Efficient Broadcasting Protocols for Regular Wireless Sensor Networks *

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Abstract

The wireless sensor network (WSN) has attracted lots of attention recently. Since the sensor nodes usually have no plug-in power, we have to conserve power so that each sensor node can operate for a longer period of time. Here, we propose power and time efficient broadcasting protocols for four different WSN topologies. Our broadcasting protocols conserve power and time by choosing as few relay nodes as possible to scatter messages to the whole network. Besides, collisions are carefully handled such that our one-to-all broadcast protocols can achieve 100% reachability. Numerical evaluation results compare the performances of the four topologies and show that our broadcasting protocols are power and time efficient.

Keywords: Broadcast, wireless sensor network (WSN).

1 Introduction

The wireless sensor network (WSN) is widely adopted in variety of areas. We can use the WSN to monitor the conditions of a place, where traditional wired network is not available, such as battlefield, forest, and human body [13]. It is known that the WSN with regular topology can communicate more efficiently than the WSN with random topology [12, 14]. Therefore, we should adopt the WSN with regular topology when the condition permits so that more time and power can be conserved, such as deploying WSN to buildings, bridges, flat areas, space vehicles [15], and human body [13].

A WSN usually consists of thousands of sensor nodes. Each sensor node is equipped with a $MEMS$ (micro-electro-mechanical systems) component, which includes sensor, radio frequency circuit, data fusion circuitry [7] and general purpose signal processing engines [11]. A sensor node uses its sensor to collect the information in the environment and exchange the information with other sensor nodes by radio frequency circuit. When a sensor node wants to transmit messages, the sender and receiver must be synchronized [6].

The sensor node is a low-cost, small size, and power-limited electronic device [4], which can still work even there is little remaining power [5, 1, 3]. However, the sensor nodes in the WSN have no plug-in power. Therefore, many researchers try to conserve the battery power of sensor nodes so that the lifetime of the network can be extended. LEACH [8] proposed a cluster-based protocol, which randomly selects cluster heads to collect information in the network. Since each cluster head has to consume more power to transmit collecting information to the base station, randomly selecting cluster heads will let every node consume about the same amount of power. To improve LEACH's work, in TEEN's protocol [10], each sensor node will decide whether it should transmit the data or not according to the variation of the collecting information and thus conserve more power. A routing protocol for the wireless access network is proposed in [9], it is also suitable for the WSN. It can evenly distribute power consumption of the unicast transmission to every node in the network and thus extend the lifetime of the network. Power efficient routing protocols for five different WSN topologies are presented in [12]. These protocols are power efficient but can not balance the power consumption of the relay nodes.

Broadcast is a fundamental operation for all kinds of networks. Here, we propose power and time efficient broadcasting protocols for the four different topologies proposed in [13, 12, 2], as we know that the broadcasting protocols for regular WSNs have not been proposed before. Our broadcasting protocols not only choose as few nodes as possible to relay the broadcast messages, but also scatter the messages along the shortest path. Besides, our broadcasting protocols can achieve 100% reachability by carefully handling collisions. Numerical analysis results show that our

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broadcasting protocols are power and time efficient. Our protocols also can be applied to the wireless network which is static and regular, such as the packet radio network or the network formed by wireless access points [9].

The rest of this paper is organized as follow. Section 2 describes the system environments. Section 3 presents the broadcasting protocols of the four different topologies. Section 4 analyzes the performance of our broadcasting protocols. Conclusions are made in Section 5.

2 System Environments

We adopt the First Order Radio Model [8] to evaluate the power consumption of each sensor node. In this model, the power consumption rate (denoted as E_{elec}) of transmitting/receiving messages is 50 nJ/bit. To avoid the transmitting message interfered by the noise in the air, the sender has to consume extra 100 $pJ/bit/m^2$ (denoted as E_{amp}) to strengthen the transmitting signal so that the receiver can receive the message correctly. If the sender wants to transmit k bits data to the receiver which is d meters away, the total power consumption is:

$$E_{Tx}(k,d) = E_{elec} \times k + E_{amp} \times k \times d^2 \qquad (1)$$

To receive the message, the power consumption of the receiver is:

$$E_{Rx}(k) = E_{elec} \times k \qquad (2)$$

According to equations 1 and 2, we can calculate the amount of power consumed by transmitting (or receiving) a packet.

Four different network topologies are considered here: namely 2D mesh with 3 neighbors (Fig. 1), 2D mesh with 4 neighbors (Fig. 2), 2D mesh with 8 neighbors (Fig. 3) and 3D mesh with 6 neighbors (Fig. 4). In the four topologies, each node is assigned a unique id according to its relative location in the network. The ids in 2D and 3D networks are denoted as (x, y) and (x, y, z), respectively. The number of neighboring nodes indicates the maximum number of directly connective nodes. All the nodes in the WSN shall have the same number of neighboring nodes, except the nodes in the boarder. We design different broadcasting protocols for the four different topologies. All the proposed protocols are power and time efficient, and thus can extend the lifetime of the network.

We assume that all the sensor nodes in the WSN are synchronized and the radio channel is symmetric, that the power required to transmit a message from node A to node B is the same as the power required to transmit a message from node B to node A.

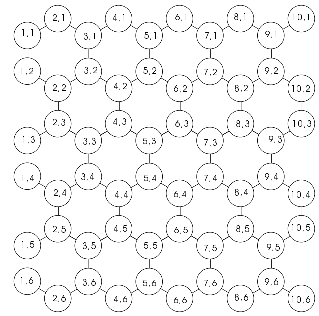

Figure 1. 2D mesh with 3 neighbors.

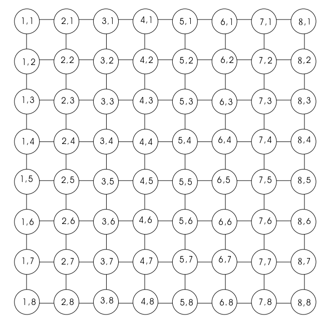

Figure 2. 2D mesh with 4 neighbors.

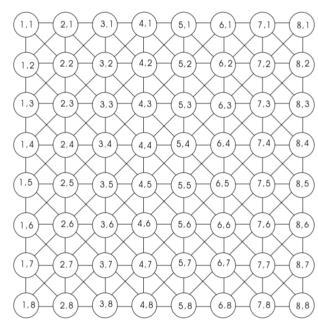

Figure 3. 2D mesh with 8 neighbors.

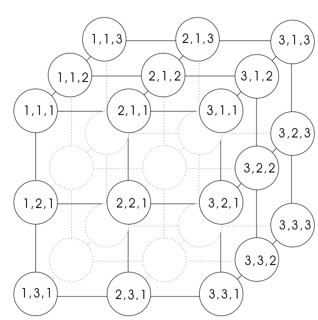

Figure 4. 3D mesh with 6 neighbors.

3 Broadcasting Protocols

The goal of the broadcasting protocol is to scatter the source node's data to all the nodes in the network. In traditional broadcasting protocols, almost all the nodes need to forward the data and thus cause severe collisions. To avoid collision, some of the nodes need to wait for a period of time before forwarding the data. However, lots of time and power are wasted when the nodes are waiting. Therefore, we have to reduce the number of relay nodes and handle collisions carefully.

Due to the broadcast nature of wireless radio (a transmission can cover all the neighboring nodes), it is not necessary for every nodes in the network to forward the broadcast message while broadcasting message to every node in the network. Since the network topologies are regular and fixed, we may choose the necessary relay nodes according to the network topology and thus avoid unnecessary forwarding and collisions. To conserve power, the number of relay nodes should be as few as possible, so that the total amount of consumed power can be decreased. Assume that the total number of neighbors is denoted as N and the number of neighbors that receive a non-duplicated message after the transmission is denoted as M. The efficient transmission ratio (ETR) is defined as $ETR = \frac{M}{N}$. The higher the ETR is, the more efficient the transmission is. Therefore, we will choose the node which has a higher ETR as the relay node. Our goal is to reduce the number of relay nodes and transmit the broadcast message along the shortest path so that the delay time and consumed power can be reduced.

Nodes in different network topology can achieve different ETR. Only the source node in the network can reach 100% ETR. For any node H_i with N neighbors, its possible optimal ETR is $\frac{N-1}{N}$. Since, one of H_i's neighbor that transmits message to H_i has already received the message, there will be at most $N-1$ nodes receive the non-duplicated message after the transmission. For example, in 2D mesh with 3 neighbors, the non-source node's optimal ETR is $\frac{2}{3}$.

Choosing relay nodes according to ETR can not guarantee a collision-free transmission. Collisions may cause some retransmissions. However, to provide a collision-free broadcast, we need to delay some transmissions, and thus increase the delay time and cause more nodes to receive duplicated messages. The larger the network is the longer the delay time is. Besides, receiving duplicated data will consume more power. Therefore, we do not delay transmission to avoid collision, instead, we let the collision occur and retransmit the collided message. Retransmit the message will consumed additional power, therefore, we choose as few nodes as possible to retransmit the message.

For the ease of describing our broadcasting protocols, we assume that the size of the 2D mesh is $m \times n$, where m and n are positive integers, and the source node's id is (i, j). Besides, we define the term "diagonal axis" as follows: For any node (i, j), where i is the coordinate in the X axis and j is the coordinate in Y axis, we define two types of diagonal axis, namely S_1 and S_2. The node (i, j) along S_1 axis is in set $S_1(c)$, if $c = i + j$, and the node (i, j) along S_2 axis is in set $S_2(c)$, if $c = i - j$. For example, nodes $(5, 7)$, $(6, 6)$, and $(7, 5)$ are in set $S_1(12)$, and nodes $(5, 3)$, $(6, 4)$, and $(7, 5)$ are in set $S_2(2)$. The nodes in a set will form a straight line in the network. The straight line formed by the nodes in $S_1(c)$ are named as the S_1 direction, and the straight line formed by the nodes in $S_2(c)$ are named as the S_2 direction.

3.1 2D Mesh with 4 Neighbors

To achieve high ETR in 2D mesh with 4 neighbors, the source node (i, j) first transmits the broadcast message along its X axis. As long as the node, whose id is $(i{+}3k, j)$, where $1 \leq i + 3k \leq m$ and k is an integer, has received the broadcast message, it will transmit the broadcast message along its Y axis. However, the nodes in the border of Y axis, whose id is $(1, y)$ or (m, y), where $1 \leq y \leq n$ and $y \neq j$, may still not receive the broadcast message. Therefore, the nodes $(1, y)$ and (m, y) need to check whether nodes $(2, y)$ and $(m-1, y)$ are relay nodes or not, respectively. If node $(2, y)$(or $(m{-}1, y)$) is not relay node, node $(1, y)$(or (m, y)) will become the relay node.

Collisions occur in nodes $(i + 1 + 3k, j + 1)$ and $(i + 1 + 3k, j - 1)$ when nodes $(i + 1 + 3k, j)$, $(i + 3k, j - 1)$, and $(i + 3k, j + 1)$ transmit message simultaneously, where $i \leq i{+}1{+}3k \leq m$ and k is an integer. Collisions also occur in nodes $(i{-}1{-}3k, j{+}1)$ and $(i{-}1{-}3k, j{-}1)$ when nodes $(i - 1 - 3k, j)$, $(i - 3k, j - 1)$, and $(i - 3k, j + 1)$ transmit message simultaneously, where $1 \leq i - 1 - 3k \leq i$. If we delay the transmissions of nodes $(i + 1 + 3k, j)$ and $(i - 1 - 3k, j)$ to avoid collisions, it will cause 3 extra time slots delay and nodes $(i + 3k, j)$, $(i - 3k, j)$, $(i + 1 + 3k, j + 1)$, $(i{+}1{+}3k, j{-}1)$, $(i{-}1{-}3k, j{+}1)$ and $(i{-}1{-}3k, j{-}1)$ will receive duplicated messages. On the other hand, if we delay the transmissions of nodes $(i + 3k, j - 1)$, $(i + 3k, j + 1)$, $(i - 3k, j - 1)$, and $(i - 3k, j + 1)$ to avoid collisions, it will cause an extra time slot delay and nodes $(i + 1 + 3k, j + 1)$, $(i + 1 + 3k, j - 1)$, $(i - 1 - 3k, j + 1)$, $(i - 1 - 3k, j - 1)$, $(i - 1 + 3k, j + 1)$, $(i - 1 + 3k, j - 1)$, $(i + 1 - 3k, j + 1)$, and $(i + 1 - 3k, j - 1)$ will receive duplicated messages and thus consume more power. Therefore, we do not try to avoid collisions, instead we let nodes $(i + 1 + 3k, j)$ and $(i - 1 - 3k, j)$ retransmit the broadcast message in next time slot, where $i \leq i + 1 + 3k \leq m$ and $1 \leq i - 1 - 3k \leq i$.

Fig. 5 is an example of the one-to-all broadcast for 2D mesh with 4 neighbors. The nodes in black or gray color are the relay nodes, the nodes in gray color need to retransmit the broadcast message, the numbers beside the edge are the

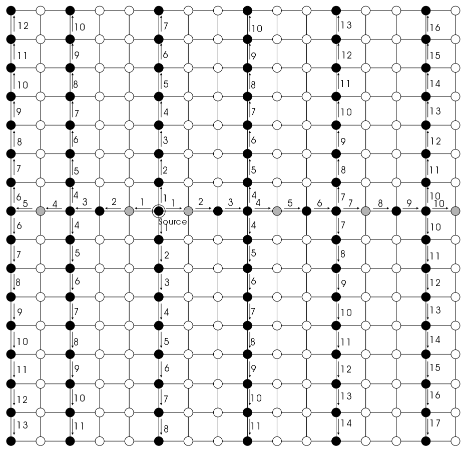

Figure 5. One-to-all broadcast for 2D mesh with 4 neighbors, where source is $(6, 8)$

transmission sequences. In Fig. 5, node $(6, 8)$ is the source. When nodes $(2, 8)$, $(5, 8)$, $(7, 8)$, $(10, 8)$, $(13, 8)$ and $(16, 8)$ transmit the broadcast message, collisions occur, therefore, we will let these nodes retransmit the message in next time slot. In this protocol, most of the relay nodes can achieve optimal $ETR\,(=\frac{3}{4})$ and thus conserve lots of power.

3.2 2D Mesh with 8 Neighbors

Compare 2D mesh with 8 neighbors to 2D mesh with 4 neighbors, in 2D mesh with 8 neighbors, node (i, j) has four additional neighbors, nodes $(i-1, j-1)$, $(i+1, j-1)$, $(i-1, j+1)$ and $(i+1, j+1)$. Therefore, the broadcast message can be transmitted along the four additional neighbors. Forwarding the broadcast message along the diagonals can not only decrease delay time but also can conserve more energy than forwarding along the X axis and Y axis. In Fig. 6, if node $(1, 4)$ transmits the broadcast message along the X axis and Y axis, it takes 6 hops to forward the message to node $(4, 1)$, however, if the message is forwarded along the diagonal, it takes only 3 hops to forward the message to node $(4, 1)$. Besides, if nodes $(2, 3)$ forwards the broadcast message to node $(3, 2)$, which is along the diagonal direction, nodes $(2, 2)$ and $(3, 3)$ will also receive the broadcast message, so the ETR of node $(3, 2)$ is $\frac{5}{8}$. However, if the broadcast message is transmitted from node $(2, 2)$ to node $(3, 2)$, which is along the X axis, nodes $(2, 1)$, $(2, 3)$, $(3, 1)$, and $(3, 3)$ will also receive the broadcast message, and the ETR of node $(3, 2)$ is $\frac{3}{8}$, which is much lower than transmitting along the diagonal direction.

Assume the source node's id is (i, j). We first choose the nodes in sets $S_1(i+j)$ and $S_2(i-j)$ as the basic relay nodes, then we choose the rest relay nodes from the S_2 (or S_1 but not both) axis. The nodes in sets $S_2(i-j+5k)$, where $-n \leq i-j+5k \leq m$, k is an integer, are chosen as the relay nodes. Collisions occur when the relay nodes those have common neighbors transmit messages simultaneously. However, not all collisions need to be resolved by retransmission. When nodes $(i+1, j+1)$ and $(i+1, j-1)$ transmit messages simultaneously, collisions occur in node $(i+2, j)$, therefore, we let node $(i+1, j-1)$ retransmit the message. When nodes $(i+3, j-3)$ and $(i+3, j-2)$ transmit messages simultaneously, collisions occur in nodes $(i+4, j-3)$ and $(i+4, j-2)$. However, when nodes $(i+4, j-4)$ and $(i+4, j-1)$ forward the message, nodes $(i+4, j-3)$ and $(i+4, j-2)$ will receive the message from them, respectively. Therefore, nodes $(i+3, j-3)$ and $(i+3, j-2)$ do not need to retransmit the message.

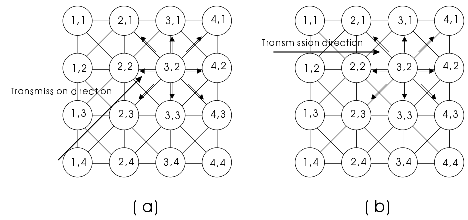

Figure 6. Transmit messages along the diagonal and the X axis have different ETR

For example, in Fig. 7, node $(5, 9)$ is the source. Nodes in $S_1(14)$, $S_2(1)$, $S_2(6)$, $S_2(11)$, $S_2(-4)$, and $S_2(-9)$ are chosen as the relay nodes. When nodes $(6, 8)$ and $(6, 10)$ transmit messages simultaneously, collisions occur in node $(7, 9)$, therefore, we let node $(6, 8)$ retransmit the message. In case of nodes $(8, 6)$ and $(8, 7)$ transmit messages simultaneously, collisions occur in nodes $(9, 6)$ and $(9, 7)$. However, when nodes $(9, 5)$ and $(9, 8)$ forward the message, nodes $(9, 6)$ and $(9, 7)$ will receive the message from them, respectively. Therefore, neither node $(8, 6)$ nor $(8, 7)$ needs to retransmit the message. In Fig. 7, the nodes in black or gray color are the relay nodes, the nodes in gray color need to retransmit the broadcast message, the numbers beside the edge are the transmission sequences. We can see that, among 196 nodes, only 3 nodes need to retransmit the message and most of the relay nodes can achieve optimal $ETR\,(=\frac{5}{8})$

3.3 2D Mesh with 3 Neighbors

The broadcasting protocol of 2D mesh with 3 neighbors is more complicated than that of the other 2D topologies. To choose proper relay nodes and achieve high ETR, we divide the network into three regions as shown in Fig. 8. First, the source node (i, j) will choose two nodes (denoted as nodes (i_a, j_a) and (i_b, j_b)) as the base nodes and then decide which region each node is located. If node

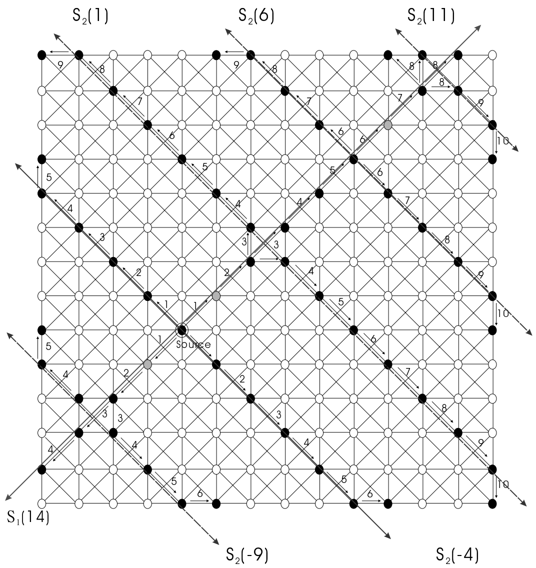

Figure 7. One-to-all broadcast for 2D mesh with 8 neighbors, where source is $(5, 9)$

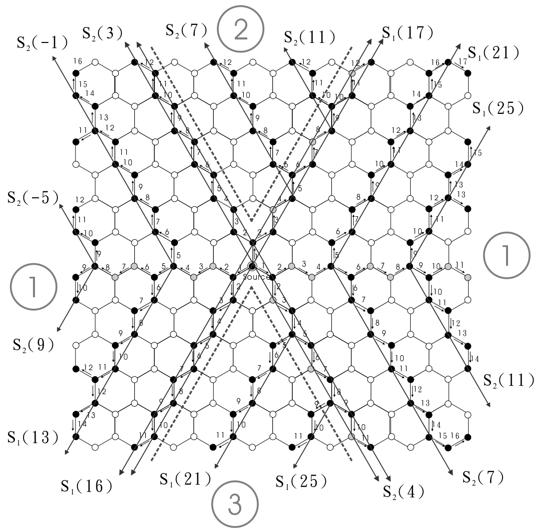

Figure 8. One-to-all broadcast for 2D mesh with 3 neighbors, where source is $(10, 7)$

$(i, j-1)$ is the neighbor of node (i, j), node (i, j) sets $(i_a, j_a) = (i, j-2)$ and $(i_b, j_b) = (i, j+1)$, otherwise, it sets $(i_a, j_a) = (i, j-1)$ and $(i_b, j_b) = (i, j+2)$. For any node (x, y), if $x + y \leq i_a + j_a$ and $x - y \geq i_a - j_a$, node (x, y) is in region 2. Otherwise, if $x + y \geq i_b + j_b$ and $x - y \leq i_b - j_b$, node (x, y) is in region 3. The node that is not in regions 2 and 3 is in region 1.

Different regions have different rules to choose relay nodes. Basically, we choose the node whose id in Y axis is the same as the source node or the nodes in the two types of diagonal axis (S_1 and S_2) as the relay nodes. For the convenience of describing our protocol, we assume that the source node's id is (i, j) and the two sets of basic relay nodes along the two diagonal axes is denoted as $B_1(i, j)$ and $B_2(i, j)$. We set $B_1(i, j)$ and $B_2(i, j)$ according to the following rules:

> **If** node $(i, j+1)$ is node (i, j)'s neighbor **then** $B_1(i, j) = S_1(i+j) \bigcup S_1(i+j+1)$ and $B_2(i, j) = S_2(i-j) \bigcup S_2(i-j-1)$
>
> **else** $B_1(i, j) = S_1(i+j) \bigcup S_1(i+j-1)$ and $B_2(i, j) = S_2(i-j) \bigcup S_2(i-j+1)$

For example in Fig. 1, node $(5, 4)$ is the source. Since node $(5, 5)$ is not node $(5, 4)$'s neighbor, we have $B_1(5, 4) = S_1(9) \bigcup S_1(8)$, and $B_2(5, 4) = S_2(1) \bigcup S_2(2)$. The nodes in $B_1(5, 4)$ and $B_2(5, 4)$ and the node $(k, 4)$ ($k \neq 5$), whose id in Y axis is the same as the source $(5, 4)$, are all chosen as the basic relay nodes.

To broadcast message to all the nodes in the network, we need to choose more relay nodes according to the following rules. We choose relay nodes in region 1 according to R1 and R2 and we choose relay nodes in regions 2 and 3 according to R3 and R4.

> For any node (x, y) where $1 \leq x \leq m$ and $1 \leq y \leq n$:
>
> **R1**: Node (x, y) is located in region 1 and in the upper right side or lower left side of node (i, j) and $(x, y) \in B_1(i + 4k, j)$, where $1 \leq i + 4k \leq m$ and k is an integer.
>
> **R2**: Node (x, y) is located in region 1 and in the upper left side or lower right side of node (i, j) and $(x, y) \in B_2(i + 4k, j)$, where $1 \leq i + 4k \leq m$ and k is an integer.
>
> **R3**: Source node (i, j) is located in the left side of the network, *i.e.* $1 \leq i \leq m/2$. (Node (x, y) is in region 3 and $(x, y) \in B_1(i + 4k, j)$) or (node (x, y) is in region 2 and $(x, y) \in B_2(i + 4k, j)$), where $1 \leq i + 4k \leq m$ and k is an integer.
>
> **R4**: Source node (i, j) is located in the right side of the network, *i.e.* $m/2 < i \leq m$. (Node (x, y) is in

region 3 and $(x, y) \in B_2(i + 4k, j)$) or (node (x, y) is in region 2 and $(x, y) \in B_1(i + 4k, j)$), where $1 \leq i + 4k \leq m$ and k is an integer.

For example in Fig. 8, the source node's id is $(10, 7)$, which is located in the left side of the network. The nodes in black or gray color are the relay nodes, the nodes in gray color need to retransmit the broadcast message, the numbers beside the edge are the transmission sequences. According to rule R1, the nodes located in region 1 and in sets $S_1(17)$, $S_1(16)$, $S_1(13)$, $S_1(12)$, $S_1(9)$, $S_1(8)$, $S_1(20)$, $S_1(21)$, $S_1(24)$, and $S_1(25)$ are chosen as the relay nodes. According to rule R2, the nodes located in region 1 and in sets $S_2(3)$, $S_2(4)$, $S_2(0)$, $S_2(-1)$, $S_2(-4)$, $S_2(-5)$, $S_2(7)$, $S_2(8)$, $S_2(11)$, and $S_2(12)$ are chosen as the relay nodes. According to rule R3, the nodes located in region 2 and in sets $S_2(7)$, $S_2(8)$, $S_2(11)$, $S_2(12)$ and the nodes located in region 3 and in sets $S_1(20)$, $S_1(21)$, $S_1(24)$, $S_1(25)$ are chosen as relay nodes. Since, most of the relay nodes can achieve optimal $ETR\,(= \frac{2}{3})$, our protocol can conserve lots of power.

When the broadcast message is transmitted along the relay nodes, some collisions may occur. Since the topology of the network is predetermined, we know where the collision will occur and which node needs to retransmit the message.

3.4 3D Mesh with 6 Neighbors

In 3D mesh with 6 neighbors, the optimal ETR is $\frac{5}{6}$. The 3D mesh with 6 neighbors can be regarded as multiple XY planes of 2D mesh with 4 neighbors. This indicates that 3D mesh with 6 neighbors has an additional transmission direction, the Z axis. For each XY plane, we can use the broadcasting protocol of 2D mesh with 4 neighbors to scatter the message to every node, however, this approach will consume more power and cause more collisions. Therefore, we divide our broadcasting protocol for 3D mesh with 6 neighbors into two parts. In the first part, we apply the broadcasting protocol of 2D mesh with 4 neighbors to scatter the message to all the nodes in the same XY plane as the source node (i, j, k). In the second part, we select some nodes in the XY plane to forward the broadcast message to other XY planes along Z axis. These selected nodes are denoted as z-relay nodes. As soon as the z-relay nodes have received the broadcast message, they can forward the message to other planes along the Z axis without waiting for the ending of part 1. Let the source be a z-relay node. We can recursively define the z-relay node as follows.

R5: Assuming the network size is $m \times n \times l$. If node (x, y, z) is a z-relay node then nodes (x, y, w), $(x - 2, y - 1, w)$, $(x - 1, y + 2, w)$, $(x + 1, y - 2, w)$ and $(x + 2, y + 1, w)$ are z-relay nodes, where $1 \leq w \leq l$.

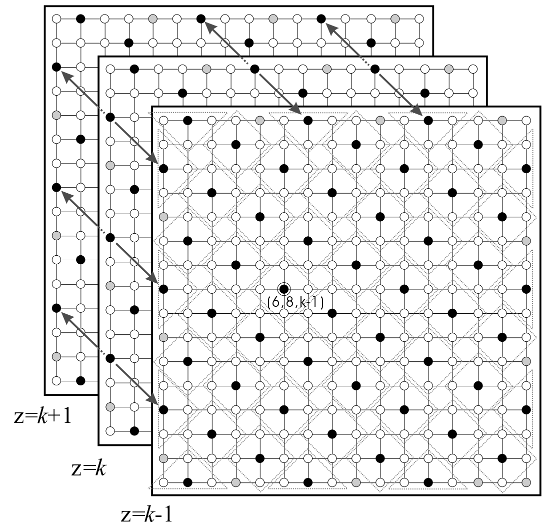

Figure 9. Scatter the broadcast message to each XY plane along the Z axis in 3D mesh with 6 neighbors, where source is $(6, 8, k)$ and black nodes are z-relay nodes

Note that, when all of the source node's neighbors forward message simultaneously, collisions occur, therefore, nodes $(i-1, j, k)$, $(i+1, j, k)$, $(i, j, k-1)$, and $(i, j, k+1)$ need to retransmit the message. However, when they retransmit the message simultaneously, collisions also occur. Therefore, relay nodes $(i - 1, j, k)$ and $(i + 1, j, k)$ will retransmit the message one slot later and z-relay nodes $(i, j, k - 1)$ and $(i, j, k + 1)$ will retransmit the message two slots later. To avoid the message collision occurring between the relay nodes and z-relay nodes in the XY plane with $z = k$, we also need to delay the z-relay nodes to forward the message one slot later.

There are still some nodes in the border of the plane will not receive the broadcast message, therefore we need to choose some additional nodes in the border. Fig. 9 is an example of scattering the broadcast message to other XY planes in 3D mesh with 6 neighbors. The nodes in black color are the z-relay nodes. The nodes in gray color are the additional relay node in the border, they will wait for two time slots and then forward the message.

For example, assume that node $(6, 8, 4)$ is the source node of a 3D mesh with 6 neighbors. The relay nodes in the XY plane of the source node are the same as shown in Fig. 5. In addition, according to rule R5, nodes $(4, 7, 4)$, $(5, 10, 4)$, $(7, 6, 4)$, $(8, 9, 4)$, ..., are also selected as z-relay nodes to forward the message to other XY planes along Z axis as shown in Fig. 9.

All of the broadcasting protocols mentioned in this section forward the broadcast message along the shortest path

Table 1. Optimal ETRs of the four topologies

Topology	Optimal ETR
2D-3	$2/3$
2D-4	$3/4$
2D-8	$5/8$
3D-6	$5/6$

and most of the relay node can achieve the optimal ETR (The optimal ETRs of the four topologies are shown in Table 1). Therefore, our broadcasting protocols can not only achieve optimal transmission time, but also conserve lots of energy. Besides, collisions are carefully handled such that our broadcasting protocols can achieve 100% reachability.

4 Performance Analysis

In this section, we will compute and analyze the performance of our broadcasting protocols. To show the efficiency of our protocols, we will compare the performance of our protocols with the ideal case. In the ideal case, each relay node can achieve optimal ETR and broadcast messages without any collision. We assume that there are 512 nodes in the network. These nodes can be constructed as a 32×16 2D mesh or an $8 \times 8 \times 8$ 3D mesh. The distance between any two neighboring nodes(d) is 0.5 meter, the packet length(k) is 512 bits. We use equations 1 and 2 mentioned in Section 2 to calculate the consumed power of each transmission. We will calculate the total number of transmissions(T_x), receptions (R_x), power consumption and delay time for each broadcast. The total number of transmissions is the total times that the message is transmitted by nodes in each broadcast. The total number of receptions is the total times that the message is received by nodes in each broadcast. The total power consumption is the total power consumed for transmitting and receiving messages in each broadcast. The total delay time is the time from the source initiated the broadcast to the time the broadcast is over. We use the time slot as the time unit.

In our broadcasting protocols, different source has different total number of transmissions, receptions, power consumption and delay time. If the source is in the center of the network, it performs better. If it is in the corner of the network, it will consume more power and has a longer delay time. Tables 2, 3 and 4 show the performances of the ideal case, the best case and the worst case of our broadcasting protocols. We can see that the total power consumption of our protocols is quite close to that of the ideal case, which indicates that our protocols are power efficient. Among the four different network topologies, the optimal ETR of 3D mesh with 6 neighbors ($= \frac{5}{6}$) is the best. However, in the first transmission part, the message is transmitted along a 2D mesh with 4 neighbors, besides, more number of neighbors will increase the total number of receptions. Therefore, 3D mesh with 6 neighbors is not the best topology. The optimal ETR of 2D mesh with 4 neighbors ($= \frac{3}{4}$) is the second best but fewer number of neighbors causes fewer number of receptions. Therefore, 2D mesh with 4 neighbors performs the best. The best case and worst case performances of 2D mesh with 3 neighbors (or 2D mesh with 8 neighbors) are quite close to each other, because 2D mesh with 3 neighbors (or 2D mesh with 8 neighbors) is not sensitive to the source node's location.

Table 5 shows the maximum delay time of the ideal case and our broadcasting protocols. The maximum delay time of our protocols is the same as the ideal case, which indicates that our protocols are time efficient. Since the diameter of the 3D mesh with 6 neighbors is the smallest, its maximum delay time is also the smallest. The diameter of 2D mesh with 8 neighbors is the smallest among all the 2D topologies, its maximum delay time is also the smallest among all the 2D topologies.

Table 2. The performance of the ideal case

Topology	T_x	R_x	Power consumption(J)
2D-3	255	765	2.61×10^{-2}
2D-4	170	680	2.18×10^{-2}
2D-8	102	816	2.35×10^{-2}
3D-6	124	744	2.22×10^{-2}

Table 3. The performance of our broadcasting protocols (best case)

Topology	T_x	R_x	Power consumption(J)
2D-3	301	798	2.81×10^{-2}
2D-4	208	714	2.36×10^{-2}
2D-8	143	895	2.66×10^{-2}
3D-6	167	815	2.51×10^{-2}

Table 4. The performance of our broadcasting protocols (worst case)

Topology	T_x	R_x	Power consumption(J)
2D-3	308	816	2.88×10^{-2}
2D-4	223	778	2.56×10^{-2}
2D-8	147	924	2.74×10^{-2}
3D-6	187	923	2.84×10^{-2}

Table 5. The maximum delay times of the ideal case and our broadcasting protocols

Topology	Ideal case	Our protocols
2D-3	46	46
2D-4	45	45
2D-8	31	31
3D-6	20	20

5 Conclusions

In this paper, we propose power and time efficient broadcasting protocols for four different WSN topologies. Since the network topologies are all regular and fixed, we can choose as few relay nodes as possible and handle collisions carefully to achieve 100% reachability. Besides, most of the relay nodes can achieve optimal ETR and avoid collisions, our broadcasting protocols are power and time efficient.

Numerical evaluating results show that, when the number of neighbors increase, the total number of transmissions decrease, but the total number of receptions increase. Therefore, the topology that can achieve high ETR and balance the total number of transmissions and receptions performs the best. Experimental results show that 2D mesh with 4 neighbors possesses the minimum power consumption and 3D mesh with 6 neighbors has the smallest maximum delay time. Our broadcasting protocols not only have good performances in regular WSNs but also can be applied to the infrastructure wireless networks, where each base station (or access point) are fixed and communicates through radio.

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