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# Energy-Efficient Regional Broadcasting Protocol Using Adaptive Probabilistic Routing and Boundary Approximation in WSNs

Qun Li[1*], Tianyu Ren[1], Chao Wang[1], Xiaohu Wang[1], and Enjie Shi[1]

[1] State Grid Beijing Electric Power Company Electric Power Research Institute, Beijing, 100075, China
lqkp0924_123@sina.com; jingke_220@163.com; havetry_wang@163.com; w007wxh@163.com; shi_enjie@163.com

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Abstract. Broadcasting is a fundamental operation for disseminating information in wireless sensor networks (WSNs). In practice, we always want to broadcast packets to the nodes inside a specific region. However, the existing broadcasting protocols are all designed for disseminating data among all the sensors, and they are scarcely inefficient in the above regional broadcasting scenario. In this paper, we present an energy-efficient regional broadcasting protocol (EERB) to deal with the above problem. Firstly, the packet needed to be broadcasted will be sent to a selected starting point in the target region, subsequently data dissemination is realized by the proposed adaptive probability routing (APR), in which not all nodes are required to forward packets. Then we propose a linear regression and region split based boundary approximation algorithm to approximate the shape of the target region. The obtained coefficients are included in the broadcasted packet to tell the nodes whether receives the packet or not, thus the un-related nodes will not be disturbed by the broadcasting operation. Simulation results demonstrates the high energy-efficiency of the proposed protocol.

Keywords: adaptive probabilistic routing, boundary approximation, energy efficiency, regional broadcasting, wireless sensor networks

## 1 Introduction

Wireless sensors networks (WSNs) are self-organized networks with large amount distributed sensors. The task of WSNs can be monitoring [1], controlling [2], and communication [3]. Broadcasting is a fundamental operation in WSNs, and it can be concluded into the following two categories [4]: one-to-all broadcasting and all-to-all broadcasting. The former one can be used by any one node in the network to send queries [5], orders [6] or some other controlling messages [7] to all the other nodes. The latter one is used for updating personalized information [8] and routing information [9] among all the nodes.

In this paper, we focus on the one-to-all broadcasting problem, and the 'one' node is specified as the base station (BS). The problem is that, in practice, we always don't want to broadcast data to all nodes in the network, but a part of them in a target region. This is because the BS usually wants to give some control directives to the nodes in a specific region, or requires them to upload data. For example, in wireless multimedia wireless networks (WMSNs), to save unnecessary energy consumption, a camera node is usually in sleep mode until it is woke up by the BS or other working nodes [10-11]. If the BS wants the cameras in a specific region to upload the video data, it has to wake up these camera nodes. On the other hand, the BS has to send commands to tell the nodes to go sleep if there is no need to keep watching. In data fusion applications, such as distributed classification [12] and detection [13], if we want to know the information of a certain area, then it is essential to send messages to tell them to upload their decisions of raw sensing data to fusion center.

The researches on broadcasting are mainly focused on improving the protocol's performance in energy

[*] Corresponding Author

efficiency [14-16], collision avoidance [17], and security [18-19]. To the best of our knowledge, existing broadcasting protocols, such as flooding [20], Gossip [21], and diffusion [22], are all designed for broadcasting data to the whole network. However, when we have to broadcast data to a certain area of the covering field, existing protocols may not be suitable used because we don't want to disturb the unrelated nodes. If the BS broadcasts data using repeating flooding to every node, the energy cost will be too high, thus it is scarcely inefficiency for practice. On the other hand, sending packets with several target nodes will cause heavy overhead on controlling messages, and repeating broadcasting is still needed. Therefore, this is a need to develop a regional broadcasting protocol to avoid high energy consumption.

In this paper, we present a location based energy-efficient regional broadcasting (EERB) protocol for information dissemination to a target region in WSNs. The proposed EERB protocol has the following three main aspects.

(1) Shortest path routing. Once the target region is determined, choose a proper node as the starting node for information dissemination. Then BS sends the data packet containing transmission direction and boundary information to the start node in shorted routing path.

(2) Adaptive probabilistic routing. Once the starting node received the packet, it then launches the broadcasting process, and uses the proposed adaptive probabilistic routing (APR) to broadcast the information. Probabilistic routing (PR) [23] is a light-weight broadcasting protocol family, in which sensors are not required to maintain a routing table to record the address of the next-hops. When a packet is received, it will be forwarded with a delivery probability, which can be predefined as fixed value, or calculated according to the historical statistical information [24]. As a result, not all nodes are required to forward packet, and energy is saved. Besides, no complex routing control operation need to done to guide the transmission of data flow, thus it is easy implementation.

(3) Boundary approximation. To avoid involving unrelated nodes, the nodes must know whether they are located inside the target region, and this boundary shape approximation process is realized by using a linear regression [25] and region split algorithm.

The rest of the paper is organized as follows. Section 2 elaborates the details of the proposed EERB protocol, including shortest path routing, adaptive probabilistic routing, and boundary approximation. Simulation results are provided in Section 3. Finally, Section 4 concludes this paper.

## 2 Energy-Efficient Regional Broadcasting Protocol

In existing broadcast protocols, information will be disseminated to the nodes in the whole network. As discussed previously, this practice will cause unexpected cost if just a part of the nodes needs the information. In this paper, we consider the regional broadcasting scenario in a wireless sensor network, in which $N$ sensors $s_1,...,s_2$ are randomly distributed in a sensing field. For simplification, we assume that the nodes are independent in routing decision with each other. The sensors and BS are able to know their own locations, which can be obtained by GPS module, or some embedded localization algorithms. The BS knows the locations all its all belonging nodes. The sensors has limited transmission capacity, and its connectivity region is a circular with radius $x_m$. As shown in Fig. 1, the BS wants to broadcast some information to a target region, but not want to disturb other unrelated nodes. Therefore, our goal is to design an energy-efficient protocol to broadcast information in the target region in the prerequisite of involving unrelated nodes as few as possible.

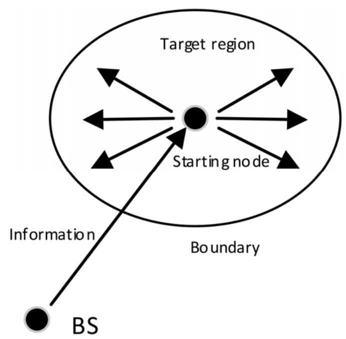


**Fig. 1**. Information broadcasting in a target region

### 2.1 Shortest Path Routing for Starting Broadcasting

Firstly, the BS decides the target region, and selects a node for starting broadcasting and a node for stopping broadcasting. Since the locations of sensors are known to the BS, thus a shortest path can be easily established to send the data to the starting. For example, a node knows the locations of its neighbors, along with the ones of the BS and the starting node. The neighbor with shortest distance to the starting node will be chosen as the next hop. In addition, acknowledgement can be used to avoid packet loss. Detail protocol of this part show in Algorithm 1.

**Algorithm 1**. Shortest path routing to starting node

The BS selects a starting node.
The BS sends a packet $p$ to the neighboring node with minimum distance to the starting node.
**if** node $s_i$ receives the packet $p$ from $s_j$ **then**
    Send acknowledgement message to $s_j$.
    **if** $s_i$ is not the starting node **then**
        Get the location of starting node $(x_{st}, y_{st})$.
        Find the neighbor $s_{next}$ with minimum distance to the starting node.
        Send $p$ to $s_{next}$.
    **End**
    Start the broadcasting process.
**end if**
**end if**

Note that in EERB, the location of a sensor is known to itself and its neighbors. Except the location of the starting node, packet $p_0$ contains all other the needed data for routing control and the information send to nodes in the target region. By using the above routing method, the packet can be sent to the target starting node with shortest path. The next step is starting the regional data broadcasting process, which will be presented in the next subsection.

### 2.2 Adaptive Probabilistic Routing for Information Broadcasting

We adopt adaptive probabilistic routing as the basic strategy for information broadcasting. Different from conventional PR, maximum delivery probability in APR can be adjusted to the sensor number of the connectivity region. For simplification, we assume the neighboring nodes of a sensor is uniformly distributed. Also, to avoid unnecessary energy cost on repeating data delivery and reverse transmitting, a same packet will be dropped if it is previously received.

In PR, packets will be forwarded with a predetermined probability. A higher delivery probability means higher energy cost on data relaying. However, a too small delivery probability isn't able to guarantee the required delivery rate, thus a proper delivery probability should be predetermined. Herein this paper we adopt the following isotropic signal intensity attenuation model

$$P_R = P_T \frac{1}{1+x^{\alpha}}, \tag{1}$$

where $P_T$ and $P_R$ are the transmitting power and receive power, respectively. $x$ is the distance and denotes the path loss exponent. Now suppose the minimum receive signal power is $P_{R,\min}$ , the maximum connectivity distance is

$$x_m = \left( \frac{P_T}{p_{R,\min}} \text{-}1 \right)^{1/\alpha}. \tag{2}$$

For a transmitting node $s_i (1 \le i \le N)$ , suppose its neighboring nodes in the connectivity region is $S_i = \{s_1^i, ..., s_{Ki}^i\}$ . For a $s_k^i \in S_i$ , we define its delivery probability as the following equation

$$P_{k,i} = P_{i,\max}\left(1 - e^{-\beta x_{k,i}}\right), \tag{3}$$

where $0 \le P_{i,\max} \le 1$ denotes the maximum delivery probability to $s_i$, $x_{k,i}$ is the distance between $s_i$ and $s_k$, parameter $\beta$ determines the shape of the above function. An example of the delivery probability function is shown in Fig. 2, in which $P_{\max} = 0.8$, and the maximum transmission distance is $20m$. Parameter $\beta$ has three values, i.e. 0.2, 0.25, 0.3, and we can see that a larger value of $\beta$ means more steep of shape of the function.

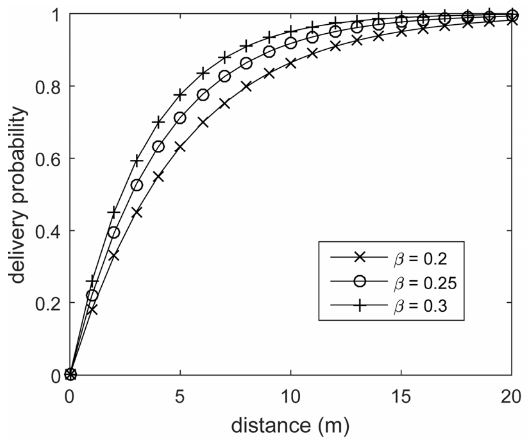


**Fig. 2.** Delivery probability as a function of transmitting distance

When $x_{k,i} = x_m$, we define the delivery probability approximately equals to the maximum probabitity, i.e. $P_{k,i} \approx P_{\max}$. Therefore, we have the following inequality

$$1 - e^{-\beta x_m} \le \varepsilon, \quad \textbf{(4)}$$

where threshold $\varepsilon$ is a value close to 0. In this paper, we define $\beta = 5 / x_m$, since $e^{-5} = 0.0067$, which satisfies the above inequality if $\varepsilon = 0.01$. Next we can calculate the expected delivery probability, as given by

$$\begin{aligned} P_i^* &= \int_0^{x_m} P_i^{\max} (1 - e^{-\beta r}) \frac{1}{x_m} dr \\ &= P_{i,\max} \left( 1 + \frac{1}{\beta x_m} \left( e^{-\beta x_m} - 1 \right) \right), \end{aligned} \quad \textbf{(5)}$$

When $\beta x_m = 5$, we have $P_i^* = 0.0813 P_{i,\max}$. The above result indicates that if the value of term $\beta x_m$ is fixed, the expected delivery probability is a just determined by the maximum achievable delivery probability. The upper bound of the expected delivery probability of all the sensors in the next-hop region is

$$P_i^G = 1 - \left(1 - P_i^*\right)^{N_i}, \quad \textbf{(6)}$$

where $N_i$ is number of the sensors in the next-hop region, i.e. the circular connectivity region with radius $x_m$. Combined with equation (2), we have

$$N_i = \left\lfloor \rho_i \pi x_m^2 \right\rfloor, \quad \textbf{(7)}$$

where $\rho_i$ is the node density. Note that if we don't know the exact sensor density or sensors are non-uniformly distributed, $N_i$ can also be obtained by finding the total number of reachable neighbors in the next-hop region by using "hello" messages or beacon frames. This is essential for non-uniformly deployed WSNs. To assure the delivery rate, we have $P_i^G \ge P_{th}$, where threshold $P_{th}$ is a probability close to 1, such as 0.95. Now, by using an inverse process, we know the delivery probability of to $s_i$ can be obtained calculated using the following inequality.

$$P_i^* \geq 1-\left(1-P_{th}\right)^{\frac{1}{N_i}}. \tag{8}$$

Combined with equation (5), we have

$$P_{i,\max} \geq \alpha\left(1-\left(1-P_{th}\right)^{\frac{1}{N_i}}\right), \tag{9}$$

where $\alpha = \beta x_m /(\beta x_m + e^{-\beta x_m} - 1)$. When we set $\beta x_m$ as a fixed value, $P_{i,\max}$ is mainly influenced by the total sensor number in the next hop region. According to the above expression, we can set a special value for every node of the network according to the above equation. Also, $P_{i,\max}$ can be dynamically updated according to its total number of reachable neighbors. By using APR, repeat delivery of packet will be avoided, and the delivery can be adjusted according distance and number of neighboring nodes.

To assure the delivery rate, we set $P_{i,\max} = \alpha\left(1-\left(1-P_{th}\right)^{\frac{1}{N_i}}\right)+\lambda$, i.e. the maximum delivery probability is $\lambda$ higher than its lower bound. The maximum delivery probability of the first hop is set as relative large value, such as $P_{i,\max} = 0.8$, because if not transmission directions are not fully covered, the delivery probability of outer-region will not be assured. As a result, the goal of energy efficient data transmission while guaranteeing delivery rate can be achieved.

### 2.3 Linear Regression for Boundary Approximation

Find out the boundary to determine a node whether to receive the information data is actually a 0-1 classification problem. The nodes located inside the boundary belongs to one class $\omega_1$, and the outside ones belongs to another class $\omega_2$. The data sample is the coordinations $C = [(x_1, y_1),...,(x_M, y_M)]$ of the nodes. Thus our goal is find the rule to map the coordinate of a sensor into the decision which class it belongs to, i.e. $(x, y) \rightarrow d \times [1,-1]$.

**Boundary approximation using linear regression.** As aforementioned, sending the packet data to target nodes using point-to-point links or flooding is an unwise practice. If the involved nodes know the boundary information, they are able to know whether to receive the packet, the above problem can be solved. Considering the energy cost, the overhead on the boundary control information should be as few as possible. The linear regression algorithm can be used to approximate complex functions by training a few coefficients, thus it is applied in boundary decision in EERB.

Suppose there are *M* coordinates data used for boundary training, let $\mathbf{Y} = [y_1,..., y_M]^T$ be the coordinate vector of Y-axis of the nodes. Denote $\mathrm{x} = [x_1,..., x_M]^T$ the arguments matrix is the coordinate vector of X-axis of the nodes. We set the arguments of the linear model as $\mathbf{x}_i^{reg} = [1, x_i,..., x_i^m]$, where *m* the maximum order of the linear model. Denote the arguments matrix as $\mathbf{X} = [\mathbf{x}_1^{reg},...,\mathbf{x}_M^{reg}]^T$. Let $\beta = [\beta_0, \beta_1,..., \beta_m]$ be the coefficient matrix, the linear model is given by

$$\mathbf{X}^T\mathbf{X}\beta = \mathbf{X}^T\mathbf{Y}, \tag{10}$$

where $\mathbf{X}$ is a non-singular matrix. The solution of the above model can easily calculated by

$$\beta = \left(\mathbf{X}^T\mathbf{X}\right)^{-1}\mathbf{X}^T\mathbf{Y}. \tag{11}$$

Generally speaking, many non-linear unclosed boundary curves can be regressed with a high enough order value *m*. However, it has to emphasize that, the elements in the argument vector $\mathbf{x}^{reg}$ can be obtained by any other proper functions of **x**, such reciprocal, Logarithmic and trigonometric functions of **x**. If the boundary is approximated with acceptable mean square error (MSE), then $\hat{\beta}$ can be packed in the disseminated packet as the boundary control messages.

**Split of Boundary region.** The target region is usually a closed area of the covering field, and it not suitable to approximate the shape using linear regression. To solve this problem, a good way is to split the boundary into several independent parts, and approximating the partial boundary lines is an easy task.

An example is shown in Figure 3, the covering field is a $200 \times 200$ rectangular area, in which blue dots denote the nodes not related to the broadcasting process, while red ones are the target nodes, and the target region is the rectangular with red nodes. The BS and starting node locate at (20, 20) and (120, 120), respectively. In this situation, the obtained boundary using linear regression is not acceptable, and we divide the boundary shape into the following four parts AB, BC, CD, DA, the MSE of linear regression will be greatly decreased.

Suppose the boundary line is divided into n parts, and the corresponding obtained coefficient vectors are $\hat{\beta}_1, \ldots, \hat{\beta}_n$. We have to define the label vector $\mathbf{c} \times [-1,1]$ to tell a node whether it locates in target region. Let $\mathbf{x} = [x, y]$ be the candidate vector, we obtain the decision vector **d** as follows

If $\mathbf{X}\beta_i - \mathbf{Y} > 0$, then $d_i = 1$, otherwise $d_i = -1$

The decision rule of judging whether the node locates in the target region or not can be simply expressed as

If $\mathbf{c} == \mathbf{d}$, then it is a target node, otherwise not.

Note that too many split part is not essential, because the accuracy is usually high enough with not more than 4 parts, and too many splits will increase the overhead of the packet.

For example, the boundary is divided into four parts, and label vector of the four parts AB, BC, CD, DA is **c** = [1,-1,-1, 1]. A node with decision **d** = **c** will be regarded as located in the target region. The Algorithm of boundary decision is shown as in Algorithm 2.

**Algorithm 2**. Boundary decision using linear regression.

// Operations in BS
Initialize: the number of split parts *n*, the argument matrix $X_1, \ldots, X_n$, and Y-axis coordinates **Y**.
$\hat{\beta}_i \leftarrow (\mathbf{X}_i^T \mathbf{X}_i)^{-1} \mathbf{X}_i^T \mathbf{Y}$
Set the label vector $\mathrm{x} = [c_1, \ldots, c_n]$
//Operations in receiving nodes
**for all** {received $\hat{\beta}_1, \ldots, \hat{\beta}_n$ } **do**
    $d_i \leftarrow \mathrm{sgn}(\mathbf{X}\hat{\beta}_i - \mathbf{Y})$
**end for**
**if c == d then**
    The node is in the region, and receive the packet.
**else**
    Drop the packet.
**end if**

Now suppose the BS generates a packet and it has been transmitted to a starting node. After the starting node launches the broadcasting process, information flow is controlled by the adaptive probabilistic routing and linear regression based boundary decision algorithm. When a node receives the packet, it will be dropped if it is not locates in the boundary or previously forward. If not dropped, then the delivery probability will be calculated according to the distance and maximum delivery probability. Finally, the packets will be forwarded with the obtained delivery probability. The protocol of data broadcasting in EERB is shown in Algorithm 3.

**Algorithm 3**. Data broadcasting.

**if** $s_k$ receives a packet p from $s_i$ && $s_i$ is in the target region && p is not previously forwarded in $s_k$ **then**
    Calculate the transmitting distance $x_{i,k} \leftarrow \sqrt{(x_i - x_k)^2 + (y_i - y_k)^2}$
    Count the total node number $N_i$.
    $P_{i,max} \leftarrow \alpha(1-(1-P_{th})^{\frac{1}{N_i}}) + \lambda$, where $\alpha = \dfrac{\beta x_m}{(\beta x_m + e^{-\beta x_m} - 1)}$.
    Calculate delivery probability $P_{i,k} \leftarrow P_{i,max}(1 - e^{-\beta x_{k,i}})$
    Broadcast packet $p_i$ with probability $P_{i,k}$.
**end if**

## 3 Simulation Results

We use the scenario in Fig. 3 to test the performance of the proposed protocol. In the $200 \times 200$ covering field, 2000 nodes are randomly deployed. Our goal is to broadcast a packet to the nodes with red color in the rectangular target region. The maximum transmission range of nodes are 20m. The packet loss is assumed to be 10%. Parameter $\lambda$ is set as 0.3. All the simulation results are obtained with 100 repeats.

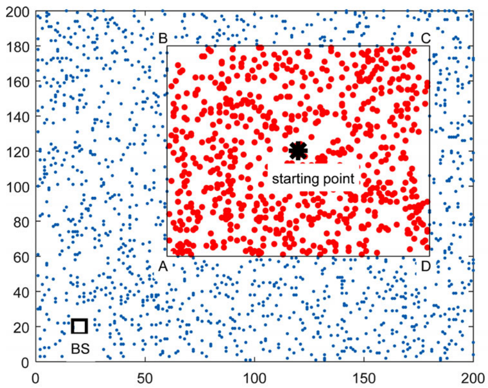


**Fig. 3**. Split of target region

Firstly, we give an example to show the whole process of information broadcasting in EERB, as shown in Fig. 4. Sub-figure 4(a) shows the shortest path to the starting node for starting, the total hops is 8. Subsequently, the starting node launches the broadcasting process, the first hops are shown in sub-figure 4(b), as denoted by black $\times$ symbols, and the next three hops are shown in 4(c)-4(f). We can see that the broadcasting process is completed within 5 hops. When the packets are forwarded over the boundary, it will be dropped, thus finally the unrelated nodes will not be involved. In the information broadcasting process, there are 664 nodes in the region, and 485(73%) of them are used as forwarding nodes.

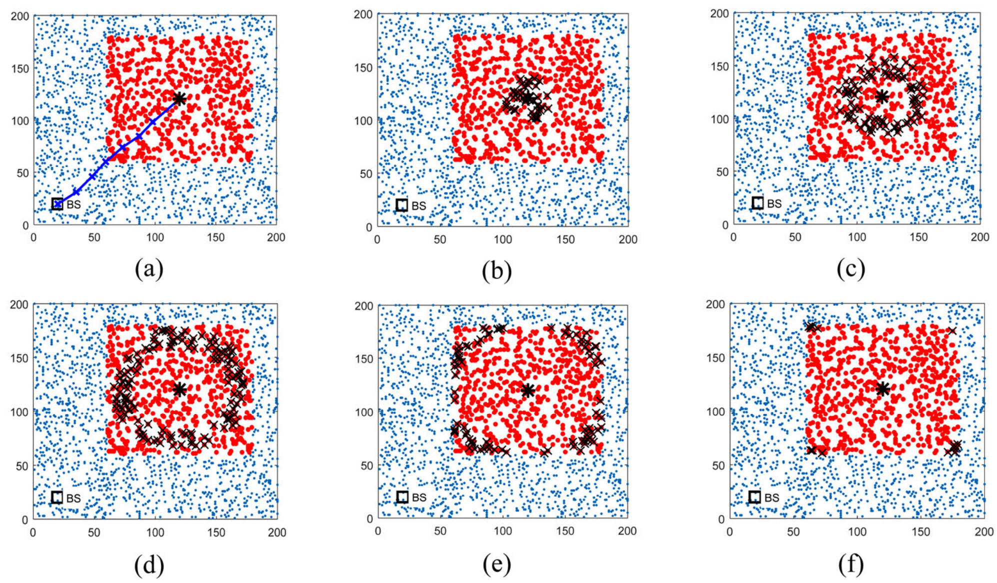


**Fig.4.** An example of the whole process of EERB, in which "x" stands for the next-hops for forwarding data, (a) shows the shortest path link to the starting node, (b)~(f) shows the information broadcasting process

Next, we test the performance of the proposed EERB protocol. The following two data disseminating protocols will be used for comparison: flooding and pure probabilistic routing (PR). The former one chooses to forward the packet if it is not previously received, the latter one uses fixed delivery probability to forward the packet.

Firstly, we test the average delivery ratio with different node numbers. It can be expected that, with the increasing of node numbers, average delivery ratio will also become higher. The reason is that, the network coverage ratio is mainly determined by the node density, if the transmit power is limited. In low coverage conditions, a node has a high probability to be isolated from others, while high coverage conditions, a node will be very likely to be connected with others.

The average delivery ratio of the three protocols is shown in Fig. 5. As expected, we can see that flooding has the highest delivery ratio in both low and high node density scenarios. This is because the packet will be forwarded in every node when it is not previously received. We can see that if there are no enough nodes, e.g N = 500, it is best to use flooding to guarantee the delivery ratio. Since the delivery probability is the same among all nodes, thus its delivery ratio is a little higher than APR. When sensor number is large enough, all delivery rations of the three protocols are close to 1, thus it is suggested using APR for its energy efficiency. Particularly, we can see that when node number is small, the delivery ratio of PR and APR are much lower than flooding, therefore, although PR and APR are more energy efficient, it is not suggested to use PR and APR in WSNs with small node number.

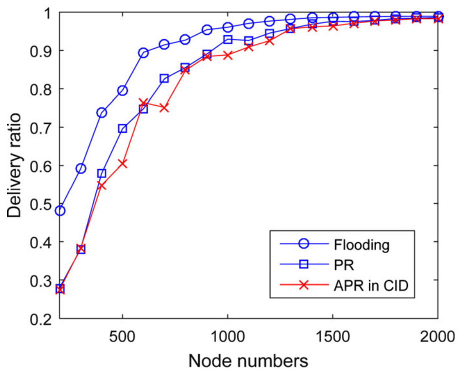


**Fig. 5**. Comparison of delivery ratio in $200m \times 200m$ field

A large average hops of the broadcasting process means higher energy consumption on delivering packets, also with high broadcasting delay. Therefore, if the delivery ratio is guaranteed, a good choice is to make the average hops as small as possible. The average hops of the three protocols with different node numbers are shown in Fig. 6, and it is obtained when all the target nodes receive the packets, thus delivery ratio is nearly to 1. Apparently, more hops means more energy cost in forwarding packet. Since in APR neighboring nodes with longer distance has higher delivery probability, we can see that APR has close performance to flooding, and its average hops are much fewer than PR. The result shows that the proposed method has better energy efficiency compared with PR protocol. Note that, in a fixed target region, the average hops will keep stable with different node numbers, if the nodes are all connected. This is because repetitive packets will be dropped, thus packets are always delivered by outside nodes in each delivery round.

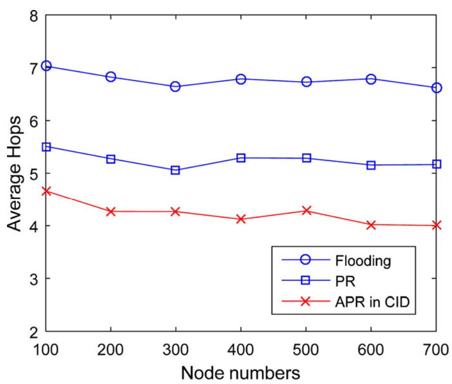


**Fig. 6**. Average hops in the target region $120m \times 120m$

Apparently, in the prerequisite of guaranteeing delivery probability, the ratio of packet forwarding probability can be used to reflect the energy efficiency. A good way to improve energy efficiency is to low down the ratio of packet forwarding probability. We record the average forwarding ratios in each hop, as shown in Fig. 7. We can observe that APR has the lowest ratio of the total nodes, which means it requires less energy cost in disseminating data. Not that the maximum delivery of the first hop is fixed as 0.8, thus the corresponding forward ratio will be higher than the second hop. We can conclude that APR is more efficient since it needs least packet forwarding probability, thus energy can be saved.

In above we just test the performance of the three protocols in information broadcasting process. Actually, the main advantage of the proposed EERB protocol is its benefit in controlling the boundary when disseminating information, and avoiding repeating flooding packets to different nodes. Although the overhead of controlling message is added by the boundary coefficients, but the overhead using flooding or point-to-point is much higher, since the packets must carry the addresses (or IDs) of the nodes, which is not scarcely efficient in practice. If BS repeats sending the packet to target nodes using flooding or probabilistic routing, the cost is even higher than adding the controlling overhead. Therefore, the proposed EERB protocol is much more efficiency for information broadcasting in scenarios with a target region.

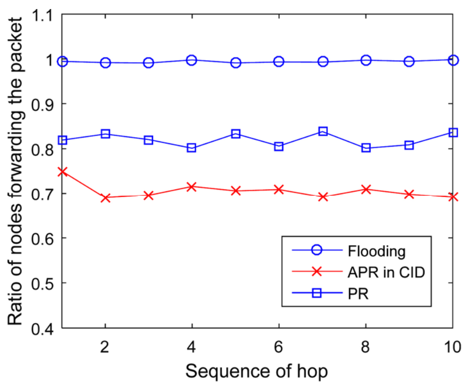


**Fig.7.** Average forwarding ratio of different hops

## 4 Conclusions

We have proposed a protocol for controlled information broadcasting (EERB) in the scenario with a target region. The proposed EERB protocol requires the nodes knows its location, and it includes the following three parts: shortest path for sending the packet to the starting node, adaptive probabilistic routing for data broadcasting, and linear regression for boundary approximation. The biggest benefit of EERB is the heavy controlling overhead or repeating flooding are avoided. Besides, it has high energy efficiency and assured delivery ration is situation with sufficient nodes. Our future work is designing more effective and efficient algorithm for identifying the target nodes.

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