An Energy-Efficient Diagonal-Based Directed Diffusion for Wireless Sensor Networks

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Abstract—**In this paper, we present a new energy-efficient directed diffusion protocol by using a proposed diagonal-based hexagonal-mesh scheme for a wireless sensor network. The wireless sensor network is more reasonable to carefully build a fixed-topological wireless network environment than the conventional MANET due to the low mobility. Therefore, all sensor nodes are arranged into a fixed-topological wireless network structure, namely the hexagonal-mesh, while the MAC protocol is adopted the periodic active-and-sleep model. Wireless sensor networks use battery-operated computing and sensing devices. The directed diffusion is mainly operated on the diagonal-paths of the hexagonal-mesh under the energy-efficient consideration. To achieve the energy-efficient purpose, our diagonal-based directed diffusion scheme has the following main contributions; (1) a periodic active-and-sleep MAC protocol on TDMA channel model is designed, (2) a periodic backbone-path-exchange scheme is periodically performed on the diagonal-mesh to consider the per-node fairness problem, (3) a directed diffusion communication application is developed based on the diagonal-based scheme. Finally, performance analysis result is finally demonstrated to illustrate the energy-efficient achievement of our proposed scheme.**

I. Introduction

Wireless sensor networks [3], [8], [12], [13] are recently investigated due to the remote environment monitoring capabilities. Such a network can greatly improve the accuracy of information via collaboration of a group of sensor nodes. Sensor nodes monitor activities of a set of objects in a sensing region, and report their observations to an interest client, or called as a sink node, through the wireless sensor networks. If sensors 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 to monitor the status of the sensing region. Wireless sensor networks can be used for tasks such as military surveillance, air-conditioner control [8], building security [10], health monitor [2], [11], and in harsh physical environments for scientific investigations, etc.

Sensor node has limited computing capacity and memory, and is operated with limited battery power. Several obstacles must be overcame for providing a wireless sensor network [4], which include (1) *energy*: wireless sensors have a limited supply of energy, energy-conserving communication protocols are necessary to be provided, (2) *computation*: sensor nodes only have limited computing power and thus cannot run a sophisticated network protocol, (3) *communication*: the bandwidth of the wireless links connecting sensor nodes is often limited, therefore it constrains the inter-sensor communication.

Some related works are reviewed. Initially, Bhuvaneswaran *et al.* [1] proposed an energy-efficient protocol that computes the sum of n numbers over any commutative and associate binary operator stored in n wireless sensor nodes arranged in a two-dimensional grid of size $\sqrt{n} \times \sqrt{n}$. Heinzelman *et al.* [3] proposed the LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol, a clustering-based protocol that utilizes randomized rotation of local cluster base stations (cluster-heads) to evenly distribute the energy load among the sensors in the network. Mirkovic *et al.* [9] organize sensors into a dynamic, self-optimizing multicast tree-based forwarding hierarchy, which is a robust scheme to tolerate the node failures. Observe that, Lindsey *et al.* [7] proposed a data gathering scheme in sensor networks, which is measured by *energy * delay* metric. In addition, Heinzelman *et al.* [4], presented the SPIN (Sensor Protocols for Information via Negotiation) protocol that efficiently disseminates information among sensors in an energy-constraint wireless sensor network. Recently, Manjeshwar *et al.* [8] proposed the TEEN (Threshold sensitive Energy Efficient sensor Network) protocol which is a new energy efficient protocol. More recently, Intanagonwiwat *et al.* [5] developed a scalable and robust communication paradigm, namely the directed diffusion, for the sensor networks.

To achieve the energy-efficient purpose, the MAC sub-layer is always adopted the most-power-saving TDMA channel model. For example, most existing results in [3], [8], [12], [13] are adopted the TDMA channel model. Unfortunately, these results [3], [8], [12], [13] do not consider the radio-interference problem. Observe that Lindsey *et al.* used the complex and the power-wasting CDMA channel model in [7]. More recently, an energy-efficient MAC protocol is presented in [14] by using a periodic listen and sleep scheme.

This work aims to present an energy-efficient directed diffusion protocol by using a diagonal-based hexagonal-mesh scheme for the wireless sensor networks, while the MAC sub-layer is adopted the similar periodic active-and-sleep model [14]. The wireless sensor nodes are reasonable to be arranged in a fixed-topological wireless network due to its low mobility. For instance, Bhuvaneswaran *et al.* in [1] arranged wireless sensor nodes in a two-dimensional grid. In this work, all sensor nodes are arranged in a special structure, namely the hexagonal-mesh, to actually exploit the energy-efficient capability. In our scheme, the directed diffusion is mainly operated on the diagonal-paths of the hexagonal-mesh under the energy-efficient consideration. To consider the per-node fairness problem, a backbone-path-exchange operation is performed on the diagonal-mesh to exchange the backbone-paths periodically. Specially, a backbone-path is a diagonal-path in a hexagonal mesh. Based on the diagonal-based scheme, a directed diffusion protocol is developed, which cover all

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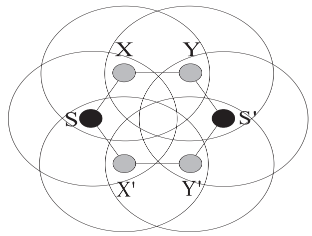

Fig. 1. Example of a hexagonal block

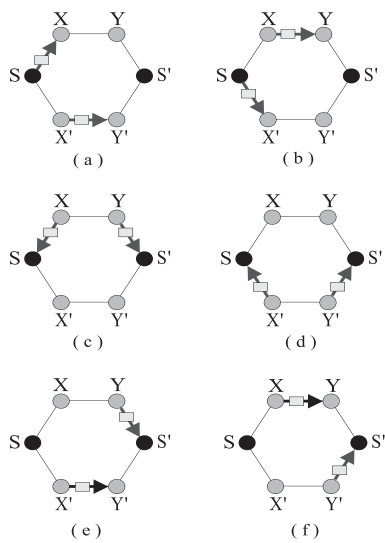

Fig. 2. Time-slot re-use capability on a hexagonal block

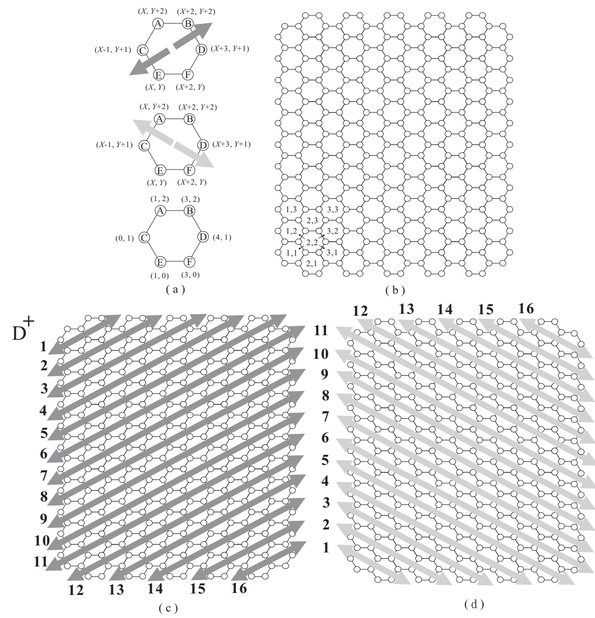

Fig. 3. Example of a hexagonal mesh and diagonal paths.

possible directed diffusion patterns in a wireless sensor network. Finally, performance analysis result is finally demonstrated to illustrate the energy-efficient achievements.

The rest of the paper is organized as follows. Section II presents basic idea and notations. A periodic backbone-path-exchange and active-and-sleep schemes are presented in Section III. The diagonal-based directed diffusion is developed in Section IV and experimental results are discussed in Section V. Section VI concludes this paper.

II. Basic Idea and Notations

In this paper, the MAC sub-layer in our model is adopted the TDMA channel model. An energy-efficient scheme, namely periodic active-and-sleep, is designed on the TDMA channel model. All of the sensor nodes are specially arranged into a fixed-topology network, namely hexagonal-mesh, to achieve the energy-efficient purpose. Initially, we formally introduce the hexagonal block, the hexagonal mesh and the diagonal path as follows.

Definition 1 Hexagonal block: *Given a pair of two distinct sensor nodes S and S', two disjoint three-hop paths (S, X, Y, S') and (S, X', Y', S') exist between sensor nodes S and S'. Denote $\left[S \begin{pmatrix} X & Y \\ X' & Y' \end{pmatrix} S'\right]$ as a hexagonal block, where sensor nodes X and X' are not 1-hop neighbors, and sensor nodes Y and Y' are not 1-hop neighbors.*

For instance, a hexagonal block $\left[S \begin{pmatrix} X & Y \\ X' & Y' \end{pmatrix} S'\right]$ is given in Fig. 1, there are two disjoint three-hop paths (S, X, Y, S') and (S, X', Y', S') between nodes S and S'. Observe that, in the general case, sensor nodes X and X' can be neighbors, and sensor nodes Y and Y' can be neighbors. However, this hexagonal-block attempts to gives a less stronger condition that sensor nodes X and X' are not 1-hop neighbors and sensor nodes Y and Y' are not 1-hop neighbors, as illustrated in Fig. 1. This result is very important for the time-slot reservation in a wireless sensor network. One important lemma is given herein, which based on a lemma defined in [6], for the time-slot reservation scheme.

Lemma 1 *A time slot t can be used by a sensor node X to send to another sensor node Y without causing collision if the following conditions are all satisfied.*
1. Slot t is not yet scheduled to send or receive in neither X nor Y.
2. For any 1-hop neighbor Z of X, slot t is not scheduled to receive in Z. Slot t can be scheduled (or reused) to send in Z, but cannot send to any other 1-hop neighbors of X (conflict with condition 1).
3. For any 1-hop neighbor Z of Y, slot t is not scheduled to send in Z. Slot t can be scheduled (or reused) to receive in Z, but cannot receive from any other 1-hop neighbors of Y (conflict with condition 1).

Given a hexagonal-block $\left[S \begin{pmatrix} X & Y \\ X' & Y' \end{pmatrix} S'\right]$ as illustrated in Fig. 1, the time-slot re-use property of six links in a hexagonal-block is listed below.

1. Time slot t scheduled in $\overrightarrow{SX}$ can be re-used in $\overrightarrow{X'Y'}$, (see Fig. 2(a)).

2. Time slot t scheduled in $\overrightarrow{XY}$ can be re-used in $\overrightarrow{SX'}$, (see Fig. 2(b)).

3. Time slot t scheduled in $\overrightarrow{XS}$ can be re-used in $\overrightarrow{YS'}$, (see Fig. 2(c)).

4. Time slot t scheduled in $\overrightarrow{X'S}$ can be re-used in $\overrightarrow{Y'S'}$, (see Fig. 2(d)).

5. Time slot t scheduled in $\overrightarrow{YS'}$ can be re-used in $\overrightarrow{X'Y'}$, (see Fig. 2(e)).

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6. Time slot t scheduled in $\overrightarrow{XY}$ can be re-used in $\overrightarrow{Y'S'}$, (see Fig. 2(f)).

A sensor node possess a fully-functional Global Position System (GPS) receiver, to logically determine the coordinate position and perform the time-synchronization operation. We define the coordinate position function as follows. Consider a hexagonal-block $\left[E\begin{pmatrix} C & A \\ F & D \end{pmatrix}B\right]$ as shown in Fig. 3(a). Assume that the coordinate position of a sensor node E is (X, Y), then the coordinate positions of sensor nodes $A, B, C, D,$ and F are $(X, Y+2)$, $(X+2, Y+2)$, $(X-1, Y+1)$, $(X+3, Y+1)$, and $(X+2, Y)$, respectively. For example as shown in Fig. 3(a), if the coordinate position of a sensor node E is $(1, 0)$, then the coordinate positions of $A, B, C, D,$ and F are $(1, 2)$, $(3, 2)$, $(0, 1)$, $(4, 1)$, and $(3, 0)$.

Let a hexagonal-block $\left[S\begin{pmatrix} X & Y \\ X' & Y' \end{pmatrix}S'\right] = B_{i,j}$ denote a i-th row and j-th column hexagonal-block, and all $B_{i,j}$, for $1 \le i, j \le n$, form a hexagonal mesh, where each $B_{i,j}$ connects to six neighboring hexagonal-block along six distinct directions.

Definition 2 Hexagonal mesh: Let $M_{n\times n}$ denote as a 2D hexagonal mesh with $n \times n$ hexagonal-blocks $B_{i,j}$, such that each $B_{i,j}$ connects to six neighboring hexagonal blocks along six distinct directions, where $1 < i, j < n$.

For example as shown in Fig. 3(b), $B_{2,2}$ connects to six neighbors $B_{2,1}$, $B_{1,1}$, $B_{1,2}$, $B_{2,3}$, $B_{3,2}$, and $B_{3,1}$. Observe that the hexagonal mesh can be $M_{m\times n}$, where $m \neq n$, but this study only considers the effect of $M_{n\times n}$.

Definition 3 Diagonal path: Given a hexagonal mesh, let $D^+_+(x), D^+_-(x), D^-_+(x)$, and $D^-_-(x)$ denote the right-up, left-down, left-up, and right-down diagonal paths, respectively, where x denotes the x-th diagonal path.

Observe that, the right-up diagonal path $D^+_+(x)$ is same with left-down diagonal path $D^-_+(x)$ with the opposite direction, we also use $D^+(x)$ to denote this right-up or left-down diagonal path. Similarly, left-up diagonal path $D^-_+(x)$ is same with right-down diagonal path $D^-_-(x)$ with the opposite direction, we also use $D^-(x)$ to denote the left-up or right-down diagonal path. The sequence of diagonal path $D^+(x)$ is from the left-up corner to the right-down corner of a hexagonal mesh. For instance, diagonal paths $D^+(1), D^+(2), \cdots, D^+(16)$ are shown in Fig. 3(c). Similarly, the sequence of diagonal path $D^-(x)$ is from the left-down corner to the right-up corner of a hexagonal mesh. For instance, diagonal paths $D^-(1), D^-(2), \cdots, D^-(16)$ are shown in Fig. 3(d).

III. The Diagonal-Based Energy-Efficient Channel Scheduling

The directed diffusion operation consists of *interest propagation, sensing phase,* and *data propagation phases* [5]. In *interest propagation phase*, a sink node sends interest message to assigned regions through the backbone paths. All sensors acquire the sensing data based on the interest message in *sensing phase*. In *data propagation phase*, sensors return observed attribute-values to the sink node through the same backbone paths. To achieve the energy-efficient purpose, a periodic backbone-path-exchange scheme, a periodic active-and-sleep time scheduling, and the time-slot scheduling for interest and data propagation phases are described.

A. The Periodic Backbone-Path-Exchange Scheme

The periodic backbone-path-exchange scheme is presented for handling the per-node fairness problem. Each sensor have equal opportunity to serve as the backbone path. We initially define the backbone path.

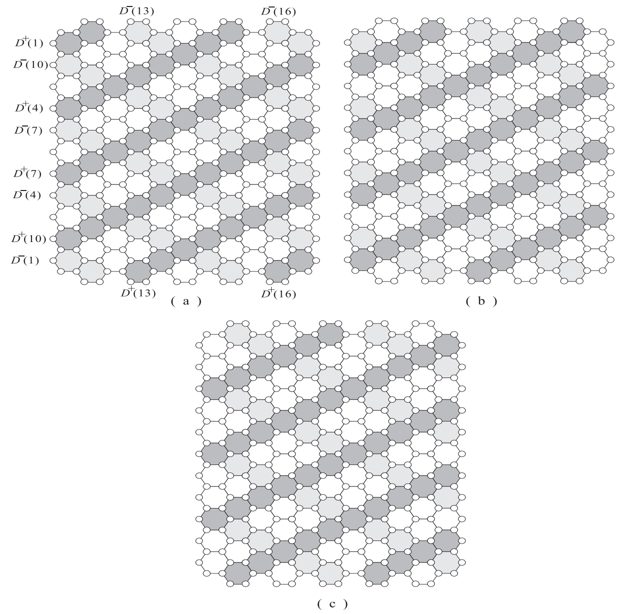

Fig. 4. Example of the periodic backbone-path-exchange scheme.

Definition 4 Backbone path: A diagonal path is said as a backbone path if all directed-diffusion data from a sink node to each sensor node must go through the diagonal path.

If there are k diagonal paths. Only x, $\lfloor \frac{k}{3} \rfloor \le x \le \lceil \frac{k}{3} \rceil$, diagonal paths are selected to be the backbone paths. To maintain the energy-load, the backbone paths are interchanged periodically. A periodic exchange operation of backbone paths is given.

1. All diagonal paths $D^-(3i-2)$ and $D^+(3i-2)$ are the backbone paths, for all $1 \le i \le t = \lfloor \frac{k}{3} \rfloor$.

2. On the next time, all diagonal paths $D^-(3i-1)$ and $D^+(3i-1)$ are the backbone paths, for all $1 \le i \le t = \lfloor \frac{k}{3} \rfloor$.

3. On the next time, all diagonal paths $D^-(3i)$ and $D^+(3i)$ are the backbone paths, for all $1 \le i \le t = \lfloor \frac{k}{3} \rfloor$.

4. Repeats the (1) to (3).

Fig. 4 shows an instance, observe that we only discuss the case of (1) in the rest of this paper. The case (2) and (3) are with the similar conditions.

B. The Periodic Active-and-Sleep Time Scheduling

Fig. 5 illustrates a possible scenario of the periodic active-and-sleep time-slot scheduling. First, all sensors are divided into two kinds of roles; sensors located at the backbone path are denoted as *backbone sensors*, and other sensors are denoted as *non-backbone sensors*.

Observation 1: Each sensor node can connect to a backbone path D^+ or D^- within 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 observation 1, non-backbone sensors directly connects with backbone path by one-hop link. Our periodic active-and-sleep time scheduling adopts four time-slot data frame. 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

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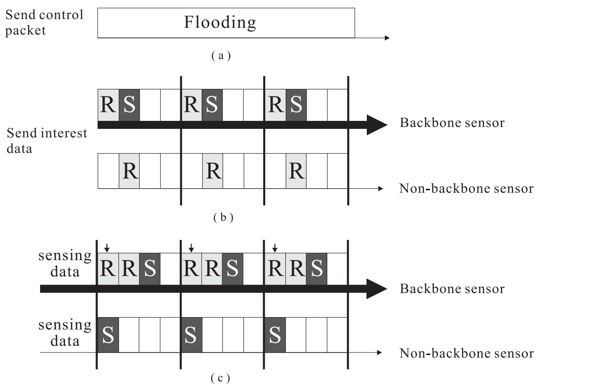

Fig. 5. Examples of (a) interest and (b) data propagation operations using four time-slot data frame.

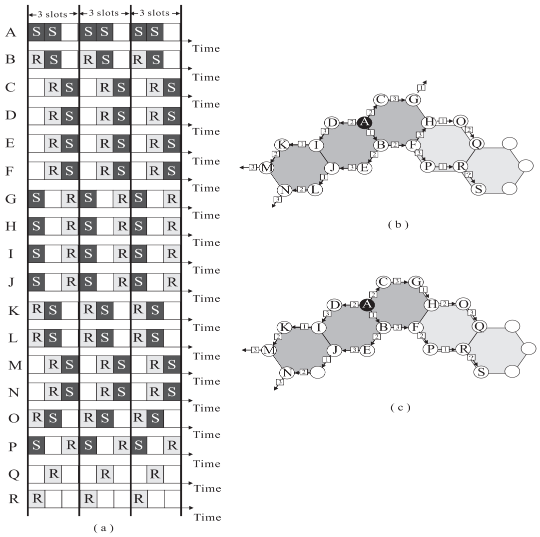

Fig. 6. Example of three time-slot data frame on a backbone path.

battery-power to achieve the energy-saving purpose. The main operations of the periodic active-and-sleep time scheduling is informally described.

E1: Fig. 5(a) shows that a sink node initially floods a short control packet, which aims to let all sensor nodes obtain the sink information. This sink information will be described in Section III.B.1, which usefully determines the energy-efficient time-slot scheduling.

E2: 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 III.B.1 and III.B.2).

E3: Fig. 5(b) illustrates a scenario of time-slot scheduling for the interest propagation phase. All backbone sensor offer two time slot to send/receive interest messages, and all non-backbone sensors only offer one time slot to receive interest message.

E4: Fig. 5(c) displays a scenario of time-slot scheduling for the data propagation phase. After all sensors obtaining the sensing data, all backbone sensors offer one time slot to send sensing data and offer two time slot to receive sensing data. In addition, all non-backbone sensors only use one slot to send sensing data.

Observe that backbone sensor offers more active slots than the non-

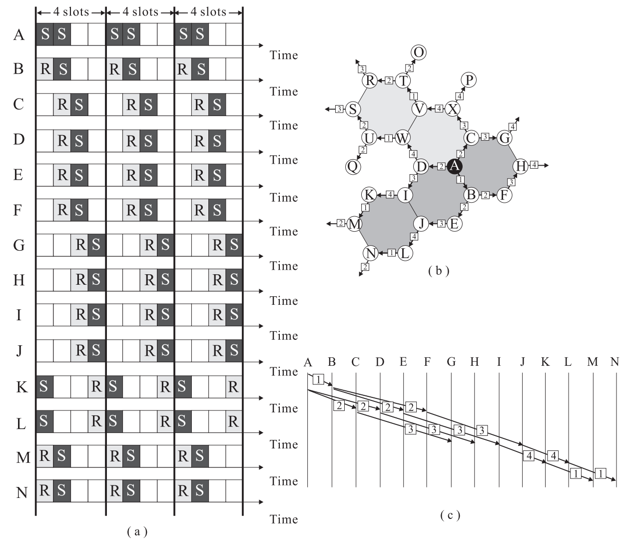

Fig. 7. Example of interest propagation operation using four time-slot data frame for sink node A.

backbone sensor. 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.

B.1 Time-Slot Scheduling for Interest Propagation Phase

It is worth pointing out that our diagonal-path is a two-path routing. The main purpose of the diagonal-path is to split the sensing area into two sensing regions; one is the *upper* sensing region, and another one is the *lower* sensing region. For example as shown in Fig. 8(a). In Fig. 7(b), sink node A initially sends interest message to B. Therefore, path (G, C, A, D, I, K, M) is responsible for sending interest message to upper sensing region, and (H, F, B, E, J, L, N) is responsible for the lower sensing region. Moreover, sensor A sends interest message to B using time slot 1. Based on the time-slot reuse property as mentioned in Section II, consider a hexagonal block $\left[A\begin{pmatrix}B & E\\ D & I\end{pmatrix}J\right]$ as shown in Fig. 6(b), sensors A and B already keep the same interest message.

1. Time slot 2 scheduled in $\overrightarrow{AD}$ can be re-used in $\overrightarrow{BE}$.
2. Time slot 3 scheduled in $\overrightarrow{DI}$ can be re-used in $\overrightarrow{EJ}$.

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

Lemma 1: The interest propagation operation can be performed on one backbone path by using only three time-slot data frame.

Observe that the interest message from a sink must go through two backbone paths D^+ and D^- to all sensors. Based on lemma 1, although we can use three time-slot data frame to perform the data propagation operation along backbone path D^+ or D^-. Unfortunately, it is impossible to use three time-slot data frame to perform the data propagation operation on both backbone paths. Figs. 6(b) and 6(c) show that 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 D^+, sensors F and H attempt to perform

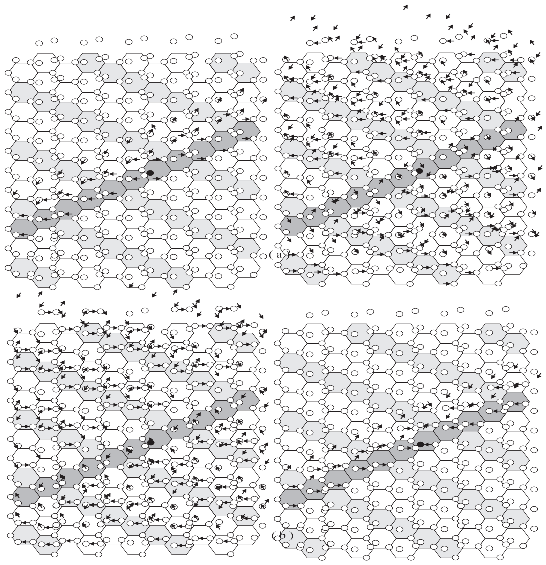

Fig. 8. Example of sink-to-all diffusion operation.

the interest propagation operation along D^- by using the same three time-slot data frame. However, it fails to do that. The detail can follow Figs. 6(b) and 6(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. 7. In fact, only two kinds of time slot scheduling are existed based on the relative location of sink node.

Consider a hexagonal block $\left[A \begin{pmatrix} B & G \\ C & F \end{pmatrix} H\right]$, if sink node is A, B, G, or H, then the four time-slot scheduling is constructed as illustrated in Figs. 7. If sink node is C or F, then the four time-slot scheduling is constructed. Therefore, this location information of the sink node must floods to all sensors, in the E1 step, before performing the interest propagation operation. Therefore, we have the following result.

Lemma 2: The interest propagation operation can be performed along two backbone paths D^+ and D^- by exactly using four time-slot data frame.

B.2 Time-Slot Scheduling for Data Propagation Phase

Basically, the data propagation operation is the reversed operation of the interest propagation operation. The successful time-slot scheduling for data propagation phase can be similarly constructed. Therefore, we have the following result.

Lemma 3: The data propagation operation can be performed along two backbone paths D^+ and D^- by exactly using four time-slot data frame.

IV. Energy-Efficient Diagonal-Based Directed Diffusion Protocol

Let the value of β denote as the number of diagonal paths D^+ or D^-. Given a hexagonal mesh, assume that there are $2 \times \beta$ distinct $D^+(x)$ and $D^-(x)$ diagonal paths in a hexagonal mesh, where $1 \leq x \leq \beta$. Therefore, there are at most $2 \times \lceil \beta/3 \rceil$ 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.

The sink-to-all diffusion operation aims to acquires 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.

Sink-to-All Diffusion Procedure (*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 $1 \leq y \leq \beta$. 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**.

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 2) 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 $1 \leq x \leq \beta$. 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 2) 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 observation 1).

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 3).

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 3).

V. Experimental Result

A simulator is developed by C++ to evaluate the performance. Lindsey *et al.* [7] proposed a data gathering scheme, which denoted as data-gathering scheme. Intanagonwiwat *et al.* [5] developed a directed diffusion scheme, which denoted as directed-diffusion scheme. To examine the effectiveness of our approach, data-gathering [7] and directed-diffusion [5] and the flooding schemes, are mainly compared with our diagonal-based scheme. The radio model mainly follows the same model defined in [7], and the performance parameters are listed below.

- In the model, the distance between two sensors is assumed $5m$.
- The 160 sensor nodes are arranged in a hexagonal mesh, thus the coverage area is $100m \times 40m$.
- A radio dissipates E_{elec} is assumed to be 50 nJ/bit, where nJ = 10^{-9} Joule [7] to support the transmitter or receiver circuitry and $\in_{amp}$ is assumed to be 100 pJ/bit/m^2, where pJ = 10^{-12} Joule [7] for the transmitter amplifier.
- Observe that the $\in_{amp}$ is a fixed value of our scheme since the distance between two sensors is constant.

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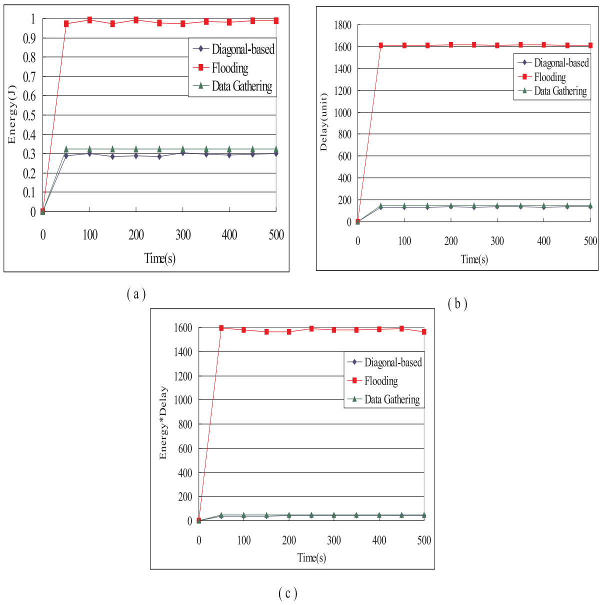

Fig. 9. Performance of sink-to-all vs. effects of (a) energy (b) delay time ,(c) energy * delay.

- 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.
- The interest propagation phase spends 5 seconds and the data propagation phase totally spends 45 seconds.
- Each transmission delay is assumed to be 1 unit time.

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.
- $Delay\ (D)$: 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*.

For sink-to-all diffusion operation, three kinds of effects are discussed.

A1) Effect of energy vs. time: The simulation result of *energy* vs. *time* is illustrated in Fig. 9(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.

A2) Effect of delay vs. time: The simulation result of delay vs. time is illustrated in Fig. 9(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.

*A3) Effect of energy * delay vs. time:* The simulation result of energy * delay vs. time is illustrated in Fig. 9(b), 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.

VI. Conclusion

This paper presents an energy-efficient diagonal-based directed diffusion protocol for a wireless sensor network. A fixed-topological wireless network structure, namely the hexagonal-mesh, is constructed, while the MAC protocol is adopted the periodic active-and-sleep model. To achieve the energy-efficient purpose, our diagonal-based directed diffusion scheme has the following main contributions. (1) A periodic active-and-sleep MAC protocol on TDMA channel model is designed. (2) To consider the per-node fairness problem, a periodic backbone-path-exchange scheme is periodically performed on the diagonal-mesh. (3) A directed diffusion communication operation is developed based on the diagonal-based scheme. The performance analysis result is finally demonstrated to illustrate the energy-efficient achievement.

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