國立中央大學

資訊工程研究所

碩士論文

在無線感應器網路的電源管理通訊協定

研究生：廖志彬

指導教授：許健平 教授

中華民國九十二年六月十九日

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研究生簽名: 廖志彬

論文名稱: 在無線感應器網路的電源管理通訊協定

指導教授姓名：許 健 平　教授

系所 ：資 訊 工 程 所 □博士 ■碩士班

學號：90522004

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中華民國　92　年　6　月　19　日

論文名稱：在無線感應器網路的電源管理通訊協定　　頁數：37
校所組別：國立中央大學 資訊工程 研究所
畢業時間及提要別：九十一學年度第二學期　　碩士學位論文提要
研 究 生：廖志彬　　指導教授：許健平 教授
論文提要內容:

無線感應器網路(Wireless Sensor Network)由許多無線感應器(sensor node)組成，感應器主要是在特定的感應範圍內監控某物體或環境的變化，感應器經由無線感應網路傳回感應結果給使用者，在民生、軍事、航太或是醫學都有廣泛的應用。其中許多的應用，無線感應器呈規則排列，像是生醫感應器，這類的感應器節點的的特性是位置為固定，而且我們可以事先決定它的位置。感應器由於需要長時間的使用，如果要節省電源的消耗或是增加網路的使用時間就必須對電源有效的管理，而一個感應節點最耗電源的部分就在無線電傳輸，所以節省電源的最好方法就是完全關閉無線電的傳輸，也就是切換至電源節省模式(power saving mode)。這篇論文裡，我們在四種規則的無線感應器網路，利用connected dominating set的概念設計我們的通訊協定，我們對於每種圖形選擇數個connected dominating sets，讓這些dominating sets輪流切換至電源節省模式，我們試著讓每個connected dominating set最小，並且讓每個節點能平均消耗電源，來達到減少節點電源的消耗而且延長網路使用時間的目的。根據模擬與分析的結果證明我們的通訊協定利用額外的傳輸時間來節省無線感應網器路總電源的消耗與延長網路的使用時間，無線感應器網路管理者可以根據我們分析結果，建構合適的網路架構。

致謝

首先，要感謝我的指導教授許健平教授，由於您的諄諄教誨與指導才有這篇論文的問世。此外，也感謝口試委員游國忠教授、周立德教授與陳彥文教授，由於您們的指導與建議這篇論文得以更加完善。

再來感謝博士班許智舜學長在論文上的指導，使我能順利完成這篇論文，也感謝其它博士班學長在這段時間的精神鼓勵與關心。

接下來感謝我的研究所同學在課業上相互砥礪生活上相互幫助，使我的研究所生活充實且順利。

最後感謝的是我的家人，我的父母和兄長，由於你們的關愛，我才能毫無憂慮的完成我的學業，在此向你們至上最深的謝意，另外特別感謝范姜畫室的好朋友多年來給我的各種幫助與鼓勵。

求學的生涯暫告一段落，新的學習即將開始，這段求學生涯謝謝許多長輩的關心與好朋友的陪伴，我將會爲每一個關心我的人繼續努力。

志彬

中華民國九十二年六月十九日

Power Management Protocols for Regular Wireless Sensor Networks

Student: **Chih-Pin Liao**

Advisor: Prof. **Jang-Ping Sheu**

Department of Computer Science and Information Engineering
National Central University
Chung-Li, 320
Taiwan, R.O.C.

Abstract

The wireless sensor networks (WSNs) have attracted lots of attention recently. Since the wireless sensor node has no plug-in power, we have to conserve power so that each node can operate for a longer period of time. The best way to conserve power is to let the sensor node switch to power saving (PS) mode. When some nodes switch to PS mode, the network still need to be connected so that the sensed information can be sent to the base station through the active nodes. Here, we propose several power management protocols based on the idea of connected dominating set. We choose several connected dominating sets for each network topology. These connected dominating sets will switch to active mode in turn to serve other PS nodes in the WSN. We try to minimize the size of each connected dominating set and balance the power consumption of each sensor node, so that we can extend the life time of the WSN. Numerical analysis and simulation results show that our power management protocols can conserve lots of power and greatly extend the lifetime of the WSN with a reasonable extra transmission delay.

Keywords: Connected dominating set, power management, power saving, wireless sensor networks.

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Chapter 1

Introduction

The wireless sensor network (WSN) is a network which consists of thousands of wireless sensor nodes. We can use the WSN to monitor the change of the environment, where traditional wired network is not available, such as battlefield, forest, vehicles [1], and human body [2].

The wireless sensor node is a low-cost, small size, and power-limited electronic device [3], which consists of three components: the sensor, the general purpose signal processing engine, and the radio circuit [4, 5]. The wireless sensor node collects the information in the environment by its sensor, processes the information by its signal processing engine, and transmits the collected information to the base station by its radio circuit. The collected information is transmitted either periodically or only when the emergency occurred. Since the sensor nodes in the WSN have no plug-in power, we have to conserve the battery power of sensor nodes so that the lifetime of the network can be extended. Among the three components of the wireless sensor node, the amount of power consumed by the radio frequency circuit is the most [6, 7, 8, 9]. Therefore, we should try to reduce the amount of power consumed by the radio frequency circuit.

Many researchers try to reduce or balance the power consumed by transmission. Power efficient routing protocols for WSN are proposed in [10, 11]. A routing protocol for the wireless access network is proposed in [12]. It can evenly distribute power consumption of the unicast transmission to every node in the network and thus extend the lifetime of the network. This protocol can also be applied to WSN. A cluster-based protocol is proposed in [13], 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. In protocol [14], 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 than the protocol in [13]. Another approach for saving power is to let the wireless sensor node switch to power saving (PS) mode by turning off its radio circuit when it has no information to transmit or receive. A power managemnet protocol for $TDMA$-based WSN is proposed in [15]. The wireless sensor node may turn off its radio circuit during its idle time slot. However, each wireless sensor node must be accurately synchronized. To improve this work, a power management protocol for WSN with two channels is proposed in [6]. In this protocol, each wireless sensor node need not to be synchronized. The wireless sensor node uses the control channel to wake up its neighbors and the data channel to transmit the collected information. However, the transmission radius of the two channels are different. A multi-channel power management protocol for WSN is proposed in [16]. This protocol intends to solve the channel assignment problem and can avoid lots of collisions and retransmissions. An energy-efficient MAC protocol for WSN is proposed in [17]. To reduce the energy consumed by idle listening, each node will switch to PS mode periodically.

It is known that the WSN with regular topology can communicate more efficiently than the WSN with random topology [11]. To reduce the power consumed by transmission, we should adopt the WSN with regular topology, such as deploying WSN to buildings, bridges, space vehicles [1], and biomedical sensors [2]. Here, we propose several novel power management protocols for four different regular WSNs. The goal of our protocols is to let as many sensor nodes as possible switch to PS mode while still maintaining the connectivity of the network so that if any emergency occurs, the sensor node, which sense the event, may transmit this information to the base stations through the active sensor nodes without need to wake up any PS node. Besides, each sensor node should switch to PS mode in turn, so that the power consumption of each node can be balanced. Note that, when a sensor node switch to PS mode, it only turn off the power of its radio circuit. Therefore, it can still monitor the change of the environment. Our protocols work as follows: first, choose several different connected dominating sets [18, 19, 20] according to the network topology and assign an id to each of the connected dominating set, and then the nodes in each connected dominating set will switch to active mode to serve the other hosts according to which dominating set they belong to in a round robin manner. For example, if there are n connected dominating sets, and the connected dominating set's id of sensor node a is i. Host a shall switch to active mode in the ith time slot of each frame, where k is a nonnegative integer and each frame contains n time slots. In the other interval, host a will switch to PS mode if there is no message to transmit. In our power management protocols, each sensor node should belong to at least one connected dominating set and the same number of connected dominating sets so that the power consumption is nearly balanced. Simulation results and numerical analysis show that our power management protocols can greatly extend the lifetime of the network with a reasonable extra transmission delay.

The rest of this paper is organized as follow. Section 2 describes the system environments. Section 3 presents the novel power management protocols for four different network topologies. Numerical analysis is shown in Section 4. Simulation results are shown in section 5. Conclusions are made in Section 6.

Chapter 2

System Environments

We adopt the First Order Radio Model [13] 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:

$$E_{Tx}(k,d) = E_{elec} \times k + E_{amp} \times k \times d^2 \tag{2.1}$$

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

$$E_{Rx}(k) = E_{elec} \times k \tag{2.2}$$

According to equations 2.1 and 2.2, 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. 2.1), 2D mesh with 4 neighbors (Fig. 2.2), 2D mesh with 8 neighbors (Fig. 2.3) and 3D mesh with 6 neighbors (Fig. 2.4). In the four topologies, each node is assigned a unique id according to its relative location in the network. The ids in

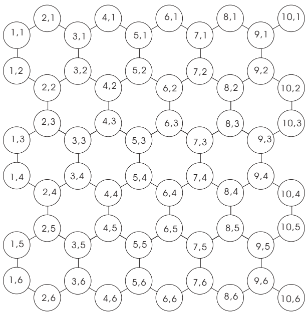


Figure 2.1: 2D mesh with 3 neighbors.

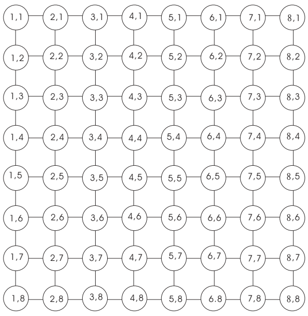


Figure 2.2: 2D mesh with 4 neighbors.

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 connected nodes. All the nodes in the WSN have the same number of neighboring nodes, except the nodes on the boarder.

We assume that the radio channel is symmetric, that the power required to transmit a message from any node A to node B is the same as the power required to transmit a message from node B to node A. There are 4 and 8 base stations located

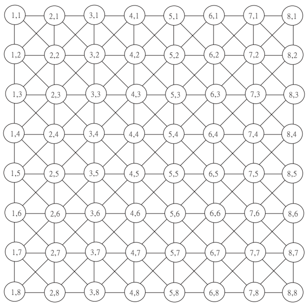


Figure 2.3: 2D mesh with 8 neighbors.

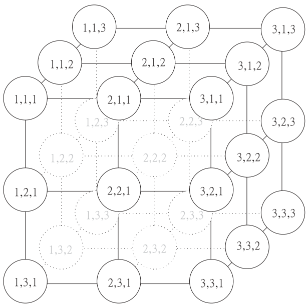


Figure 2.4: 3D mesh with 6 neighbors.

in the corners of the 2D and 3D WSNs, respectively. When a sensor node detects any emergency, it will turn on its radio circuit and transmit the sensed information through the active nodes to the base station.

Chapter 3

Power Management Protocols

The wireless sensor nodes have no plug-in power. Therefore, how to conserve the battery power of wireless sensor nodes so that we can extend the network lifetime is a critical issue for the WSNs. The best way to conserve power is to let the wireless sensor nodes switch to PS mode. When a wireless sensor node switches to PS mode, it shall turn off its radio circuit and keeps its sensor active, so that it can still do its duty. There are two goals that must be achieved when designing our power management protocols: first, every wireless sensor node should have the chance to switch to PS mode so that the power consumption can be balanced. Second, the wireless sensor nodes in active mode should be connected and dominate all the nodes in the network so that any sensed information can be transmitted to the base stations through the active nodes.

Our protocols work as follows: first, choose several different connected dominating sets according to the network topology and assign an id to each of the connected dominating set, and then the nodes in each connected dominating set will keep active to serve the other hosts based on the dominating set they belong to in a round robin manner. Note that, the union of all the connected dominating sets should equal to the set formed by all the sensor nodes in the WSN. Moreover, most of the sensor nodes shall belong to only one of the connected dominating set so that the power consumption is nearly balanced. To guarantee each node in the same connected dominating set sleeps and wakes up at about the same time, synchronization is necessary in our protocols. In the following, we first describe our synchronization protocol, and then we will show our power management protocols.

For the ease of describing our protocols, we assume that the size of the 2D mesh is $m \times n$, where m and n are positive integers. The node (x, y) is located in the xth column and yth row of the mesh, where $1 \leq x \leq m$ and $1 \leq y \leq n$. There are c different connected dominating sets and c time slots in each frame, the ith connected dominating set is denoted as CDS_i, the length of each time slot is T_a seconds, and the maximum clock drift between any two nodes in T_a seconds is Δt.

3.1 Synchronization

To guarantee each node in the same connected dominating set sleeps and wakes up at about the same time, we have to synchronize these nodes. However, global synchronization is not necessary in our power management protocol. Only the active node need to be synchronized. Our synchronization protocol works as follows: In the beginning, a designated base station broadcasts the synchronization message, which contains the timestamp (denoted as TS) of the base station, to its neighboring wireless sensor nodes. On receiving the synchronization message, the wireless sensor node adjusts its timestamp as $TS + T_{sy}$, where T_{sy} is the time required to broadcast a synchronization message to neighbors. After adjusting the timestamp, the nodes in active CDS will broadcast its own synchronization message, and the other nodes will switch to PS mode.

To tolerate the clock drift between the current active nodes and their successors, each active node should keep active until its successor takes over, so that we can

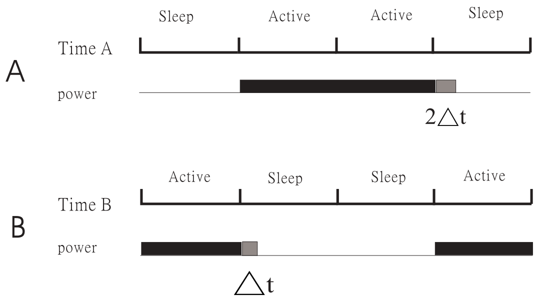


Figure 3.1: Extra active time to tolerate clock drift.

guarantee a seamless handover. Assume that the current active connected dominating set is CDS_i, the nodes in CDS_i should keep active for extra $S_{i \bmod c+1} \times \Delta t$ seconds in the ith time slot of each frame, where $S_{i \bmod c+1}$ is the maximum number of consecutive sleeping time slots of the nodes in $CDS_{i \bmod c+1}$ and the nodes in $CDS_{i \bmod c+1}$ are the successors of the nodes in CDS_i. For example in Fig. 3.1, host B needs to keep active for extra Δt seconds at the end of the first time slot because its successor A has slept for a time slot. Similarly, host A needs to keep active for extra $2\Delta t$ seconds at the end of the third time slot because its successor B has slept for two time slots.

Every time after the end of the ith time slot, where $1 \leq i \leq c$, the designated base station will broadcast its timestamp $S_i \times \Delta t$ seconds later and only the currently active nodes will adjust their timestamps and broadcast their synchronization message along the connected dominating set. To reduce the cost of synchronization, the base station need not to broadcast the synchronization message in every frame. The synchronization interval may be lengthened to k frames, where k is set according to the requirement of the clock accuracy. However, when the synchronization interval becomes longer, the clock drift problem becomes more serious and thus the extra active time becomes longer.

3.2 Power mode switch

The connected dominating sets are chosen according to the following guidelines: first, choose nodes from certain columns, rows or diagonals to form several different basic dominating sets. These basic dominating sets are the bases of the connected dominating sets. With the basic dominating sets, we can choose some nodes to join each basic dominating set, so that each basic dominating set can be connected and form one or several connected dominating sets.

When the connected dominating sets are chosen and the nodes in the current active connected dominating set are synchronized, each node switches its power mode according to the following rules:

R1 Any node that belongs to CDS_i shall wake up and serve the other nodes in the ith time slot of each frame.

R2 The other nodes that not belong to CDS_i and have no message to transmit will switch to PS mode.

R3 The nodes that belong to $CDS_{i \bmod c+1}$ are the successor of the nodes in CDS_i.

R4 If the node in CDS_i is going to sleep and still have messages to transmit, it will pass these messages to any of its neighbors in $CDS_{i \bmod c+1}$ and then switch to PS mode.

In the following subsections, we will show how we choose the connected dominating sets in four different WSN topologies.

3.3 2D Mesh with 4 Neighbors

In 2D mesh with 4 neighbors, each node can dominate 4 of its neighbors. Therefore, in the ideal case, only $\frac{1}{5}$ of the nodes need to be chosen as the members of the dominating set. However, only $\frac{1}{5}$ of the nodes in the dominating set are not enough to form a connected dominating set. To form a connected dominating set, two neighbors of the members in the dominating set also need to join the dominating set.

For the simplicity of chosen the connected dominating set, once a node becomes a member of the connected dominating set, the nodes in the same column (or the same row) will also become the members of the connected dominating set. As Fig. 3.2(a) shows, we can choose the nodes in columns $1, 4, 7, \ldots, 3k+1$, where $3k+1 \leq m$, to form the first basic dominating set(denoted as BDS_1). Similarly, as Fig. 3.2(b) shows, we can choose the nodes in columns $2, 5, 8, \ldots, 3k+2$, where $3k+2 \leq m$, to form the second basic dominating set(denoted as BDS_2). However, we will not choose the nodes in columns $3, 6, 9, \ldots, 3k+3$, where $3k+3 \leq m$, to form the third basic dominating set(denoted as BDS_3). If they become the third BDS, the nodes in the first column are not dominated by any nodes. Thus, nodes in the first column also need to join BDS_3. Then, the nodes in the first column need to keep active in BDS_1 and BDS_3 for every three time slots, which is not a good approach for power saving protocol. To balance the power consumption, the nodes in the $(3k+3)$th column will not become the third BDS, for $3k+3 \leq m$. Instead, we will choose the nodes in the $(3l+1)$th and $(3l+2)$th rows, where $l \geq 0$ and $3l+2 \leq n$ to form the third (BDS_3) and fourth (BDS_4) basic dominating sets as shown in Fig. 3.2 (c) and Fig. 3.2 (d). With the similar reason as the $(3k+3)$-th column, we will not choose the nodes in the $(3l+3)$-th row to form a basic dominating set, for $3l+3 \leq n$. The nodes in BDS_1, BDS_2, BDS_3 and BDS_4 will switch to active mode to serve other hosts in the $(4k+1)$th, $(4k+2)$th, $(4k+3)$th and $(4k+4)$th time slots of each frame, respectively, where k is an nonnegative integer.

Since BSD_1 and BSD_2 are not connected dominating sets, we need to choose a row to join BDS_1 and BDS_2 whenever any of them becomes active, so that the union of the basic dominating sets and the nodes in the chosen row can form one or several connected dominating sets. Similarly, we need to choose a column to join BDS_3 and BDS_4 whenever any of them becomes active. Since most of the nodes in the $(3k+3)$th column and $(3l+3)$th row do not belong to any of the four basic dominating sets, we will choose the nodes in the $(3l+3)$th row to join BDS_1 and BDS_2 and the nodes in $(3k+3)$th column to join BDS_3 and BDS_4. Therefore, the nodes in the $(6l+3)$th row will join BDS_1 in the $(4l+1)$th time slot and the nodes in the $(6l+6)$th row will join BDS_2 in the $(4l+2)$-th time slot. Similarly, the nodes in the $(6k+3)$th column will join BDS_3 in the $(4k+3)$th time slot and the nodes in the $(6k+6)$th column will join BDS_4 in the $(4k+4)$-th time slot.

Fig. 3.2 shows the power mode switch with four connected dominating sets in an 8×8 2D mesh with 4 neighbors. We choose the nodes in columns 1, 4 and 7 to form BDS_1, the nodes in columns 2, 5, and 8 to form BDS_2, the nodes in rows 1, 4 and 7 to form BDS_3, and the nodes in rows 2, 5, and 8 to from BDS_4. The union of BDS_1 and the nodes in row 3 form CDS_1, the union of BDS_2 and the nodes in row 6 form CDS_2, the union of BDS_3 and the nodes in column 3 form CDS_3, and the union of BDS_4 and the nodes in column 6 form CDS_4. The frame length is $4 \times T_a$ and the nodes in CDS_1, CDS_2, CDS_3, and CDS_4 will switch to active mode to serve other hosts in the first, second, third, and fourth time slots of each frame, respectively.

Note that, the protocol proposed above can work properly only when (m mod 3) = 2 and (n mod 3) = 2. When (m mod 3) = 1 and the nodes in BDS_2 wake up to serve other hosts, the nodes in column m will not be dominated by any node.

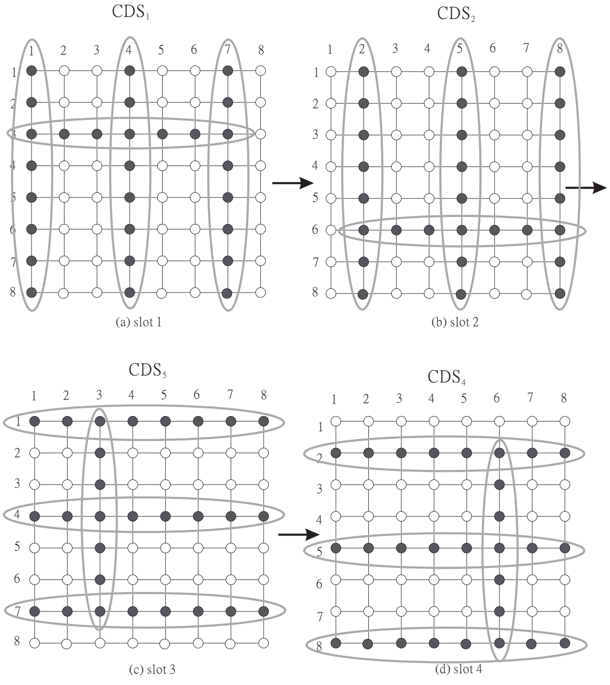


Figure 3.2: The power mode switch with four connected dominating sets in an 8 × 8 2D mesh with 4 neighbors.

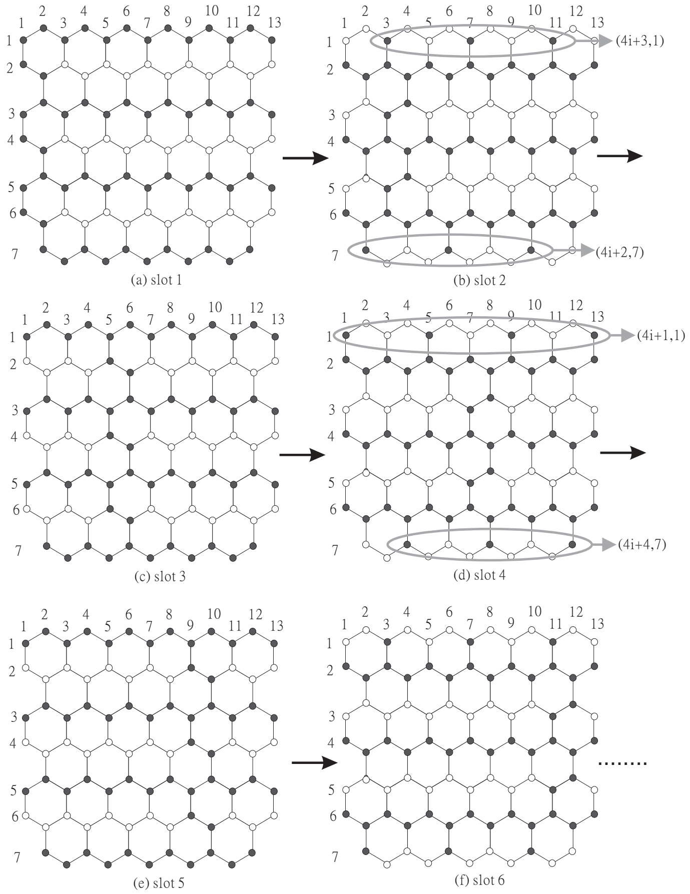
Therefore, the nodes in column m also need to join BDS_2 when $(m \bmod 3) = 1$. When $(m \bmod 3) = 0$ and the nodes in BDS_1 wake up to serve other hosts, the nodes in column m will not be dominated by any node. Therefore, the nodes in column m also need to join BDS_1 when $(m \bmod 3) = 0$. Similarly, when $(n \bmod 3) = 1$ and the nodes in BDS_4 become active, the nodes in row n also need to join BDS_4. When $(n \bmod 3) = 0$ and the nodes in BDS_3 become active, the nodes in row n also need to join BDS_3. Overall, in case of $(m \bmod 3) = 2$ and $(n \bmod 3) = 2$, no extra nodes need to be active and thus conserve most power.

3.4 2D Mesh with 3 Neighbors

As Fig. 2.1 shows, in 2D mesh with 3 neighbors, the nodes in the ith row can cover half of the nodes in the $(i-1)$th and $(i+1)$th rows, respectively. Therefore, as shown in Fig. 3.3(a) and Fig. 3.3(b), we can choose the nodes in the odd and even rows to form the first (denoted as BDS_1) and second (denoted as BDS_2) basic dominating sets, respectively. For the ease of synchronization and balancing power consumption, the nodes in BDS_1 and BDS_2 will switch to active mode to serve other hosts in the $(2k+1)$th and $(2k+2)$th time slots of each frame, respectively, where k is an nonnegative integer. Since BSD_1 and BSD_2 are not connected dominating sets, we need to choose two consecutive columns to join BDS_1 and BDS_2 whenever any of them becomes active, so that the union of the basic dominating sets and the nodes in the chosen columns can form one or several connected dominating sets. The nodes in columns $4i+1$ and $4i+2$, where $i \geq 0$ and $4i+2 \leq m$, will join BDS_1 in the $(2i+1)$th time slot of each frame. Similarly, the nodes in columns $4i+3$ and $4i+4$, where $i \geq 0$ and $4i+4 \leq m$, will join BDS_2 in the $(2i+2)$th time slot of each frame.

When n is an odd number, the nodes in BDS_1 can dominate all the nodes, but the nodes in BDS_2 can not dominate nodes $(x_1, 1)$ and (x_2, n), where x_1 is an even number and x_2 is an odd number. Therefore, we need to choose some extra nodes to join BDS_2 so that every node can be dominated by BDS_2. In the $(4k+2)$th time slot, nodes $(4i+3, 1)$ and $(4i+2, n)$ will join BDS_2 as shown in Fig. 3.3(b). To balance power consumption, in the $(4k+4)$th time slot, nodes $(4i+1, 1)$ and $(4i+4, n)$ will join BDS_2 as shown in Fig. 3.3(d). When n is an even number, the nodes in BDS_1 can not dominate node (x_1, n) and the nodes in BDS_2 can not dominate node $(x_2, 1)$. Therefore, we need to choose some extra nodes to join BDS_1 and BDS_2 so that every node can be dominated by BDS_1 and BDS_2. In the $(4k+1)$th and $(4k+3)$th time slots, nodes $(4i+3, n)$ and $(4i+1, n)$ will join BDS_1, respectively. Similarly, in the $(4k+2)$th and $(4k+4)$th time slots, nodes $(4i+3, 1)$ and $(4i+1, 1)$ will join BDS_2, respectively.

Fig. 3.3 shows the power mode switch in a 13 × 7 2D mesh with 3 neighbors. We



(a) slot 1 (b) slot 2 (c) slot 3 (d) slot 4 (e) slot 5 (f) slot 6

Figure 3.3: The power mode switch in a 13 × 7 2D mesh with 3 neighbors.

choose the nodes in the odd rows to form BDS_1 and the nodes in the even rows to form BDS_2. The union of BDS_1 and the nodes in columns 1 and 2 form CDS_1, the union of BDS_2 and the nodes in columns 3 and 4 form CDS_2, the union of BDS_1 and the nodes in columns 5 and 6 form CDS_3, the union of BDS_2 and the nodes in columns 7 and 8 form CDS_4, and so on. Notably, since m and n are both odd numbers, we will choose the nodes in BDS_1 and columns 2 and 3 to form CDS_7 and the nodes in BDS_2 and columns 4 and 5 to form CDS_8 so that the nodes in column 13 will have the chance to serve other hosts and thus the power consumption can be balanced. Overall, there will be total twelve different connected dominating sets.

3.5 2D Mesh with 8 Neighbors

In 2D mesh with 8 neighbors, we may apply the same rules as in 2D mesh with 4 neighbors to choose the dominating sets. However, as Fig. 3.4 shows, if we choose the nodes in columns 1, 4, 7, 10, and 13 to form the basic dominating set, the set will contain 65 nodes. On the other hand, if we choose the nodes (x, y), where $x + y = 4k + 2$ and $1 \leq x, y \leq 13$, to form the basic dominating set, the set will contain only 43 nodes. Therefore, we will choose the nodes (x_1, y_1), (x_2, y_2), (x_3, y_3), and (x_4, y_4), where $x_i + y_i = 4k + 1 + i$, $1 \leq x_i \leq m$, $1 \leq y_i \leq n$, and $1 \leq i \leq 4$, to form the first(denoted as BDS_1), second(denoted as BDS_2), third(denoted as BDS_3), and fourth basic dominating sets(denoted as BDS_4), respectively, as shown in Fig. 3.4. Since the four basic dominating sets are not connected dominating sets, we will choose the nodes (x, x) in diagonal A, $(x, x+1)$ in diagonal B, or $(x+1, x)$ in diagonal C to connect the separated diagonals in the four basic dominating sets in turn as shown in Fig. 3.5. We can choose the nodes in BDS_1 and nodes in diagonals A, B, or C to form CDS_1, CDS_2, and CDS_3, respectively. Similarly, we can choose the nodes in BDS_2 and nodes in diagonals A, B, or C to form CDS_4, CDS_5, and CDS_6, respectively. Since there are four different basic dominating sets and three different diagonals to connect the basic dominating sets in turn. There are twelve different connected dominating sets.

Note that, when $m \neq n$, the nodes in diagonals A, B, or C can not connect all the nodes in the basic dominating sets. When $m > n$, we choose the nodes (x, x) and $(n - 1 + k, n - 1)$ to form diagonal A, the nodes $(x, x + 1)$ and $(n + k, n)$ to form diagonal B, and the nodes $(k + 1, 1)$ and $(m - n + 1 + x, x)$ to form diagonal C, where $1 \leq x \leq n - 1$ and $1 \leq k \leq m - n$. Figure 3.6 shows how we choose the A, B, and C diagonals in a 13×7 2D mesh with 8 neighbors. Similarly, when

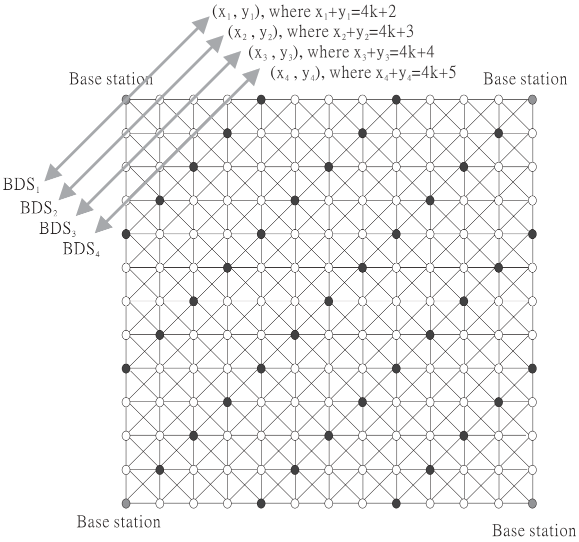


Figure 3.4: The basic dominating sets in 2D mesh with 8 neighbors.

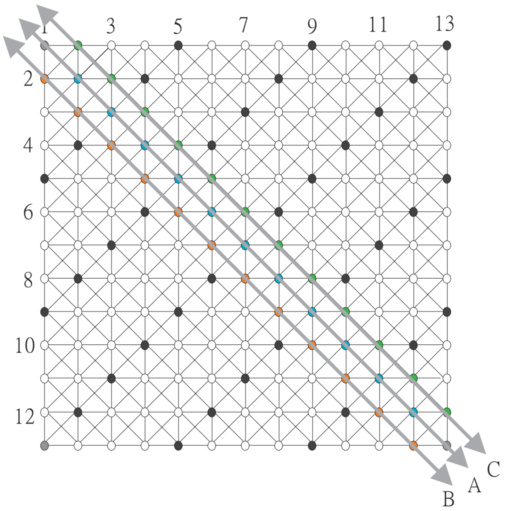


Figure 3.5: The power mode switch in a 13×13 2D mesh with 8 neighbors.

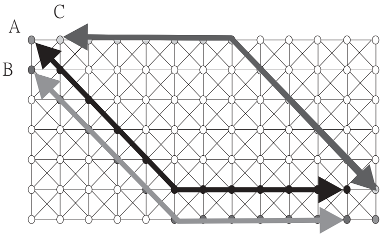


Figure 3.6: Choose the A, B, and C diagonals in a 13×7 2D mesh with 8 neighbors.

$m < n$, we choose the nodes (x, x) and $(m-1, m-1+k)$ to form diagonal A, the nodes $(x+1, x)$ and $(m, m+k)$ to form diagonal C, and the nodes $(1, k+1)$ and $(x, n-m+1+x)$ to form diagonal B, where $1 \leq x \leq m-1$ and $1 \leq k \leq n-m$.

3.6 3D Mesh with 6 Neighbors

Since the 3D mesh with 6 neighbors consists of several planes, we will first show how to choose the basic dominating set in a plane, and then we will show how to connect these basic dominating sets in different planes. Assume that the size of a 3D mesh with 6 neighbors is $p \times q \times r$, where p, q, and r are positive integers. We can recursively choose the dominating nodes in a plane according to the following rules.

R5 If node (x, y, z) is a dominating node then nodes $(x-2, y-1, z)$, $(x-1, y+2, z)$, $(x+1, y-2, z)$ and $(x+2, y+1, z)$ will also be chosen as the dominating nodes.

As Fig. 3.7 shows, if node $(6, 8, k-1)$ is chosen as the dominating node, nodes $(4, 7, k-1)$, $(5, 10, k-1)$, $(7, 6, k-1)$, and $(8, 9, k-1)$ will also be chosen as the dominating nodes. However, chosen dominating nodes according to $R5$ can not dominate all the nodes in the plane. There are still some nodes in the border not dominated by any of the dominating nodes. Therefore, the node in the border, that is not dominated by any other node, will also be chosen as the dominating node. Fig. 3.7 shows how we choose the basic dominating set in a plane. The nodes in

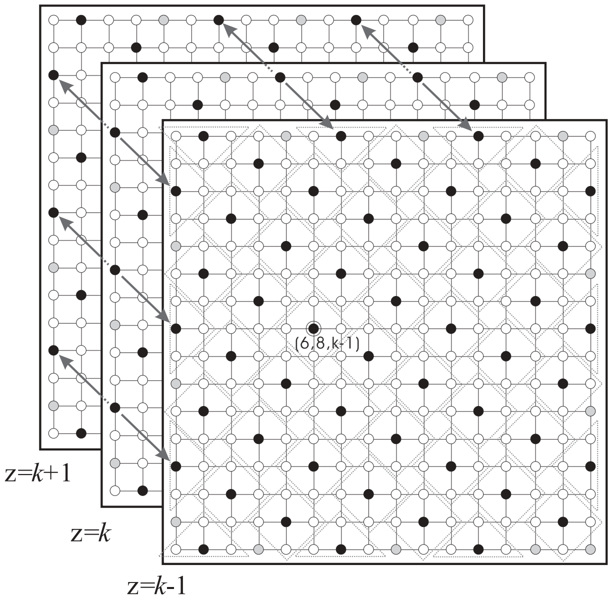


Figure 3.7: The basic dominating set in a plane and its connection to other plane through the z axis

black color are the dominating nodes chosen according to R5; the nodes in gray color are the additional dominating nodes in the border. For the ease of chosen dominating nodes and connected the dominating nodes in other planes, we also choose the dominating nodes according to the following rules.

R6 If node (x, y, z) is a dominating node then the node (x, y, w) is also chosen as the dominating node, where $1 \leq w \leq r$.

When node (x, y, z) is chosen as the basic dominating node in BDS_1, we may choose nodes $(x+1, y, z)$, $(x, y+1, z)$, $(x-1, y, z)$, and $(x, y-1, z)$ as the basic dominating nodes in BDS_2, BDS_3, BDS_4, and BDS_5, respectively. According to rule R5 and R6, we can use the five basic dominating nodes to form five different basic dominating sets. The nodes in BDS_1, BDS_2, BDS_3, BDS_4, and BDS_5 will switch to active mode to serve other hosts in the $(5k+1)$th, $(5k+2)$th, $(5k+3)$th, $(5k+4)$th and $(5k+5)$th time slots of each frame, respectively, where k is an nonnegative integer. Since the dominating nodes in the same plane are not connected, we will choose an XY plane to join the basic dominating set in each time slot so that the nodes in the same basic dominating set can be connected. The nodes in the $(5k+i)$th XY plane will become active and join BDS_i in the $(5k+i)$th time slot of each frame, where $1 \leq i \leq 5$ and $1 \leq 5k+i \leq r$.

Choosing only one plane to join the basic dominating set will cause lots of extra transmission delay, because most of the sensed information need to be transmitted to the only one active plane, and then transmitted to the corner of the active plane, and finally transmitted to the base station. To reduce the extra transmission delay, we may choose an additional plane to join the connected dominating set in each time slot. When the ith XY plane becomes active, the $((i + \lceil r/2 \rceil) \bmod r + 1)$th XY plane will also become active and thus reduces the distances between the sender and the active plane and between the active plane and the base station. However, this approach will increase the ratio of active nodes in each time slot. To conserve energy, not all the nodes in the chosen plane need to join the connected dominating set. Instead, we will choose the connected dominating set in the chosen plane according to the rules of 2D mesh with 4 neighbors and R5. To balance the power consumption of each plane, we will also choose the connected dominating sets from the XZ and YZ planes with the similar manners.

Chapter 4

Performance Analysis

In this section, we will evaluate the ratio of active nodes for our power management protocols. The ratio of active nodes is defined as the average number of active nodes in a time slot over the total number of nodes in the WSN. With the ratio of active nodes, we can estimate the total amount of power that can be conserved in the WSN. The lower the ratio is the better the performance is. To show the efficiency of our protocols, we will compare the performance of our protocols with that of the ideal case.

In 2D mesh with 4 neighbors, each node can dominate 4 neighbors. Therefore, without considering connection, only $\frac{1}{5}$ of the nodes need to be chosen as the members of the dominating set. However, only $\frac{1}{5}$ of the nodes in the dominating set are not enough to form a connected dominating set. To form a connected dominating set, two neighbors of the members in the dominating set also need to join the dominating set. Therefore, each dominating node can only dominate two non-dominating nodes. In the ideal case, at least $\frac{1}{3}$ of the nodes need to join the connected dominating set. In our protocol, since $\frac{1}{3}$ of the columns (or rows) will be chosen to join the connected dominating set, the ratio of active nodes of our protocol is quite close to the ideal case, except that we need to pick an extra row (or column) to join the connected dominating set and connect the separated columns (or rows).

Similarly, in 2D mesh with 3 neighbors, each node can dominate 3 neighbors. When considering connection, two neighbors of the members in the dominating set also need to join the dominating set. Therefore, each dominating node can only dominate a non-dominating node. In the ideal case, at least $\frac{1}{2}$ of the nodes need to join the connected dominating set. In our protocol, since $\frac{1}{2}$ of the rows will be chosen to join the connected dominating set, the ratio of active nodes of our protocol is quite close to the ideal case, except that we need to pick two extra columns to join the connected dominating set and connect the separated rows.

In 2D mesh with 8 neighbors, each node can dominate 8 neighbors. When considering connection, two neighbors of the members in the dominating set also need to join the dominating set. Therefore, each dominating node can dominate six non-dominating nodes. However, as shown in Fig. 3.4, each of the non-dominating nodes is dominated by two dominating nodes. Therefore, in average, each dominating node can dominate only three non-dominating nodes. In the ideal case, at least $\frac{1}{4}$ of the nodes need to join the connected dominating set. In our protocol, since $\frac{1}{4}$ of the diagonals will be chosen to join the connected dominating set, the ratio of active nodes of our protocol is quite close to the ideal case, except that we need to pick an extra diagonal to join the connected dominating set and connect the separated diagonals.

In 3D mesh with 6 neighbors, each node can dominate 6 nodes. However, as Fig. 3.7 shows, if a node, whose coordinate is (i, j, k), is in the dominating set, nodes $(i, j, k+1)$ and $(i, j, k-1)$ will also be in the dominating set, otherwise, the dominating nodes can not connect to the dominating nodes in the other planes. Therefore, each node can dominate only 4 nodes. In the ideal case, at least $\frac{1}{5}$ of the nodes need to join the connected dominating set. The ratio of active nodes of our protocol is quite close to the ideal case, except that we need to pick an extra plane to join the connected dominating set. According to the above analysis, the ratio of active nodes of our protocols is quite close to that of the ideal case, which indicates that our protocols are near optimal and can conserve lots of energy.

Chapter 5

Simulation Results

To evaluate the performance of the proposed power management protocols, we have developed a simulator using C. The distance between each sensor node is 10 meter, the transmission rate is 8K bits/sec, the battery power of each sensor node is 10 J, the packet size is 1K bytes, the length of a time slot is 10 seconds, the synchronization message is transmitted every 10 seconds. We will randomly choose a sensor node to transmit a packet to the base station every 10 seconds. We use equations 2.1 and 2.2 mentioned in Section 2 to calculate the consumed power of each transmission. To show the efficiency of our protocols, we will compare the performance of our protocols with that of the always active scheme. In the always active scheme, every node in the WSN shall keep active all the time until it run out of its battery.

Three performance metrics are used in the simulations:

- the ratio of active nodes: the average number of active nodes in a time slot over the total number of nodes in the WSN. This metric represents the total consumed power of our protocol over that of the always active scheme.
- the network life time: the time from the WSN starts operation to the time the first sensor node runs out of its battery.
- transmission delay: the time from the sensor start transmits the sensed infor-

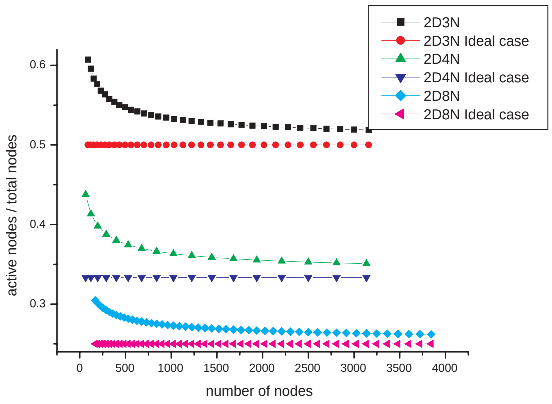


Figure 5.1: The ratio of active nodes for the three 2D WSN topologies.

mation to the time a base station receive the information. Here, we use hop counts to represent the transmission delay.

For the ease of demonstrating the simulation results, the power management protocols of 2D mesh with 3 neighbors, 2D mesh with 4 neighbors, 2D mesh with 8 neighbors, 3D mesh with 6 neighbors and one active plane, and 3D mesh with 6 neighbors and two active planes are denoted as $2D3N$, $2D4N$, $2D8N$, $3D6N(1)$, and $3D6N(2)$, respectively.

Fig. 5.1 and 5.2 shows the ratio of active nodes for the 2D and 3D WSN topologies, respectively. Compared with the always active scheme, our power management protocols consume only $\frac{1}{2}$ to $\frac{1}{5}$ of the total power. Among the three 2D WSN topologies, $2D8N$ has the lowest ratio of active nodes, which indicates that it can conserve most power. The ratio of active nodes of $3D6N(2)$ is slightly higher than that of $3D6N(1)$ because $3D6N(2)$ has an extra active plane. As the number of nodes increased, the ratios of active nodes of our protocols become lower and approach the ratio of the ideal case mentioned in Section 4. It is because the ratio of extra active nodes becomes lower as the number of nodes increased.

The network life time of the always active scheme and our protocols are shown in

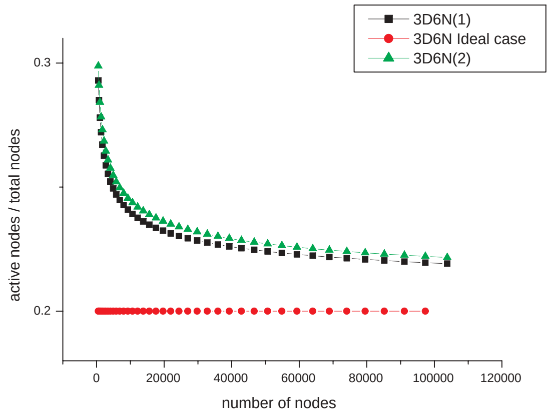


Figure 5.2: The ratio of active nodes for the 3D WSN topology.

Table 5.1: The network life time (minutes) of the always active scheme and our protocols

Topology Number of nodes	2D3N 559	2D4N 529	2D8N 529	3D6N(1) 1000	3D6N(2) 1000
Always active	350	323	246	280	280
Power saving	458	641	510	449	434
Improved rate	31%	98%	107%	60%	55%

Table 5.1. As we can see that our protocols can greatly extend the network life time. In the best case, our protocol can extend over 100% of the network life time. Among the five protocols, $2D8N$ performs the best because its first exhausted node's active ratio (the active ratio is defined as the total active time over the total operation time) is low. $2D4N$ also performs quite well. $2D3N$ performs the worst because its first exhausted node's active ratio is the highest.

When the message is transmitted along the connected dominating set to the base station, it may not go through the shortest path. Therefore, our protocols may cause some extra transmission delays. As Table 5.2 shows, our protocols do cause some extra transmission delay. In the worst case, it will cause 53% extra transmission delay. Among the five protocols, $2D8N$ performs the best. In average, it causes only 7.6% extra transmission delay, which indicates that the message can be transmitted

Table 5.2: The transmission delay (hops) of the always active scheme and our protocols

Topology	2D3N	2D4N	2D8N	3D6N(1)	3D6N(2)
number of nodes	3160	3136	3136	3375	3375
Always active	34.3	27.2	18.5	11.25	11.25
Power saving	42.3	30.2	19.9	17.25	14.3
Extra delay rate	23%	11%	7.6%	53%	27%

along the shortest path in most cases. $3D6N(1)$ causes the most extra transmission delay because most of the messages need to be transmitted to the only one active plane, and then transmitted to the corner of the active plane, and finally transmitted to the base station. $3D6N(2)$ performs much better than $3D6N(1)$ because the distances between the sender and the active plane and between the active plane and the base station are reduced and thus reduces the extra transmission delay.

Overall, $2D8N$ performs the best. It has the longest network life time and causes the least extra transmission delay. Besides, its ratio of active nodes is only about $\frac{1}{4}$.

Chapter 6

Conclusions

In this paper, we have proposed several power management protocols based on the idea of connected dominating set for regular WSNs. We try to find several different small size connected dominating sets for each of the four WSN topologies. The nodes in each of the different connected dominating set will switch to active mode in turn to serve other nodes in power saving mode and thus conserve and balance the power of each node. Numerical analysis and simulation results show that our protocols can conserve lots of power and greatly extend the network life time with reasonable transmission delays. In the best case, our protocols consume about $\frac{1}{5}$ of the total power of the always active scheme and extend over 100% of the network life time. Besides, our protocols cause only 7.6% to 53% extra transmission delays. Among the four WSN topologies, 2D mesh with 8 neighbors performs the best. It has the longest network life time and causes the least extra transmission delay. Besides, its ratio of active nodes is only about $\frac{1}{4}$.

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