GB: Distributed Reachability-Tunable Broadcast Algorithms for Wireless Sensor Networks

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***Abstract*— In this paper, we propose Guided Broadcast algorithms (*GB*) – a family of distributed broadcast algorithms for Wireless Sensor Networks (*WSN*s). *GB* is based on the recently proposed Self-organizing Redundancy Cellular Architecture (*SoRCA*) for *WSN*s. It utilizes spatial diversity to cover the sensor nodes in the *WSN* for a tunable number of times to ensure that at least η portion, a parameter specified by *QoS*-requirements, of nodes will receive the Broadcast Message (*BM*), instead of striving for a 100% delivery ratio which can be costly and unnecessary in some *WSN* applications. Specifically, the Coverage Assurance Algorithm (*CAA*) in the *GB* family ensures that, in the ideal scenario, all nodes in the *WSN* receive any *BM* with probability that is at least η; the Propagation Assurance Algorithm (*PAA*) is invoked to circumvent obstacles and to ensure that *BM*s propagate through the entire *WSN*. Additionally, the Load Balancing and Equal Exposure scheme (*LBEE*) is proposed to balance broadcast energy cost. Our performance evaluations show that the proposed schemes possess several nice characteristics that fit well for many applications of *WSN*s.**

I. INTRODUCTION

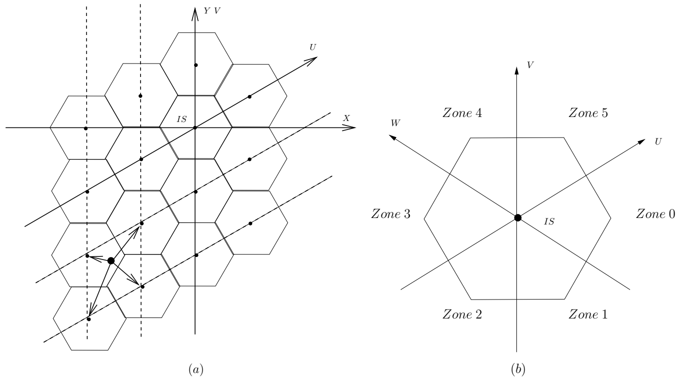
Wireless Sensor Networks (*WSN*s) are formed by sensor nodes that are randomly and usually densely distributed over an area. The number of nodes in *WSN*s is usually large. In many *WSN* applications, sensors do not have mobility; once deployed, the positions of nodes remain fixed. One or more Information Sinks (*IS*s) in the network collect and process the data generated by the sensors. Due to their limited physical size, sensors are expected to be extremely constraint in energy. Such a low level of energy reserve limits the lifetime of a *WSN*. However, many *WSN* applications require an extensive period of operation; it is therefore imperative to optimize energy efficiency. Another constraint resource is bandwidth; because the number of nodes in *WSN*s is large and they all share the same wireless medium, spectrum is scarce.

A fundamental operation frequently performed in wireless networks is broadcast. Flooding whereby each node rebroadcasts received **Broadcast Message (*BM*)** is not only inefficient in energy, it has also been shown to cause the *broadcast storm problem* [1] in dense wireless networks. Many alternative broadcast algorithms have been proposed for wireless ad hoc and sensor networks [1]–[13].

These algorithms can be roughly divided into three classes: 1) The first class of algorithms attempts to minimize the number of broadcasting nodes, while assuming that each sensor has a deterministic transmission radius r_t, i.e., all sensors within distance r_t from a broadcasting node will receive the *BM*. Examples hereof are [2]–[5]; 2) The second class of algorithms is based on neighborhood information acquired by broadcasting "Hello" messages locally. Decisions on which nodes should subsequently re-broadcast are made at each node or at the upstream broadcasting nodes based on either one- or two-hop neighborhood knowledge [7]–[10]. This class of algorithms are much less prone to signal propagation unpredictability, such as shadow fading, than the first class. They can usually guarantee that all nodes in a connected network receive all *BM*s; 3) The third class of algorithms recognize that wireless channels are unreliable due to transmission errors and wave propagation imperfections; various techniques are implemented to compensate for the unreliable wireless transmissions to achieve reachability $\eta \simeq 1$, defined as the average ratio of nodes that receive *BM*s [11]–[13].

Each of the above algorithms strives to deliver *BM*s to every node in the network. However, such an effort may not be necessary in *WSN*s. Sensors in *WSN*s are often densely deployed; the degree of both data and routing redundancy can be very high. In many cases, it would be sufficient to deliver a *BM* to only $\eta * 100\%$ of the nodes in the network, where $\eta < 1$. For example, in data-on-demand *WSN* applications, the *IS* could decide to collect $N/2$ random data samples with N being the total number of nodes in the network. Delivering the request packet to much more than $N/2$ nodes is undesirable since such an approach requires much of the scarce resources such as energy and spectrum in the process of broadcasting messages and collecting the sensed data. Similarly, due to route redundancy, it might be enough to broadcast the routing request to, say, $0.6N$ nodes. On the other hand, mission-critical information such as the location of the *IS* needs to be delivered to almost every sensor. The clearly different requirements need to be addressed differently during the broadcast process.

We therefore expect that there exist various classes of *BM*s in sensor networks, each with different broadcast requirements. For example, if a *BM* belongs to Class B, it is then associated with a reachability η_B. Furthermore, it is expected that the nodes reachable by the *BM*s should be distributed throughout the entire network rather randomly, instead of being concentrated in certain local neighborhood. These requirements are



(a) (b)

Fig. 1. Partitioning and routing directions in *WSN*

somewhat similar to $manycast$ [14]. It differs from $manycast$ in that the receiving nodes are randomly located rather than pre-determined.

When a node transmits a *BM*, only a subset of surrounding sensors will receive the *BM* successfully due to blockage, collisions, etc.[1] If spatial diversity is exploited, i.e., the same *BM* is broadcasted from several locations, the nodes in the overlapping areas of these broadcasts have a much higher probability of successful reception. The recently proposed Self-organizing Redundancy Cellular Architecture (*SoRCA*) for *WSN*s provides a framework to achieve controllable reachability, η, through spatial diversity [15]. In *SoRCA*, sensors autonomously divide the network coverage area into equal-sized partitions called **Redundancy Cells (*RC*s)**, as shown in Fig. 1.(a).

In this paper, we propose Guided Broadcast (*GB*) – a family of distributed broadcast algorithms. Using the inherent structure of *SoRCA*, *GB* covers each *RC* with just sufficient number of broadcasts from different locations to achieve the required reachability η specified by the *QoS*, i.e., *GB* devotes just as much resources as absolutely necessary to broadcasting. The set of reachable nodes are generally guaranteed to be randomly located throughout the entire *WSN* by the design of the Coverage Assurance Algorithm (*CAA*) and the Propagation Assurance Algorithm (*PAA*). Moreover, *GB* algorithms provide extra degrees of freedom of power control and resolution control in *WSN* applications.

The rest of the paper is organized as follows. Related work is discussed in Section II; Section III summarizes the *SoRCA* technique; the assumptions are listed in Section IV; The *CAA* and the *PAA* algorithms are presented in Section V and VI, respectively; in Section VII, the Load Balancing and Equal Exposure scheme (*LBEE*) that balances nodal broadcast exposure and energy expenditure is proposed; simulation results are given in Section VIII; conclusions and several potential topics for future research are presented in Section IX.

II. RELATED WORK

In general, all broadcast algorithms attempt to deliver *BM*s to each node; their main purpose is to minimize the total number of broadcasts while maintaining the value of η close to 1. Consequently, they do not have the flexibility to trade off reachability for energy savings such as those used on sending and forwarding excessive reactive replies, such as delivering much more than $N/2$ data samples to the *IS* in the example discussed in Section I.

The Optimized Flooding Protocol (*OFP*) is location-based and assumes that nodes have a constant r_t [4]. It solves the modified covering problem, i.e., covering an area with circles of radius r_t with the condition that centers of circles being placed on the circumferences of at least one other circle. In an ideal scenario, the *OFP* scheme may result in a hexagonal broadcast constellation. It can only guarantee that each node is covered by two separate broadcasts. Therefore, the reachability of the *OFP* scheme is similar to our $GB(n = 2)$ algorithm (presented in Section V). When radio propagation unpredictability is taken into account, *OFP* cannot precisely follow the hexagonal pattern. As a result, the number of re-broadcasts is expected to increase. However, η will increase in a rather uncontrollable manner. The *honeycomb stateful broadcast* using *TBP* follows a similar broadcast pattern [2]. A performance similar to $GB(n = 2)$ is expected when non-ideal channel condition is incorporated.

The neighborhood knowledge based algorithms such as self-pruning, dominant pruning, *SBA* and *AHBP* are based on one- or two-hop neighbor information acquired by the measurement and the reception of "Hello" messages and hence guarantees that $\eta = 1$ for connected networks [7]–[9]. However, such a high value of η may not be necessary in sensor networks and is often associated with excessive energy expenditure. They should be avoided whenever a lower η is sufficient.

The reachability in probabilistic and counter-based schemes can be somewhat adjusted by varying their parameters. However, these two types of schemes are relatively energy inefficient; such probabilistic schemes also have the undesirable bimodal behavior: either the broadcast is successful in covering most of the network, or it dies very early, covering only a small portion of nodes around the source [1], [2], [6].

In [16], the authors focused on the self-stabilization problem of communication among sensors spread in a geographic region. Imaginary polygons such as triangle, square, and hexagon were presented to tile the region for communication coverage purpose.

III. *SoRCA*

The *SoRCA* structure is centered at the *IS* and, using geographical information, sensors autonomously divide the network coverage area into hexagonal *RC*s and then calculates to which *RC* they belong. To facilitate easier *RC* notations, we introduce a new set of coordinates (u, v), where the V-axis coincides with the Y-axis and U-axis is 30 degrees tilted counterclockwise from the X-axis. The *RC* is said to have

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[1] Note that *ACK* packets cannot be used to guarantee broadcast reachability because it leads to the *ACK implosion problem* [13].

the coordinates (u,v) in the $U-V$ system if its geographical center has the coordinates $(x,y)=(\frac{3r}{2}u, \frac{\sqrt{3}r}{2}(u+2v))$.

SoRCA has two modes of operations [15]. In the first mode, only one node per *RC* is maintained active while the others are put into sleep for energy conservation purposes. The **Active Nodes (*AN*s)** are responsible for the collection and transmission of the local information; they are also responsible for forwarding data packets originated at other *RC*s that are en route to the *IS*. Since there is only one active node per *RC*, this operation mode requires accurate sensors and more reliable communication channels, i.e., higher reception probability p_r, which can be provided by increasing spatial channel reuse separations in the channel allocation process [17].

SoRCA can also operate in the second mode, in which each *RC* contains multiple active sensor nodes. This operation mode is necessary if, for example, the sensors are not reliable or if the *WSN* is consisted of a mixture of different types of sensors. In this mode, one active node is elected for each *RC* as the head active node (again referred to as the *AN*). Other active nodes in the *RC* (referred to as *aN*s) collect local information and transmit this data to the *AN*, where it is processed, compressed and transmitted. Furthermore, only *AN*s participate in the packet forwarding process. In both modes, *AN*s are the broadcasting nodes. The latter case is clearly more relevant for broadcasting.

Note that in *SoRCA* each sensor needs to bear a distinct ID, a system requirement that is similar to those in schemes such as *LEACH*, *SMACS*, and *SPAN* [18]–[20].

IV. ASSUMPTIONS

Sensors are assumed to be Poisson distributed with a mean of $\lambda\ nodes/m^2$. Similarly as in [1], [2], [4], each node is assumed to know its location (x,y), which can be either absolute, as produced by GPS, or relative, as estimated using acoustic signals or algorithms proposed in [21] and [22]. We argue that this assumption is realistic since many envisioned *WSN* applications, such as fire or enemy detection, are location-based; in these applications, location information should already be available to sensors for meaningful data (occurrence and location of events) delivery [15]. Sensor localization is currently an active research field and it is out of the scope of this work.

We assume that, when a node initiates a *BM*, it is aware of the *BM*'s class and the associate reachability η. Nodes maintain a list of packets that they have broadcasted, to prevent themselves from re-broadcasting multiple copies of the same packet. Furthermore, it is assumed that the underlying *SoRCA* is already formed.

Given *SoRCA*, broadcast channels can be allocated to each *RC* by the *DRAA* algorithm in such a way that if any *AN* broadcasts at maximal power, all nodes within its coverage area (its own *RC* and the first-tier *RC*s) will receive the packet with probability that is at least p_r, taking into account that nodes can be located at the maximal distance $\sqrt{13}r$, r being the radius of the *RC* [17]. In the case that there are multiple active nodes per *RC*, the intra-cell communications are assumed not to influence the broadcast channel, e.g., each *RC* is allocated a time slot. During that slot, broadcast messages are first sent out, then intra-cell communications commence; alternatively, intra-cell and inter-cell communications can use different channels (partitioned by code, frequency, time or combinations thereof).

TABLE I

NUMERICAL REPRESENTATIONS OF ROUTING DIRECTIONS

Dir.	+U	-W	-V	-U	+W	+V
i	0	1	2	3	4	5
$S(i)$	$(1,0)$	$(1,-1)$	$(0,-1)$	$(-1,0)$	$(-1,1)$	$(0,1)$

V. THE COVERAGE ASSURANCE ALGORITHM

Once the hexagonal topology is set up, for any given *RC*, there are only six directions in which an *AN* can transmit packets, $\pm U$, $\pm V$ and $\pm W$, as shown in Fig. 1.(b). If we denote these directions numerically by $i \in \{0,1,2,3,4,5\}$, then for any given i and j, the operation $i+j \doteq mod(i+j,6)$ is equivalent to shifting direction i clockwise for $j*60$ degrees. The area between direction i and direction $i+1$ is referred to as Zone i centered at *RC* (u,v). The directions, their numerical notation i, and the change in *RC* coordinates associated with one step in these directions, $S(i)$, are given in Table I.

Each broadcast message has the structure shown below.

(u_0,v_0)	seq	sch	$stage$	(u_b,v_b)	R	D	C	$data$

The field (u_0,v_0) records the ID of the source *RC*; seq is the sequence number; sch is a number representing one of the seven broadcast schemes ($1 \le sch \le 7$) that will be described below; $stage$ is the stage that the broadcast process is currently in ($0 \le stage \le 3$); (u_b,v_b) is the ID of the current broadcasting *RC*; R is the relay flag with $R=1$ indicating that this message is in the relay mode; D is the current direction of propagation; C is a counter and the remainder of the *BM* contains data.

The *CAA* is consisted of seven broadcast schemes, namely, $GB(n)$ schemes with $1 \le n \le 7$. The $GB(n)$ scheme guarantees that every node in the *WSN* is covered by at least n broadcasts of the same *BM* by n different broadcasting *AN*s. A node is said to be covered by a broadcast if the transmitting *AN* is in the same *RC* as the node or if the *AN* is located in one of the six direct neighboring *RC*s.

As previously mentioned, the broadcast channels can be allocated in such a way that if a node is covered by a broadcast, the node has a probability $\Phi_r \ge p_r$ that it will successfully receive the *BM*, where p_r is a pre-defined reception probability that affects broadcast channel allocation and transmission power [17]. Let us assume that node S is covered by n broadcasts of the same *BM* broadcasted from *AN*s at different locations, then for the k-th broadcast, the event that S does not receive the *BM* is associated with the probability $p_{k,nr} \le 1-p_r$. Assuming that the broadcast channels are independent,

Algorithm 1 Pseudo codes for stage 0 broadcasts

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$(u_o, v_o) \leftarrow (u, v)$, $(u_b, v_b) \leftarrow (u, v)$, $R \leftarrow 0$      ▷ set flags in header
$seq \leftarrow j + 1$, $C \leftarrow 0$, $sch \leftarrow n$, $stage \leftarrow 0$, $D \leftarrow 0$      ▷ initialization
$\mathcal{L} \leftarrow \{0, 1, 2, 3, 4, 5\}$      ▷ add RCs in all directions to $\mathcal{L}$
broadcast BM, $monitor(\mathcal{L}, T)$      ▷ monitor $\mathcal{L}$ broadcast BM
```

the probability of S receiving the *BM* is

$$\Phi_r = 1 - \prod_{k=1}^{n} p_{k,nr} \geq 1 - (1 - p_r)^n \ .$$

If each of the N nodes in the *WSN* is guaranteed to be covered for at least n times, the expected percentage of nodes in the *WSN* that successfully receive the *BM* is

$$\eta \ = \ \frac{\Phi_r N}{N} \geq 1 - (1 - p_r)^n \ . \tag{1}$$

If a packet to be broadcasted is of class B and the *QoS* requires that $\eta_B * 100\%$ of nodes in the network should receive it, the number of broadcast coverage is

$$n = \left\lceil \frac{\log(1 - \eta_B)}{\log(1 - p_r)} \right\rceil \ ,$$

provided that $0 < p_r < 1$. Based on (1), when $p_r > 0.5$ and $n = 7$, we have $\eta > 0.9922$; if $p_r > 0.6$ and $n = 7$, then $\eta > 0.9984$. Therefore, we consider *GB*, consisted of seven broadcast schemes, to be able to provide reachability that are sufficient for most viable cases.

We now present the details of the *CAA* scheme. In this section's discussions, we assume that a *BM* will always be received by downstream broadcasting *AN*s; the extension to non-ideal cases will be discussed in Section VI. Generally speaking, all broadcast schemes have four stages:

Stage 0: An *RC* (u_o, v_o) initiates broadcast by transmitting a *BM*.

Stage 1: The *BM* is broadcasted along the direction i starting from the direct neighbor of (u_o, v_o) located in the i^{th} direction to (u_o, v_o), $i \in \{0, 1, 2, 3, 4, 5\}$.

Stage 2: After receiving a *BM* that is broadcasted in Stage 1 along the direction i, $i \in \{0, 1, 2, 3, 4, 5\}$, the *BM* is subsequently broadcasted along the direction $i + 1$.

Stage 3: Depending on the broadcast scheme, after receiving a Stage 1 or Stage 2 *BM*, an *AN* may re-broadcast it once. It is also referred to as leaf broadcast.

These four stages are depicted in Fig. 2 for the $GB(n = 1)$ scheme. As shown in Fig. 2, *BM*s should propagate along the arrows. If an arrow head is not contained by any *RC*, it indicates that *BM*s should continue to propagate along the same direction to the edge of the *WSN*; an arrow head that is completely contained by an *RC* is associated with a leaf broadcast and indicates that this *RC* should be the last one to broadcast the *BM* in the present direction.

Stage 0 broadcast is the same for all seven schemes. Assuming that the source with ID (u, v) has broadcasted j messages and needs to broadcast a new *BM* with coverage number n, it executes Algorithm 1.

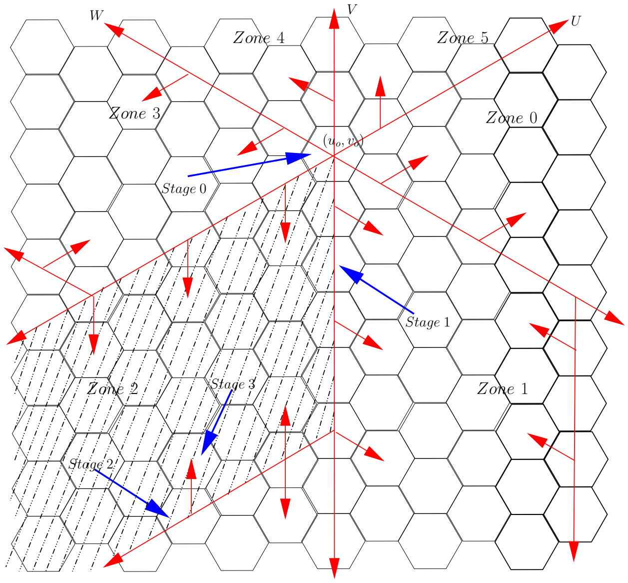

Fig. 2. The $GB(n = 1)$ Scheme, $\Phi_r \geq p_r$

Define $list((u_o, v_o), seq)$, henceforth denoted as $\mathcal{L}$, as the list containing neighboring *AN*s that should subsequently broadcast the *BM* $((u_o, v_o), seq)$ after reception, the function $monitor(\mathcal{L}, T)$ is used to monitor that all subsequent broadcasters would indeed continue sending the *BM* to ensure that the *BM* propagates throughout the entire network. They are trivial in the ideal scenario assumed in this section, but are essential for the functionality of *GB* when we extend the broadcast algorithm to the non-ideal scenarios.

Another common feature of the broadcast schemes is that *AN*s only re-broadcast *BM*s that they receive from one of six of their direct neighboring *AN*s. When a *BM* is received by the *AN* with ID (u, v), the *AN* first calculates the relative coordinates between itself and the broadcasting *AN* by $d_c = (u_d, v_d) = (u, v) - (u_b, v_b)$; the message propagation direction can then be calculated by

$$d = \begin{cases} i & \text{if } d_c = S(i), i \in \{0, 1, 2, 3, 4, 5\} \\ \text{inf} & \text{otherwise} \end{cases} \ . \tag{2}$$

A. The $GB(n = 1)$ Scheme

The $GB(n = 1)$ scheme guarantees $n = 1$, i.e., every *RC* in the *WSN* is covered by at least one broadcast of any *BM*. It is depicted in Fig. 2 and its operation at the *AN*s can be represented by the pseudo codes in Algorithm 2, in which d is calculated by (2), and (u_o, v_o), seq, sch, $stage$, R, D, C are fields in the header of the received *BM*. It will become clear that (u_o, v_o), seq, sch do not change from broadcast to broadcast while $stage$, R, D and C will be modified by *AN*s.

An *AN* only re-broadcasts *BM*s that it received from its neighbors ($d \neq \text{inf}$). However, nodes can choose to process the data originated from *AN*s further away to increase the reception probability Φ_r; alternatively, they can choose to turn off their receivers after decoding only the *BM* header and discovering that $d = \text{inf}$, hence ignore the remainder of the

Algorithm 2 Pseudo code for the $GB(n=1)$ scheme

```
 1: if $d \neq \inf$ then
 2:     process data
 3:     if message $seq$ from $(u_o, v_o)$ is already broadcasted then
 4:         $\mathcal{L} \leftarrow \mathcal{L} - d$
 5:     else
 6:         *************** Pseudo code below can be represent by matrix form ***************
 7:         $b\_flag \leftarrow 0$        ▷ $b\_flag = 1$ means should re-broadcast
 8:         $\mathcal{L} \leftarrow \emptyset$
 9:         if stage = 0 then
10:             $stage \leftarrow 1$, $D \leftarrow d$, $C \leftarrow 0$
11:             $\mathcal{L} \leftarrow \{d, d-1\}$,$b\_flag \leftarrow 1$
12:         else if  stage =1 then
13:             if $d = D$ then
14:                 $\mathcal{L} \leftarrow d$
15:                 if $mod(C, 2) = 1$ then
16:                     $\mathcal{L} \leftarrow \mathcal{L} \cup d - 1$
17:                 end if
18:                 if $mod(C, 5) = 3$ then
19:                     $\mathcal{L} \leftarrow \mathcal{L} \cup d + 1$
20:                 end if
21:                 $C \leftarrow C + 1$, $b\_flag \leftarrow 1$
22:             else if $(d = D - 1)$ & $(mod(C, 2) = 0)$ then
23:                 $stage \leftarrow 3$, $b\_flag \leftarrow 1$
24:             else if $(d = D + 1)$ & $(mod(C, 5) = 4)$ then
25:                 $stage \leftarrow 2$, $C \leftarrow 0$, $D \leftarrow d$
26:                 $\mathcal{L} \leftarrow \{d, d-1, d+2\}, b\_flag \leftarrow 1$
27:             end if
28:         else if stage =2 then
29:             if $d = D$ then
30:                 $\mathcal{L} \leftarrow d$
31:                 if $mod(C, 2) = 1$ then
32:                     $\mathcal{L} \leftarrow \mathcal{L} \cup \{d-1, d+2\}$
33:                 end if
34:                 $C \leftarrow C + 1$, $b\_flag \leftarrow 1$
35:             else if $((d = D - 1)|(d = D + 2))\&(mod(C, 2) = 0)$
                    then
36:                 $stage \leftarrow 3$, $b\_flag \leftarrow 1$
37:             end if
38:         end if
39:         if b_flag = 1 then
40:             $(u_b, v_b) \leftarrow (u, v)$, broadcast modified BM
41:             monitor($\mathcal{L}$,T)
42:         end if
43:         *************** Pseudo code above can be represent by matrix form ***************
44:     end if
45: end if
```

BM to conserve energy. If a new *BM* (message $((u_o, v_o), seq)$ has not been re-broadcasted by the receiving *AN*) arrives with $d \neq \inf$, the *AN*'s behavior is dependent on which stage the *BM* is currently in. If $stage = 3$, no action is undertaken since Stage 3 broadcast does not propagate; if $stage = 0$, i.e., the transmitting *AN* is the source node, the receiving *AN* must ensure that the *BM* will continue propagating in Stage 1 mode along direction d; if $stage = 1$, the receiving *AN* should guarantee that the *BM* should propagate in the D direction as well as branch off to the Stage 2 and Stage 3 broadcast directions according to the design of the $GB(n = 1)$ scheme; in this aspect, the *AN*'s behavior when $stage = 3$ is very similar to that when $stage = 2$.

The pseudo code between Line 6 and Line 43 of the $GB(n = 1)$ scheme in Algorithm 2 can also be summarized by the matrix shown in Table II. The *AN* should execute all actions that satisfy $C1\&C2\&C3 = 1$ in the descending order. If a condition spans across several rows, it is a common condition for each of the rows.

Theorem 1: The $GB(n = 1)$ scheme guarantees that $n = 1$, i.e., for any *BM*, every sensor node in the *WSN* will be exposed to the *BM* at least once.

Proof: To show that the $GB(n = 1)$ scheme guarantees $n = 1$, it is equivalent to show that for any *RC* in the *WSN*, the $GB(n = 1)$ scheme ensures that there will be an *AN* broadcasting in that *RC* or in one of its six neighboring *RC*s. It is easily observed from the pseudo code and from Fig. 2 that the $GB(n = 1)$ scheme is exactly the same for each Zone i centered at (u_o, v_o), $i \in \{0, 1, 2, 3, 4, 5\}$. It suffices to show that the $GB(n = 1)$ scheme guarantees $n = 1$ for Zone 2 (*RC*s with ID $(u_o + u, v_o + v)$, $u \leq 0$, $v \leq 0$). Similarly, the $GB(n = 1)$ scheme repeats the same broadcast pattern within the blocks of *RC*s with ID $(u_o + u, v_o + v)$, $u \leq 0, 5j \leq v \leq 5(j + 1)$, $j \in \{0, -1, -2, \cdots\}$. Without loss of generality, we assume that $(u_o, v_o) = (0, 0)$, the original problem reduces to proving that for every *RC* with ID (u, v), $u \leq 0, -5 \leq v \leq 0$ (depicted as the shaded area in Fig. 2), the $GB(n = 1)$ scheme dictates that an *AN* in either (u, v) or in one of its six neighboring *RC*s should participate in the broadcast process.

The *AN* in *RC* $(-1, 0)$ must broadcast, because when it receives the Stage 0 *BM* from (u_o, v_o), it initiates Stage 1 broadcast in direction $-U$ (direction 3) with $C = 0$ according to the $GB(n = 1)$ scheme. If *AN* in *RC* $(u, 0), u < 0$, broadcasts Stage 1 *BM* with $C = -u - 1$, then the *AN* in *RC* $(u - 1, 0)$ will also broadcast Stage 1 *BM* with $C = -u$. Therefore all *RC*s with ID $(u, 0), u < 0$ are covered by the *BM*. Since *RC*s with ID $(u, -1), u < 0$ are the direction $-V$ neighbors of *RC*s $(u, 0)$, they are covered by the *BM* as well. After receiving the *BM* from *RC* $(u, 0), u < 0, u\ odd$ with $C = -u-1$, each *RC* with ID $(u, -1), u < 0, u\ odd$ will satisfy the conditions $stage = 1, mod(C, 2) = 0, d = 3-1 = 2$, therefore it will broadcast the *BM* in Stage 3 of the $GB(n = 1)$ scheme. Its neighboring *RC*s in the directions 1 and 2 with ID $(u, -2)$ and $(u + 1, -2)$ are covered by this Stage 3 broadcast of the *BM*. Using similar arguments, we can show that *RC*s with ID $(u, v), u < 0, -5 \leq v \leq -3$ are covered by the *BM*. Hence, the $GB(n = 1)$ scheme guarantees that $n = 1$ for all *RC*s in the *WSN*. ■

B. The $GB(n)$ Schemes, $2 \leq n \leq 7$

The $GB(n)$ schemes, $2 \leq n \leq 7$, are depicted in Figs. 3-8, respectively. The proofs of correctness for these *GB* schemes are similar to that of the $GB(n = 1)$ scheme. The discussions and matrix representations of these schemes are omitted due to page limit and can be found in [23].

VI. THE PROPAGATION ASSURANCE ALGORITHM

The *PAA* ensures that *AN*s specified by the *GB* schemes indeed broadcast *BM*s and that the *BM*s propagate through the entire *WSN*. It is invoked by the function $monitor(\mathcal{L}, T)$. Let $t_{b,((u_o,v_o),seq)}$ be the broadcast time for the packet $((u_o, v_o), seq)$, and t be the current time, the function $monitor$ can be represented by the pseudo code given in Algorithm 3.

TABLE II

MATRIX REPRESENTATION OF THE $GB(n=1)$ SCHEME

C 1	C 2	C 3	Action if $C1\&C2\&C3 = 1$
1	1	1	$b\_flag \leftarrow 0$; $\mathcal{L} \leftarrow \emptyset$
$stage = 0$	1	1	$stage \leftarrow 1$; $D \leftarrow d$; $C \leftarrow 0$; $b\_flag \leftarrow 1$; $\mathcal{L} \leftarrow \{d, d-1\}$
$stage = 1$	$d = D$	$mod(C,2) = 1$	$\mathcal{L} \leftarrow d-1$
		$mod(C,5) = 3$	$\mathcal{L} \leftarrow d+1$
		1	$C \leftarrow C+1$; $b\_flag \leftarrow 1$; $\mathcal{L} \leftarrow \mathcal{L} \cup d$
	$d = D-1$	$mod(C,2) = 0$	$stage \leftarrow 3$; $b\_flag \leftarrow 1$
	$d = D+1$	$mod(C,5) = 4$	$stage \leftarrow 2$; $D \leftarrow d$;$C \leftarrow 0$; $b\_flag \leftarrow 1$; $\mathcal{L} \leftarrow \{d, d-1, d+2\}$
$stage = 2$	$d = D$	$mod(C,2) = 1$	$\mathcal{L} \leftarrow \{d-1, d+2\}$
		1	$b\_flag \leftarrow 1$; $C \leftarrow C+1$; $\mathcal{L} \leftarrow \mathcal{L} \cup d$
	$d = D-1$	$mod(C,2) = 0$	$stage \leftarrow 3$; $b\_flag \leftarrow 1$
	$d = D+2$	$mod(C,2) = 0$	$stage \leftarrow 3$; $b\_flag \leftarrow 1$
$b\_flag = 1$	1	1	$(u_b, v_b) \leftarrow (u, v)$; broadcast modified *BM*; monitor $(\mathcal{L}, T)$

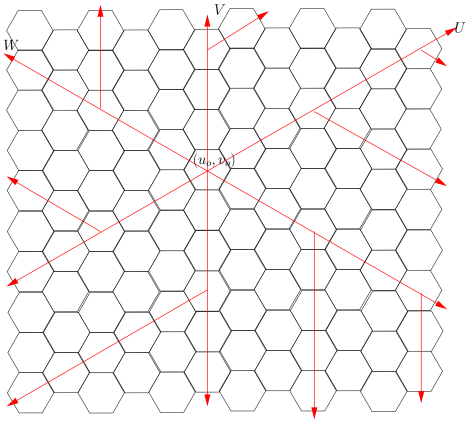

Fig. 3. The $GB(n=2)$ Scheme, $\Phi_r \geq 1-(1-p_r)^2$

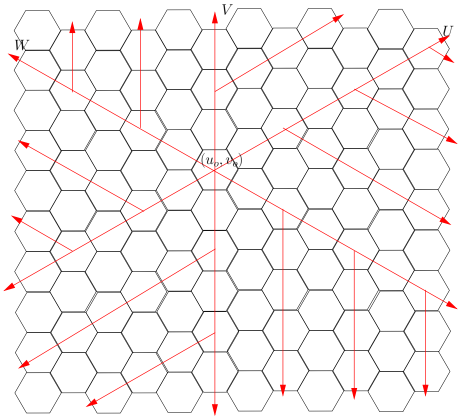

Fig. 4. The $GB(n=3)$ Scheme, $\Phi_r \geq 1-(1-p_r)^3$

Algorithm 3 Function $monitor(\mathcal{L}, T)$

```
if $\mathcal{L} \neq \emptyset$ then
    $blocked \leftarrow \mathcal{L} \bigcap \mathcal{BL}$
    if $blocked \neq \emptyset$ then
        $Relay(blocked, ((u_o, v_o), seq))$
    end if
    if $t - t_{b,((u_o,v_o),seq)} \geq T$ then
        $\mathcal{BL} \leftarrow \mathcal{BL} \bigcup \mathcal{L}$
        $Relay(\mathcal{L}, ((u_o, v_o), seq))$
    end if
end if
```

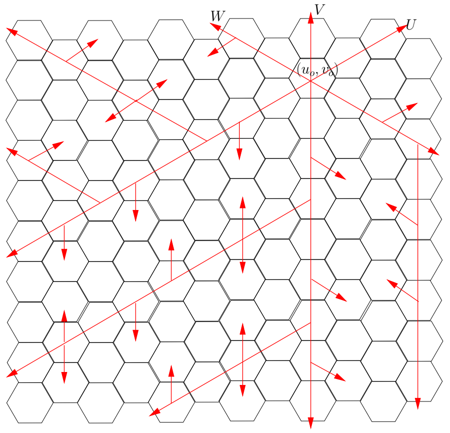

Fig. 5. The $GB(n=4)$, $\Phi_r \geq 1-(1-p_r)^4$

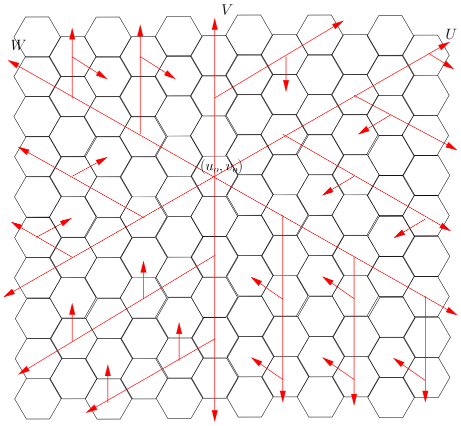

Fig. 6. The $GB(n=5)$ Scheme, $\Phi_r \geq 1-(1-p_r)^5$

Each *AN* maintains $\mathcal{BL}$, a list of blocked neighboring *AN*s (inaccessible from itself). If the *AN* transmits a *BM* and finds that some neighborings *AN*s are in $\mathcal{L} \bigcap \mathcal{BL}$, it can directly initiate function *Relay* to circumvent obstacles or bad links. *Relay* is also called when no subsequent broadcast is received from the downstream re-broadcaster contained in $\mathcal{L}$ within time T. Clearly, routing decisions for regular packets should also be made on the basis of $\mathcal{BL}$. A Routing Structure Building

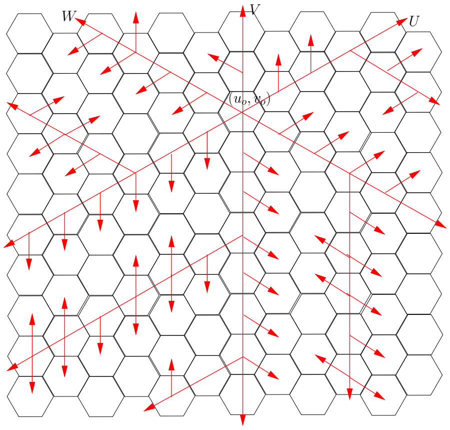

Fig. 7. The $GB(n = 6)$ Scheme, $\Phi_r \geq 1 - (1 - p_r)^6$

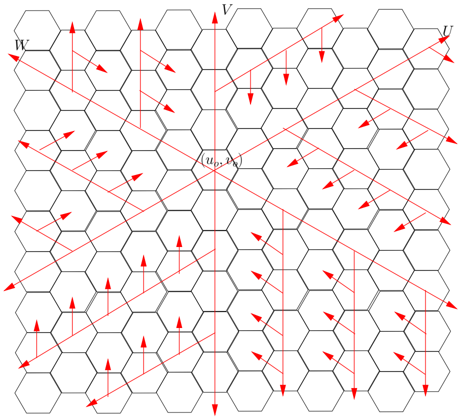

Fig. 8. The $GB(n = 7)$ Scheme, $\Phi_r \geq 1 - (1 - p_r)^7$

Algorithm 4 Function $Relay(\mathcal{L}, ((v_o, v_o), seq))$

```
1: $ds \leftarrow 0$, $rStage \leftarrow stage$, $C_r \leftarrow C_{max}$
2: if $sch \in \{1, 4, 6\}$ then
3:     $ds \leftarrow 1$
4: end if
5: if $stage = 0$ then
6:     for every $i \in \mathcal{L}$ do
7:         $RelayStep(((v_o, v_o), seq), rStage, C_r, ds, i)$
8:     end for
9: else if $stage = 1 \bigcup stage = 2$ then
10:    for every $i \in \mathcal{L}$ do
11:        if $i = D + 1$ then                ▷ Stage 2 branch off
12:            $rStage \leftarrow 2$
13:        else if $i \neq D$ then            ▷ Stage 3 broadcast
14:            $rStage \leftarrow 3$, $C_r \leftarrow 2$, $ds \leftarrow 0$
15:        end if
16:        $RelayStep(((v_o, v_o), seq), rStage, C_r, ds, i)$
17:    end for
18: end if
```

Algorithm 5 Function $RelayStep(((v_o, v_o), seq), rStage, C_r, ds, i)$

```
1: $(u_b, v_b) \leftarrow (u, v)$, $(u_r, v_r) = (u, v)$, $stage \leftarrow rStage$, $D \leftarrow i$,
       $l\_r \leftarrow 0$
2: $R \leftarrow 1$, $dir \leftarrow \{i + 1, i + 2, i + 3\} \bigcap \mathcal{BL}$
3: if $dir = \emptyset$ then
4:     if $stage \neq 3$ then
5:         $ds \leftarrow 1$
6:     end if
7: else
8:     $relayer \leftarrow \arg\min_k k - i, k \in dir$
9:     broadcast BM
10: end if
11: if $ds = 1$ then
12:    $l\_r \leftarrow 1$, $dir \leftarrow \{i - 1, i - 2, i - 3\} \bigcap \mathcal{BL}$
13:    if $dir \neq \emptyset$ then
14:        $relayer \leftarrow \arg\max_k k - i, k \in dir$
15:        broadcast BM
16:    end if
17: end if
```

Algorithm (*RSB*) is proposed in [23] to discover local routing structures and to initialize and maintain $\mathcal{BL}$.

In *Relay*, the left-hand rule is used to relay *BM*s. However, if $GB(n = 1, 4, 6)$ are used, both the left- and right-hand rules must be utilized (indicated by $ds = 1$) to avoid loss of coverage. A packet is relayed for at most C_{max} steps. If $stage = 0$, each $i \in \mathcal{L}$ must be individually relayed in their own direction; Stage 3 *BM*s are not relayed; as can be observed from Section V, $D + 1 \in \mathcal{L}$ indicates stage 2 broadcasts branching off Stage 1 axis, and $i \in \mathcal{L}, i \notin \{D, D+1\}$ indicates Stage 3 broadcasts. The parameters must be set accordingly when calling for *RelayStep*. *RelayStep* by default uses the left-hand rule (Line 2-9). However, right-hand rule (indicated by $l\_r = 1$) can also implemented (Line 12-15).

The pseudo code given in Algorithm 6 should be added between Line 8 and Line 9 in the $GB(n)$ schemes to check whether the *BM*s are being relayed. Line 4-9 check whether the *BM* has arrived on the extension of the original propagation direction. Line 10-19 examine whether the packet arrives at a stage 2 axis when the *BM* is in Stage 0 or 1 relay mode (since Stage 2 broadcasts branch off from Stage 1 axis in the $D+1$ direction, Stage 2 broadcast must also commence according to the current $GB(n)$). If so, the relay counter C_r should be reset to C_{max}, and the code between Line 32 and Line 39 should be executed. Line 19-31 continue to relay the packet if $C_r > 0$ and if the *BM* is still not propagating along the correct path. $P(n)$ is given by

$$P(n) = \begin{cases} 5 & \text{if n = 1} \\ 3 & \text{if n = 2, 4, 6} \\ 2 & \text{if n = 3, 5, 7} \end{cases} . \tag{3}$$

VII. LOAD BALANCING AND EQUAL EXPOSURE

It can be observed from the Figs. 2-8 that, when n is small, the *BM*s propagate through only a selected set of *RC*s in the *WSN*. If some *RC*, e.g., the *IS* broadcasts a large number of *BM*s, then its selected set of *RC*s must devote much more resources to the broadcast process. This problem is particularly severe for the *RC*s on the Stage 1 axes since they must broadcast every time. Excessive use of a set of *RC*s may cause long delays or early death for these *RC*s, which in turn can lead to significant reduction of network functionalities or even network partition. It is thus desirable to balance the traffic load among all *RC*s. Moreover, using different sets of *RC*s for broadcasting can lead to more balanced exposure to the *BM*s for the nodes in the network. Such balanced traffic

Algorithm 6 Pseudo code for relaying *BM* after receiving a *BM* in relay mode in the $GB(n)$ scheme

```
if $R = 1$ then                                          ▷ check if in relay mode
    $stop \leftarrow 0,\ continu \leftarrow 1$ ▷ 1 = continue check for all $stage$ cases
    $2nd\_r \leftarrow 0$          ▷ 1 means it should continue 2nd stage broadcast
    if $(u, v) - (u_r, v_r) = nS(D),\ n \in \mathcal{N}$ then
        $R \leftarrow 0,\ C \leftarrow C + n - 1,\ stop \leftarrow 1$
        remove flags $C_r$, $(u_r, v_r)$, $l\_r$, $relayer$ from BM
        if $stage = 0$ then
            $stage \leftarrow 1,\ C \leftarrow C - 1$
        end if
    else if $(u, v) - (u_r, v_r) = nS(D) + mS(D + 1)\ m, n \in$
        $\mathcal{N} \bigcap stage < 2$ then
        $C \leftarrow C + n - 1$
        if $stage = 0$ then
            $stage \leftarrow 1,\ C \leftarrow C - 1$
        end if
        if $mod(C, P(sch)) = P(sch) - 2$ then            ▷ do 2nd stage
            $C_r \leftarrow C_{max},\ 2nd\_r \leftarrow 1,\ C \leftarrow m - 2$
        end if
    end if
    if $(d = i) \bigcap (relayer = i + 3) \bigcap (C_r > 0) \bigcap (stop = 0)$ then
        if $l\_r = 0$ then
            $dir \leftarrow \{i - 1, i, i + 1, i + 2\} \bigcap \mathcal{BL}$
            $relayer \leftarrow \arg\min_k k - i + 1, k \in dir$
        else
            $dir \leftarrow \{i + 1, i, i - 1, i - 2\} \bigcap \mathcal{BL}$
            $relayer \leftarrow \arg\max_k k - i - 2, k \in dir$
        end if
        if $relayer \neq \emptyset$ then
            $C_r \leftarrow C_r - 1, (u_b, v_b) \leftarrow (u, v),\ continu \leftarrow 0$
            broadcast BM                                  ▷ continue relay
        end if
    end if
    if $2nd\_r = 1$ then
        $stage \leftarrow 2,\ D \leftarrow D + 1,\ continu \leftarrow 1$
        remove flags $C_r$, $(u_r, v_r)$, $l\_r$, $relayer$ from BM
        if $sch = 5 \bigcap mod(n, 4) = 2$ then
            $C \leftarrow C + 1$
        end if
    end if
    if $continu = 0$ then
        exit                               ▷ skipping all $stage$ cases below
    end if
end if
```

and exposure can be produced by applying *LBEE*, which sends *BM*s through one-to-one traffic to different *RC*s that use different Stage 1 axes; these *RC*s then broadcast as if the *BM*s are originated from themselves.

In *LBEE*, if the *AN* in an *RC* that broadcasts often needs to send a *BM* using $GB(n)$, it randomly generates two numbers, Δu and Δv, both picked uniformly from the set $\{0, \pm 1, \cdots, \pm hP(n)\}$, $h \in \mathcal{N}$. Then the *AN* routes the *BM* to to *RC* $(u, v) + (\Delta u, \Delta v)$ using *DPRA* [17] and requests it to broadcast the *BM*. An example is given in Fig. 9 where the *IS* requests *RC* $(2, 2)$ to broadcast a *BM* with $n = 2$.

When h is large, the broadcast traffic around *IS* can be significantly lowered and thus it will not aggravate much the high-volume traffic situation at the *IS* that is expected to be the worst in the network due to the many-to-one traffic pattern (*hot-spot problem*) and performance-limiting for the *WSN* [17]. However, larger h means that the *BM* must travel a relatively long path before it can be broadcasted. The tolerable delay and energy expended for routing the packet to its eventual broadcaster should also be taken into account.

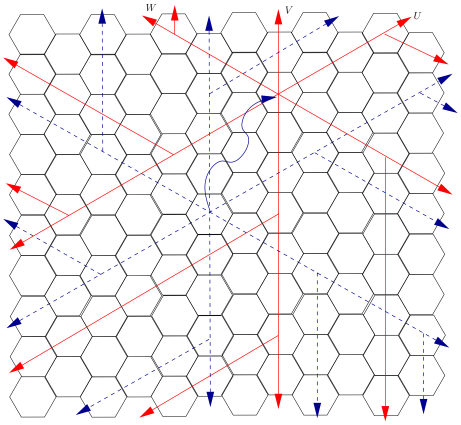

Fig. 9. Scheme for balancing broadcast load and obtaining equal exposure

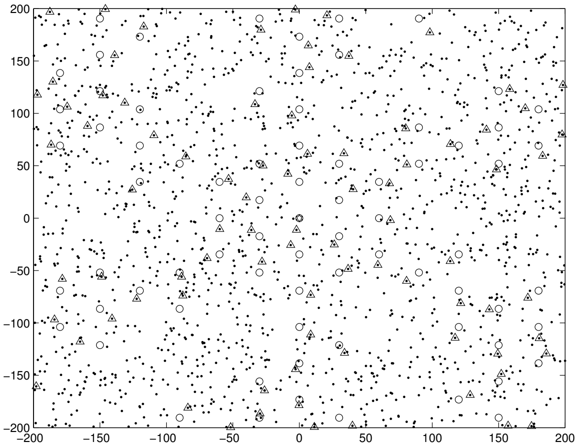

Fig. 10. An example of broadcasting *RC*s and *AN*s. Nodes are represented as small dots. Each of the circles is the geographical center of a broadcasting *RC*. The triangle represents the *AN* that sends the broadcast.

VIII. SIMULATIONS AND DISCUSSIONS

Due to the complexity of the theoretical analysis of the proposed schemes, we turn to simulations to evaluate their performance under different settings. In the simulations, sensor nodes are distributed over a square area of 400 m by 400 m according to the 2-D Poisson distribution, unless specified otherwise. The source of *BM*s is located at the center. The radius of *RC*s is $r = 20\ m$. *BM*s should be broadcasted to the entire area. We evaluated the proposed $GB(n)$ schemes with $1 \leq n \leq 7$ under different pre-defined reception probability, p_r. Our simulations were written in *MATLAB*.

In Fig. 10, we show an example of the sensor node deployment and how our $GB(n = 1)$ scheme distributes *BM* from the source to the entire network. The structure of the broadcast paths of the $GB(n = 1)$ scheme can be seen from the circles. It is verified that every node in the network is covered by at least one *BM* broadcast that is at most $\sqrt{13}r\ m$ away. Therefore, each node receives the *BM*s with an aggregate probability, Φ_r, that is higher than p_r.

Figure 11 illustrates the difference of the aggregate recep-

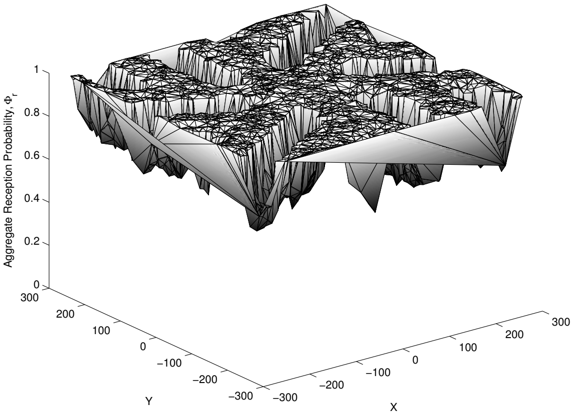

Fig. 11. The aggregate reception probability, Φ_r, for different regions. The pre-defined probability of reception is $p_r = 0.6$. Scheme $GB(n = 1)$.

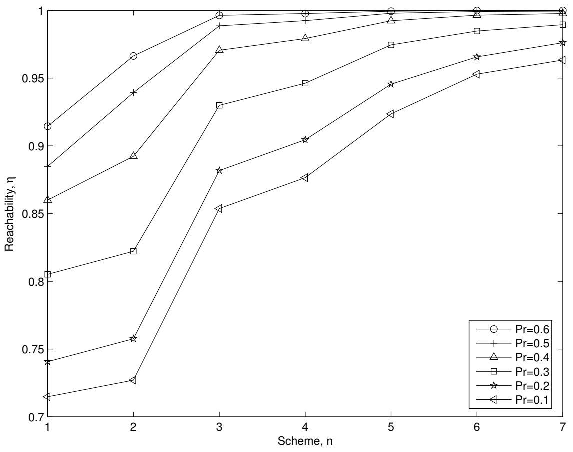

Fig. 12. The performance of reachability of different $GB(n)$ schemes and different pre-defined reception probability, p_r.

tion probabilities, Φ_r, of nodes in different regions. In this figure, we fixed the pre-defined probability of reception at $p_r = 0.6$. The area is 600 m by 600 m. All nodes receive *BM*s with an aggregate reception probability, $\Phi_r > p_r = 0.6$.

Nodes that are located in *RC*s on the six Stage 1 axes have significantly higher reachability than nodes elsewhere, as can be observed in Fig. 11. In data-on-demand type of applications, this property can be exploited to increase resolution in area of interests. If, for example, an event is detected in an area A, the *LBEE* algorithm can be used to rotate one of the six Stage 1 axes in such a way that it passes through A. Request packets can be broadcasted as usual using $GB(n)$ with n being small. As a result, more nodes in A are reached and will send requested data to the *IS*. In this way, the *IS* achieves an improved observation resolution of A.

We have also evaluated the reachability of the $GB(n)$ schemes. The reachability, η, is defined as the average of nodes' aggregate reception probability. The probabilities are shown in Fig. 12 with different pre-defined reception probability, p_r. As n increases, there are more redundancy in the $GB(n)$ scheme; the reachability also increases. The average

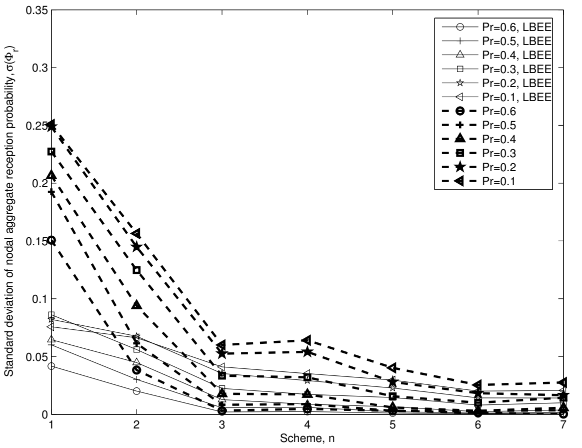

Fig. 13. The standard deviation of all nodes' overall reception probability.

reception probability increases with p_r as well.

It can be seen that *GB* offers η values tunable over a range of 25% only when p_r is small. This is because p_r is evaluated at the worst-case distance $\sqrt{13}r$ (*AN* at a vertex of its *RC* and the receiving node is at the farthest vertex of the first-tier *RC*). Most nodes are much closer and the effective Φ_r is much higher. Channels can still be allocated in the same way so that with high power, *AN* can reach nodes at distance $\sqrt{13}r$ with a reasonable p_r to guarantee one-to-one inter-cell communications; when broadcasting, the *AN* can decrease its transmit power to a level associated with lower p_r to create a wider range of tunable η and to conserve energy. Alternatively, p_r can be defined as reception probability evaluated at a much more reasonable distance. The required n can then be calculated for a given η using (1).

Since nodes in different locations may experience different aggregate reception probability and we should ensure that such probabilities are relatively balanced throughout the network, we investigated the standard deviation of all nodes' aggregate reception probabilities, $\sigma(\Phi_r)$. The results are presented in Fig. 13. The curves with dashed lines represent $\sigma(\Phi_r)$ for $GB(n)$ schemes with a fixed source, while the curves with solid lines show $\sigma(\Phi_r)$ when *LBEE* is employed with $h = 1$. It is clear that the *LBEE* reduces $\sigma(\Phi_r)$ significantly. We can also observe that $\sigma(\Phi_r)$ generally decreases if p_r increases.

TABLE III

AVERAGE ENERGY CONSUMPTION RATE

n	1	2	3	4	5	6	7
$\overline{E_c}$	0.5030	0.4181	0.5617	0.6352	0.7735	0.8903	1.0000

In Table III, the energy consumption rate of *RC*s are shown. Since it has only relative significance, we show the average energy consumption rate of each *RC*, E_c, as the average number of broadcasts sent by the *RC*. It can be observed that the energy consumption rate increases with n, except when $n = 2$. The energy consumption rate of the $GB(n = 7)$ scheme is 1 because every *RC* sends the *BM*. The reason for

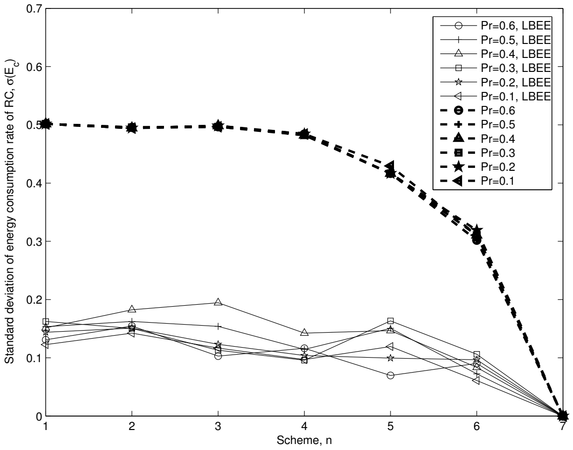

Fig. 14. The standard deviation of all *RC*s' energy consumption rate due to broadcasting *BM* s.

the lower energy consumption rate of *RC*s in the $GB(n=2)$ scheme lies in its nice structure of re-broadcasting *RC*s (see Fig. 3). Note that the node-based energy consumption rate is $\overline{E_c}$ divided by the average number of nodes in an *RC*. Though varying transmission power can also achieve a tunable range of η, power consumption increases exponentially with p_r [17] though $\overline{E_c}$ increases much slower with n. An even wider range of η can be achieved by adjusting both n and power.

In Fig. 14, we investigated the $GB(n)$ schemes with respect to $\sigma(E_c)$, the standard deviation of energy consumption rate due to broadcast. We recorded the number of broadcasts sent by each *RC* and then calculated the standard deviation of these numbers for all *RC*s. Fig. 14 clearly shows that *LBEE* can significantly reduce the standard variance of *RC*s' energy consumption rates. As n increases, more *RC* s re-broadcast *BM*s and balance E_c among different *RC*s. When $n=7$, all *RC*s re-broadcast, leading to the same energy consumption rate, i.e., $\sigma(E_c)=0$.

IX. CONCLUSIONS AND FUTURE WORK

In this paper, we have proposed the Guided Broadcast algorithms – a family of distributed broadcasting algorithms for wireless sensor networks. *GB* is based on *SoRCA* and utilizes spatial diversity. It contains seven schemes, where $GB(n)$, $1 \leq n \leq 7$, in combination of *PAA*, guarantees that each node in the *WSN*s are covered by n broadcasts. The reachability η of nodes can be dynamically adjusted by varying n and a pre-defined reception probability, p_r.

In general, η increases with n. However, $GB(n=2)$ provides a higher reachability while consuming less energy than $GB(n=1)$. η has a tunable range of 25% ($71\% - 96\%$ for $1 \leq n \leq 7$) for $p_r = 0.1$, and a tunable range of about 29% ($71\% - 100\%$) when varying both transmit power and n. Nodes reachable by *BM*s are located rather randomly throughout the *WSN*. It is worth pointing out that varying n at lower broadcast power level is preferred over varying broadcast power only since it is more energy efficient and offers wider η range. *GB* performs quite well in terms of covering the entire network with small number of broadcasts and balancing the aggregate reception probability of different regions. They can offer adjustable resolution as well in certain *WSN* applications.

As directions of future work, we will work on the comparison between *GB* and other related schemes. One of the problems toward such comparision is the diffculty of identifying schemes with similar purpose as *GB*. We are also in the process of extending and simplifying the algorithm presentation of *GB* to more general *WSN* settings.

X. ACKNOWLEDGMENT

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