Wireless Broadcasting with Optimized Transmission Efficiency

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Broadcasting is one of the fundamental operations to disseminate information throughout a wireless network. Flooding is a simple method to realize broadcasting. However, flooding will incur a large number of redundant retransmissions, leading to low transmission efficiency, which is the ratio of the effective transmission area to the total transmission area. In this paper, we propose a geometry-based wireless broadcast protocol, called Optimized Broadcast Protocol (OBP), to improve the transmission efficiency. In OBP, each node calculates the retransmission locations based on a hexagon ring pattern in order to minimize the number of retransmissions, and only the nodes nearest to the calculated locations need to retransmit the broadcast packet. As shown by analysis, the transmission efficiency bound of OBP is 0.55, which is about 90% of the theoretical optimal bound 0.61 and is better than that of BPS, the geometry-based broadcast protocol with the highest transmission efficiency 0.41 known so far. Since the transmission efficiency is inversely proportional to the number of required nodes to cover a network area, in a static deployed network, the number of deployed nodes is minimized by OBP. However, in a randomly deployed network or a mobile network, when the node density is not high, the network area of interest may not be fully covered and OBP has worse reachability than BPS for some cases. We thus propose an extension of OBP, called OBPE, to improve the reachability when the node density is not high. We make comparisons for OBP, OBPE and BPS in terms of transmission efficiency, reachability, transmission redundancy, and the number of transmissions, energy consumption to show the advantages of OBP and OBPE.

Keywords: broadcasting, flooding, covering problem, hexagonal lattice, transmission efficiency, wireless network

1. INTRODUCTION

Broadcasting is one of the fundamental operations to disseminate information throughout a wireless network. The operation has many applications; for example, disseminating control packets for controlling each node or distributing codes for reprogramming each node. Flooding is an intuitive approach in the implementation of broadcasting. In flooding, a node retransmits a packet when it receives the packet for the first time. Flooding is simple and reliable; however, it is not suitable for dense networks, since nearby nodes tend to retransmit the packet at the same time, causing packet collision and bandwidth contention, which are characteristics of the *broadcast storm problem* [1]. Furthermore, flooding has low *transmission efficiency*, the ratio of the effective transmission area to the total transmission area. Specifically, when the node density increases, the transmission efficiency of flooding decreases due to the growing overlap areas of transmissions.

As shown in [2], the theoretical upper bound of transmission efficiency is 0.61 for connected nodes. To take two communicating nodes A and B in Fig. 1 as an example, the transmission efficiency is the area covered by circles C_A or C_B (i.e., $|C_A \cup C_B|$) to the summation of areas of C_A and C_B (i.e., $|C_A|+|C_B|$), where C_A and C_B are the circles centered respectively at A and B with the radius of the transmission range R. When the distance between nodes A and B equals to R, the transmission efficiency reaches the theoretical upper bound 0.61.

Some broadcast protocols for wireless networks have been proposed in the literature [1-2][3-7]. Some of the protocols are centralized approaches assuming the entire network topology is known in advance, while the others are localized approaches using neighborhood information to improve transmission efficiency. Among the localized approaches, geometry-based protocols, which assume that each node is aware of its own location to make retransmission decisions, have good transmission efficiency. For example, *Broadcast Protocol for Sensor networks* (BPS) [4] was shown to have transmission efficiency of 0.41, which is about 67% of the theoretical upper bound. The idea of BPS is based on a regular hexagonal partition of the network with the hexagon side length being the transmission range R, where only the nodes nearest to hexagon vertexes need to retransmit the broadcast packet sent by the source node S (please refer to Fig. 2). As far as we know, BPS has the highest transmission efficiency among all existed geometry-based broadcast protocols.

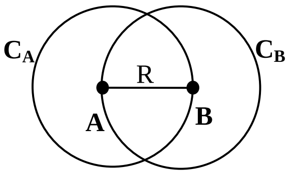

Fig. 1. Illustration of optimal transmission efficiency

This paper focuses on optimizing the transmission efficiency of wireless broadcasting and proposes a geometry-based broadcast protocol, called *Optimized Broadcast Protocol* (OBP), for wireless networks, such as mobile ad hoc networks (MANETs), wireless sensor networks (WSNs), or vehicular ad hoc networks (VANETs), consisting of dense nodes with location information. OBP has higher transmission efficiency than BPS; it tries to optimize the transmission efficiency by keeping as few as possible retransmissions. In OBP, a node counts on hexagon rings centered at the source node S to decide if it should retransmit a packet when it is received for the first time. Fig. 3 shows the hexagon rings centered at the source node S, where only nodes nearest to hexagon centers (represented as ●) or specific hexagon vertexes (represented as ▲) need to retransmit the packet. As we will show, OBP has transmission efficiency of 0.55, which is about 90% of the theoretical upper bound 0.61. Since the transmission efficiency is inversely proportional to the number of nodes required to cover a network area, such high transmission efficiency implies a low number of nodes by the OBP.

OBP works well when the node density is high. However, when the node density is not high, the retransmitting node may deviate from the hexagon centers (or vertexes), leading to the problem that some nodes may not receive the broadcast packet. The problem decreases *reachability*, the percentage of the nodes receiving the broadcast packet. We thus develop an extension of OBP, called OBPE, to solve the problem to improve reachability while maintaining high transmission efficiency. OBP and OBPE perform broadcasting by specifying the absolute locations (e.g., the location of a hexagon center) of forwarding nodes, so they are suitable for wireless networks of stationary or low-mobility nodes. Mobile nodes make the network situations similar to those of low-density networks in the sense that the retransmitting node deviates from the specified location. This paper thus concentrates on investigating the effects caused by different node densities. We will make comparisons for OBP, OBPE and BPS in terms of the transmission efficiency, reachability, transmission redundancy, number of transmissions, and energy consumption to show the advantages of OBP and OBPE.

The rest of this paper is organized as follows. In Section 2, we introduce some related work. In Section 3, we describe the details of OBP and OBPE. The transmission efficiency analysis is given in Section 4 and performance evaluation is described in Section 5. Finally, some concluding remarks are drawn in Section 6.

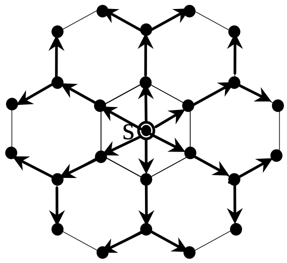

Fig. 2. Broadcasting in BPS, where ● is a hexagon vertex node responsible for transmission

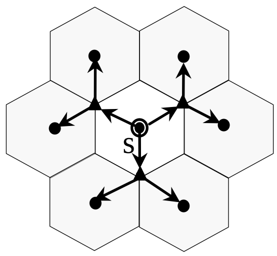

Fig. 3. Broadcasting in OBP, where ● is a hexagon node and ▲ is a vertex node for transmission

2. RELATED WORK

Flooding is an intuitive method to broadcast a packet throughout the entire network.

In the flooding protocol, each node retransmits a packet when it is received for the first time. The flooding protocol is simple, but may lead to a large number of redundant forwarding packets, which consumes much energy and raises the possibility of packet collision. Besides the flooding protocol, many broadcast protocols are proposed in the literature [1-7]. They can be generally classified as the centralized approaches and the localized approaches.

Centralized approaches assume the entire network topology is known a priori. Some centralized approaches use the concept of the *connected dominating set (CDS)* to improve transmission efficiency. They select a number of nodes for retransmitting a packet to reach all nodes on the basis of a priori known *unit disk graph*, where two nodes have an edge between them if they are within each other's transmission range. Given a graph G(V,E), where V is a node set and E is an edge set, a CDS is a subset V' of connected nodes of V such that each node in V−V' connects to at least one node in V'. To find a CDS for any given graph is proved to be an NP-hard problem in [8]. Certainly, to find a *minimum connected dominating set (MCDS)*, the CDS with the minimum number of nodes, is also NP-hard [9]. Assuming each node knows the global topology of the network, Das and Bhargavan in [3] proposed two algorithms to find the MCDS based on Guha's approximation algorithm for finding the CDS [10].

Localized broadcast approaches use neighborhood information to improve transmission efficiency. In a counter-based scheme [1], a node does not retransmit a packet if it overhears the same packet from its neighbor over a pre-specified number of times. In a distance-based scheme, a node does not retransmit a packet if it overhears the packet retransmitted by a neighboring node within a threshold distance. In some schemes, a node decides whether or not to retransmit a packet on the basis of two-hop neighborhood information, obtained via *hello messages* which are sent by all nodes periodically and contain the information (e.g., IDs) of the sender and its neighbors. For example, Wu and Li in [11] proposed a localized, distributed, pruning-based algorithm to find a CDS and then prune redundant nodes based on two-hop neighbor list to approximate the MCDS. Besides to the algorithm proposed in [11], several pruning-based algorithms [6,13] are proposed in the literature. As shown in [12], pruning-based algorithms achieve good reliability and small numbers of retransmissions. However, periodic hello messages may cause significant communication overheads, especially for dense networks.

Some localized broadcast protocols assume that each node is aware of its own location to make retransmission decisions; they are called *geometry-based* protocols. With the help of accurate node position information, geometry-based protocols usually have good transmission efficiency. For example, Durresi and Paruchuri et al. in [5] proposed a hexagon-based broadcast protocol, called Optimal Flooding Protocol (OFP), which was shown in [2] to have transmission efficiency of 0.41 (i.e., 67% of the theoretical bound). To the best of our knowledge, OFP has the highest transmission efficiency among all existed geometry-based protocols. OFP is based on a regular hexagonal partition of the network and only the nodes nearest to hexagon vertex locations need to retransmit the packet. Fig. 4 shows an example of OFP. The source node *S* of a broadcast packet first selects six hexagon vertex locations (1),.., (6) around *S* and appends them in the packet. There are two rules for intermediate nodes to choose new retransmission locations to append in the packet. The first rule is for the nodes nearest to the six source-selected locations. The rule says that a new retransmission location should satisfy the condition that a source-selected location just bisects the line joining the new retransmission location and the location of *S*. For example, the node nearest to the location (1) will choose the location (11) as the new retransmission location. The second rule is for other intermediate nodes, and it says that retransmission locations should be R apart, and the lines joining four nearby retransmission locations should make an angle of $2\pi/3$ radians with each other. For example, the node nearest to the location (11) selects locations (111) and (112) for retransmitting the packet. By the two rules, every node nearest to a hexagon vertex location retransmits the broadcast packet. Thus, the whole network area is covered, and the broadcast packet can be transmitted to all network nodes.

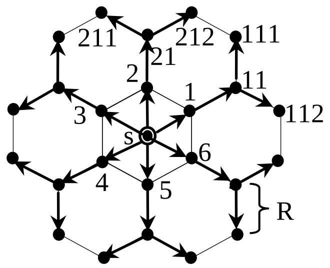

Fig. 4. The illustration of transmissions in OFP

Note that in OFP, on receiving the broadcast packet, a node can decide if it is closest to one of the selected locations by retransmitting the packet after a backoff time that is proportional to the distance between the node's location and the nearest selected location. If a node hears the transmission of the same packet during the backoff period, a node gives up retransmitting the packet. In this way, it is likely that only the node closest to a certain selected location retransmits the packet.

Kim and Maxemchuk in [2] showed the following two observations for OFP. First, the source node in OFP is located at the center of a hexagon, which makes intermediate nodes apply two different rules for selecting retransmission locations. Second, there are redundant transmissions of a packet associated with a same hexagon location. For example, as shown in Fig. 4, a node near location (212) and a node near location (11) may make two different nodes near location (111) retransmit the packet. This occurs when the two retransmitting nodes are at a distance over R, and one node is near locations (212) and (111) and the other node is near locations (11) and (111).

A protocol called *hexagon flooding* is proposed in [2] for improving OFP. In the hexagon flooding protocol, the source node of a broadcast packet is located at a hexagon vertex location and it selects only three adjacent vertex locations for transmitting the broadcast packet. This makes all intermediate nodes apply the same rule for retransmitting the packet. Furthermore, the hexagon flooding protocol uses three stopping rules to prevent the repeated (redundant) retransmission associated with the same location. Another related work is Hexagonal Wireless Sensor Network Protocol (HWSNP) proposed in [14] for providing *convergecast* services in the wireless sensor network for sensor nodes to deliver sensed data to the data collection node (or *sink node*). HWSNP also partitions the network area into a set of hexagons and selects the nodes at the centers of hexagons as aggregation points to relay data packets to the sink node. A distributed algorithm to help node selection at the centers of hexagons is developed in [15]. However, HWSNP mainly aims at convergecast, which is not applicable to broadcasting packets.

Based on OFP, Durresi et al. in [4] proposed a protocol called *Broadcast Protocol for Sensor networks (BPS)*. BPS adopts a *distance threshold mechanism*, described below, to reduce the number of retransmitting nodes. In BPS, a node keeps track of the distance D from itself to the nearest node that has transmitted the broadcast packet, and the node retransmits the packet only when D is greater than a threshold Th. In this way, BPS prohibits the nodes that are too close to the retransmitting node from retransmitting the broadcast packet. Hence, the distance between any pair of retransmitting nodes will be larger than the threshold Th to control the number of retransmitting nodes. As shown in [4], the threshold Th affects the number of retransmitting nodes and the *reachability* (or *delivery ratio*), the percentage of nodes that receives the broadcast packet. It is suggested that Th should be $0.4\times R$ (i.e., 40% of the transmission range).

Since OFP, BPS, and the hexagon flooding protocol are similar and all suppose a hexagonal pattern (partition) for selecting nodes near hexagon vertexes to retransmit packets, we take BPS as the representative of the three protocols in the following context. When the node density is sufficiently high, only the nodes at the *supposed hexagon vertex* locations will retransmit the broadcast packet. However, when the density is not so high, the selected retransmitting nodes may be away from the supposed hexagon vertex locations and the hexagonal pattern is distorted. If BPS selects new retransmitting nodes according to the bias positions of the selected nodes, the hexagon pattern distortion will become worse and worse. Fortunately, the distortion may be mitigated by always selecting the nodes nearest to the locations of the supposed hexagon vertexes as retransmitting nodes. Below, we assume that BPS works in this manner.

The design idea of the above-mentioned hexagon-based broadcast protocols is related to the covering problem [19], which asks "How to arrange circles such that the minimum number of circles can completely cover a given area?" To quantify the efficiency of the solutions to this problem, Kershner in [19] defined the *covering efficiency* $\rho=A_T/A_E$, where A_T is the total summation of circles' areas and A_E is the effective covered area. Smaller ρ is preferred. If a solution uses fewer circles to cover the given area, then the summation of circles' areas (A_T) will become smaller, and ρ will thus become smaller. Note that if we assume the center of each circle has a transmitting node with the circle being the transmission range, then the circles' covering efficiency is the reciprocal of the nodes' transmission efficiency.

As shown in [19], the lower bound of covering efficiency ρ is $2\sqrt{3}\pi/9$ ($\approx$1.209), which is achieved by placing circles according to a *regular hexagonal lattice*, as shown in Fig. 5. It is remarkable that some uncovered regions exist near the boundary of the given area. This is called the *boundary effect*. However, the boundary effect becomes slighter when the ratio of the circle size to the given area becomes smaller. The uncovered regions approximate zero and the boundary effect can be ignored if the circle is much far smaller than the given area of interest.

Broadcasting may be designed for different classes of wireless networks, such as the heterogeneous wireless network or the energy-constrained network. Duresi and Paruchuri in [16] studied broadcasting for the heterogeneous wireless network consisting of nodes of various transmission ranges, and proposed a protocol called *Adaptive Coordination Protocol* (*ACP*) based on the hexagonal network concept of their previous BPS protocol [4]. Moreover, they in [17] extended the ideas of BPS for broadcasting in the energy-constrained network consisting of nodes that sleep and wake up alternatively. They proposed a protocol called *Activecast* to effectively transmit a packet to all active (awake) nodes. However, this paper does not consider the heterogeneous networks or the energy-constrained network, but considers the homogeneous network consisting of nodes that have the identical transmission range and that are always active without energy constraints.

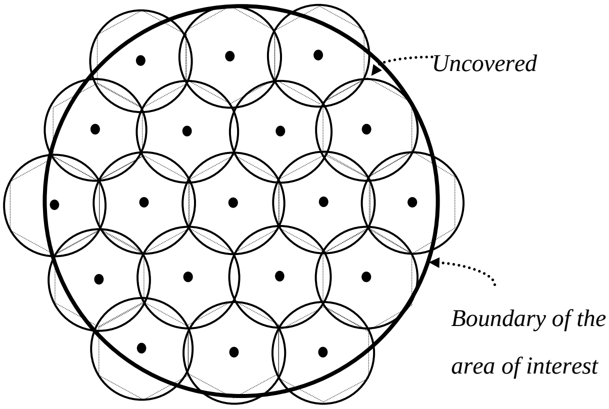

Fig. 5. The illustration of the covering problem

3. OPTIMIZED BROADCAST PROTOCOL

In this section, we will present our proposed Optimized Broadcast Protocol (OBP) and its extension, OBPE. We first present the basic idea of OBP in subsection 3.1, and then present two main mechanisms, geometric mapping and activation mapping, in subsections 3.2 and 3.3, respectively. In subsection 3.4, we present the adaptive activation mechanism adopted by OBPE.

3.1 Basic Idea

The basic idea of OBP is simple and is described as follows. The entire area of interest is partitioned into hexagon rings centered at the broadcast source node S, where hexagons have the side length of R, the transmission range (see Fig. 6). If every node nearest to a hexagon center is selected to forward the broadcast packet, then the total transmission area covers the entire network area of interest and all nodes can properly receive the broadcast packet when the node density is sufficiently high. Note that below we say a node is "*activated*" if it is selected for forwarding the broadcast packet. And for the sake of simplicity, we use the term "*center node*" C (resp., "*vertex node*" V) to refer to a node nearest to a hexagon center C (resp., hexagon vertex V) in the following context.

The hexagon rings have only one hexagon in the central (level-0) ring, and have six hexagons in the level-1 ring, and so on. In general, there are 6k hexagons in the level-k ring, when k=1, 2, …, etc. A hexagon center in the level-k ring is denoted as $C_{k,i}$, where i is an index ranging from 0 to 6k-1. Centers indexed by 0 lie on the horizontal axis staring from S towards the right, and other centers are then indexed counterclockwise. The relative location $LC_{k,i}$ of $C_{k,i}$ relative to S can be derived handily by a *geometric mapping* $M(C_{k,i}) \rightarrow LC_{k,i}$. The geometric mapping will be precisely defined in subsection 3.2.

In OBP, the source node S (associated with $C_{0,0}$) should send the broadcast packet and activate six center nodes $C_{1,0},\ldots,C_{1,5}$ in the level-1 ring to forward the packet. And each center node $C_{k,i}$ in the level-k ring, $k\geq1$, should either activate no node or activate two neighboring center nodes in the next level. Actually, for $k\geq1$, each of the 3(k+1) center nodes in the level-k ring needs to activate 2 neighboring center nodes in the level-(k+1) ring, but 3(k–1) nodes do not need to activate any nodes (note that $3(k-1)=6k-3(k+1)$). For example, each of the 6 level-1 center nodes needs to activate 2 level-2 center nodes, and thus all 12 level-2 center nodes can be activated properly. For another example, each of some 9 level-2 center nodes needs to activate 2 level-3 center nodes so that all 18 level-3 center nodes can be activated properly; however, 3 level-2 center nodes need not activate any nodes. We devise a mapping called the *activation target mapping* $T(C_{k,i})$ that outputs an empty set or a set $\{C_{k+1,w}, C_{k+1,w+1}\}$ of two center nodes for center node $C_{k,i}$, $k\geq1$, to activate. Note that center node $C_{k+1,w}$ (or $C_{k+1,w+1}$) in the returning set must be a next-level neighboring center node of node $C_{k,i}$; i.e., the associated hexagons of $C_{k,i}$ and $C_{k+1,w}$ (or $C_{k+1,w+1}$) must share a common edge. The activation target mapping will be precisely defined in subsection 3.3.

By the node activation process just mentioned, all center nodes can be activated to transmit the packet to cover the entire network area of interest. However, since two center nodes cannot communicate with each other directly, we need intermediate nodes between them for relaying the packet. OBP chooses vertex nodes (i.e., the nodes nearest to hexagon vertexes) as the intermediate nodes to take the advantage that a vertex node can reach two center nodes. Note that we say a node v can reach another node u if u can receive node v's packet properly (i.e., u is within v's transmission range).

In OBP, the source node S (i.e., center node $C_{0,0}$) takes (or activates) 3 vertex nodes $V_{1,0}$, $V_{1,1}$, and $V_{1,2}$ as intermediate nodes, while another center node $C_{k,i}$, $k\geq1$, takes only 1 vertex node $V_{k+1,i}$, or takes no vertex node if it does not need to activate other center nodes. To take nodes in Fig. 6 as an example, the center node $C_{1,0}$ takes only one vertex node $V_{2,0}$, while the center node $C_{2,1}$ takes no vertex node.

The broadcast packet of OBP is of the format P(LS, F), where LS is the absolute location of the source node, and F is the set of relative locations of center or vertex nodes selected for forwarding the packet. Note that each packet is sent along with a unique packet ID so that a node can decide if the packet has ever been received. Also note that the relative locations are sent along with the indexes of center nodes or vertex nodes. That is, when a location $LC_{k,i}$ or $LV_{k,i}$ is sent, the indexes k and i are also sent in the packet. Those indexes are very important for a node to calculate the relative locations of new forwarding nodes, if necessary, by the activation target mapping and the geometric mapping.

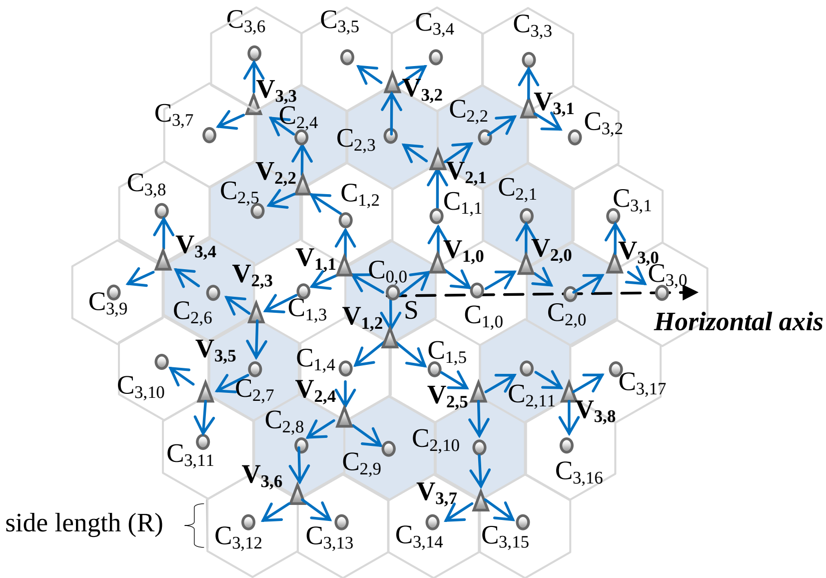

Fig. 6. Transmissions of OBP in hexagon rings

The pseudo code of OBP (optimized broadcast protocol) is shown in Fig. 7, in which the source node needs to execute only one step, while other nodes have 4 steps. Step S1 for the source node S is to transmit the broadcast packet and to activate the three vertex nodes $V_{1,0}$, $V_{1,1}$, and $V_{1,2}$. When a node X, X≠S, receives the packet, it will first execute Step X1. In Step X1, if X finds that it has transmitted the packet before, it just stops (and skips all other steps). In Step X2, if X is not a node nearest to any target locations specified in the packet, it stops. In Step X3, if X is a center node nearest to a target location specified in the packet, then X decides whether it needs to activate any center nodes by calling activation target mapping T(·). If the mapping returns an empty set, then X does not need to activate any nodes; it just retransmits the broadcast packet without specifying any nodes to activate. Otherwise, X needs to activate two center nodes via an intermediate vertex node. Therefore, X calculates the location of the vertex node, sets F′ as the singleton set of the location, transmits the packet along with F′, and finally stops. In Step X4, if X is a vertex node nearest to a target location specified in the packet, it transmits the packet to activate two center nodes, whose location can be indirectly derived by calling activation target mapping T(·), and then stops.

Optimized Broadcast Protocol

The step for the source node S to broadcast a packet P:

S1. S transmits the packet P(LS, F) with F={$LV_{1,0}$, $LV_{1,1}$, $LV_{1,2}$}.

The steps for node X, X≠S, receiving P(LS, F):

X1: **IF** X has transmitted P before, **THEN** it stops.

X2: **IF** X is not a node nearest to a location in F, **THEN** it stops.

X3: **IF** X is a center node $C_{k,i}$ of a location in F, **THEN**
  IF $T(C_{k,i}) = \emptyset$, **THEN** X sets $F' = \emptyset$, transmits P(LS, F′), and stops
  ELSE X derives $\{LV_{k,i}\}$ by calling $T(C_{k,i})$, sets $F' = \{LV_{k,i}\}$, transmits
   P(LS,F′), and stops.

X4: **IF** X is a vertex node $V_{k,i}$ of a location in F, **THEN**
  X derives $\{C_{k,w}, C_{k,w+1}\}$ by calling $T(C_{k-1,i})$, sets $F' = \{LC_{k,w}, LC_{k,w+1}\}$, transmits P(LS, F′), and stops.

Fig. 7. The pseudo code of OBP

Below we discuss how a node X can decide that it is the node nearest to a given location. There are two schemes proposed in the literature [20] for the purpose. The first mechanism is to make nodes periodically exchange location information with neighboring nodes so that each node can properly elect the node nearest to the given location. The second mechanism is for a node to set a backoff timer proportional to the distance between the node's location and the given location. The node nearest to the given location thus has the shortest backoff timer and will issue a response at the earliest time, which in turn will prohibit other nodes from responding. OBP can adopt either scheme to make the node nearest to a given location retransmit the broadcast packet. The first scheme allows nodes to respond faster, and is thus more suitable for networks of mobile nodes. The second scheme has longer response delay due to the backoff timer, so it is more suitable to networks of stationary nodes. However, the second scheme has the following two merits. First, nodes do not need to exchange their locations periodically. Second, the probability that no node responds is low. This is because if the node that is nearest to the given location does not respond due to collision or another reason, the node that is the second nearest to the given location will respond instead. According to the back-off timer, every node receiving the given location has a chance to respond. The second scheme is thus more robust.

We now discuss the broadcast packet overheads of OBP. Like BPS [4] that carries two locations of latitude and longitude information by embedding few bytes (16 bytes per location) in the broadcast packet, OBP stores in the packet the location of the source node along with the locations and the indexes of the selected node(s) in with few bytes (16 bytes per location, 1 byte per index and extra 1 bit for differentiating between the center node and the vertex node).

3.2 Geometric Mapping

In this subsection we present the geometric mapping for the center node and the vertex node.

Geometric Mapping for Center Node:

$M(C_{k,i})$ that maps a hexagon center node $C_{k,i}$ to a location $L_{k,i}$ that is relative to the location of the source node S. As shown in Fig. 8, each hexagon ring can be partitioned into six sectors, indexed by 0,..,5, each having a starting axis A_0, A_1, … or A_5. Each sector has *k* hexagon centers in the level-*k* ring. Let $Z_{k,q}$ denote the location relative to S of the starting hexagon center in the sector *q* (i.e., the center node at axis A_q) of the level-*k* hexagon ring. We have $Z_{k,q} = (k\sqrt{3}R \cdot \cos(q \cdot 60°), k\sqrt{3}R \cdot \sin(q \cdot 60°))$ for *q*=0,..,5, where R is the transmission range or the hexagon side length. Since each sector has *k* hexagon centers, we can figure out that hexagon center $C_{k,i}$ is within sector *q*, where $q = \lfloor i/k \rfloor$. Note that "+" represents the vector addition operator, which is defined as $LC1+LC2=(LC1_x,LC1_y)+(LC2_x,LC2_y)=(LC1_x+LC2_x,LC1_y+LC2_y)$. Now we can define the geometric mapping $M(C_{k,i})$ as follows.

Let $q=\lfloor i/k \rfloor$, where $\lfloor\cdot\rfloor$ is the floor function in mathematics.

If *i* is a multiple of *k*, $M(C_{k,i})=Z_{k,q}$.

$$\text{Otherwise}, M(C_{k,i}) = \begin{cases} Z_{k,0} + (-i\frac{\sqrt{3}R}{2}, i\frac{3R}{2}), \text{if } q=0 \\ Z_{k,1} + ((k-i)\sqrt{3}R, 0), \text{if } q=1 \\ Z_{k,2} + ((q\cdot k-i)\frac{\sqrt{3}R}{2}, (q\cdot k-i)\frac{3R}{2}), \text{if } q=2 \\ Z_{k,3} + ((i-q\cdot k)\frac{\sqrt{3}R}{2}, (q\cdot k-i)\frac{3R}{2}), \text{if } q=3 \\ Z_{k,4} + ((i-q\cdot k)\sqrt{3}R, 0), \text{if } q=4 \\ Z_{k,5} + \left((i-q\cdot k)\frac{\sqrt{3}R}{2}, (i-q\cdot k)\frac{3R}{2}\right), \text{if } q=5 \end{cases} \quad (1)$$

In Fig. 8, we illustrate the above mapping by two examples. The first example is about $M(C_{2,1})$. Since $q=\lfloor 1/2 \rfloor=0$, we have $Z_{2,0} = \left(2\sqrt{3}R\cdot\cos(0), 2\sqrt{3}R\cdot\sin(0)\right) = (2\sqrt{3}R, 0)$. We then have $M(C_{2,1}) = Z_{2,0} + \left(-\frac{\sqrt{3}R}{2}, \frac{3R}{2}\right)$. The second example is about $M(C_{2,7})$. Since $q=\lfloor 7/2 \rfloor=3$, we calculate $Z_{2,3} = \left(2\sqrt{3}R\cdot\cos(180°), 2\sqrt{3}R\cdot\sin(180°)\right) = (-2\sqrt{3}R, 0)$. We then have $M(C_{2,7}) = Z_{2,3} + \left(\frac{\sqrt{3}R}{2}, -\frac{3R}{2}\right)$.

Geometric Mapping for Vertex Node:

The geometric mapping of vertex node $V_{k,i}$ is defined as follows, which has two cases.

For *k*>1 case, $$M(V_{k,i}) = \frac{LC_{k-1,i} + LC_{k,w} + LC_{k,w+1}}{3} \quad (2)$$

The index *w* is calculated by the activation mapping $T(C_{k-1,i})=\{C_{k,w}, C_{k,w+1}\}$ which is defined in subsection 3.3.

For k=1 case, $$M(V_{k,i}) = \frac{LC_{1,2i} + LC_{1,2i+1} + LS}{3} \quad (3)$$

Note that the LS is the location of source node S and $i \in \{0,1,2\}$.

We illustrate the above mapping by the illustration example $M(V_{2,5})$. Since the activation mapping $T(C_{1,5})=\{C_{2,10},C_{2,11}\}$, the $M(V_{2,5})=\frac{LC_{1,5}+LC_{2,10}+LC_{2,11}}{3}$.

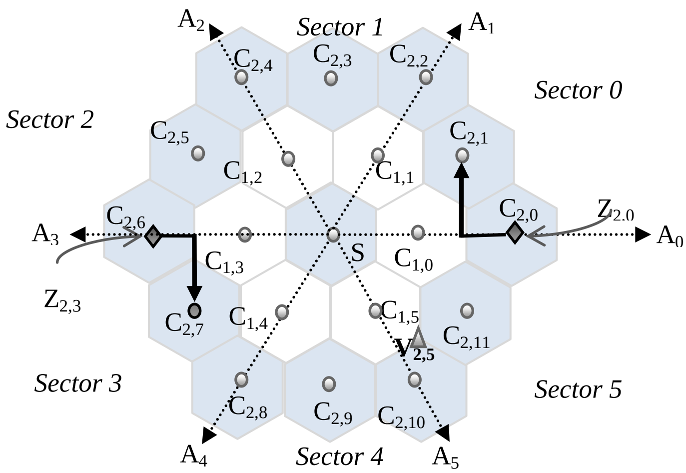

Fig. 8. The illustration of geometric mapping with six sectors (Sector 0, …, Sector 5), each having one starting axis (i.e. A_0, … A_5) on which the starting center node in the sector resides.

3.3 Activation Target Mapping

In this subsection we present the activation target mapping $T(C_{k,i})$. The input of $T(C_{k,i})$ is a center node $C_{k,i}$ for $k \geq 1$. $T(C_{k,i})$ is to find two center nodes $C_{k+1,w}$ and $C_{k+1,w+1}$ that are next-level neighboring nodes of $C_{k,i}$ with the restriction that w is even. If such neighboring nodes both exit, the output of $T(C_{k,i})$ is $\{C_{k+1,w}, C_{k+1,w+1}\}$; otherwise, the output is an empty set. For example, $T(C_{1,0})=\{C_{2,0}, C_{2,1}\}$ since $C_{1,0}$ has two next-level neighboring center nodes $C_{2,0}$ and $C_{2,1}$, and we can take $C_{k+1,w}$ as $C_{2,0}$ and $C_{k+1,w+1}$ as $C_{2,1}$ with w=0. For another example, $T(C_{2,1})= \emptyset$, since $C_{2,1}$ has two next-level neighboring center nodes $C_{3,1}$ and $C_{3,2}$, and we should take $C_{k+1,w}$ as $C_{3,1}$ and $C_{k+1,w+1}$ as $C_{3,2}$ with w=1.

As shown in Fig. 9, each hexagon ring can be partitioned into six sectors, indexed by 0,..,5, each having a starting axis (i.e., A_0, ,…, A_5). Let $q=\lfloor i/k \rfloor$ denote the index of the sector in which $C_{k,i}$ resides. $T(C_{k,i})$ is defined as follows.

$$\mathrm{T}(\mathrm{C}_{k,i}) = \begin{cases} \{\mathrm{C}_{k+1,i}, \mathrm{C}_{k+1,i+1}\}, & \text{if } q=0 \text{ and } i \text{ is even} \\ \{\mathrm{C}_{k+1,i+1}, \mathrm{C}_{k+1,i+2}\}, & \text{if } q=1 \text{ and } i \text{ is odd} \\ \{\mathrm{C}_{k+1,i}, \mathrm{C}_{k+1,i+1}\}, & \text{if } q=1, (i \bmod k)=0 \text{ and } i \text{ is even} \\ \{\mathrm{C}_{k+1,i+2}, \mathrm{C}_{k+1,i+3}\}, & \text{if } q=2 \text{ and } i \text{ is even} \\ \{\mathrm{C}_{k+1,i+3}, \mathrm{C}_{k+1,i+4}\}, & \text{if } q=3 \text{ and } i \text{ is odd} \\ \{\mathrm{C}_{k+1,i+2}, \mathrm{C}_{k+1,i+3}\}, & \text{if } q=3, (i \bmod k)=0 \text{ and } i \text{ is even} \\ \{\mathrm{C}_{k+1,i+4}, \mathrm{C}_{k+1,i+5}\}, & \text{if } q=4 \text{ and } i \text{ is even} \\ \{\mathrm{C}_{k+1,i+5}, \mathrm{C}_{k+1,i+6}\}, & \text{if } q=5 \text{ and } i \text{ is odd} \\ \{\mathrm{C}_{k+1,i+4}, \mathrm{C}_{k+1,i+5}\}, & \text{if } q=5, (i \bmod k)=0 \text{ and } i \text{ is even} \\ \emptyset, & \text{otherwise} \end{cases} \quad (4)$$

The definition of $\mathrm{T}(\mathrm{C}_{k,i})$ contains 10 cases of different conditions. The first case (q=0 and i is even) is for the center node $\mathrm{C}_{k,i}$ to activate two next-level neighboring center nodes $\mathrm{C}_{k+1,i}$ and $\mathrm{C}_{k+1,i+1}$ only when $\mathrm{C}_{k,i}$ is in sector 0 and i is even. The second case (q=1 and i is odd) is for node $\mathrm{C}_{k,i}$ to activate $\mathrm{C}_{k+1,i+1}$ and $\mathrm{C}_{k+1,i+2}$ only when $\mathrm{C}_{k,i}$ is in sector 1 and i is odd. The third case (q=1, (i mod k)=0 and i is even) is for $\mathrm{C}_{k,i}$ to activate $\mathrm{C}_{k+1,i}$ and $\mathrm{C}_{k+1,i+1}$ only when $\mathrm{C}_{k,i}$ is in sector 1, $\mathrm{C}_{k,i}$ is on the starting axis of sector 1 (i.e. A1), and i is even. Similarly, the fourth, ..., and the ninth cases are for $\mathrm{C}_{k,i}$ in the sectors 2, …, and 5 to activate two center nodes for specific conditions. The last case is for $\mathrm{C}_{k,i}$ not to activate any node when none of the first nine conditions is satisfied.

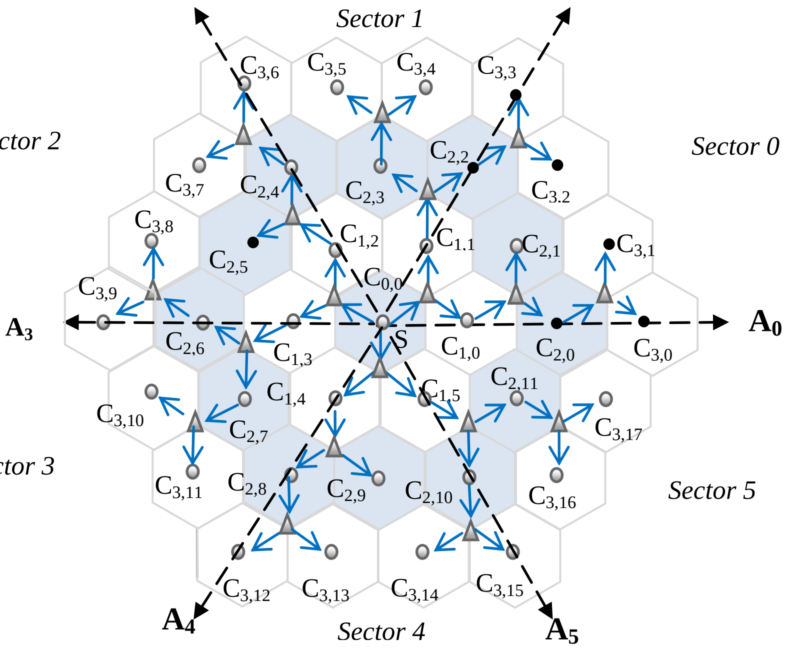

Fig. 9. The illustration of the activation target mapping with six sectors (Sector 0, …, Sector 5), each having one starting axis (i.e. A_0, … A_5) on which the starting center node in the sector resides

In Fig. 9, we illustrate $T(C_{k,i})$ by three examples. The first example is about $T(C_{2,0})$. Let $q=\lfloor 0/2 \rfloor=0$. Since q is 0 and i (=0) is even, we have $T(C_{2,0})=\{C_{3,0},C_{3,1}\}$. The second example is about $T(C_{2,5})$. Let $q=\lfloor 5/2 \rfloor=2$. Since q is 2 and i (=5) is not even, we have $T(C_{2,5})=\emptyset$, which means the node $C_{2,5}$ needs not to activate any node. The third example is about $T(C_{2,2})$. Let $q=\lfloor 2/2 \rfloor=1$. Since q is 1, i (=2) is even, and i is a multiple of k (=2), we have $T(C_{2,2})=\{C_{3,2},C_{3,3}\}$.

3.4 Adaptive Activation Mechanism

Since OBP selects retransmitting nodes on the basis of the regular hexagonal lattice used for solving the covering problem [19], it can achieve 100% reachability (the percentage of nodes receiving the broadcast packet) for a statically deployed network or a randomly deployed network with sufficiently high node density. However, in a randomly deployed network, we can foresee that the reachability may become lower when the node density is not sufficiently high. This is because the retransmitting nodes may deviate from the hexagon centers (or vertexes) and leaves some areas uncovered by wireless signals, and hence some nodes in the uncovered areas cannot receive the broadcast packet. To improve reachability, we can activate more nodes to retransmit the broadcast packet when the retransmitting node chosen by OBP is too far away from the target location.

Based on the above discussions, we propose below an *adaptive activation mechanism*. The basic concept of the mechanism is for the retransmitting node to check if it is more than D_TH away from the target location, where D_TH is a pre-specified distance threshold. If so, the node needs to activate another node, called the *repairing node*, to retransmit the packet. Below, we illustrate the concept by Fig. 10. As shown in Fig. 10(a), we assume node A sends the broadcast packet to activate a node nearest to location Z. We also assume that among all the nodes receiving A's packet, B is the node nearest to Z (Note that Y is closer to Z than B, but Y cannot receive A's packet.) Based on the adaptive activation mechanism, when node B is activated to retransmit the packet, it first derives the distance D_B between itself and location Z. Then, B checks if D_B is larger than the threshold value D_TH. If so, B will append Z to the broadcast packet to activate another node which is closer to Z than B. As shown in Fig. 10(b), node Y can receive B's packet and is now the node closest to Z. Node Y is thus a repairing node to be activated to retransmit the packet. As shown in Fig. 10(c), the distance between B and Z is less than D_TH. Therefore, B does not need to activate any repairing nodes. By Fig. 10(b), we can observe that the repairing node Y leads to an additional covered area, which in turn improves the reachability and mitigates the deviation of retransmitting nodes.

The distance threshold D_TH is defined as $\alpha \cdot R$, where R is the transmission range and α, $0<\alpha<1$, is a scale factor. D_TH can be adjusted adaptively and locally. When a node finds that the node density is lower (resp., higher), it sets a smaller (resp., larger) α value. We can easily see that a smaller α value causes more repairing nodes, which in turn lead to higher reachability.

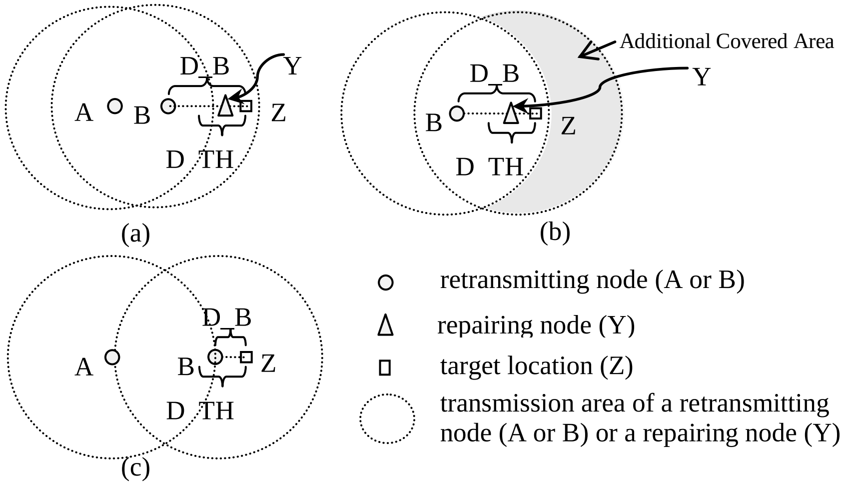

Fig. 10. Relationship between the retransmitting node, repairing node and target location

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Extended Optimized Broadcast Protocol (OBPE)

The step for the source node S to broadcast a packet P:

S1: S sends the packet P(LS, F) with F={$LV_{1,0}$, $LV_{1,1}$, $LV_{1,2}$}.

The steps for node X, X≠S, receiving P(LS, F):

X1: **IF** X has transmitted P before, **THEN** it stops.

X2: **IF** X is not a node nearest to a location in F, **THEN** it stops.

X3: **IF** X is a center node $C_{k,i}$ of a location in F, **THEN**
IF T($C_{k,i}$) ≠ Ø, **THEN** X derives { $LV_{k,i}$ } by calling T($C_{k,i}$), and sets F′={ $LV_{k,i}$ } .
ELSE X sets F′= Ø .

IF the distance between X and $LC_{k,i}$ is greater than D_TH, **THEN**
X transmits Q(LS, F′, Z) and stops, where Z=$LC_{k,i}$.
ELSE X transmits P(LS, F′), and stops.

X4: **IF** X is a vertex $V_{k,i}$ of a location in F, **THEN**
X derives {$C_{k,w}$, $C_{k,w+1}$} by calling T($C_{k-1,i}$), sets F′={$LC_{k,w}$, $LC_{k,w+1}$},
IF the distance between X and $LV_{k,i}$ is greater than D_TH, **THEN**
X transmits Q(LS, F′, Z) and stops, where Z=$LV_{k,i}$.
ELSE X transmits P(LS, F′), and stops.

The steps for node Y, receiving Q(LS, F, Z):

Y1: **IF** Y has ever transmitted the same packet, **THEN** it stops.

Y2: **IF** Y is the node nearest to Z, **THEN** it transmits P(LS, F) and stops.

Fig. 11. The pseudo code of OBPE

The extended OBP (called OBPE) adopting the adaptive activation mechanism is shown in Fig. 11. In the OBPE, the Step S1, Step X1, and Step X2 are the same as those in OBP. In Step X3, if X is a center node nearest to a target location specified in the broadcast packet, X will check whether it needs to activate any nodes. If so, X sets F′ as the set of the location of the intermediate vertex node for the activation. If not so, X sets F′ as an empty set. Afterwards, X checks if the distance between X and its target location Z is larger than D_TH. If so, X transmits a special repair-requesting packet Q embedding F′ and Z, and stops. (Note that Q also contains all the broadcast information contained in P.) If not so, X just transmits the broadcast packet P embedding F′, and stops.

In Step X4, if X is a vertex node nearest to a target location specified in the packet, then X needs to activate two center nodes. X first sets F′ as the set of the locations of the two center nodes. X then checks if the distance from itself to its target location Z is greater than D_TH. If so, X transmits a repair-requesting packet Q embedding F′ and Z, and stops. If not so, X just transmits the packet P embedding F′, and stops.

Besides, when a node Y receives the Q packet, it executes Steps Y1 and Y2 sequentially. In Step Y1, if Y finds that it has ever transmitted the same packet, then Y stops. In Step Y2, if Y is the node nearest to location Z, then Y will convert Q to be normal broadcast packet P, transmits P, and stops.

3. PERFORMANCE ANALYSIS

In this section, we analyze the upper bound of transmission efficiency of the proposed protocol OBP. As defined in [2], the transmission efficiency η is the ratio of the effective transmission area to the total summation of nodes' transmission areas. That is,

$$\eta = \frac{T_A}{N_T A_R} = \frac{T_A}{N_T \pi R^2} \tag{5}$$

In Eq. (5), T_A is the total effective transmission area, N_T is the number of transmitting nodes involved in broadcasting, and A_R is the transmission area of the value πR^2. In OBP, N_T equals to the number N_C of center nodes plus the number N_V of selected vertex nodes; i.e., $N_T=N_C+N_V$. The broadcasting in OBP is performed from the source node S to the center or vertex nodes of outer hexagon rings level by level. As shown earlier, there are 6*k* hexagons in the level-*k* hexagon ring. If the entire network area of interest is of the shape of a level-*h* hexagon ring with all inner hexagon rings (rings of level 0, level 1,⋯, to level (*h*-1)) included, we have

$$N_C = 1 + \sum_{k=1}^{h} 6k = 1 + 3h(h+1) \tag{6}$$

In OBP, two center nodes require one vertex node for the purpose of relaying the broadcast packet. We thus have

$$\mathrm{N_V} = \sum_{k=1}^{h} 6k/2 = 3h(h+1)/2 \tag{7}$$

Since $N_T = N_C + N_V$, by Eqs. (6) and (7) we have

$$\mathrm{N_T} = \mathrm{N_C} + \mathrm{N_V} = 1 + 3h(h+1) + \frac{3h(h+1)}{2} = 1 + \frac{9h(h+1)}{2} \tag{8}$$

Since T_A is the summation of all hexagon areas, by Eqs. (5) and (8) we have

$$\mathrm{T_A} = \mathrm{N_C}(3\sqrt{3}\mathrm{R}^2/2) \tag{9}$$

With Eqs. (5), (8) and (9), if h is large enough, the transmission efficiency upper bound η_{OBP} of OBP can be derived as follows.

$$\eta_{\mathrm{OBP}} = \lim_{h\to\infty} \frac{\mathrm{T}_A}{\mathrm{N_T}\pi\mathrm{R}^2} = \lim_{h\to\infty} \frac{\mathrm{N_C}\left(\frac{3\sqrt{3}\mathrm{R}^2}{2}\right)}{\mathrm{N_T}\pi\mathrm{R}^2} = \lim_{h\to\infty} \frac{(1+3h(h+1))(3\sqrt{3}\mathrm{R}^2/2)}{(1+\frac{9h(h+1)}{2})\pi\mathrm{R}^2} =$$

$$\lim h \quad \to \quad \infty \quad (1+3h(h+1))(33)(2+9hh+1)\pi$$

$$L'Hosptal\ Rule \quad 3\pi \approx 0.55 \tag{10}$$

In Eq. (10), the famous *L'Hospital Rule* [18] is used to derive the limit of η_{OBP}. Since $h \to \infty$ and the numerator and denominator are both differentiable, the limit value is $\sqrt{3}/\pi$, which is approximately 0.55.

The above analysis result can be confirmed by Kenniser's result about the covering ratio (ρ) of the covering problem [19], where the covering ratio is introduced in Section 2 of paper [19]. By definition, the covering ratio (ρ) is the inverse of the transmission efficiency. And, the required number of nodes in OBP is 1.5 times of the number of nodes in hexagonal based method (the extra 0.5 times is required for the vertical nodes). Mathematically speaking,

$$\eta_{\mathrm{OBP}} = \frac{1/\rho}{1.5} = \frac{2}{3} \times \frac{9}{2\sqrt{3}\pi} = \frac{3}{\sqrt{3}\pi} = \frac{\sqrt{3}}{\pi} \tag{11}$$

As shown in [2], the theoretical upper bound η_{U} of transmission efficiency is 0.61. We have that OBP approximates the theoretical upper bound of transmission efficiency by a ratio of $\eta_{\mathrm{OBP}}/\eta_{\mathrm{U}} \approx 90\%$. We can see that OBP has better transmission efficiency than BPS, the geometry-based broadcast protocol with the highest transmission efficiency so far.

We compare OBP and BPS by analysis in terms of the number of transmissions for broadcasting a packet. Since OBP and BPS are hexagon based approaches, we evaluate them with the assumption that the entire network area is of the shape of a hexagon ring pattern.

The number of transmissions in broadcasting N_{T_BPS} of BPS is analyzed in section 4 of [4], which is approximated as follows when the area of network (A_{NET}) is enough large compared to the area of one hexagon:

$$N_{T\_BPS} \approx \frac{2 \cdot A_{NET}}{A_{HEX}} = \frac{2 \cdot (N_C \cdot A_{HEX})}{A_{HEX}} = 2 \cdot N_C \quad (12)$$

Where A_{NET} is the area of network, A_{HEX} is the area of hexagon

Since the area of network is modeled as the hexagonal rings, the A_{NET} is equal to the product of number of hexagons (N_C) and the area of hexagon (A_{HEX}). From Eq. (12) and Eq. (9), we can derive the ratio of number nodes required in broadcasting for OBP and BPS as:

$$R_{OBP\_BPS} = \frac{N_T}{N_{T\_BPS}} = \frac{N_C + N_V}{2N_C} = \frac{1}{2}\left(1 + \frac{N_V}{N_C}\right) = \frac{1}{2}\left(1 + \frac{3h(h+1)/2}{1+3h(h+1)}\right) \quad (13)$$

When $h \to \infty$, the limit of R_{OBP_BPS} is derived by *L'Hospital Rule* as follows.

$$R_{OBP\_BPS} \to 3/4, \text{ as } h \to \infty \quad (14)$$

Hence, the OBP only requires 3/4 transmissions of BPS. Fig. 12 shows the number of required transmissions for the area of the 1-, 2-, 4-, 6-, and 8-level hexagon rings with all inner rings included. As shown in Fig. 12, OBP requires fewer transmissions than BPS. This is because BPS requires all vertex nodes to retransmit the broadcast packet, while OBP requires only all center nodes plus specific vertex nodes to transmit the packet. The fact that BPS has transmission efficiency of 0.41 and OBP has transmission efficiency of 0.55 also accounts for the results. It can also be checked that the ratio of the number of transmissions of OBP to that of BPS is approaching 0.75 (i.e., 3/4) when the level grows. For example, the ratios are 0.7459 (i.e., 91/122), 0.7480 (i.e., 190/254), and 0.7488 (i.e., 325/434) for the 4-, 6-, and 8-level hexagon rings, respectively.

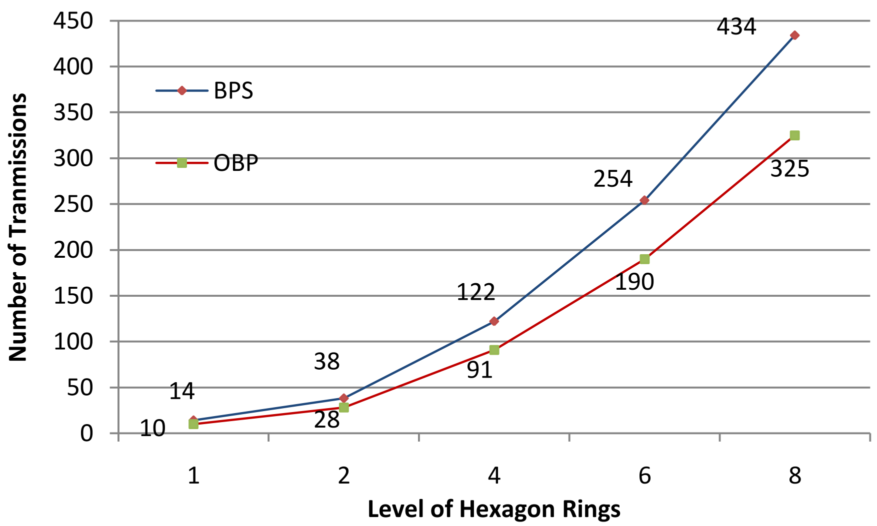

Fig. 12. Comparisons of required transmissions in the specific hexagon ring for BPS

and OBP.

5. SIMULATION EXPERIMENTS

In this section, we compare the performance of BPS, OBP, and OBPE by simulation experiments in terms of four metrics: (1) the number of transmissions, (2) transmission redundancy, (3) reachability, (4) energy consumption, and (5) collision probability. The number of transmissions reflects the transmission efficiency of the protocols. The transmission redundancy is defined as the average number of received packets per node for a broadcast packet; it can reflect the degree of redundancy of transmissions. The reachability is the percentage of nodes that receive the broadcast packet successfully. The energy consumption concerns the energy consumed by nodes when they transmit and receive the broadcast packet.

When performing simulation experiments, we assume the transmission range R of nodes is set to be 100m and nodes are uniformly deployed with different densities from $5/R^2$ (nodes per transmission area), $10/R^2$,…, to $45/R^2$ over the entire network area shaped by a circle with radius 4R. We also assume that nodes exchange location information periodically so that they can precisely decide which node is nearest to the location of a selected hexagon center or vertex. The distance threshold, Th, in BPS protocol is set to be 0.4R. And, the default value of α in OBPE is 0.4 (i.e., D_TH=0.4R). Since the paper focuses on optimizing transmission efficiency of wireless broadcasting and does not address the problems caused by packet collisions and node mobility, we run the Matlab software [21] instead of networked-based simulators to simulate the proposed protocols. However, we further conduct simulation experiments in terms of collision probability according to parameter settings adopted in ns-2 simulator [22] to show that the collision probability can be quite low to justify the neglect of packet collisions. Under the above settings, each simulation experiment case is run 40 times for evaluating protocols' performance.

Note that the boundary effect is ignored in simulation experiments. That is, the uncovered regions near the boundary are not considered in the simulations for both OBP and BPS. This is because in some extreme cases, many nodes near the boundary may not receive the broadcast packet properly. In this paper, we regard the area within R distance to the boundary as the *boundary area*, in which nodes not receiving the broadcast packet are ignored.

5.1 The Number of Transmissions

The number of transmissions is an important metric for evaluating the broadcast protocols. The lower the number of transmissions is, the more efficient the protocol is. Fig. 13 shows the number of transmissions of BPS, OBP, and OBPE for node densities $5/R^2$, $10/R^2$, …, $45/R^2$. By Fig. 13, we can see that BPS requires higher numbers of transmissions than OBP and OBPE for node densities higher than $5/R^2$. Moreover, as shown in Fig. 13, when the node density is sufficiently high, the number of transmissions of OBPE is near those of OBP. This is because OBPE does not need to activate the repairing node when the node density is sufficiently high. However, when the node density is very low (say $5/R^2$), the number of transmissions of OBPE goes up, but those of OBP and BPS go down. This is because fewer nodes are near the target locations when the node density is low. Thus, OBPE needs to adaptively activate many repairing nodes, while OBP and BPS have fewer nodes to forward the packet. Consequently, as will be shown later, OBPE achieves the highest reachability among the three protocols.

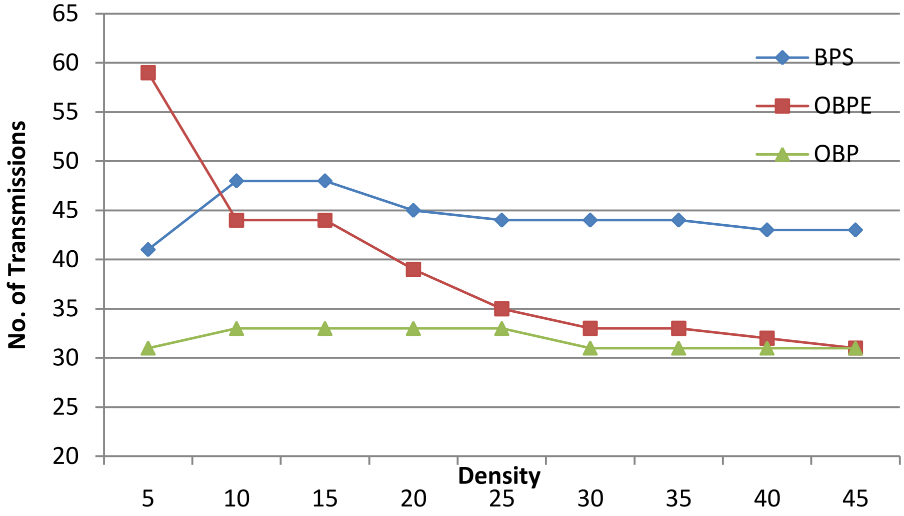

Fig. 13. Numbers of transmissions of BPS, OBP and OBPE for different node densities

5.2 Transmission Redundancy

To evaluate transmission redundancy, we measure the average number of received packets per node. A higher number of the received packets per node implies a higher degree of transmission redundancy, which in turn leads to higher energy consumption of receiving packets and higher possibility of packet collision. As shown in Fig. 14, the average number of received packets per node of BPS is usually higher than that of OBP and OBPE. It implies the OBP and OBPE are with lower redundancy, which leads to lower possibility of collisions and lower energy consumption in receiving packets in OBP and OBPE. However, when the node density is very low (say $5/R^2$), the number of received packets of OBPE goes up, but those of OBP and BPS go down. This is because OBPE needs to adaptively activate many repairing nodes to forward the packet, but OBP and BPS have even fewer nodes to forward the packet. As will be shown later, the overheads of OBPE for the very low node density case make it achieve the highest reachability among the three protocols.

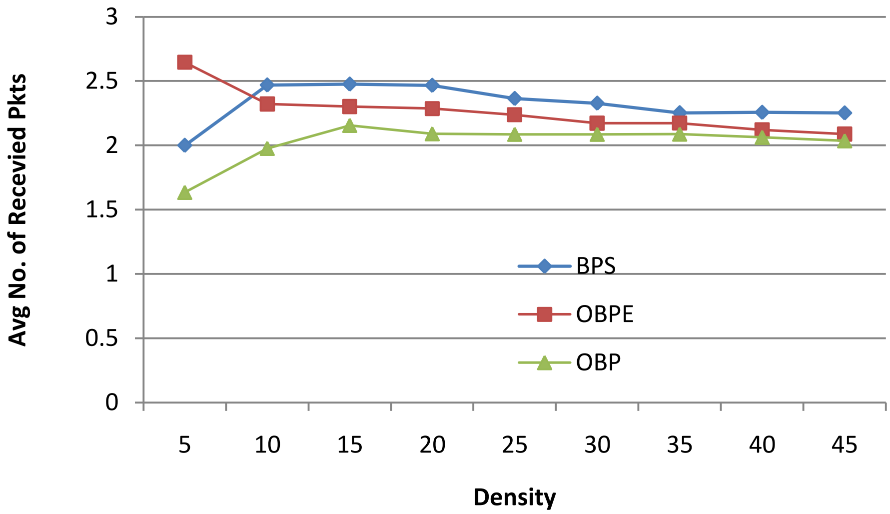

Fig. 14. Average numbers of received packets per node for BPS, OBP and OBPE

5.3 Reachability

In this subsection, we evaluate the protocols' reachability, the percentage of the nodes receiving the broadcast packet for different node densities $5/R^2$, $10/R^2$, …, $45/R^2$. Theoretically, OBP and BPS have 100% reachability when the node density is sufficiently high. When the node density is not high, retransmitting nodes may be deviated from hexagon center or vertex locations, so the network area of interest may not be fully covered for some cases. By OBPE that uses the adaptive activation mechanism, the location deviation is mitigated to improve reachability at the expense of the increased number of transmission nodes and the increased number of received packets. As shown in Fig. 15, when the node density is high (e.g., $25/R^2$ or higher), all three protocols have reachability higher than 99%. Specifically, OBPE and BPS even have reachability of 99% or higher when the node density is higher than $10/R^2$. In practice, OBPE has the highest reachability when the node density is $25/R^2$ or lower, while BPS has the highest reachability when the node density is $30/R^2$ or higher.

5.3 Energy Consumption

In this subsection, we evaluate the protocols in terms of the energy consumption per node. To measure the total energy consumption of transmitting nodes in the network, we adopt the energy consumption model mentioned in [23]. The energy consumption per bit of the transmitting nodes consists of two parts: (1) energy consumption E_{elec} of transceiver electronics and (2) energy consumption E_{com} of radiated power necessary to transmit one bit over a distance D between the sending node and the receiving node. For each transmitting node, the energy consumption E_{TX} required to transmit L bits is a distance-dependent formula as follows:

$$E_{TX}(L, D)= L\cdot E_{elec}+L\cdot E_{com}\cdot D^{\beta} \quad (11)$$

In Eq. (11), D is the transmission distance, and β is the path loss exponent (usually, $2\leq\beta\leq5$). We assume signal propagation follows the free space channel model, so we set β=2, as suggested in [23]. According to [23], we also set E_{elec}=50 nJ/bit, E_{com} =10 pJ/bit/m^2, and L=10^3.

To measure the energy consumption of receiving nodes, we again adopt the energy consumption model mentioned in [23]. The energy consumption E_{RCV} of a receiving node to receive L bits of data is modeled as follows:

$$E_{RCV}(L, D)= L\cdot E_{elec} \quad (12)$$

By Eqs. (11) and (12), we can calculate the total energy consumption of all nodes in the network, and we can then calculate the energy consumption per node. The simulation results of the energy consumption per node (ECPN) of BPS, OBP, and OBPE are reported in Fig. 15. For all node densities, OBP has the least energy consumption per node, which is the consequence of OBP optimizing transmission efficiency. When the node density is 25/R^2 or higher, BPS has the highest energy consumption per node. However, when the node density is 20/R^2 or lower, OBPE has the highest energy consumption per node. This is because OBPE adopts the adaptive mechanism leading to many repairing nodes to achieve high reachability for low node density cases. In practice, the per-node energy consumption of OBPE decreases with the node density. For BPS and OBP, the energy consumption is maximum when the node density is 15/R^2; it decreases when the node density goes up and goes down from 15/R^2. This is because when the node density goes lower from 15/R^2, fewer nodes are near the specified target locations, leading to lower energy consumption (and certainly, lower reachability). On the contrary, when the node density goes higher from 15/R^2, the forwarding nodes comply with the hexagon-based pattern and the number of transmissions remains unchanged, leading to the decreasing energy consumption per node.

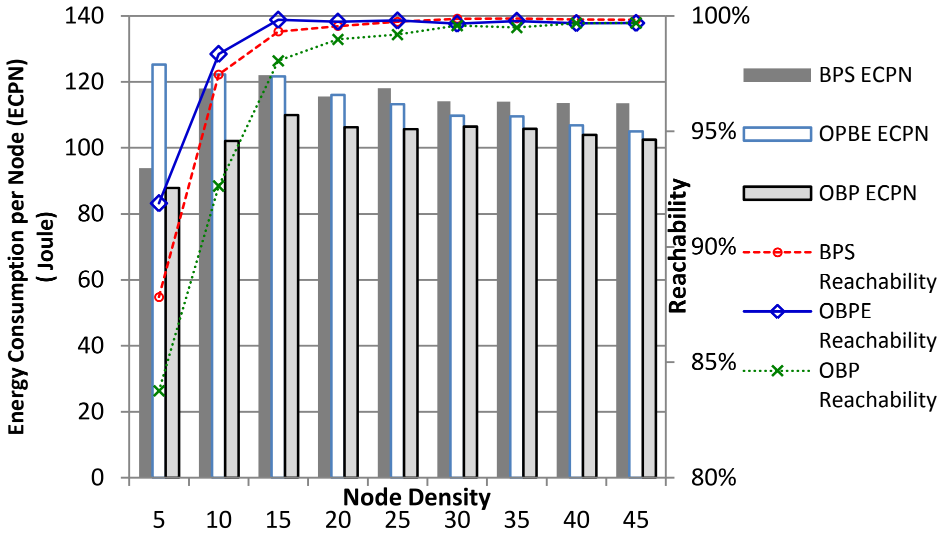

Fig. 15. Energy consumption per node (ECPN) and reachability of BPS, OBP, and OBPE for various node densities

Furthermore, we conduct experiments to evaluate the impact of adjusting different α values: 0.3, 0.4 and 0.5. The simulation results are reported in Fig. 16, which shows the energy consumption per node in different α values. As shown in Fig. 16, OBPE consumes less energy and requires the less number of transmitting nodes (i.e., number of transmissions) when α value is higher. And as shown in Fig. 17, OBPE requires lower number of repairing nodes when α value is higher.

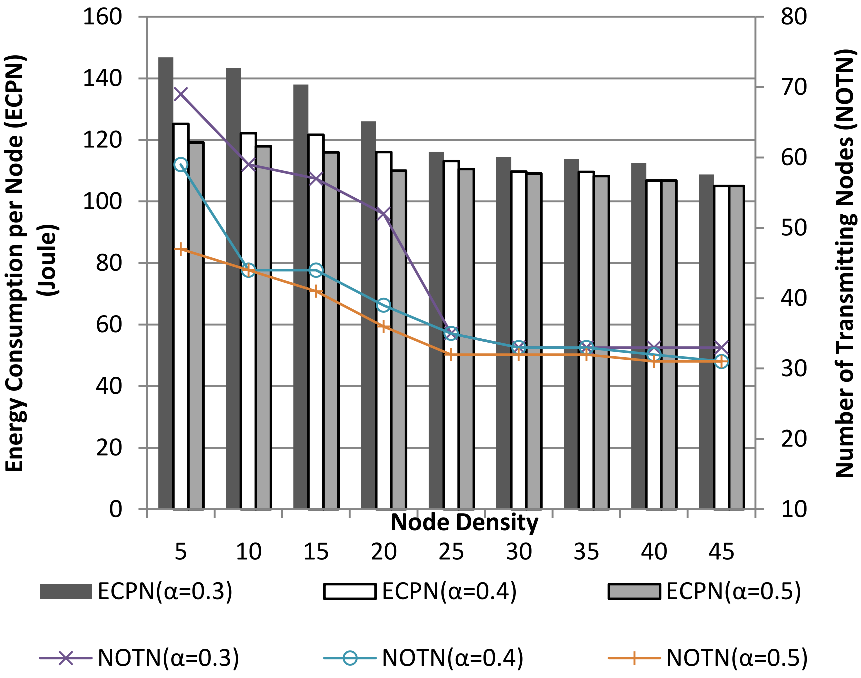

Fig. 17. Energy consumption per node of OBPE for various node densities and α values

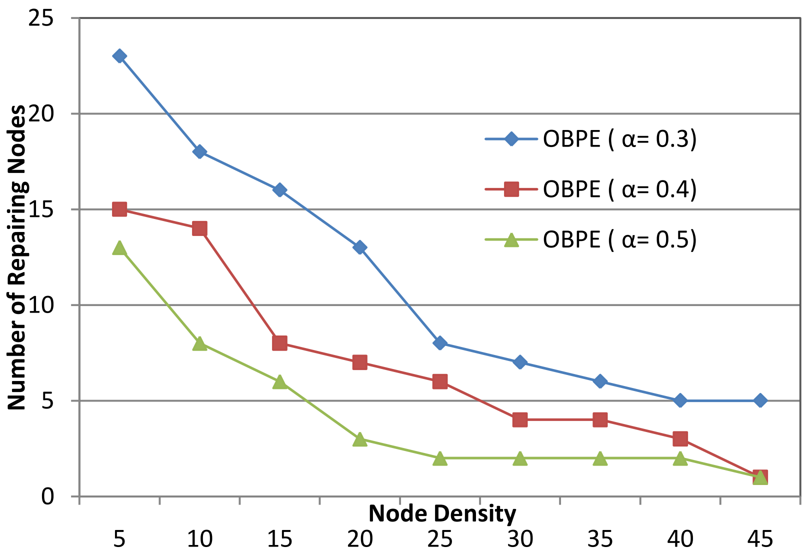

Fig. 18. Number of repairing nodes of OBPE for various node densities and α values

5.4 Collision Probability

As shown earlier, a node uses the backoff mechanism to forward the broadcast packet in a specific timeslot which is chosen from a number of timeslots indexed by 0,…, $n-1$. The smaller is the distance from the node to the target location of the forwarding node, the smaller is the index of the specific timeslot. Since a node will not forward the broadcast packet after receiving the same packet from its neighboring node, it is likely that only the node closest to the target location will forward the packet. We have neglected the occurrence of collisions; however, it is possible to have multiple forwarding nodes at the same time, leading to collisions and impairing the performance of the proposed protocols.

Below in this subsection, we perform simulation experiments to evaluate the packet collision probability by varying the number n of backoff timeslots to show that the collision probability can be quite low to justify the neglect of packet collisions. The *collision probability* is defined as the ratio of the total number of collisions to the total number of nodes during the period of broadcasting a packet. The simulation assumes the IEEE 802.11b MAC specification of 11Mbps data rate, and the parameter settings, which are shown below, conforming to the IEEE 802.11 module of the ns-2 simulator [22]. The duration of a backoff timeslot is 20 μs; the PHY header size, the MAC header size, and the FCS (frame check sequence) size are 24, 24, and 4 bytes, respectively. The simulation experiments are conducted for the node density of $45/R^2$ with the number of backoff timeslots being 32, 64, 128, and 256. The simulation results are reported in Fig. 19, which shows the collision probability is as low as 0.0283% and 0.0848% for OBP and OBPE, respectively, with the number of backoff timeslots being 256. It can be easily observed that the collision probability decreases with the number of backoff timeslots. A larger number of timeslots provides more timeslots for nodes to choose, so the collision probability is lower. However, a larger number of backoff timeslots does not necessarily imply a larger latency of forwarding the packet. For example, when the node density is not low, the node closest to the target location will not be too far away from the target location and will perform the packet forwarding with a short delay.

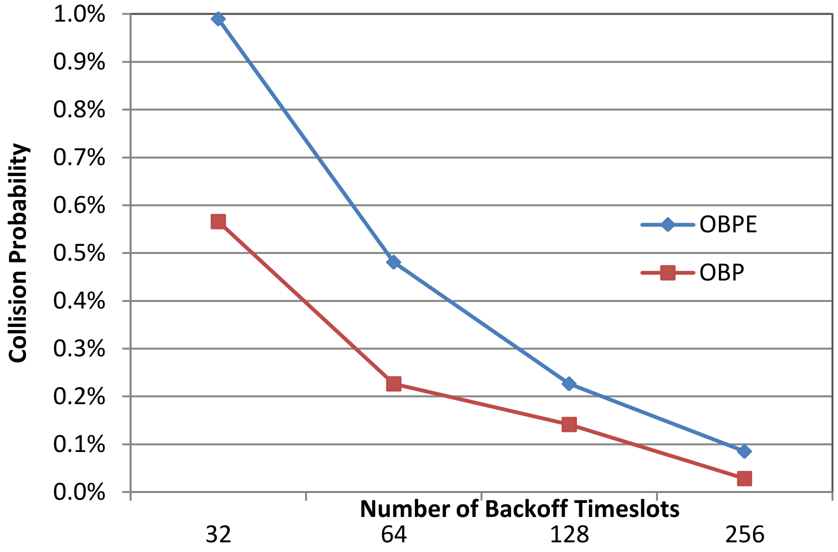

Fig. 19. Collision probability for various numbers of backoff timeslots

6. CONCLUSION

We have proposed a broadcast protocol, called Optimized Broadcast Protocol (OBP), for the wireless network to disseminate a broadcast packet throughout the entire network. OBP is a geometry-based broadcast protocol, in which each node knows the locations of itself. Its key idea is to select nodes based on a hexagon ring pattern to minimize the number of retransmissions for better transmission efficiency. Only nodes nearest to hexagon centers and some specific hexagon vertexes should retransmit the broadcast packet. The analysis result shows that OBP's transmission efficiency is 0.55, which is about 90% of the theoretical upper bound and is better than that of BPS, the geometry-based broadcast protocol with the highest transmission efficiency 0.41 known so far. The simulation results show that OBP indeed has lower averaged energy consumption. Theoretically, OBP has 100% reachability when the node density is sufficiently high. However, when the node density is not high, the network area of interest may not be fully covered and OBP has worse reachability than BPS for some cases. Fortunately, the reachability of OBP is higher than 99% when the node density is greater than $25/R^2$. Moreover, we have proposed OBPE, the extended version of OBP, to adopt the adaptive activation mechanism for a retransmitting node to be adaptive to the local node density to activate extra repairing nodes to retransmit the broadcast packet for improving reachability. As shown by our simulation results, OBPE has approximately the same reachability as BPS when the node density is higher than $25/R^2$, and OBPE outperforms BPS in terms of the number of transmissions, transmission redundancy and averaged energy consumption for all node densities. Furthermore, when the node density is

$25/R^2$ or lower, OBPE has the highest reachability among the three protocols. In summary, we suggest using OBP when transmission efficiency is the main concern and suggest using OBPE when reachability and transmission efficiency are both considered.

When the source node is near or at the boundary of the network area, many geometry-based broadcast protocols, including BPS and the proposed OBP and OBPE, may not work well because some target locations specified in the broadcast packet of the source node may be out of the boundary and thus the packet is not forwarded properly to form an expanding hexagon ring pattern. If the boundary is known in advance, one remedy to this problem is to allow nodes near the boundary to ask a node near the center of the network area to act as a *delegated source node* to help broadcast the packet. If the boundary is unknown in advance, then the repairing node in OBPE may reduce the negative effects caused by the source nodes near the boundary. We plan to address the problem that source nodes are close to the boundary in the future.

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