一個在無線感測網路上以對角線為基礎的省能源的繞徑協定

An Energy-Efficient Diagonal-Based Routing Scheme for Wireless Sensor Networks[12]

陳裕賢 [I]　林宗宏 [I]　粘耀文 [II]　許健平 [II]

Yuh-Shyan Chen, Tsung-Hung Lin, Yau-Wen Nian, and Jang-Ping Sheu

國立中正大學資訊工程系

[I]Department of Computer Science and Information Engineering,
National Chung Cheng University, Chiayi. Taiwan, R.O.C.

國立中央大學資訊工程系

[II]Departmemt of Computer Science and Information Engineering,
National Central University, Taiwan, R.O.C.

摘　要

在本論文中，我們提出在無線感測網路上一個有效節省能源的路徑協定方法。在比較適合室內的無線監控環境下將所有的無線感測節點架構成一種特別架構，稱之為六角形網狀架構，也可算是網格計算的應用。六角形網狀網路的形成是由許多的相鄰的六角形對角線路徑所組合，部分的六角形對角線路徑會被週期性選為主傳輸幹線，主幹線的無線感測節點的有較高的耗電量，所有的資料傳輸將以主傳輸幹線為主要傳輸的路徑。為了進一步提供的節省能源的策略，我們也提出了一種週期性主幹線交換機制並配合 MAC 子層的協定以達到節省能源的目的。在此機制下，我們更提出在無線六角形網狀架構下的節省電源的繞徑協定策略，稱之為有向性資料散佈繞徑協定方法。最後在實驗數據的驗證下，將說明本繞徑協定策略在省電效能的改善。

關鍵詞：無線感測網路、六角形網狀網路、對角線路徑、資料散佈、網格計算。

Abstract

In this paper, we propose a power-efficient routing scheme on a wireless sensor network. In this work, all of the sensors are arranged into a fixed topology, namely *hexagonal-mesh*, to form a wireless sensor network for the indoor wireless sensing environment. This is a special application of the popular grid-computing. The hexagonal-mesh is constructed by many disjoint *hexagonal-paths*, while some hexagonal-paths are used to be the backbone paths. Sensors at the backbone path normally need more energy than the sensors not at the backbone path. To consider the power-fairness problem, a periodic backbone-path-exchange mechanism is developed to offer a power-saving scheme. Further, a periodic active-and-sleep time-slot scheduling is presented under the TDMA channel model to support the backbone-path-exchange mechanism with the purpose of power-saving. Based on such mechanism, a power-efficient routing, *directed diffusion*, protocol is developed on the hexagonal-mesh network. Finally, the simulation result illustrates this power-saving improvement.

Keyword：Wireless sensor network, hexagonal-mesh, diagonal-paths, directed diffusion, grid computing.

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1. Introduction

Owing to the remote environment monitoring capabilities, wireless sensor networks recently are investigated in [2][9][11][12]. Wireless sensor nodes have the same power problems as the portable devices. Without plug-in power, wireless sensor nodes only use their on-board power to work until the power is out. Saving energy of sensor node is the most important and interesting problem. The wireless sensor networks collaborate with low cost and low power sensor nodes in order to improve greatly the accuracy of information. Sensor nodes monitor activities of a set of objects in a sensing region, and report their observations to an interest client through the wireless sensor networks. We call the interest client as a *sink node*. If sensor nodes share their observations and process these observations so that meaningful information is available at the sink node, users can retrieve information from the sink node and monitor the status of the sensing region. Wireless sensor networks can be used for tasks such as military surveillance (probe enemy movement and information), air-conditioner control [9], building security (parking lot surveillance and invader warning) [6], health monitor (patient heartbeat detection) [1][7], and environment monitoring (water and air pollution surveillance) etc. Sensor nodes often work to overcome the different environmental problems by means of the self-organizing scheme.

The classification of a wireless sensor network (WSNet) can be divided into *micro sensor networks*, *indoor sensor networks*, and *outdoor sensor networks* by its scale. Micro sensor networks belong to a topology-less mini-scale network, which is composed of a number of very lightweight sensor nodes devices. Usually, micro sensor nodes are used to detect the humidity and temperature in the environment. Micro sensor node even can be injected into the human body to detect the organs status [7]. The outdoor sensor network should be a large-scale non-topological network. Outdoor sensor nodes are applied to the outdoor environment for sensing environment with abnormal changes. The indoor sensor network can be a small-scale topological network. Indoor sensor nodes are usually installed in the ceiling of the building to monitor the environmental changes. The wireless sensor nodes are arranged in a fixed-topological wireless network due to its low mobility. Bhuvaneswaran *et al*. arrange wireless sensor nodes in a two-dimensional grid [10]. All sensor nodes are arranged in a special hexagonal-mesh to easily exploit the energy-efficient capability.

Recently, MAC layer protocols are adopted for saving energy in wireless sensor nodes. A number of researchers [2][8][11][12][17] have begun to collect empirical evidence regarding the various energy saving protocols on MAC layer. Schurgers *et al*. [17] proposed to allow the sensor nodes be the sleeping mode in general and wake up periodically to listen to the beacons. Schurgers *et al*. [17] also proposed a FDMA (Frequency Division Multiple Access) channel model to implement energy serving scheme on MAC layer. Every sensor node has two frequency bands in order to diminish the collisions of data transformation. Nevertheless, how to decrease the data collisions and how to decrease the costs of hardware is in a dilemma for Schurgers *et al*. In addition, TDMA channel model are considered to provide the energy-saving MAC protocols in [2][8][11][12]. The synchronization mechanism for TDMA time-slot channel model is important to avoid the data collisions. Moreover, sensor nodes periodically wake up to receive and send data in order to spare unnecessary energies. Without any mechanism to control the states of sleep and wake, there are unnecessary energies will be wasted. Sohrabi *et al*. [12] proposed two MAC protocols, SMACS (Self-Organizing Medium Access Control for Sensor Network) and EAR (Eavesdrop-And-Register), under TDMA channel model. In the SMACS, the links of each pair of sensor nodes are connected by the fixed frequency without the help of the master nodes. However, this protocol only to apply to a WSNet with the low mobility. Lindsey *et al*. proposed a complex power-wasting CDMA (Code Division Multiple Access) channel model in [5]. More recently, an energy-efficient MAC protocol is developed in [18] by using a periodic listen and sleep scheme.

In this paper, we propose a power-efficient routing scheme on a indoor sensor network. In this work, all of the sensors are arranged into a fixed topology, namely *hexagonal-mesh*, to form a wireless sensor network for the indoor wireless sensing environment. The hexagonal-mesh is constructed by many disjoint *hexagonal-paths*, while some hexagonal-paths are used to be the backbone paths. Sensors at the backbone path normally need more energy than the sensors not at the backbone path. To consider the power-fairness problem, a periodic backbone-path-exchange mechanism is developed to offer a power-saving scheme. Further, a periodic active-and-sleep time-slot scheduling is presented under the TDMA channel model to support the backbone-path-exchange mechanism with the purpose of power-saving. Based on such mechanism, a power-efficient routing, *directed diffusion*, protocol is developed on the hexagonal-mesh network. Finally, the simulation result illustrates this power-saving improvement.

The rest of the paper is organized as follows. Section 2 describes basic ideas and notations. Section 3 presents the power-efficient backbone-path-exchange scheme. Section 4 presents the active-and-sleep time scheduling scheme. The diagonal-based directed diffusion is developed in Section 5. Section 6 illustrates the formative evaluation and statistical results of our designed protocols. And, Section 7 concludes this paper.

2. Basic Ideas and Notations

Wireless sensor network owning the distinguishing characteristics of monitoring and the real time responsible capabilities, it is different from the traditional network. The limitations of power and communication scope still were the weakness of wireless sensor nodes. So, how to design an efficiently data diffusion protocol is our major project. In this paper, we try to provide an efficient data diffusion protocol in the WSNet. Our main idea is to develop an energy-efficient scheme, namely periodic active-and-sleep scheme, over the TDMA channel model on the MAC sub-layer

In this work, data diffusion propagating is consisting of single sink to all network sensors, single sink to single region sensors, and single sink to multi-region sensors. Unlike the MANET, the low mobility is the property of wireless sensor nodes. Therefore, in this work, we consider the network topology as follows; all of the sensors nodes are arranged into a topological network, namely hexagonal-mesh as shown in Fig. 2, to achieve the energy-efficient purpose. Initially, we formally introduce the hexagonal block and the diagonal path as follows.

Definition 1 Hexagonal Block: Given six nodes *A, B, C, D, E, F* and six undirected connections (*A, B*), (*B, C*), (*C, D*), (*D, E*), (*E, F*), (*F, A*) as shown in Fig. 1. Six nodes are the six vertices of hexagonal block. Six undirected connections are the six edges of the hexagonal block. Each sensor node possesses a fully-functional Global Position System (GPS) receiver, to logically determine the coordinate position and perform the time-synchronization

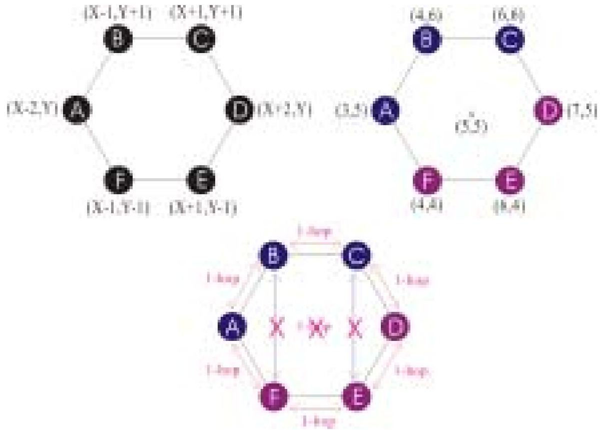


Figure 1: Hexagonal block

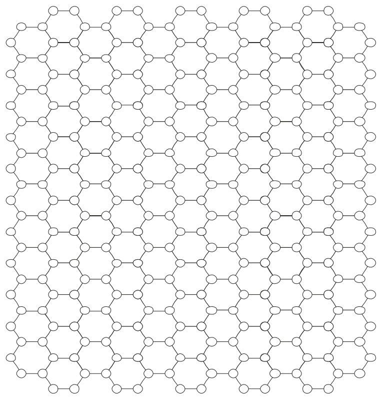


Figure 2: Hexagonal mesh

operation. The coordinates of six nodes are given as *A*(*X*-2, *Y*), *B*(*X*-1, *Y*+1), *C*(*X*+1, *Y*+1), *D*(*X*+2, *Y*), *E*(*X*+1, *Y*-1) and *F*(*X*-1, *Y*-1), and the central point of the hexagonal block is located in (*X, Y*).

For example as shown in Fig. 1, if the coordinate positions of *A* is (3, 5), then the coordinate positions of *B, C, D, E,* and *F* are (4, 6), (6, 6), (7, 5), (6, 4) and (4, 4). Those six vertices and six edges comprise the hexagonal block, as illustrated in Fig. 1. Denote $\left[A\begin{pmatrix}B & C\\ F & E\end{pmatrix}D\right]$ as such hexagonal block.

Fig. 1 illustrated that only the double sides of each edge are 1-hop neighbors in the definition of hexagonal blocks. And, only 1-hop neighbors can send (or receive) the message to (or from) each other. For example, sensor nodes *A* and *B* are 1-hop neighbor; five pairs (*B, C*), (*C, D*), (*D, E*), (*E, F*) and (*F, A*) are still 1-hop neighbors, respectively.

However, the pairs (*B, F*) and (*C, E*) are not 1-hop neighbors. This limitation is important for the time-slot reservation.

<u>Definition 2</u> Hexagonal Mesh: Let $M_{n x n}$ denote as a 2*D* hexagonal mesh with *n* x *n* hexagonal blocks $B_{i,j}$. Each block connects to six neighboring hexagonal blocks along six distinct edges of hexagon, where $1 < i, j < n$.

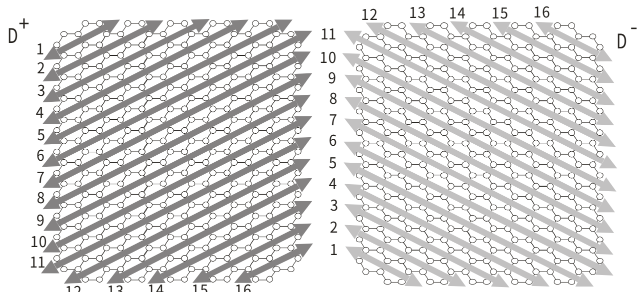
Let a hexagonal-block $\left[A\begin{pmatrix}B & C\\ F & E\end{pmatrix}D\right] = B_{i,j}$, denote an *i*-th row and *j*-th column hexagonal-block, and all $B_{i,j}$, for $1 < i, j < n$, form a hexagonal mesh, where each $B_{i,j}$, connects to six neighboring hexagonal blocks along six distinct directions, as shown in Fig. 2, every block has six neighboring hexagonal blocks. In general, the hexagonal mesh can be $M_{m x n}$, where $m \neq n$, but our study only assume the case of $M_{n x n}$.

<u>Definition 3</u> Diagonal Path: Given a hexagonal mesh, let $D^+(x)$ denote the path between right-up and left-down, where $D^+_+(x)$ is the right-up path and $D^+_-(x)$ is the left-down path. Let $D^-(x)$ denote the path between left-up and right-down, where $D^-_+(x)$ is the left-up path and $D^-_-(x)$ is the right-down path.

Each diagonal path is given a sequence number. The sequence of diagonal path $D^+(x)$ is anticlockwise, starting from the left-up corner and right down to the most right-down corner. For instance, diagonal paths $D^+(1)$, $D^+(2)$, …, $D^+(16)$ are shown in Fig. 3(a). Similarly, the sequence of diagonal path $D^-(x)$ is clockwise, starting from the left-up corner and right down to the most right-down corner. For instance, diagonal paths $D^-(1)$, $D^-(2)$, …, $D^-(16)$ are shown in Fig. 3(b).

<u>Lemma 1:</u> A time slot *t* can be reused by a sensor node *X* to send message to another sensor node *Y* without causing collision if the following conditions are all satisfied, (as shown in Fig. 4).

1. Time slot *t* is neither scheduled to send in *X* nor *Y*.
2. Time slot *t* is neither scheduled to receive in *X* nor *Y*.
3. For any 1-hop neighbor *Z* of *X*, time slot t is not scheduled to receive in *Z*.
   (If not, *Z* receives two messages (from *X* and another) and some errors happened.)
4. For any 1-hop neighbor *Z* of *Y*, time slot *t* is not scheduled to send in *Z*.



3(a) **3(b)**

Figure 3: Example of hexagonal paths

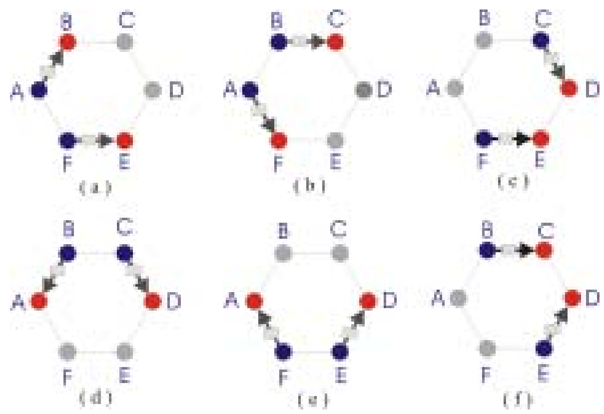


Figure 4: Time slot reuse capability

5. For any 1-hop neighbor *Z* of *Y*, time slot *t* is not scheduled to send in *Z*.
   (If not, *Y* receives two messages (from *Z* and *X*) and some errors happened.)
6. For any 1-hop neighbor *Z* of *X*, time slot *t* can reuse to schedule to send in *Z*.
7. For any 1-hop neighbor *Z* of *Y*, time slot *t* can reuse to schedule to receive in *Z*.

3. The Power-Efficient Backbone Path Exchange Scheme

In general, the directed diffusion operation consists of three phases, *interest propagation* phase, *sensing* phase, and *data propagation* phase from [3]. In interest propagation phase, a sink node sends the interest message to assign target regions through the backbone paths. Then, in sensing phase all sensors sensing and acquire the sensing data based on the interest message. Final, the sensors of target regions return observed attribute-values back to the sink node.

To achieve the energy-efficient purpose, we develop a periodic backbone-path-exchange scheme over the hexagonal-mesh network. A periodic active-and-sleep time scheduling and a reused time-slot scheduling for the interest and data propagation phases are also proposed in next Section.

3.1. The Periodic Backbone-Path-Exchange Scheme

The periodic backbone-path-exchange scheme is presented for handling the power fairness problem. Under our definition, each diagonal-path of the hexagonal-mesh has the equally chance to serve as the backbone path.

<u>**Definition 4**</u> **Backbone Path:** If all of the directed diffusion data from a sink node to each target sensor node must go through the diagonal path, we called the diagonal path as backbone path. Suppose that there are k diagonal paths in the sensor network. Every period of time, only x, $\left\lfloor \frac{k}{3} \right\rfloor \leqq x \leqq \left\lceil \frac{k}{3} \right\rceil$, diagonal paths are used to be the backbone paths.

For example, if $D^+(1)$, $D^+(4)$, $D^+(7)$ are backbone paths then $D^+(2)$, $D^+(3)$, $D^+(5)$, $D^+(6)$ are not backbone path. The backbone paths are interchanged periodically to maintain the load balance of energy-consumption. The detail operation is given.

1. All diagonal paths $D^+(3n\text{-}2)$ and $D^-(3n\text{-}2)$ are the backbone paths, for $1 \leqq n \leqq t = \left\lfloor \frac{k}{3} \right\rfloor$.
2. On the next period of time, diagonal paths $D^+(3n\text{-}1)$ and $D^-(3n\text{-}1)$ become the backbone paths, for all $1 \leqq n \leqq t = \left\lfloor \frac{k}{3} \right\rfloor$.
3. On the next period of time, diagonal paths $D^+(3n)$ and $D^-(3n)$ become the backbone paths, for all $1 \leqq n \leqq t = \left\lfloor \frac{k}{3} \right\rfloor$.
4. Repeat the operations from (1) to (3).

An instance is illustrated in Fig. 5, where the darken nodes is denoted as the backbone. Each diagonal path plays one of the backbone paths periodically. The first case will be used as an

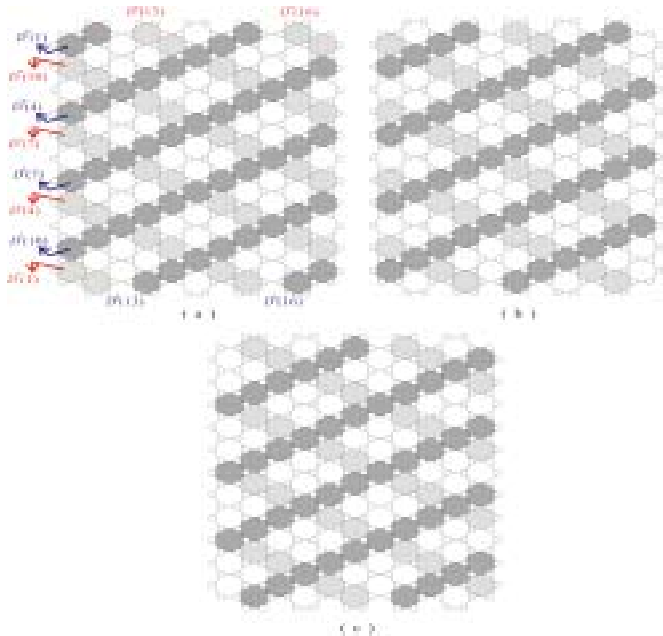


Figure 5: Example of backbone-path exchange example in the following expressions.

3.2. The Power-State Diagram

In our protocol, we proposed the energy saving protocol in the MAC layer. To consider the power-fairness problem, a periodic backbone-path-exchange mechanism is developed to offer a power-saving scheme. The sensor nodes at backbone paths or at sensing regions need to consume more power than other sensor nodes. To consider the different power states, we illustrate the overview diagram in Fig. 6(c). To illustrate the power consumption, all sensor nodes are divided into two types; (1) sensor nodes at the backbone path, and (2) sensor nodes not at the backbone path, as shown in Fig. 6(a) and Fig. 6(b). Two cases are considered as follows.

Case 1: The Power-State Diagram for Sensor Node at Backbone Path

The wireless sensor node at the backbone path always plays the major role to process all information and data of the sink in our protocol. By the way, the sensor nodes of backbone paths must always turn on their power. The power-state diagram is given to illustrate the details.

1. **Initialization:** All of the sensor nodes are set to be the medium power mode and enter the

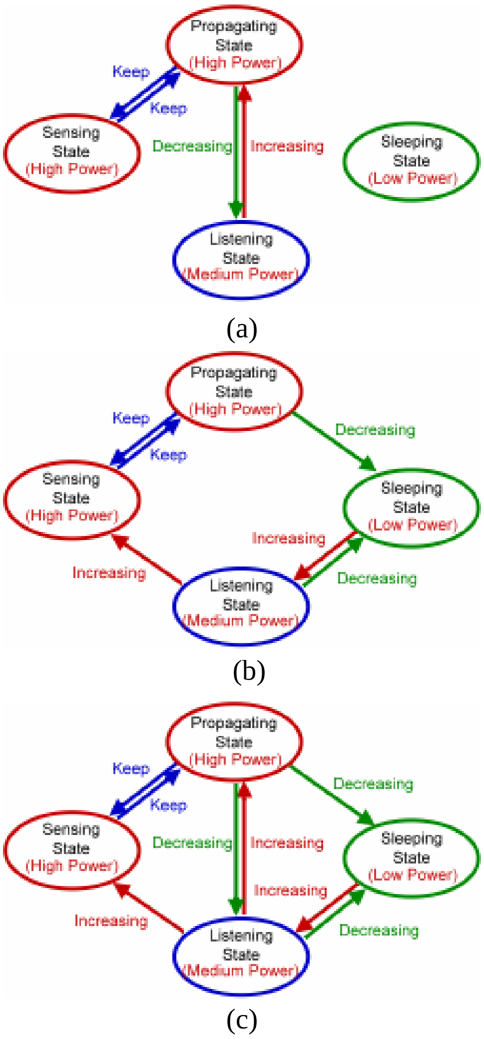


Figure 6: (a) Backbone path, (b) non-backbone path, (c) overview of power state diagram

listening state.

2. Medium Power's Listening State: Under medium power's listening state, we perform the following operations.

(a) If the sink node wants to send the sink information to the sensing regions, the sensor nodes at backbone paths have to increase their power to be the high power mode and enter the propagating state to propagate the sink information.

(b) If the sensor nodes receive the beacons for data propagating, these nodes have to increase their power into the high power mode and enter the propagating state to propagate the sink data.

3. High Power's Propagating State: Under high power's propagating state, we perform the following operations.

(a) If the sink information is transferred, then
- (i) sensor nodes, at sensing regions, enter into the sensing state to sense data, or
- (ii) sensor nodes, at non-sensing regions, decrease the power into the medium power mode and enter the listening state to wait for the beacons.

(b) If the partial sink results are transferred, the sensor nodes in sensing regions re-enter into the sensing state to sensing data again.

(c) If all of the sink data are transferred, then sensor node decreases their power into the medium power mode and enter into the listening state to wait for the beacons.

4. High Power's Sensing State: Under high power's sensing state, if the sensing operation is terminated, the sensor node, at sensing region, goes back to the propagating state.

Case 2: The Power-State Diagram for Sensor Node at Non-Backbone Path

Wireless sensor nodes on the non-backbone paths need not to transfer the sensing information. The detail operation is given as follows.

1. Initialization: All of the sensor nodes are set into the medium power mode and enter the listening state.

2. Medium Power's Listening State: Under medium power's listening state, if a sink node wants to send the sink information to the sensing regions, the sensor nodes of non-backbone paths are passive to be notified if the sensor is located at the sensing region or not.

(a) If the sensor nodes are notified located at the target region, they increase the power to be the high power mode and enter into the sensing state.

(b) If the sensor nodes are notified not located at the target region or no any notification, they decrease their power to be the low power mode and enter into the sleeping state. Sensor node will periodically wakes up.

3. High Power's Sensing State: Under high power's sensing state, if the sensing operation is terminated, the sensor nodes located at non-backbone paths of target regions, go back to the propagating state.

4. **High Power's Propagating State:** Under high power's propagating state, the following operations are performed.

(a) If the partial sink results are transferred, the sensor nodes at non-backbone paths of target regions re-enter into the sensing state.

(b) If all of the sink data are transferred, the sensor nodes in the target regions decrease the power to be the medium power mode and enter into the sleeping state.

5. **Low Power's Sleeping State:** The sleeping sensor nodes periodically wake up automatically. The wake-up sensor nodes increase their power into the medium power mode and enter into the listening state.

4. The Periodic Active-and-Sleep Time Scheduling Scheme

This section describes the periodic active-and-sleep time-slot scheduling scheme, which an example is illustrated in Fig. 7.

<u>**Lemma 2:**</u> Each sensor node can connect to a backbone path only one hop if the sensor node is not located at the backbone path.

This observation is very important for the energy-efficient TDMA channel scheduling in the MAC sub-layer. By Lemma 2, non-backbone sensors directly connect with backbone path by one-hop link. Our extended periodic active-and-sleep time scheduling adopts four time-slot data frame to complete the 2-way diagonal routing. Observe that if any one time slot has not been scheduled to be active mode (may be sensing, sending, or receiving data) then the time-slot will be entering the sleep mode to turn off the battery-power to achieve the energy-saving purpose. The main operation of the periodic active-and-sleep time scheduling is informally described.

Step 1: First, the sink node initially flooding a short control packet to all sensor nodes to show the sink information. This useful sink information determines the energy efficient time-slot scheduling will be described in Section 4.1. If each sensor knows the sink information from the flooding operations, then all backbone and non-backbone sensors can determine the exact time-slot scheduling (the detail will be presented in Sections 4.1 and 4.2). An example is shown in Fig. 7(a).

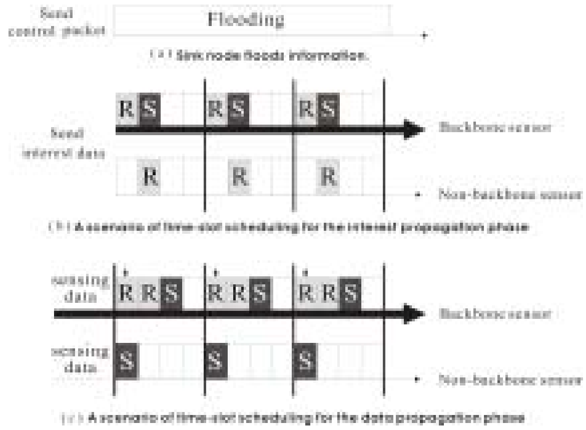


Figure 7: A possible scenario of the periodic active-and-sleep time-slot scheduling

Step 2: Continue, in the interest propagation phase the time-slot scheduling is proposed. All backbone sensors offer two time slots to send/receive interest messages, and all non-backbone sensors only need offer one time slot to receive interest message. We show it in Fig. 7(b).

Step 3: The last phase is the data propagation phase. After all target sensors obtaining the sensing data, all backbone sensors offer one time slot to send sensing data back to the postfix node and offer two time slots to receive sensing data from the postfix nodes. In addition, all non-backbone sensors only use one slot to send sensing data back to the node of backbone diagonal path. We show it in Fig. 7(c).

We know that all backbone sensors offer more active slots than the non-backbone sensors in the upper three phases. Therefore, the less power consumption for non-backbone sensors will be. This is the main value of our proposed diagonal-based scheme. In the following, we will present the detail time-slot scheduling for interest and data propagation phases.

4.1 Time-Slot Scheduling for Interest Propagation Phase

An important rule in our proposed is that our diagonal-path is a two-path routing. The main purpose is to split the sensing area into two sensing regions; one is the *upper* sensing region, and another one is the *lower* sensing region.

Our example is shown in Fig. 8. In Fig. 8(b), sink node *A* initially sends interest message to node *B*. Therefore, the path (*G, C, A, D, I, K, M*) is responsible for sending interest message to upper sensing region, and the path (*H, F, B, E, J, L, N*) is responsible for the lower sensing region. Moreover, the sensor *A* sends interest message to *B* using time slot 1. Based on the time-slot re-use property as mentioned in Section 2, consider a hexagonal block $\left[A\begin{pmatrix}C & G\\ B & F\end{pmatrix}H\right]$ as shown in Fig. 8(b), sensors *A* and *B* already keep the same interest message. We describe the actions of three time slots as under.

1. Time slot 1 is scheduled for sending messages from *A* to *B*.
2. Time slot 2 is scheduled for sending messages from *A* to *D*, and we re-use to sending messages from *B* to *E*.
3. Time slot 3 is scheduled for sending messages from *D* to *I*, and we re-use to sending messages from *E* to *J*.

It is easily to see that we can repeatedly use time slots 2, 3 and 1 for sending interest data along paths (*A, D, I, K …*) and (*B, E, J, L …*). Similarly, we can use time slots 2, 3 and 1 for sending interest data along paths *(A, C, G …)* and *(B, F, H …)*. Therefore, we have the following result.

<u>**Lemma 3:**</u> The interest propagation operations can be performed on one backbone path by using only three time-slot data frames.

Observe that the interest message from a sink must go through one backbone path D^+ and one backbone path D^- to all sensors. Based on Lemma 3, we know that it's only need three time-slot data frame to perform the data propagation operation along backbone path D^+ or D^-. Unfortunately, it

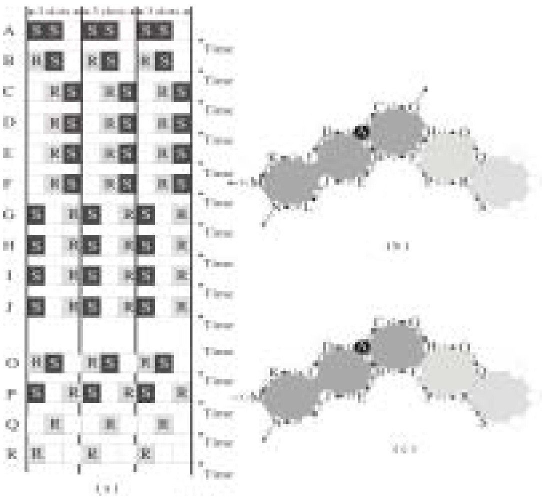


Figure 8: Example of three time-slot data frame on a backbone path

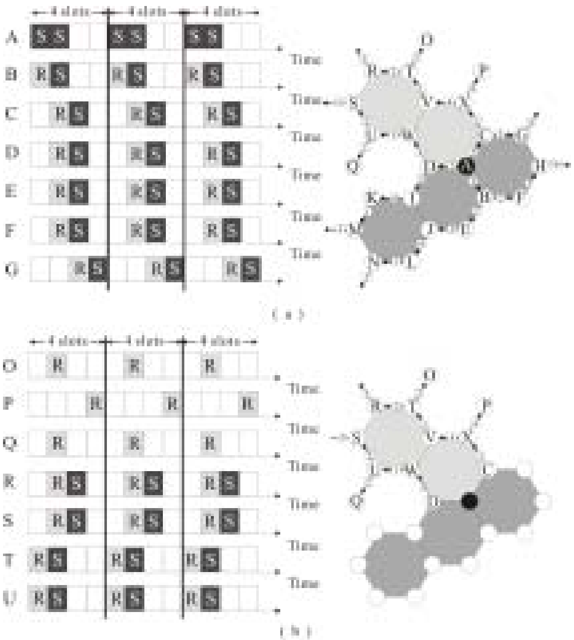


Figure 9: Example of four time-slot data frame on (a) interest propagation (b) data propagation.

is impossible to use three time-slot data frame to perform the data propagation operation on both backbone paths. It means that the collision will be happened when the data transfer to the orthogonal diagonal path. Fig. 8(b) and 8(c) show that path D^+ uses three time-slot data frame to perform the interest propagation operation. Sensors F and H received interest message from sink node A along path D^+, sensors F and H attempt to perform the interest propagation operation along path D^- by using the same three time-slot data frame.

However, it fails to do that. When the data along one backbone path D^+ (D^-) to D^- (D^+), the collision is happened. The detail can follow Fig. 8(b) and 8(c). Therefore, we perform the interest propagation operation by using at least four time-slot data frame. Consequently, the successful examples are illustrated in Fig. 9(a). In fact, only two kinds of time slot scheduling are existed based on the relative location of sink node.

Consider a hexagonal block, if sink node is *A, B, G* or *H* then the four time-slot scheduling is constructed as illustrated in Fig. 9(a). Therefore, this location information of the sink node must floods to all sensors, in the step 1, before performing the interest propagation operation. We have the result as follow.

<u>Lemma 4:</u> The interest propagation operation can be performed along two backbone paths D^+ and D^- by exactly using four time-slot data frame.

4.2 Time-Slot Scheduling for Data Propagation Phase

Basically, the data propagation operation is the reversed operation of the interest propagation operation. Example of successful time-slot scheduling for data propagation phase are shown in Fig. 9(b). Therefore, we have the following result.

<u>Lemma 5:</u> The data propagation operation can be performed along two backbone paths D^+ and D^- by exactly using four time-slot data frame.

For example as shown in Fig. 9(b), if non-backbone sensors *O, P* and *Q* have obtained their sensing data, then sensors *O, P* and *Q* send the sensing data to backbone path on time slot 1 (by Lemma 2). All of the sensing data is performed the data propagation operation by backbone path D^- by using the four time-slot data frame.

5. Energy-Efficient Diagonal-Based Directed Diffusion Protocol

Given an interest, an attribute-value pair indicates the satisfied interest status for a given sensing region [3], where a sensing region can be represented as a large sensing area or a small sensing region. Based on the important results of Section 2, our directed diffusion protocol is constructed, which includes (1) sink-to-all diffusion and (2) sink-to-region diffusion operations. Let the value of denote as the number of diagonal paths D^+ or D^-. Given a hexagonal mesh, assume that there are 2 x β distinct $D^+(x)$ and $D^-(x)$ diagonal paths in a hexagonal mesh, where $1 \leqq x \leqq \beta$. Therefore, there are at most 2 x $\lceil \beta/3 \rceil$ backbone paths. Each sensor can directly connect to backbone path. Observe that, the periodic backbone-path-exchange and periodic active-and-sleep schemes are used, all diagonal-based diffusion operations are presented as follows.

5.1. Sink-to-All Diffusion Operation

The sink-to-all diffusion operation aims to acquire all attribute-values from a sink node. Consider a sensor node S intending to acquire all attribute-values based on an interest, we formally give the sink-to-all diffusion procedure.

<u>Sink-to-All Diffusion Procedure</u> (*Default-Interest, S*)

Input: If all sensors nodes have a default interest, then set *Default-Interest* = TRUE. Otherwise, set *Default-Interest* =FALSE. Let a sink node S can connect to a backbone path $D^+(y)$ within one-hop or the sink node S is exactly located in the backbone path $D^+(y)$, where $1 < y < \beta$. Observe that a simple flooding operation is executed to let all sensors know the location information of sink node.

Output: A sink node S acquires attribute-values from all sensor nodes in a hexagonal mesh.

/* *Interest Propagation Phase* */

Step 1: If *Default-Interest* = TRUE, then skip the interest propagation phase and go to Step 6.

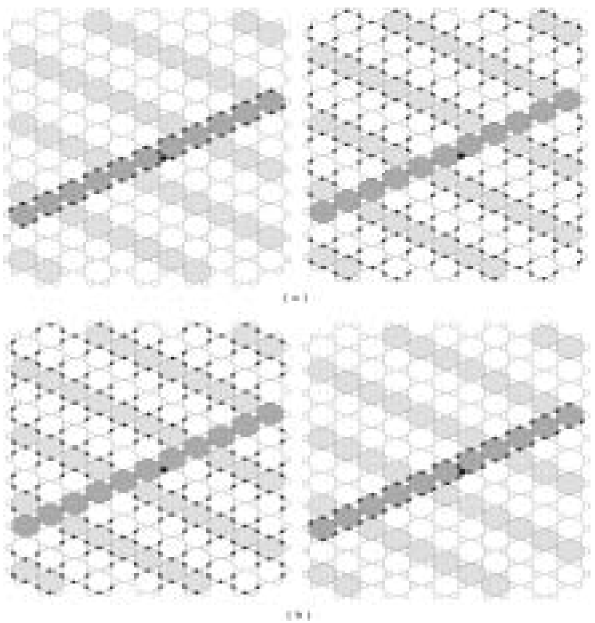


Figure 10: Example of sink-to-all diffusion operation

Step 2: If *Default-Interest* = FALSE, then sink node S should send interest message to all sensor nodes by Step 3 through Step 6.

Step 3: The interest message is propagated along $D_+^+(y)$ and $D_-^+(y)$ from sink node S by using the four time-slot data frame (by Lemma 3) such that all sensor nodes in backbone path $D^+(y)$ contain the interest messages.

Step 4: Let sensor node *C* denote as each cross-point of $D^+(y)$ with one of $\lceil \beta/3 \rceil$ $D^-(x)$ backbone path, where $1 \leqq x \leqq \beta$. The interest message is propagated along $D_+^-(x)$ and $D_-^-(x)$ from sensor node *C* by using the four time-slot data frame (by Lemma 4) such that all sensor nodes on all backbone nodes have the interest message.

Step 5: All nodes on backbone paths propagate to one-hop neighboring sensor node, which is not on the backbone path. Therefore, each sensor node on the hexagonal mesh keeps the interest message.

/* *Sensing Phase* */

Step 6: All sensor nodes perform the sensing process based on the interest message (or default interest) to obtain all attribute-values.

/* *Data Propagation Phase* */

Step 7: The reserved operation of Step 5 is applied such that all attribute-values are collected into $\lceil \beta/3 \rceil$ $D^-(x)$ backbone paths (by Lemma 4).

Step 8: The reserved operation of Step 4 is performed such that all attribute-values are accumulated into the $D^+(y)$ backbone path by using the four time-slot data frame (by Lemma 5).

Step 9: The reserved operation of **Step 3** is executed such that all attribute-values are obtained by the sink node *S* by using the four time-slot data frame (by Lemma 5).

An instance is given in Fig. 10.

5.2. Sink-to-Region Diffusion Operation

Let *R* denote as a sensing region and sensing region *R* is a rectangle, denoted as $R(x, y, x', y')$, where left-up and right-down corners of the rectangle are (x, y) and (x', y'), respectively. Further, let (c_1, c_2) denote as the center point of the rectangle *R*, where $c_1 = \lceil \frac{x+x'}{2} \rceil$ and $c_2 = \lceil \frac{y+y'}{2} \rceil$. For a sink node *S*, the sink-to-region diffusion operation acquires all attribute-values from a sensing region *R*. Based on Lemmas 4 and 5, we have the following results.

<u>Lemma 6:</u> Given a hexagonal mesh, two backbone paths D^+ and D^- are exactly used from a sink node *S* to the sensing region *R*.

<u>Lemma 7:</u> Given any a sink node *S* in a hexagonal mesh, sink node can perform interest and data propagation operations to any sensing region using four time-slot data frame.

A sink node traverses to a sensing region by two backbone paths, denoted as first and second backbone paths. We firstly describe how to construct the first backbone path as follows. Let a sink node is located in a hexagonal block *B*.

Assume that there are two backbone paths $D^+(a)$ and $D^-(b)$, and *B* is the cross hexagonal block of $D^+(a)$ and $D^-(b)$. From the sink node (s_1, s_2), we must determine the first backbone path, which is selected from one of $D_+^+(a)$, $D_-^+(a)$, $D_+^-(b)$ and $D_-^-(b)$, where (c_1, c_2) is the center point of the rectangle R.

- The $D_+^+(a)$ is used as the first backbone path if $c_1 \geqq s_1$ and $c_2 \geqq s_2$.
- The $D_-^+(a)$ is used as the first backbone path if $s_1 \geqq c_1$ and $s_2 \geqq c_2$.
- The $D_+^-(b)$ is used as the first backbone path if $s_1 \geqq c_1$ and $c_2 \geqq s_2$.
- The $D_-^-(b)$ is used as the first backbone path if $c_1 \geqq s_1$ and $s_2 \geqq c_2$.

If the first backbone path is determined, then the second backbone path is therefore constructed as follows.

Step 1: If the first backbone path is $D_+^+(a)$ then the second backbone path is $D_+^-(b)$ when the sensing region is located at upper area of $D_+^+(a)$ where $D_+^-(\alpha_1)$ passes through the sensing region. Otherwise, the second backbone path is $D_-^-(\alpha_2)$ if the sensing region is located at lower area of $D_+^+(a)$ where $D_-^-(\alpha_2)$ passes through the sensing region, (see Fig. 11(a)).

Step 2: If the first backbone path is $D_-^+(a)$ then the second backbone path is $D_+^-(\alpha_1)$ when the sensing region is located at upper area of $D_-^+(a)$ where $D_+^-(\alpha_1)$ passes through the sensing region. Otherwise, the second backbone path is $D_-^-(\alpha_2)$ if the sensing region is located at lower area of $D_-^+(a)$ where $D_-^-(\alpha_2)$ passes through the sensing region, (see Fig. 11(a)).

Step 3: If the first backbone path is $D_+^-(b)$ then the second backbone path is $D_+^+(\alpha_1)$ when the sensing region is located at upper area of $D_+^-(b)$ where $D_+^+(\alpha_1)$ passes through the sensing region. Otherwise, the second backbone path is $D_-^+(\alpha_2)$ if the sensing region is located at lower area of $D_+^-(b)$ where $D_-^+(\alpha_2)$ passes through the sensing region, (see Fig. 11(a)).

Step 4: If the first backbone path is $D_-^-(b)$ then the second backbone path is $D_+^+(\alpha_1)$ when the sensing region is located at upper area of $D_-^-(b)$ where $D_+^+(\alpha_1)$ passes through the sensing region. Otherwise, the second backbone path is $D_-^+(\alpha_2)$ if the sensing region is located at lower area of $D_-^-(b)$

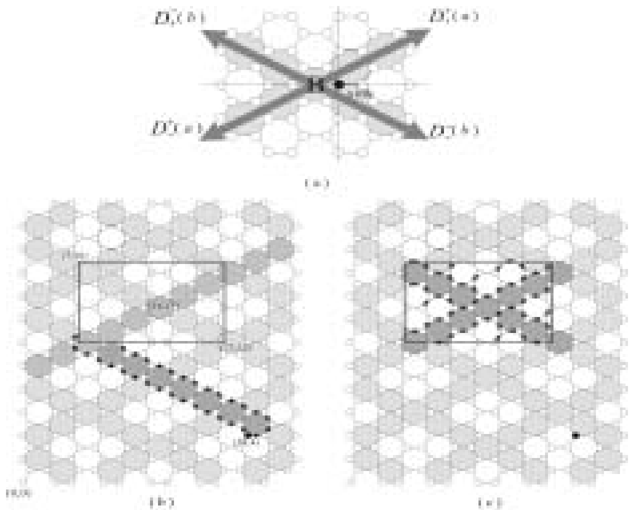


Figure 11: Example of sink-to-region diffusion operation

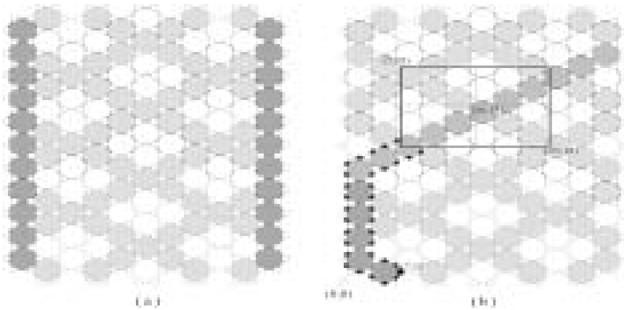


Figure 12: Example of handling the boundary sensors

where $D_{-}^{+}(\alpha_2)$ passes through the sensing region, (see Fig. 11(a)).

As example of first and second backbone paths are shown in Fig. 11(b) and Fig. 11(c), respectively. If no first backbone path exists for some boundary sensor nodes, the alternative path is used as follows. We use the column path as the first backbone path, which as shown in 12(a). The second backbone path is constructed by the similar way, which as illustrated in 12(b). Observe that, it violates the energy-efficient issue for handling the boundary sensor nodes.

Sink-to-Region Diffusion Procedure (*S*, *R*)

Input: A sink node *S* and a sensing region *R*. Observe that a simple flooding operation is executed to let all sensors know the location information of sink node.

Output: A sink node *S* acquires attribute-values from sensing region *R*.

Step 1: Determine the first and second backbone paths for the sink node *S* and the sensing region *R*.

Step 2: The sink node *S* sends interest to sensing region *R* along first and second backbone paths by using a four time-slot data frame (by Lemma 4), and connect to region *R* at a sensor node *C*.

Step 3: Execute the sink-to-all diffusion procedure to let sensor node *C* obtain all attribute-values in the region *R*.

Step 4: All attribute-values are reversely sent from sensor node *C* to sink node *S* along second and first backbone paths by using the four time-slot data frame (by Lemma 5). An instance is given in Fig. 11.

6. Experimental Result

A simulator is developed by C++ to evaluate the performance. Lindsey *et al.* [5] proposed a data gathering scheme, which denoted as data-gathering scheme in our simulation. Intanagonwiwat *et al.* [3] developed a directed diffusion scheme, which denoted as directed-diffusion scheme. To examine the effectiveness of our approach, data-gathering [5] and directed-diffusion [3] and the flooding schemes, are mainly compared with our diagonal-based scheme. The radio model mainly follows the same model defined in [5], and the performance parameters are listed below.

- In the model, the distance between two sensors is assumed 5*m*.
- A packet length *k* is assumed to be 2000 bits.
- The sensors return the observation result per *5* seconds.
- The backbone-path exchange period is assumed to be 50 seconds.
- Each transmission delay is assumed to be 1 unit time.
- The 160 sensor nodes are arranged in a hexagonal mesh, thus the coverage area is $100m \times 40m$.
- The interest propagation phase spends 5 seconds and the data propagation phase totally spends 45 seconds.
- A radio dissipates E_{elec} is assumed to be 50 *nJ/bit*, where $nJ = 10^{-9}$ *Joule* [5] to support the transmitter or receiver circuitry and $\in_{amp}$ is assumed to be 100 $pJ/bit/m^2$, where $pJ = 10^{-12}$ *Joule* [5] for the transmitter amplifier.
- Observe that the $\in_{amp}$ is a fixed value of our scheme since the distance between two sensors is constant.

The radios can be turned off to receiving unintended transmissions. In our simulation, the simulation time is 500 seconds and the interests are sent to sensing regions between 50 seconds. Consequently, the formula of calculating the transmitting cost for a k -bit message is

$$E_{Tx}(k) = E_{elec} \times k + \in_{amp} \times k.$$

The formula of calculating the receiving cost for a *k*-bit message is

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

The performance metrics contain.

- *Energy*(*E*): The total energy cost that the sensors dissipate of transmitting/receiving messages for a request interest.

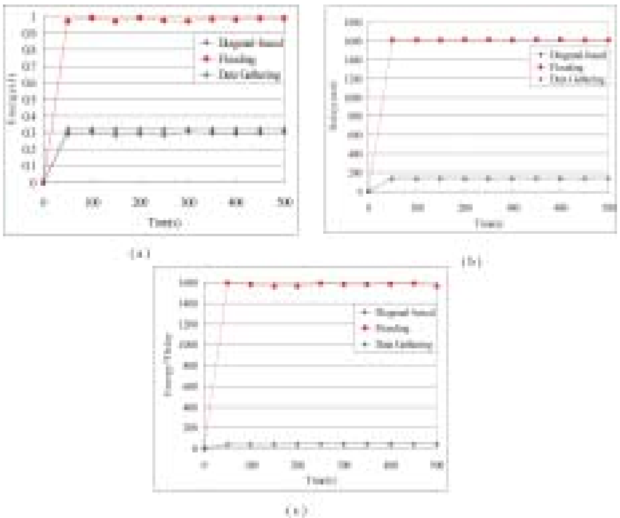


Figure 13: Performance of sink-to-all vs. effects of (a) energy (b) delay time (c) energy*delay

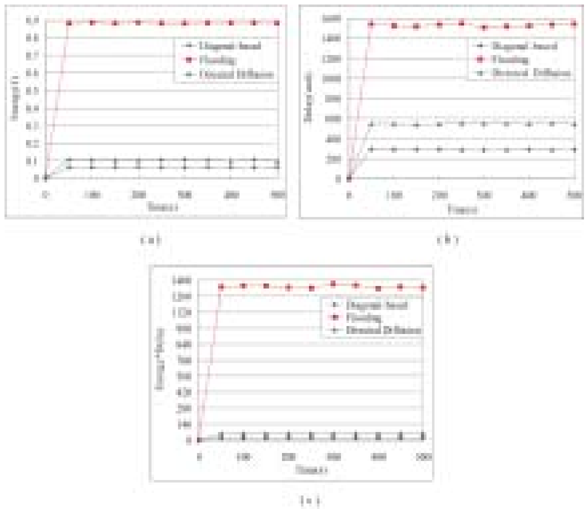


Figure 14: Performance of sink-to-region vs. effects of (a) energy (b) delay time (c) energy*delay

- *Delay*(*D*): The total delay time that all sensors spend on transmitting/receiving messages for a request interest.

- *Energy* * *Delay*(*E, D*): Multiply the value of energy by the value of delay.

It is worth mentioning that an energy-efficient directed diffusion is achieved by having a low *E*, a low *D*, and a low *E*D*. In the following, we illustrate our simulation results of *E, D,* and *E*D* from various prospects.

6.1 Performance of sink-to-all diffusion operation

The simulation results of sink-to-all operation of data-gathering scheme [5], the flooding scheme, and our diagonal based scheme, are illustrated in Fig. 13. For sink-to-all diffusion operation, three kinds of effects are discussed.

- *Effect of energy vs. time:* The simulation result of *energy* vs. *time* is illustrated in Fig. 18(a), where the time interval is ranging from 50 ˜500 seconds. For example, if the time interval is 50 seconds, then the energy consumptions of the diagonal-based scheme, the flooding scheme, and the data-gathering scheme are 0.2877, 0.9883 and 0.32544, respectively. Our scheme averagely saves about 71% and 11% of energy consumptions of flooding scheme and data gathering scheme. This indicates that our proposed scheme actually is an energy-efficient due to using the periodic active-and-sleep scheme.

- *Effect of delay vs. time:* The simulation result of delay vs. time is illustrated in Fig. 13(b), where the time interval is ranging from 50 ˜500 seconds. For instance, if the time interval is *50* seconds, then the average delay time of our scheme, flooding scheme, and data-gathering schemes are 132.797, 1588.76, and 150, respectively. Observe that our scheme averagely saves about 88.04% of delay time than the flooding scheme, and saves about 14% of delay time than the data-gathering scheme. Observe that our scheme only use four time-slot data frame for the interest and data propagation operations.

- *Effect of energy * delay vs. time:* The simulation result of *energy * delay* vs. *time* is illustrated in Fig. 13(c), where the time interval is ranging from 50 ˜500 seconds. For instance, if the time interval is *50* seconds, then the value of *energy * delay* of our scheme, flooding scheme, and data-gathering scheme are 38.979, 1599.265, and 48.816, respectively. Our scheme just has about

2.44 of *energy * delay* value than flooding has, and our scheme has about 79.85 of *energy * delay* value than data-gathering scheme has.

6.2. Performance of sink-to-region diffusion operation

The simulation results of sink-to-region operation of directed-diffusion scheme [3], the flooding scheme, and our diagonal-based scheme, are illustrated in Fig. 14. For sink-to-region diffusion operation, three kinds of effects are discussed.

- *Effect of energy vs. time:* The simulation result of *energy vs. time* is illustrated in Fig. 14 (a), where the time interval is ranging from 50 to 500 seconds. For example, if the time interval is *50* seconds, then the energy consumptions of the diagonal-based scheme, the flooding scheme, and the directed-diffusion scheme are 0.0617, 0.8768 and 0.1091, respectively. Our scheme averagely saves about 90% and 43% of energy consumptions of flooding scheme and data gathering scheme. This indicates that our proposed scheme actually is an energy-efficient due to using the periodic active-and-sleep scheme.

- *Effect of delay vs. time***:** The simulation result of *delay vs. time* is illustrated in Fig. 14(b), where the time interval is ranging from 50 to 500 seconds. For instance, if the time interval is 50 seconds, then the average delay time of our scheme, flooding scheme, and directed-diffusion schemes are 294.4933, 1515.197 and 544.035, respectively. Observe that our scheme averagely saves about 80% of delay time than the flooding scheme, and saves about 46% of delay time than the data-gathering scheme. This indicates that our proposed scheme actually is an energy-efficient due to using the periodic active-and-sleep scheme.

- *Effect of energy * delay vs. time:* The simulation result of *energy * delay* vs. time is illustrated in Fig. 14(c), where the time interval is ranging from 50 *to* 500 seconds. For instance, if the time interval is *50* seconds, then the value of *energy * delay* of our scheme, flooding scheme, and directed-diffusion scheme are 18.225, 1358.94 and 57.257, respectively. Our scheme just has about 95 of *energy * delay* value than flooding has, and our scheme has about 69 of *energy * delay* value than data-gathering scheme has.

7. Conclusion

This paper has presented a new power-efficient routing scheme on a wireless sensor network. In this work, all of the sensors are arranged into a fixed topology, namely *hexagonal-mesh*, to form a wireless sensor network for the indoor wireless sensing environment. To achieve the energy-efficient purpose, our diagonal-based directed diffusion scheme has the following main contributions. (1) To consider the power-fairness problem, a periodic backbone-path-exchange mechanism is developed to offer a power-saving scheme. (2) A periodic active-and-sleep time-slot scheduling is presented under the TDMA channel model to support the backbone-path-exchange mechanism with the purpose of power-saving. (3) A power-efficient routing, *directed diffusion*, protocol is developed on the hexagonal-mesh network. (4) Two kinds of directed diffusion communication operations based on the diagonal-based scheme are developed. (5) The performance analysis is finally demonstrated to illustrate the energy-efficient achievement. However, the technique presented in this paper may be useful in prolong the life of indoor wireless sensor networks. The further research is to extend our protocol to fit the outdoor sensor networks and micro sensor networks.

8. References

[1] D. Estrin, R. Govindan, and J. Heidemann, and S. Kumar. "Next Century Challenges: Scalable Coordination in Wireless Networks". In *Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM)*, pages 263-270, 1999.

[2] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan. "Energy-Efficient Communication Protocols for Wireless Microsensor Networks". In *Proceedings of Hawaiian International Conference on Systems Science*, January 2000.

[3] C. Intanagonwiwat, R. Govindan and D. Estrin. "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks". In *Proceedings of the 6th Annual ACM/IEEE International Conference on Mobile Computing*

and Networking (MOBICOM), pages 56-67, August 2000.

[4] W. R. Heinzelman, J. Kulik, and H. Balakrishman, "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks". *ACM MOBICOM'99*, 1999.

[5] S. Lindsey, C. S. Raghavendra, "PEGASIS: Power Efficient GAthering in Sensor Information Systems". *Submitted to ICC 2001*.

[6] G. J. Pottie and W. J. Kaiser. "Wireless Integrated Network Sensors". *Communications of ACM*, May 2000.

[7] Loren Schwiebert, Sandeep K.S. Gupta, Jennifer Weinmann. "Research Challenges in Wireless Networks of Biomedical Sensors". *The seventh annual international conference on Mobile computing and networking*, July 2001.

[8] D. Estrin, L. Girod, G. Pottie, M. Srivastava. "Instrumenting the world with wireless sensor networks". *Acoustics, Speech, and Signal Processing,* 2001. Proceedings. 2001 IEEE International Conference on, Volume 4, Pages 2033-2036, 2001.

[9] A. Manjeshwar, D. P. Agrawal. "TEEN: a routing protocol for enhanced efficiency in wireless sensor networks". *Parallel and Distributed Processing Symposium.*, Proceedings 15th International, Pages 2009–2015, 2001.

[10] R. S. Bhuvaneswaran, J. L. Bordim, Cui Jiangtao, K. Nakano. "Fundamental protocols for wireless sensor networks". *Parallel and Distributed Processing Symposium.,* Proceedings 15th International, Pages 1369-1376, 2001.

[11] K. Sohrabi, J. Gao, V. Ailawadhi, G. J. Pottie. "Protocols for self-organization of a wireless sensor network". *IEEE Personal Communications*, Volume 7, Issue 5, Pages 16-27, Oct. 2000

[12] K. Sohrabi, G. J. Pottie. "Performance of a novel self-organization protocol for wireless ad-hoc sensor networks". *Vehicular Technology Conference*, 1999. VTC 1999-Fall. IEEE VTS 50th, Volume 2 , Pages: 1222-1226, 1999.

[13] S. Lindsey, C. Raghavendra, K. Sivalingam, "Data gathering in sensor networks using the energy*delay metric". *Parallel and Distributed Processing Symposium*., Proceedings 15th International, Pages 2001-2008, 2001.

[14] J. Mirkovic, G. P. Venkataramani, Lu Songwu, Zhang Lixia. "A self-organizing approach to data forwarding in large-scale sensor networks". *Communications, 2001. ICC 2001. IEEE International Conference* on , Volume 5 , Pages 1357-1361, 2001.

[15] Wen-Hwa Liao, Yu-Chee Tseng, Kuei-Ping Shih. "A TDMA-based Bandwidth Reservation Protocol for QoS Routing in a Wireless Ad Hoc Network". *Technical Report of National Central Univ, Taiwan*, R.O.C., 2001.

[16] Yuh-Shyan Chen, , Wu-Chen Chen. "A Hexagonal TDMA-based QoS Routing for Wireless Mobile Ad Hoc Networks", in Proceedings of Cross-Strait Information Technology Conference (CSIT2001), National Central University, Taiwan, Sep. 20-22, 2001.

[17] Schurgers, C., Srivastava, M.B.; Tsiatsis, V. "STEM: topology management for energy efficient sensor networks". *Aerospace Conference Proceedings, 2002. IEEE*, Volume: 3, 2002 Page(s):1099-1108.

[18] W. Ye, J. Heidemann, and D. Estrin.. "An Energy-Efficient MAC Protocol for Wireless Sensor Networks". In *Proceedings of IEE INFOCOM 2002*, April, 2002.