

Essential Topics on Constructing WCDS-based Virtual Backbone in Wireless Sensor/Mesh Networks

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Received 2013

ABSTRACT

Clustering or connected dominating set (CDS) both approaches can establish a virtual backbone (VB) in wireless sensor networks (WSNs) or wireless mesh networks (WMNs). Each cluster consisting of a cluster head (CH) and its neighboring nodes can form a dominating set. After some bridging nodes were selected, cluster heads (CHs) connected through these bridging nodes naturally formed a CDS. Although CDS provides obvious backbone architecture, however, the number of cluster heads and bridging nodes may be too large, this may cause the loss of advantages of virtual backbone. When we effectively reduce their numbers, more effectively WCDS (Weakly Connected Dominating Set) can be fine-tuned out. Some essential topics on constructing WCDS-based VB in WSN/WMN are discussed in this paper. From the point of view of three different protocol layers, including network (NWK) layer, MAC layer, and physical (PHY) layer, we explore their cross-layer research topics and design algorithms. For NWK layer, area-based WCDS algorithms and routing strategies including via VB and not via VB are discussed. For MAC layer, a WCDS-based energy-efficient MAC protocol is presented. For PHY layer, battery-aware alternative VB selections and sensor nodes with different transmission ranges are addressed.

Keywords: Weakly Connected Dominating Set; Wireless Sensor/Mesh Networks; Virtual Backbone; Cross-Layer Design

1. Introduction

The main advantages of establishing virtual backbones in WSN/WMN are as follows. First, it can reduce the heavy exchange of routing control messages, to avoid the expansion of broadcasting storm problem. Because that all routing control messages exchanged need only be carried out on the virtual backbone. Second, it can solve the problem of network scalability. A large number of nodes in a sensor network may have a small but beautiful virtual backbone. Even if the new node is added, it will not be that great an impact on the virtual backbone. Third, when the event occurs, all sensing nodes of this event will send data to the CH, and the CH will filter the excess information to avoid repeated transmissions to reduce the amount of communication.

Since finding out CDS/WCDS is a NP-hard problem, the identification of CDS/WCDS is not unique. How to effectively identify WCDS, and a fair assessment of the performance between the different WCDS algorithms, is an important issue. Several WCDS algorithms, including centralized and distributed two classes, were proposed in [1]. In [2], WSN/WMN is first divided into several areas, and then each area builds its own WCDS. So that each area will have a smaller size of WCDS and has a smaller

Control&management's overhead. The concept of CDS/WCDS with bounded diameters has been proposed in [3]. The diameter of a CDS/WCDS is defined as the longest path length that could be between any two CHs on the VB. It has been shown in [3] that nodes transmission ranges will affect the efficiency of WCDS algorithms in terms of the resulting WCDS size and the value of ABPL (Average Backbone Path Length). In [4-5], the concepts of disjoint CDSs/WCDSs were proposed. That is, VB can alternate between two or more disjoint CDSs/WCDSs to avoid more serious power consumption of the CHs and the bridging nodes on the VB. If we do not plan for replacement, it may cause the shortening of the life expectancy of these nodes. In [4] the solution to the CDP (Connected Domatic Partition) problem in graph theory is used to identify the disjoint groups of CDSs/WCDSs. In addition, the battery recharge recovery principle was mentioned in [4] for periodically rotation between the disjoint CDSs/WCDSs, to extend the life-time of VB nodes. The authors of [5] proposed a power-aware disjoint CDSs concept that the VB nodes participating replacement their power level must be above a certain threshold level. In [6,7] the authors proposed CDS/WCDS localized formation algorithms, which have a

great difference to the centralized algorithms proposed in [1,2,8,9]. Centralized algorithms require the coordinator to use of the entire network topology to form the WCDS. Localized formation algorithms use the interconnection information between neighboring nodes to identify the most suitable dominating node in local. These selected dominating nodes are then used to form the CDS/WCDS. In [8], the authors use the entire network topology to establish the DAT (Data Aggregation Tree) for all nodes, and then use it to form the WCDS. In [9] all nodes together are used for WCDS formation, and then cut-vertices are identified from the WCDS created. Because cut-vertex will cause leaf block and cut-vertex failure will cause greater network failure. The concept of the 2-Connected virtual backbone was adopted in [9] to increase the number of dominating nodes in the WCDS, to eliminate the problem of the cut-vertex. In [10-12], CDS/WCDS-based routing algorithms were proposed. It was pointed out in [10] that not all messages must make use of the CDS/WCDS according to the specified routing cost constraints, especially short-distance transmission path is even more so. The use of establishing routing table for each node was proposed in [11]. The contents of the routing table include its dominating node, its one-hop neighbors, its neighbors' distances to sink, and its neighbors' remaining energies. Routing path is set according to the routing information stored in the routing tables. In [12], power-aware alternative path selection was used in addition to the adoption of WCDS-based shortest path routing. When the remaining power of nodes on the primary path is insufficient, then shift to go alternative path. In [13], CDS/WCDS algorithm using UBG (Unit Ball Graphs) concept was proposed in the three-dimensional environments, as opposed to the general use of UDG (Unit Disk Graphs) in the two-dimensional environments. In [14], UDG radius with different sizes was proposed to finding out CDS/WCDS. That is, nodes with different transmission ranges were considered. In [15], the authors proposed algorithm to finding out load-balanced VB in WSNs.

In this paper, some essential topics on constructing WCDS-based VB in WSN/WMN are addressed. From the point of view of three different protocol layers, including NWK (network) layer, MAC layer, and PHY (physical) layer, we explore their cross-layer research topics and algorithms. The rest of the paper is structured as follows. Section 2 discusses the NWK layer issues of WCDS-based algorithms, including the construction of VB, routing strategies and self-configuration. In section 3, a WCDS-based energy-efficient MAC protocol is presented. Section 4 discusses the PHY layer issues related to WCDS-based VB construction, including battery-aware alternative VB selections, nodes with different transmission ranges. Section 5 concludes the contributions of the

paper.

2. NWK Layer Related Issues

2.1. WCDS Algorithms

In the WCDS algorithms proposed in [1], a piece is used to specify a particular sub-configuration diagram; a white piece refers to the piece that contains only one white node; a black piece is a black node with all its adjacent one-hop gray nodes. As shown in **Figure 1**, node 1, 2, 3 each forms a black piece, and each of the remaining white nodes forms a white piece. In this paper, we adapted two WCDS algorithms proposed in [1] to use by the following subject matter discussed. The first algorithm we called it *Maximum-Neighbor* (MN) algorithm. The second algorithm we called it *Two-Hop Maximum-Neighbor* (2H-MN) algorithm.

Maximum-Neighbor algorithm:

(Using **Figure 1** as an example)

Step 1: Initially all nodes are colored in white.

Step 2: Find the node with the maximum number of one-hop adjacent nodes; set this node to be the starting point and be the first chosen CH labeled with 1 (colored in black); and then marked all its one-hop neighboring nodes in gray.

Step 3: Find the node from the remaining white nodes with the maximum number of one-hop adjacent nodes, and set it to be the next chosen CH, i.e., node 2 in **Figure 1**; then marked all its one-hop neighboring nodes in gray.

Step 4: Repeat step 3 to find the third CH; i.e., node 3.

(Now, three small black pieces including CH1, CH2 and CH3 are combined into one large black piece, and there have two white pieces left. Among the remaining white nodes, if there has more than one that has the same maximum number of one-hop adjacent nodes, then choose the one that can merge most pieces as the CH.)

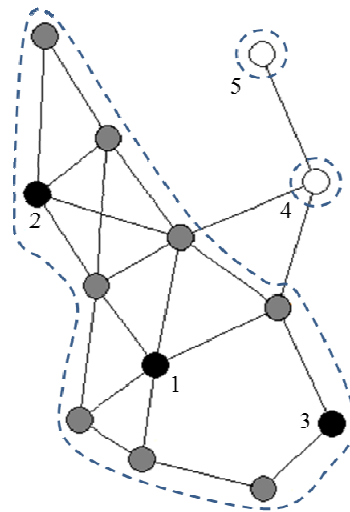


Figure 1. A snapshot of pieces in WCDS algorithms.

Step 5: Choose node 4 as the CH, and stop the algorithm.

Two-Hop Maximum-Neighbor (2H-MN) algorithm:
(Using **Figure 2** as an example)

Step 1: Initially all nodes are colored in white.

Step 2: Randomly choose a node as the first CH, i.e., CH1, and labeled it with 1 (colored in black); and then marked all its one-hop neighboring nodes in gray.

Step 3: Find the node from the CH1's two-hop neighboring nodes which has the maximum number of one-hop adjacent nodes, and set it to be the next chosen CH, i.e., node 2 in **Figure 2**; then marked all its one-hop neighboring nodes in gray.

Step 4: For all chosen CHs, find the node from their two-hop neighboring nodes which has the maximum number of one-hop adjacent nodes, and set it to be the next chosen CH; then marked all its one-hop neighboring nodes in gray. So on and so forth until all white nodes are marked either in black or gray.

In the example shown in **Figure 2**, the repetitions of step 4 will produce node 3 and node 4 as new CHs, and finally choose node 6 as the last CH and ending the algorithm. However, node 6 in **Figure 2** is a leaf node, and it is trivial to select a leaf node to be a CH. So the algorithm chooses node 5 as a CH and marked node 6 in gray. This is an exceptional case.

This paper combines the area-based concept proposed in [2] with the MN and 2H-MN algorithms to form the following two area-based WCDS algorithms: *Area-based MN algorithm* and *Area-based 2 H-MN algorithms*. Shown in **Figures 3** and **4** are two examples used to explain how to construct WCDS-based VB by using these two area-based WCDS algorithms, respectively. Both examples use the same sensor nodes deployment. Fifty nodes are randomly deployed in a 5 by 5 squared area. All nodes have the same transmission radius 0.89.

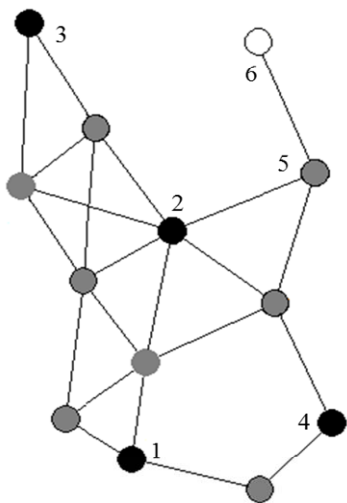


Figure 2. A snapshot of the 2H-MN algorithm.

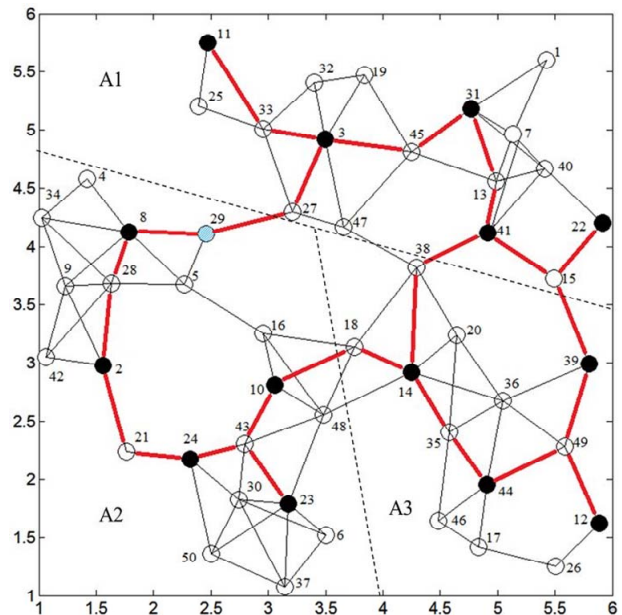


Figure 3. An example of the area-based MN algorithm.

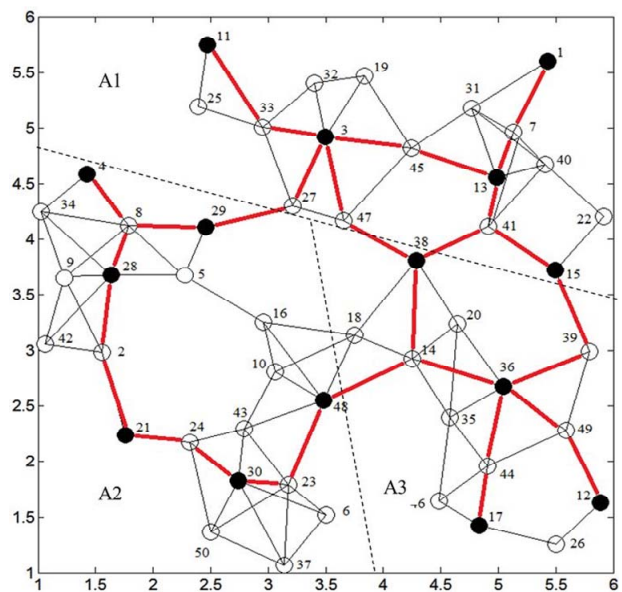


Figure 4. An example of the area-based 2H-MN algorithm.

Area-based MN algorithm:

(Using **Figure 3** as an example)

Step 1: Select Root-CHs and partitions the whole area into sub-areas according to the number of selected Root-CHs. The selected Root-CHs must own the most one-hop adjacent nodes. (Of course, the locations of the selected Root-CHs may not suitable for partitioning the whole areas. In addition, to draw boundaries between sub-areas is a difficult problem that have to be manipulated by the network organizer or people.) In **Figure 3**, nodes 3, 8, 44 are selected as the Root-CHs, and three sub-areas A1, A2, and A3 are built accordingly.

Step 2: For each sub-area, use MN algorithm to construct its respective WCDS. For example, nodes 2, 10, 23, and 24 are selected as CHs in area A2, as shown in **Figure 3**.

Step 3: On the border between any two adjacent areas, border nodes are supplemented for linking two adjacent WCDSs. For example, node 29 is selected as the border node between A1 and A2, as shown in **Figure 3**.

Area-based 2H-MN algorithm:

(Using **Figure 4** as an example)

All steps are the same as *Area-based MN algorithm*, except that 2H-MN algorithm is used to construct the respective WCDS for each sub-area.

WCDS-based VBs constructed for both cases are drawn by the bolded lines marked in red. The calculated values of ABPL are 5.98 and 5.33 for the two VBs shown in **Figures 3** and **4**, respectively. This indicates that the VB shown in **Figure 4** is more efficient than that shown in **Figure 3** in some sense.

2.2. WCDS-based VB Routing Strategies

It was pointed out in [10] that not all messages must make use of the CDS/WCDS-based VB according to the specified routing cost constraints, especially short distance transmission path is even more so. In this paper, we suggest that the routing paths can be classified into via virtual backbone and not via virtual backbone two types, in order to increase the performance efficiency of WCDS-based routing strategy. The routing paths that are not going through VB are especially suitable for short distance transmissions. If the shortest path length between a pair of communicating nodes is less than two or three hops, then not via VB routing strategy should be considered. On the contrary, if the path length is larger than three hops then we suggest that the routing path should go via VB. Shown in **Figure 5** is an example of WCDS-based VB, where nodes 1, 7, 8, 9 are CHs. Using node 1 (CH1) as the center, its one-hop neighboring nodes are 2, 3, 4, 5; and its two-hop neighboring nodes are 6, 7, 8, 9. Node 10 is within its three-hop range. If we assume that node 5 wants to communicate with node 10, the best route selected is 5-1-3-9-10, which has to go through the VB. But if we assume that node 2 wants to communicate with node 10, the best route selected is 2-6-10, which needs not to go through the VB. The use of establishing routing table for each node was proposed in [11]. The contents of the routing table include: its dominating node, its one-hop neighbors, its neighbors' distances to sink, and its neighbors' remaining energies. Routing path is set according to the routing information stored in the routing tables. Here we suggest that the routing table for each node should also include its two-hop or even three-hop neighbors. So that node 2 knows that node 10 is its two-hop neighbor and the shortest

routing path is 2-6-10 and should not go via VB.

2.3. Self-Configuration WCDS Algorithms

Because the virtual backbone network brings together most of the traffic on the network, CHs and bridging nodes on the backbone network, compared to the other sensor nodes on the network, will inevitably consume more power. The design of a WCDS algorithm with self-configuration capability is important. The WCDS algorithm should be able to start by its own, when the remaining power of the CH and its affiliated bridging nodes below some thresholds. New CH and its affiliated bridging nodes need to be dynamically selected to extend the life cycle of wireless sensor/mesh networks. In [4-5], the concepts of disjoint CDSs/WCDSs were proposed. That is, the selected VB can alternate between two or more CDSs/WCDSs to avoid more power consumption of the CHs and the bridging nodes on the VB.

3. MAC Layer Related Issues

Very little literature considered in conjunction with the WCDS algorithms and MAC protocols to do cross-layer design. In this paper, we propose a new WCDS-based energy-efficient MAC protocol to address this important issue. The literature [16] proposed a Sensor-MAC (S-MAC), which belongs to a common active period protocol. S-MAC takes periodic wakeup, that is, each node according to the schedule has a fixed length listen cycle with a fixed length sleep cycle in turn. In the common active cycle, S-MAC will adjust the schedule of the adjacent nodes. The literature [17] proposed the Z-MAC, which is a combination of TDMA and CSMA hybrid MAC design. The literature [18] proposed a funneling MAC, which is a funnel-shaped WSN that is divided into two tiers, the outer tier using the pure-CSMA and the inner tier using the combination of TDMA/CSMA. Literature [19] proposed a power aware clustered TDMA

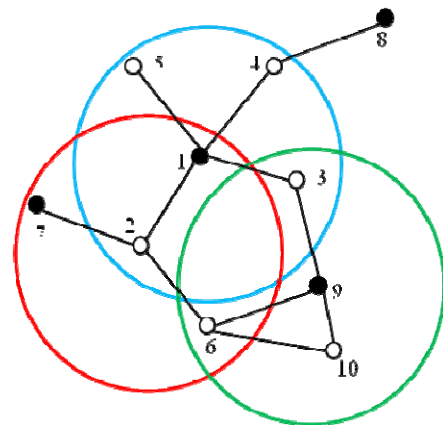


Figure 5. An example of WCDS-based VB routing.

(PACT) MAC, which belongs to the scheduled protocol. PACT determines the duty cycle of a node in accordance with the node's traffic. PACT selects qualified CHs based on the remaining battery energies of nodes, and those CHs will become the backbone of the entire network. PACT only allows CHs and gateway nodes to transmit routing requests, thus reducing the flooding messages. PACT classifies nodes into four classes: CH, gateway, ordinary and LES (low energy state). PACT adopts TDMA superframe structure. Sending node uses controlled mini-slots to broadcast the addresses at the receiving nodes of the following subsequent data slots.

WCDS-based Energy-Efficient MAC Protocols

The proposed WCDS-based energy-efficient MAC protocol combines the mechanisms used in the common active period protocol (S-MAC) and in the scheduled protocol (PACT). We use the example shown in **Figure 5** to explain the concepts adopted in the proposed MAC protocol. Since node 10 is a two-hop neighbor of node 2, when node 2 wants to communicate with node 10, it must send a request to CH1 in the active period of CH1. After receiving the request, CH1 will allocate some time interval to node 2 to do RTS-CTS-Data-ACK exchange with node 6. This means that not only node 2 but also node 6 has to wake up together with CH1. So, the proposed WCDS-based MAC protocol requires that when CH1 is wake up, all its two-hop neighboring nodes as well as one-hop neighboring nodes must be wake up. **Figure 6** shows the timing diagram of the proposed WCDS-based MAC protocol. Using CH1 as an example, when it wakes up, we assume that node 5 has message to be sent to node 3, and node 2 wants to communicate with node 6 simultaneously. Node 5 and node 2 both have to send their requests to CH1 in the Rx. request interval (marked in red color) using controlled mini-slot competition mechanism. After a timer setting with duration t_A (marked in green color), if there has no requests sending to CH1 by any one-hop neighboring nodes during this time interval, CH1 will then broadcast the schedule (marked in yellow color) for the following message exchange sequences within this active period (marked in blue color) to all its one-hop neighboring nodes. For instance, at what time node 5 should send message to CH1 and at what time CH1 will send message to node 3, and at what time node 2 may send message to node 6. This broadcasting schedule is the competition result of the controlled mini-slot mechanism. For any two-hop neighboring node of CH1, if no requests from any CH1's one-hop neighboring nodes have been sent to it during the mini-slot competition interval, it can go to sleep immediately after the request competition interval. For any one-hop neighboring node of CH1 that has no messages to send to any other nodes,

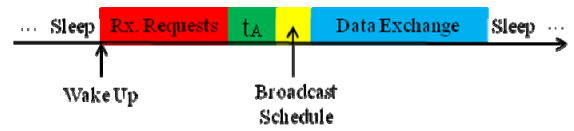


Figure 6. The timing diagram of the proposed WCDS-based MAC protocol.

after having received the broadcasted schedule for the following data exchange period and found that it was not in the schedule (i.e., no other nodes have messages to send to it), it can then go to sleep immediately. In our proposed MAC protocol, we assume that only messages collected in the previous active/sleep cycle can be sent in the current active cycle. For any one-hop neighboring node of CH1 that has been scheduled in the current active cycle, it can go to sleep immediately after it has completed its data exchange task(s) during the data exchange period. The current active cycle of CH1 is ended when all data exchange tasks in the schedule have been completed. For all black nodes (CHs) shown in **Figure 5**, i.e., nodes 1, 7, 8, 9, we will use TDMA to arrange who should sleep and who should wake up among them. The details about the associated TDMA protocol and the overall performance of the proposed WCDS-based MAC protocol will be presented in the results to come.

4. PHY Layer Related Issues

4.1. Battery-aware Alternative VB Selections

Using battery model can help us in understanding the battery internal changes and cell characteristics, and to assist us in designing the system simulation. Literature [20] reviewed a variety of battery models using in wireless devices. The battery model we used is an analytical battery model which was proposed by Rakhmatov and Vrudhula in 2001. This model is based on the diffusion characteristics of the ions in the electrolyte. Using a given load current value, we can simulate the charging status of the battery, and thus to predict the life cycle of the battery. Such battery model using equations (1) and (2) to calculate the battery power consumption.

$$\alpha_i = I_i \times F(t, t + \delta_i, \beta), \quad (1)$$

$$F(t, t + \delta_i, \beta) = \delta_i + 2 \sum_{m=1}^{\infty} \left[\frac{e^{-\beta^2 m^2 t} - e^{-\beta^2 m^2 (t + \delta_i)}}{\beta^2 m^2} \right] \quad (2)$$

Assuming the i -th battery discharge time is δ_i , t is the starting time of the discharge, the load current is I_i , $\beta (> 0)$ is the diffusion constant, α_i is the power consumption of the i -th battery discharge. In (2), the power consumption can be divided into two parts. The first part $I_i \times \delta_i$ is the portion of the real battery charge consumed, and the second part is the loss of the battery's discharge. Equation (3) is used for computation of the remnant of

the discharge loss, when the recovery time is Δt .

$$\phi_i(\Delta t) = 2I_i \times \sum_{m=1}^{\infty} \left[\frac{e^{-\beta^2 m^2 (t+\Delta t)} - e^{-\beta^2 m^2 (t+\delta_i + \Delta t)}}{\beta^2 m^2} \right] \quad (3)$$

From (1)-(3), we can calculate the battery power consumption and understand the characteristics of the battery recharge recovery.

It has been shown that battery performance can be greatly improved by using pulsed discharge instead of constant discharge. The battery recharge recovery principle was mentioned in [4] for periodically rotation between the disjoint CDSs/WCDSs, to extend the life-time of virtual backbone nodes. By scheduling the CDS rotation periodically, a simple mechanism that combines load balancing and rest times for lifetime extension was proposed in [4]. Besides load balancing, the rotation of CDS breaks the continuous operation of high battery discharge by introducing a rest time to allow the recharge recovery effect in electrochemical batteries in extending the battery lifetime. This allows a pulsed discharge in the battery to prevent from having a long continuous battery discharge in any node of network. The operating CDS is rotated among CDPs (Connected Domotic Partitions) so that each CDS is given a rest period to recharge. For a large-size CDP, the rest period is larger. It has been shown in [4] that the longer the rest period, the greater the battery recovery effect. Thus, the large sizes of CDP enable substantial extension of the battery lifetime, resulting in enhanced network lifetime.

In order to exploits the advantages of battery recharge recovery, periodically rotation between disjoint CDSs/WCDSs to extend the life-time of virtual backbone nodes is a topic worth exploring. There are many factors that affect the rest period that a CH may be taken. In general, different CHs may have different rest periods. This is a cross-layer design issue that should take WCDS-based energy-efficient MAC issues into considerations, such as the TDMA scheduling among different CHs discussed above. Even different WCDS-based routing strategies will result in different settings of CHs' rest periods. Using (1)-(3) to evaluate the performance of cross-layer algorithms for battery-aware alternative VB selections is a topic that worth further studying.

4.2. Sensor Nodes with Different Transmission Ranges

In [14], UDG radius with different sizes was proposed to finding out CDS/WCDS. That is, nodes with different transmission ranges were considered. **Figure 7** shows an example of nodes with different sizes UDG radius in a WMN. In **Figure 7**, the transmission ranges of black nodes (CHs) are drawn in solid lines and that of white nodes are drawn in dotted lines. **Figure 8** shows an ex-

ample of nodes with different sizes UDG radius in a WSN. It is well known that the nodes near the sink will consume more power than that of the nodes located in outer tiers. Hence, the transmission ranges of the nodes in inner tiers should smaller than that of the nodes in outer tiers. In addition, a sensor node with several different transmission power levels is in common practice. If a network always adopts larger transmission power for its nodes, then a smaller size WCDS can be obtained; however, this will increase the interferences generated simultaneously. This is because to enlarge node's transmission power is to shorten the routing path, that is, to minimize the number of hops on the routing path. This phenomenon has been demonstrated by the results presented in [14].

5. Conclusions

Essential topics on constructing WCDS-based VB in WSN/WMN are addressed from different protocol layers. We explore their cross-layer research topics and design algorithms. In this paper, two area-based WCDS algorithms

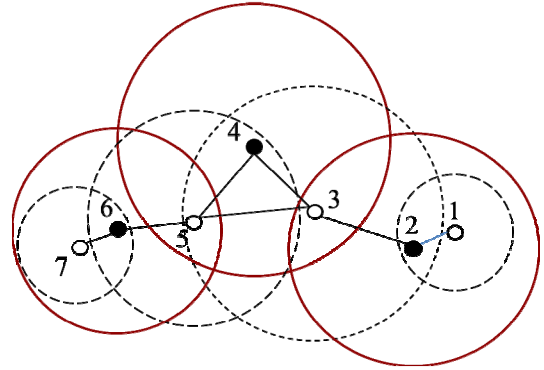


Figure 7. Nodes with different sizes UDG radius in WMN.

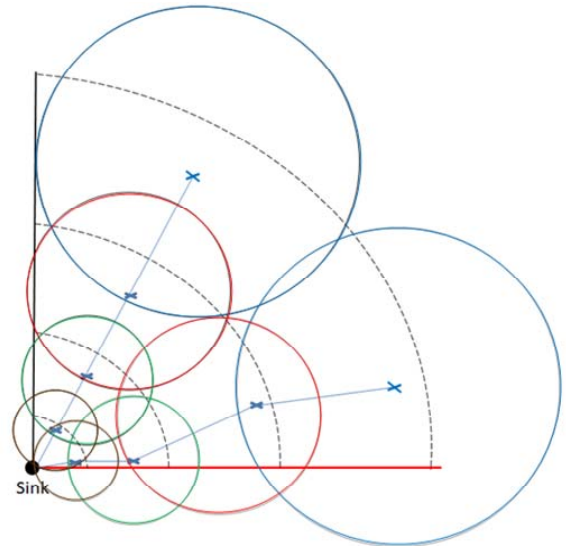


Figure 8. Nodes with different sizes UDG radius in WSN.

are presented, and their constructed VBs are compared by using ABPL. Via VB and not via VB two routing strategies are considered. A novel WCDS-based energy-efficient MAC protocol is proposed. Cross-layer design for battery-aware alternative VB selections is discussed. Comments on the issue of sensor nodes with different transmission ranges are given.

6. Acknowledgements

This work was supported by National Science Council, Taiwan, under the Grant NSC 100-2221-E-224-056.

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