%

TABLE II. STATISTICS OF DATA ROUTING

	Scenario I	**Scenario II**	**Scenario III**
Number of annluses	4	6	8
Average number of hops	5.32	8.35	10.59
% of successful transmissions	99.40%	99.12%	99.24%

Some key observations can be made as follows: (a) The statistics of cluster formation are independent on the sink locations. (b) The number of CHs is about 6% of the total number of sensor nodes and the average cluster size is around 18 nodes indicate that the entire network is efficiently managed by a small number of nodes, and most of the sensor nodes are in the sensing mode (c) The average number of hops from a outer annulus to the sink increases with the number of annuluses. Nevertheless, the average number of hops per annulus is relatively constant at 1.35 hops/annulus (d) The high percentage of successful transmissions to the sink is reasonable for a medium dense network.

TABLE III. STATISTICS OF GRADIENT AND SECTOR INDEX

	Scenario I	**Scenario II**	**Scenario III**
% of nodes covered by gradient index	100%	100%	100%
% of nodes covered by sector index	92.96%	99.01%	99.59%
% of clusters covered by sector index	85.92%	95.82%	98.45%

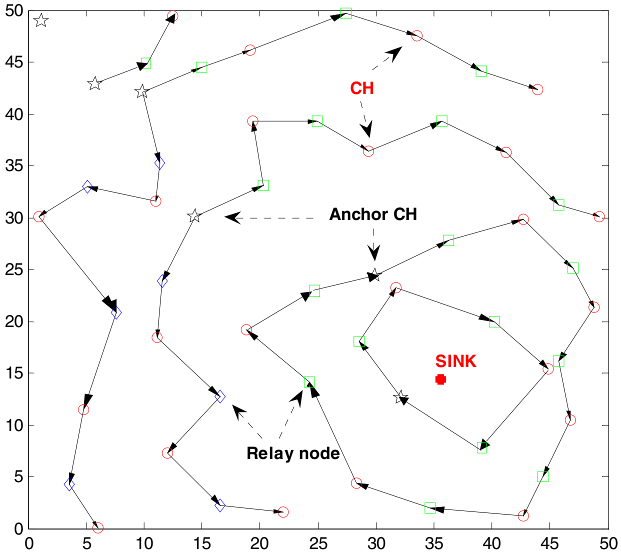

Figure 6. Sector index flow in each annulus of the network in Fig. 5

The statistics of the sensor network covered by gradient and sector indices are also presented in Table III. All of the sensor nodes are assigned a gradient index in all scenarios. This means an arbitrary node always can find a node in the lower annulus of the medium dense network. The differences in the coverage of sector index come from the dead zone situation in which a cluster cannot connect to the other clusters in the same annulus. The number of dead zones in three network scenarios is 4, 3 and 0, respectively. Thus, the percentage of clusters covered by sector index increases from scenario I to scenario III. However, these clusters are typically located at the small corners of the field, and consist of a few sensor nodes. The differences in the percentage of sensor nodes covered by sector index also confirm the statement above. Finally, Fig. 6 presents the sector index flow for the network shown in Fig. 5. The Anchor CHs in the first and second annuluses can hear the *hello* message indicating that both annuluses are complete. Although the third and fourth annuluses are incomplete, all clusters are assigned sector indices properly. Two out of four clusters in the fifth annulus have been covered by sector index since the annulus has two dead zones. However, each uncovered cluster only has two nodes.

VI. CONCLUSIONS

A gradient cluster-based protocol is proposed for a class of UWB wireless ad-hoc sensor networks. All the sensor nodes have the same characteristics and are equally limited in capabilities. Each sensor is equipped with a UWB transceiver, a random generator, and a memory bank of orthogonal PR codes. The network exhibits the ability of self-organization and the awareness of its cluster locations. The self-organization process is activated by a sink node, and completed when the nodes of the network are grouped into clusters. More importantly, each cluster in most scenarios becomes identifiable with a gradient index and a sector index, thereby avoiding the use of ID numbers. When an agent of interest is detected, the information can then be routed to the sink along a path defined by the steep descent of the gradient index. Simulation results convincingly confirm the feasibility of the protocol.

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