

An Area-Based WCDS-Induced Routing Protocol for Large-Scale Wireless Sensor/Mesh Networks

C. Dou, Y. H. Chang, and J. S. Ruan

Abstract—This paper proposes an area-based WCDS-induced routing protocol for large-scale wireless sensor/mesh networks (WSN/WMNs). A large network is divided into a number of smaller sub-networks, called area sub-networks (ASNs). Both centralized and distributed area-based WCDS formation algorithms are presented. Within an ASN, a novel virtual cluster (VC) based Intra-ASN routing protocol is proposed. The VC-based routing protocol classifies the routing paths into Intra-VC and Inter-VC two types. The Intra-VC routing eliminates the unavailability of shortest paths when WCDS virtual backbone is used. The Inter-VC routing guarantees the shortest path between two communicating VCs is obtained, associated with the minimum number of traversed VCs. A hybrid table driven and on-demand routing protocol, namely *Area Border Routing Protocol (ABRP)*, is proposed for Inter-ASN communications. The *ABRP* also guarantees that the shortest path is obtained for any pair of communicating VCs that belong to two different ASNs. Finally, performance issues as well as problems and mitigation of the proposed WCDS-induced routing protocol are discussed.

Index Terms—Weakly connected dominating set, large-scale wireless sensor/mesh networks, routing protocol, virtual cluster.

I. INTRODUCTION

Clustering approach is one of the most promising solutions for establishing virtual backbones (VBs) in wireless ad hoc networks and wireless sensor/mesh networks (WSN/WMNs). Within each cluster a particular vertex called cluster head (CH) may be designated to oversee channel allocation and message routing. The most basic network clustering structure that has been investigated is based on dominating sets. A node set is a dominating set (DS) if every node in the network is either in the set or a neighbor of a node in the set. A connected dominating set (CDS) of a graph $G=(V, E)$ is a set of vertices with two properties: 1) D is a dominating set in G ; 2) D induces a connected subgraph of G . Messages can be routed from the source node to a neighbor in the dominating set, along the CDS to the dominating set member closest to the destination node, and then finally to the destination [1]. Message routing via the CDS results in a significant reduction in message overhead associated with routing updates [2]. In the literatures it has been termed dominating set based routing [3], [4], or backbone based routing [5].

Although the CDS provides an obvious virtual backbone for message routing, however, the connectivity requirement

causes the size of CDS to be rather large. Relaxing this requirement can reduce the size effectively. A minimum CDS (MCDS) is a CDS that has the minimum number of nodes. Many researchers have focused on MCDS-based virtual backbone construction in the past years [3], [6]-[9]. Weakly connected dominating set (WCDS) is another approach that can reduce the size effectively. A WCDS is a node set that is dominating and all the edges with at least one end point in the set form a connected subgraph (weakly induced subgraph). Using an underlying cluster-based virtual backbone induced by the WCDS can be a very promising approach to enhance network efficiency [10]-[12]. The problem of finding CDS or MCDS or WCDS is NP-hard. CDS or MCDS or WCDS-induced routing algorithms with routing cost constraints were proposed in [9], [13]-[15]. It was pointed out in [9] and [15] that not all messages must make use of the CDS/MCDS/WCDS virtual backbone according to the specified routing cost constraints, especially short-distance routing are even more so. CDS or WCDS virtual backbone routing could lead to some routing paths that are longer than the shortest paths in the original graph.

In a large-scale network, the deployment of the nodes becomes denser and routing paths become longer [16]-[19]. Accordingly, the routing protocols must scale well to the network scope extension and node density increases. A survey on routing protocols for large-scale wireless sensor networks was made in [16]. In [16], the authors pointed out that the hierarchical routing protocol is the mainstream method to solve the scalability problem of large-scale networks, but the factors affecting the cluster formation and cluster head communication are worth further investigation. And the routing protocol could be much more scalable through making the complexity of the routing protocol reduced or not related to the network size. In [17], a hierarchical network architecture that consists of clusters of sensor nodes to enable the chain-type sensor networks to be scalable to cover typically long range infrastructures with tolerable delay in network wide data collection was proposed. In [18], a routing algorithm, called AR-LWMN, for large scale wireless mesh network was proposed. The route between the source and the destination can be constructed in two ways by using AR-LWMN. One is an internal route. It is constructed restrictively in WMNs. The other is an external route. It is constructed via gateways between WMNs and the outside high-speed external networks. In [19], the authors considered the scenario in which a large number of sensor nodes are densely deployed and sensor readings are spatially correlated.

In this paper, an area-based WCDS-induced routing protocol for large-scale WSN/WMNs is proposed. A large

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network is first divided into a number of smaller sub-networks, called ASNs. Within an ASN, a novel virtual cluster (VC) based Intra-ASN routing protocol is proposed. A hybrid table driven and on-demand routing protocol, namely *Area Border Routing Protocol (ABRP)*, is proposed for Inter-ASN communications. The ABRP guarantees that the shortest path is obtained for any pair of communicating VCs that belong to two different ASNs. The main advantages of the *ABRP* protocol are as follows. First, it provides the network with high reliability. Second, it enables the routing protocol more scalable by making the complexity of the routing protocol reduced and not related to the network size. Third, it improves the robustness of large-scale networks.

The rest of the paper is structured as follows. Section II gives a brief review of WCDS formation algorithms. In Section III, both centralized and distributed area-based WCDS algorithms are presented. In Section IV, a novel VC-based Intra-ASN routing protocol is proposed. Section V presents the *ABRP* protocol, which is a hybrid table driven and on-demand routing protocol for Inter-ASN communications. Performance issues as well as problems and mitigation of the proposed WCDS-induced routing protocol for large-scale WSN/WMNs are discussed in Section VI. Section VI also briefly concludes the contributions of the paper.

II. WCDS FORMATION ALGORITHMS

Both centralized and distributed algorithms for WCDS construction in clustering mobile ad hoc networks were proposed in [20]. In [21], the authors proposed localized algorithms for CDS formation in ad hoc wireless networks. The difference between centralized and localized CDS/WCDS formation algorithms is that centralized algorithms require the coordinator to use of the entire network topology to form the CDS/WCDS, but localized 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 this paper, we adapted a distributed WCDS algorithms proposed in [20], called the Maximum-Neighbor (MN) algorithm, to use by the following subject matter discussed.

A. Maximum-Neighbor (MN) Algorithm

(Using Fig. 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 Fig. 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 chooses the one that can merge most pieces as the CH.)

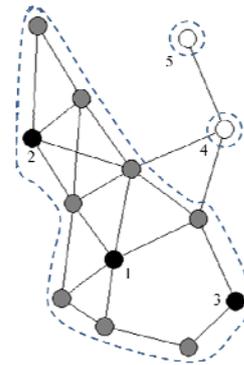


Fig. 1. A snapshot of the MN algorithm.

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

An example is provided to demonstrate how to use the MN algorithm to construct WCDS-based VB as follows. Seventy nodes with their node IDs are randomly deployed in a 7 by 7 squared area. All nodes have the same transmission radius 1. The MN algorithm selects a node to be the starting point and be the first chosen CH labeled with 1. The WCDS VB constructed by the MN algorithm is shown in Fig. 2 (bold lines colored in red). In Fig. 2, CH_i denotes the *i*th CH chosen by the algorithm. Clearly, the cluster heads election between CH_i and CH_{i-1} are not directly related. Unless the complementary black nodes are added, the WCDS VB constructed by the MN algorithm could not be completed. Moreover, the connection structure of the VB between the selected black nodes shown in Fig. 2 are not unique. Five pairs of nodes are marked in blue. Each pair must select a node to colored in black to complete the WCDS VB. Thus, total 23 CHs are chosen to form the WCDS VB.

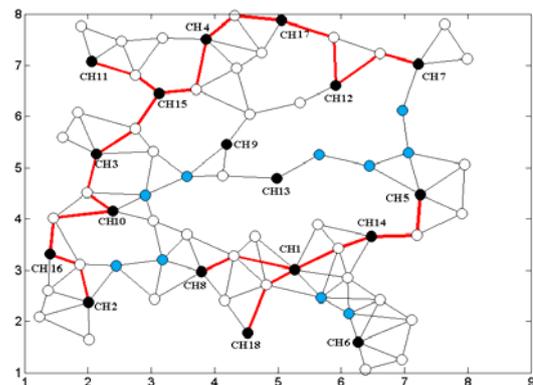


Fig. 2. WCDS VB formation by the MN algorithm.

III. AREA-BASED WCDS FORMATION ALGORITHMS

In this paper, a large-scale network is divided into a number of smaller sub-networks, called area sub-networks (ASNs). Both centralized and distributed area-based WCDS formation algorithms are presented in this section. In [12], an area-based distributed algorithm for WCDS construction in wireless ad hoc networks was proposed. The area-based distributed algorithm is divided into three phases: area partition, WCDS construction for each area, and adjustment along the area borders. The following example is used to illustrate the procedure of the distributed algorithm proposed

in [12]. The example simply assumes fifty nodes are randomly deployed in a 5 by 5 squared area and all nodes have the same transmission radius 0.89.

A. Area-Based Distributed Algorithm

(Using Fig. 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 area into sub-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 Fig. 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, we use the MN algorithm to construct its own WCDS. For example, nodes 2, 10, 23, and 24 are selected as CHs in area A2.

Step 3: On the border between any two adjacent areas, border nodes are supplemented for linking two adjacent WCDSs. For example, nodes 27 and 29 are selected as the border nodes between A1 and A2.

In this paper, we enhance the above distributed algorithm with some useful concepts and propose an area-based centralized WCDS formation algorithm. First, we use the concept of bounded diameter to determine a reasonable size of a sub-area.

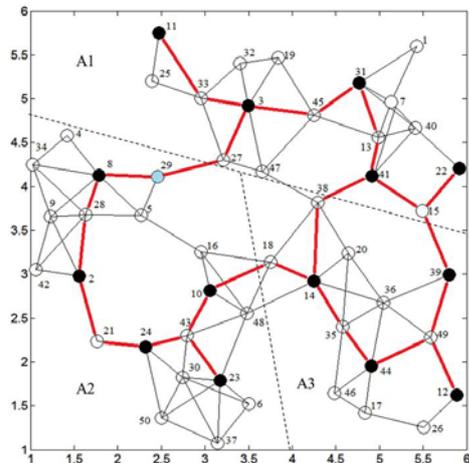


Fig. 3. An illustration of area-based distributed algorithm.

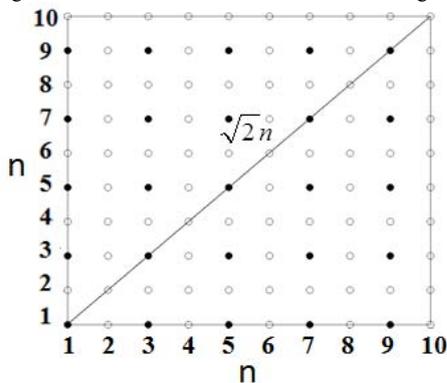


Fig. 4. An n by n node deployment with $n=10$, bounded diameter=8.

B. The Concept of Bounded Diameter

Constructing MCDS with bounded diameter was proposed in [22]. The diameter of a CDS/MCDS/WCDS is defined as the longest path length between two CHs on the VB. It has

been shown in [22] 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). The following example is used to explain how to use the concept of bounded diameter to determine the size of a sub-area. Fig. 4 shows a regular node deployment in an n by n square area ($n=10$). We can simply assume that the longest path between two CHs on the VB is just along the diagonal line. Thus, the bounded diameter of the 10 by 10 node deployment is just about 10 if the transmission radius is $\sqrt{2}$. This value is 8 for the example shown in Fig. 4. Theoretically, if the transmission radius is 1, the bounded diameter of an n by n node deployment is $\sqrt{2}n$; and for an m by n node deployment in a rectangular area, a reasonable estimated value of the bounded diameter is $\sqrt{m^2+n^2}$. Clearly, the estimated value of the total number of black nodes (CHs) on the longest path in a WCDS can be given by $\left\lceil \frac{\sqrt{2} \times n}{2} \right\rceil$ and

$$\left\lceil \frac{\sqrt{m^2+n^2}}{2} \right\rceil$$

respectively, if the node transmission radius is 1.

Once the bounded diameter for each sub-area is determined, the borderlines between sub-areas can be drawn. We suggest that the border between two sub-areas should be drawn according to the geographical determinant and network applications and practical node deployments. To mitigate the overhead caused by the border nodes supplementation in step 3 of the distributed algorithm, we propose a centralized concept to build a single WCDS for the whole network. Due to the WCDS formation is performed individually for each sub-area in the distributed algorithm. It could be a difficult task for finding out the appropriate border nodes to link two adjacent WCDSs. In some cases, these border nodes have to be marked in black, to serve as the supplemental cluster heads. The advantage of using the whole network to form a complete WCDS is that border nodes between sub-areas can be easily identified and assured. Any pair of two adjacent black nodes that are located at the both sides of the borderline forms a border nodes pair. Thus, the nodes connectivity of a complete WCDS determines all the border nodes pairs between any two adjacent sub-areas. The following example is used to illustrate the procedure of our proposed centralized algorithm. The example assumes 400 nodes are randomly deployed in a 350 by 300 rectangular area and all nodes have the same transmission radius 20.

C. Area-Based Centralized Algorithm:

(Using Fig. 5 as an example)

Step 1: Select an appropriate bounded diameter. In this example we choose the bounded diameter to be 14.

Step 2: Divide the whole network into a number of area sub-networks (ASNs). In Fig. 5, the number of ASNs is 4 and the total node number in each sub-area is about 100.

Step 3: Determine the borderlines between ASNs, according to the geographical determinant and network applications and practical node deployments.

Step 4: Construct a single WCDS for the whole network. In this example, we use the MN algorithm.

Step 5: Build a table to record all the border nodes pairs between any two adjacent sub-areas. As shown in Fig. 5, the border nodes pairs are colored in green. And the border nodes pairs between ASN₁ and ASN₂ are (18, 252) and (337, 249); between ASN₂ and ASN₃ are (166, 99), (68, 212) and (12, 94);

between ASN₃ and ASN₄ are (159, 390), (299, 58), (259, 44), (400, 92) and (146, 179); between ASN₄ and ASN₁ are: (390, 281) and (103, 209). Here we note that border nodes supplementation is not necessary in the proposed centralized algorithm.

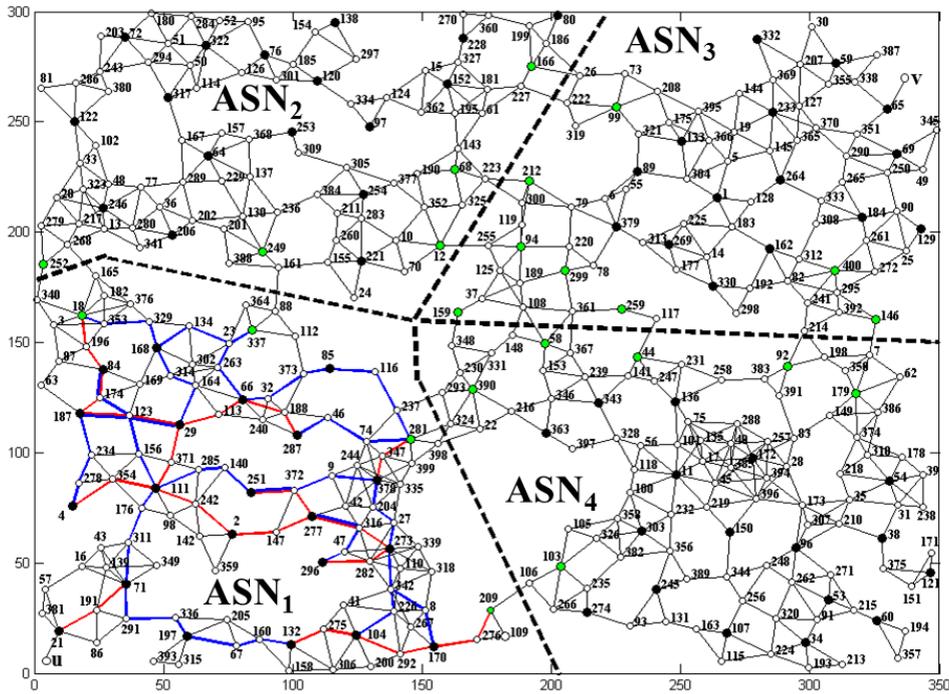


Fig. 5. An example to illustrate the area-based centralized algorithm.

IV. INTRA-ASN ROUTING PROTOCOL

A. WCDS Virtual Cluster (VC) Formation

Each VC consists of a CH, which serves as the center and the coordinator of the VC, and all its one-hop (1-D) and two-hop (2-D) neighboring nodes. For example, as shown in Fig. 6, a VC, namely VC₁₂, is formed by node 12, which serves as the CH, and its 1-D neighbors (nodes 13, 66, 53, 42, 5, 55, and 8), and its 2-D neighbors (nodes 2, 40, 26, 35, 33, 41, and 39). Clearly, blue nodes Pair (66, 2) are two member nodes of the VC₁₂. They are also the member nodes of the VC₁₀. So, we regarded that VC₁₂ and VC₁₀ are connected through node 66 and node 2 in our VC-based virtual backbone, and there has no need to mark any one of the two blue nodes in black. As the same it is regarded that VC₆ and VC₃₇ are connected through node 69 and node 57. This is quite different to the method of WCDS VB construction mentioned in the previous subsection concerning the nodes pairs colored in blue. More specifically, that is the VC-based VB construction method proposed in this paper allows the node pattern in a WCDS not only in the form of B-W-B (B: Black node, W: White node) but also in the form of B-W-W-B. Therefore, all nodes colored in blue in Fig. 2 is changed back to white in our VC-based VB formation, and the number of CHs on the VB can be lessened. All the member nodes in the VC follow the same active/sleep schedule adopted by the CH. That is, when the CH of the VC is wakeup, all the member nodes in the VC must wakeup together. During the active period of the VC, the CH has to

coordinate all data exchange requests issued by its 1-D neighbors; no matter these data exchanges occurred within the coverage of the VC or between two different VCs. The Intra-VC routing eliminates the unavailability of shortest paths when WCDS virtual backbone is used. The Inter-VC routing guarantees the shortest path between two communicating VCs is obtained, associated with the minimum number of traversed VCs.

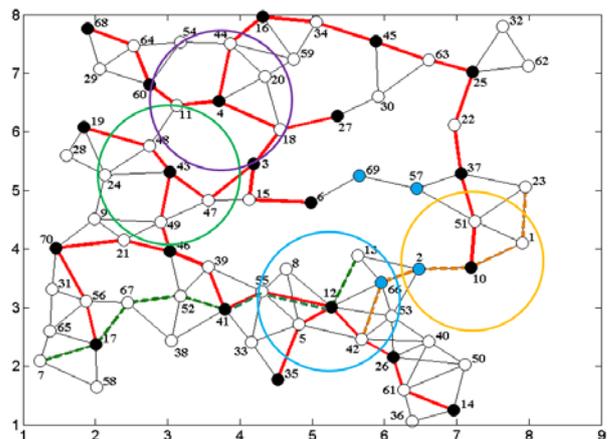


Fig. 6. An example to illustrate the VC-based routing protocol.

B. VC-Based Routing Protocol

The proposed VC-based routing protocol classifies the routing paths into Intra-VC and Inter-VC two types.

- 1) An Intra-VC routing path is defined as that all data exchanges occurred on the route can be managed by the CH of the VC.

- 2) An Inter-VC routing path is defined as that all data exchanges occurred on the route cannot be managed by a single CH but at least two CHs on the VB.

The proposed VC-based Intra-VC routing protocol guarantees that the routing path that is within three-hop distance will go directly through the shortest path and will not go through the VB. If the path length is larger than three hops then the proposed VC-based Inter-VC routing protocol guarantees that the shortest path associated with the minimum number of traversed VCs is obtained. For each VC, only the CH of the VC has to maintain the routing tables. Two categories of routing tables have to be built in the CH of the VC. One is the Intra-ASN routing table, and the other is the Inter-ASN routing table. The contents of the Intra-ASN routing table include all intra-VC routing paths within the coverage of the VC, and all inter-VC connectivity information between the corresponding VC and every other VC within the same ASN. The contents of the Inter-ASN routing table will be addressed in the next subsection.

C. VC-Based Intra-VC Routing

The Intra-VC routing paths can be further classified into the direct one-hop (D1H), direct two-hop (D2H), and direct three-hop (D3H) three types. The definition of these three types of Intra-VC routing paths are given as below, using the example shown in Fig. 6.

- 1) Direct one-hop (D1H) routing path: For example, within VC₁₂ node 13 wants to communicate with node 2, abbreviated as 13→2; more examples are 42→5, 5→12, 12→13, etc. Note that path 13→2 has only one node (node 13) within the one-hop distance of VC₁₂, but the other three paths have both transmitting and receiving nodes within the one-hop distance of VC₁₂.
- 2) Direct two-hop (D2H) routing path: Routing path 12→13→2 is an example which has CH₁₂ serves as the transmitting node, and path 8→12→42 is an example that the CH₁₂ is the middle node on the route. More examples, such as 8→55→39 is the shortest path since VC₁₂ knows that node 39 is within its two-hop coverage, so the routing path needs not go through CH₄₁. Routing path 13→66→42 is another example that the routing path needs not have to go via CH₁₂.
- 3) Direct three-hop (D3H) routing path: For example, route 13→12→5→33 and route 42→5→55→39. One has to go via CH₁₂ and the other does not have to.

All Intra-VC routing paths, including D1H, D2H and D3H, are stored in the Intra-VC routing table of the CH.

D. VC-Based Inter-VC Routing

If the destination node of a data request is not within the coverage of the VC, that is beyond the distance of 2-hop from the CH, then the CH will recognize it as an Inter-VC routing. The CH first performs a table lookup from the HLLT (Home Location Lookup Table) in the routing table to find the VC where the destination node belongs; and then finds the Inter-VC routing path from the source VC to the destination VC. Since the proposed VC-based VB construction method allows the node pattern not only in the form of B-W-B but also in the form of B-W-W-B, the Inter-VC routing paths must take the both node patterns into consideration. In the

following, a routing path is given to illustrate how Inter-VC routing can be accomplished, using the example shown in Fig. 6. The routing example is that we assume node 13 in VC₁₂ wants to communicate with node 7 which is a 1-D member of VC₁₇. Clearly, this is an Inter-VC routing between the source VC₁₂ and the destination VC₁₇, with an intermediate VC₄₁. In this example, the node pattern between node 12 and node 41 is B-W-B (12-55-41), and the node pattern between node 41 and node 17 is B-W-W-B (41-52-67-17). The end-to-end routing path is divided into three sections governed by VC₁₂, VC₄₁ and VC₁₇, respectively. The first section is 13→12→55→41, which is a D3H Intra-VC routing path governed by the CH of VC₁₂. The second section is 41→52→67, which is a D2H Intra-VC routing path governed by the CH of VC₄₁. The third section is 67→17→7, which is a D2H Intra-VC routing path governed by the CH of VC₁₇. The Inter-VC routing path that has been recorded in the routing table (including only black nodes) of this example is VC₁₂→VC₄₁→VC₁₇.

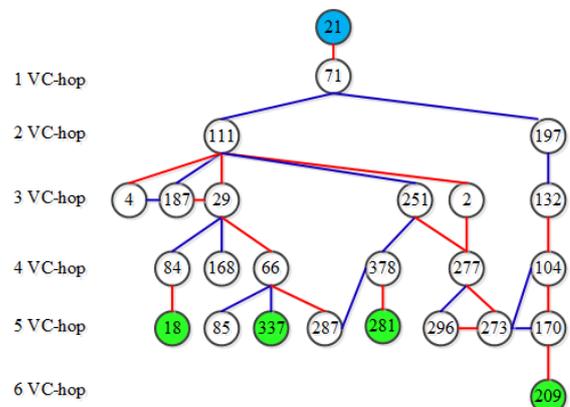


Fig. 7. A spanning tree example using VC₂₁ as the source VC.

All Inter-VC routing paths stored in the CH can be obtained through constructing a spanning tree from the CH of the corresponding VC to the CH of every other VC within the same ASN. Fig. 7 shows a well-constructed spanning tree example using VC₂₁ in the ASN₁ of Fig. 5 as the source VC. In Fig. 7, we use VC hop-count to measure the distance between the source VC and the destination VC. In the spanning tree shown in Fig. 7, the WCDS node pattern between VC₂₁ and VC₇₁ is B-W-B (21-191-71), which is colored in red. The WCDS node pattern between VC₇₁ and VC₁₁₁ is B-W-W-B (71-311-176-111), which is colored in blue. The VC hop-count from root node 21 to node 111 is 2. The traversed VC path from the CH of VC₂₁ to the CH of every other VC within the ASN₁ can be obtained by tracing the spanning tree. For example, the Inter-VC routing path between VC₂₁ and VC₁₈, where CH₁₈ is a border node of ASN₁, is as below:

VC₂₁→VC₇₁→VC₁₁₁→VC₂₉→VC₈₄→VC₁₈.

The VC hop-count of this routing path is 5. There are two paths with the same VC hop-count from VC₂₁ to VC₂₈₇. However, the path go through VC₂₉ and VC₆₆ is shorter than the path go through VC₂₅₁ and VC₃₇₈. Hence the former path is recorded in the routing table with higher priority than the latter one. The comparison of the path length between these two paths can be done by comparing the

number of WCDS node patterns. Clearly, the path length of node pattern B-W-B (colored in red) is shorter than that of node pattern B-W-W-B (colored in blue). Thus, the path with more B-W-B node patterns is shorter when the VC hop-count is the same. In the spanning tree, all black nodes (CHs) in the area of ASN_1 are included. For every CH in ASN_1 , a spanning tree is constructed to obtain the Inter-VC routing paths for its associated VC. Of course, all the Inter-VC routing paths discussed in this subsection are Intra-ASN communication.

V. INTER-ASN ROUTING PROTOCOL

A. Cluster Name Server (CNS)

In the proposed area-based WCDS-induced routing protocol, each ASN has a coordinator, named Cluster Name Server (CNS); to coordinate all routing issues and to store routing information related to both Intra-ASN and Inter-ASN communications. The CNS of an ASN is a particular CH selected from the CHs within the ASN. The CNS should have more powerful computing capability and larger memory storage than the common sensor node. A CNS provides the following three functions. First, it contains a complete HLLT (Home Location Lookup Table) for all nodes in the whole network. By searching the HLLT, the VC of which a particular network node belongs can be found. Thus, an end-to-end communication between a source node and a destination node can be transformed to a VC-to-VC communication; even both nodes are resided in different ASNs. Note that the HLLT stored in the CH of a VC is a subset of the HLLT stored in the CNS. This is because the HLLT stored in a CH is built only for those nodes resided in the same ASN. The routing information recorded in a CH for those nodes resided in other ASNs is stored in the CH's ABRP routing table on an on-demand basis. Second, it is responsible for computing all the spanning trees, same as that shown in Fig. 7, using the CHs within the corresponding ASN as the source VCs; and constructing a big Inter-VC routing table for all VC-to-VC routing paths within the ASN. The CNS duplicates a subset of its Inter-VC routing table, which is related to a particular VC, and sends a copy of it to the CH of the VC. Third, it constructs an ABRP routing table for all Inter-ASN VC-to-VC routing paths, from its own ASN (the source ASN) to every other ASN (the destination ASN). The details of the ABRP routing protocol is presented in the next subsection.

B. Area Border Routing Protocol (ABRP)

The CNS extracts the VC hop-counts from each border node to all other CHs, from its Intra-ASN Inter-VC routing table, which stores all VC-to-VC routing paths within the associated ASN, and forms a table as shown in Table I, which uses ASN_1 in Fig. 5 as an example. The VC hop-counts from four border nodes to VC_{21} that are recorded in Table I can be easily observed from Fig. 7. In Fig. 7, all border nodes are the leaf nodes in the spanning tree and are colored in green. From Table I, the VC hop-count from a border node to another border node within the same ASN can further be obtained. This border-to-border information is needed by the ABRP. In the proposed ABRP protocol, every CNS must have not only its own Intra-ASN border-to-CHs VC

hop-count table, but also have a duplication of every other CNS's Intra-ASN border-to-CHs VC hop-count table. Using a 3 by 3 magic square with 9 ASNs shown in Fig. 8 as an example, every CNS have nine Intra-ASN border-to-CHs VC hop-count tables, each table associated with a respective ASN. In Fig. 8, the border nodes for each ASN are represented by a green node. For simplicity, we assume there is only one border node on each side. For instance, ASN_5 has four border nodes on its four sides that were labeled as 'E' (East), 'W' (West), 'S' (South), and 'N' (North), respectively.

TABLE I: INTRA-ASN BORDER TO CHS VC HOP-COUNT TABLE

CH ID	Border Node ID				CH ID	Border Node ID			
	18	337	281	209		18	337	281	209
18	—	2	4	7	281	4	2	—	4
84	1	2	4	6	378	4	3	1	3
187	2	2	4	6	273	5	4	2	2
4	3	3	4	6	209	7	6	4	—
71	4	4	4	5	170	6	5	3	1
21	5	5	5	6	104	6	5	3	2
111	3	3	3	5	132	6	6	4	3
29	2	2	2	5	197	5	5	5	4
168	1	1	3	6	296	6	5	3	3
66	2	1	2	5	277	5	4	2	3
337	2	—	2	6	251	4	4	2	4
85	3	1	1	5	2	4	4	3	4
287	3	2	1	4					

TABLE II: THE FIELD TEMPLATE OF AN ABRP ROUTING TABLE

Source ASN	Intermediate ASNs		Dest. ASN		Pri.
VC_i	Out_ID	$ASN_g(In_ID, Out_ID)$ $ASN_h(In_ID, Out_ID)$ \vdots	In_ID	VC_j	1
\vdots		\vdots	\vdots		\vdots

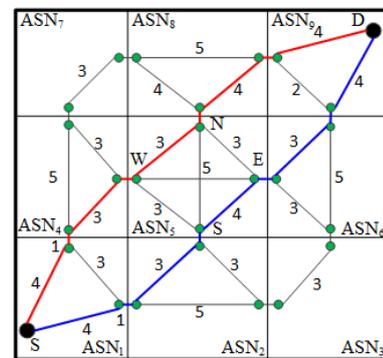


Fig. 8. A 3 by 3 magic square with nine ASNs.

The template of an ABRP routing path which has four fields that are necessary for computing the path's VC hop-count is defined in Table II. The ABRP routing path from a source node, named S within ASN_1 , to a destination node, named D within ASN_9 , can be computed as follows.

Step 1: The CNS of ASN_1 computes the VC hop-counts of

all possible paths from an outlet border node of ASN_1 to an inlet border node of ASN_9 . For example, a possible path from the outlet border node 'E' of ASN_1 to the inlet border node 'S' of ASN_9 is marked in blue lines. An ABRP routing path has four fields: Source ASN, Intermediate ASNs, Destination ASN, and Priority. The source ASN field has two attributes: source VC_ID and the outlet border node of the source ASN. The intermediate ASNs field has an ordered sequence of $ASN_k(\text{Inlet_ID}, \text{Outlet_ID})$. In this example, $k=2, 5, 6$; and the ordered sequence is $ASN_2('W', 'N')$, $ASN_5('S', 'E')$ and $ASN_6('W', 'N')$. The destination ASN field has two attributes: destination VC_ID and the inlet border node of the destination ASN. The priority field indicates the priority of the associated routing path in the routing table. To compute the VC hop-count of the routing path traversed $ASN_2('W', 'N')$, $ASN_5('S', 'E')$ and $ASN_6('W', 'N')$, the CNS of ASN_1 performs a table lookup for the VC hop-count of every $ASN_k(\text{Inlet_ID}, \text{Outlet_ID})$, $k=2, 5, 6$. The VC hop-count of the path from the outlet border node 'E' of ASN_1 to the inlet border node 'S' of ASN_9 , including the VC hop-counts for four border nodes pairs (each with one VC hop), is obtained by summing $1+3+1+4+1+3+1=14$. Another possible path from the outlet border node 'N' of ASN_1 to the inlet border node 'W' of ASN_9 , which is colored in red, can be computed similarly by summing $1+3+1+3+1+4+1=14$.

Step 2: The VC hop-count of an end-to-end ABRP routing path from any given source node within ASN_1 to any given destination node within ASN_9 , can be computed by adding the VC hop-counts occurred in ASN_1 and ASN_9 , respectively, to the summing result obtained in the previous step. For example, the VC hop-count from the source VC to the outlet border node 'E' of ASN_1 is 4, and from the destination VC to the inlet border node 'S' of ASN_9 is also 4, as shown in Fig. 8. Thus, the VC hop-count of the end-to-end ABRP routing path from node S to node D which goes through the blue lines is $4+14+4=22$.

Step 3: Determine the priorities of all possible ABRP routing paths from a source node within ASN_1 to a destination node within ASN_9 , according to the values of their VC hop-counts computed in the previous step. The path with smaller VC hop-count has higher priority. The ABRP selects the routing paths corresponding to the first three priorities and recorded them in the ABRP routing table stored in the CNS.

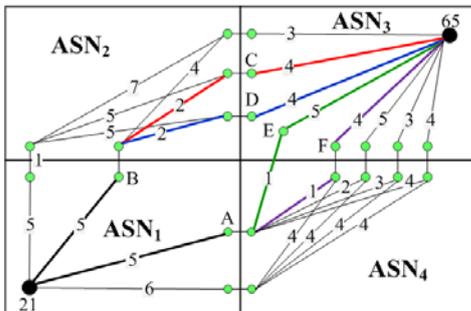


Fig. 9. All possible ABRP routing paths from VC_21 to VC_65.

C. ABRP Routing Table

The node deployment shown in Fig. 5 is used as an example to illustrate the procedure for constructing an ABRP routing table described above. Fig. 9 shows all possible

ABRP routing paths from VC_21 (within ASN_1) to VC_65 (within ASN_9). There are total four outlet border nodes of ASN_1 and eight inlet border nodes of ASN_9 . But there has no possibility from the east two outlet border nodes of ASN_1 to the west three inlet border nodes of ASN_9 . Also, there has no possibility from the north two outlet border nodes of ASN_1 to the south five inlet border nodes of ASN_9 . From all possible 16 ABRP routing paths, the CNS of ASN_1 selects three of them with smaller VC hop-counts, and labeled them with priority 1, 2 and 3, respectively, in the routing table.

In Table III, the routing path from VC_21 to VC_65 with the first priority is colored in purple with two border nodes labeled with 'A' and 'F', respectively, shown in Fig. 9. Its associated VC hop-count is $5+1+1+1+4=12$. The second priority routing path is colored in green with two border nodes labeled with 'A' and 'E', respectively; and its associated VC hop-count is $5+1+1+5=12$. Both paths have the same VC hop-count, but the first priority path has more B-W-B node pattern than the second priority path. The third priority routing path is colored in red with two border nodes labeled with 'B' and 'C', respectively; and its associated VC hop-count is $5+1+2+1+4=13$. The first three shortest ABRP routing paths from VC_21 to VC_69 (within ASN_3) are also shown in Table III.

TABLE III: A SAMPLE ABRP ROUTING TABLE

ASN ₁		Intermediate ASNs	ASN ₃		Pr.
VC	CH	ASN _k (CH_ID, CH_ID)	CH	VC	
21	281	ASN ₄ (CH_390, CH_58)	299	65	1
21	281	ASN ₄ (CH_390, CH_390)	159	65	2
21	337	ASN ₂ (CH_249, CH_68)	212	65	3
21	281	ASN ₄ (CH_390, CH_58)	299	69	1
21	281	ASN ₄ (CH_390, CH_390)	159	69	2
21	337	ASN ₂ (CH_249, CH_12)	94	69	3
⋮	⋮	⋮	⋮	⋮	⋮

D. Hybrid Table Driven and On-Demand Routing

The ABRP routing table described above is built in the CNS of the associated ASN. It contains all end-to-end ABRP routing paths between any pair of two network nodes resided in two different ASNs. Its size is certainly enormous for a large-scale network. In general, it is even not suitable for the CH of a VC to store a large ABRP routing table that contains all Inter-ASN routing information related to the associated VC. Thus, a hybrid table driven and on-demand routing is used in our proposed Inter-ASN routing protocol. We use the node deployment shown in Fig. 5 again in the following example to illustrate the procedure of the proposed hybrid table driven and on-demand routing protocol. Now, we assume a node u in VC_21 (within ASN_1) wants to communicate with a node v in VC_65 (within ASN_3).

Step 1: The CH of VC_21 (CH_21) checks whether the destination node v is within its 2-hop coverage. If yes, then searches the Intra-VC routing table in the CH for the shortest routing path. Else, go to step 2.

Step 2: The CH₂₁ checks whether the destination node v belongs to a VC within the same ASN. If yes, then searches the Inter-VC routing table in the CH for the shortest routing path. Else, go to Step 3.

Step 3: The CH₂₁ checks whether the destination node v has already appeared in its Inter-ASN destination nodes list. If yes, it means CH₂₁ has already had the corresponding ABRP routing path. Else, go to Step 4.

Step 4: The CH₂₁ sends an ABRP search request to its CNS. The CNS searches its HLLT to find the destination VC and ASN where the node v is resided.

Step 5: The CNS checks whether the CH₂₁ has already had the ABRP routing path between VC₂₁ and VC₆₅. If yes, it means that the CH₂₁ had sent a similar ABRP search request to the CNS in the past, for some nodes in VC₆₅ other than the node v . Then, the CNS answers CH₂₁ that the destination node v is in VC₆₅ (within ASN₃), and CH₂₁ can find the ABRP routing path directly from its own ABRP routing table. The CH₂₁ has to add the node v into its Inter-ASN destination nodes list. Else, go to Step 6.

Step 6: (The CNS finds that there has no such communication between VC₂₁ and VC₆₅ occurred before.) The CNS sends the information including the destination VC, the destination ASN and the corresponding ABRP routing paths (the first three priorities) to the CH₂₁. The CH₂₁ adds the node v into its Inter-ASN destination nodes list, and adds the newly obtained ABRP routing paths into its Inter-ASN ABRP routing table, accordingly.

VI. PERFORMANCE ISSUES AND DISCUSSIONS

A. Routing Efficiency

This paper proposes an area-based WCDS-induced routing protocol for large-scale wireless sensor/mesh networks (WSN/WMNs). A large network is divided into a number of smaller sub-networks, called area sub-networks (ASNs). The proposed Intra-VC routing eliminates the unavailability of shortest paths when WCDS virtual backbone is used. The Inter-VC routing guarantees the shortest path between two communicating VCs is obtained, associated with the minimum number of traversed VCs. The ABRP, a hybrid table driven and on-demand routing protocol, is proposed for Inter-ASN communications. The ABRP also guarantees that the shortest path is obtained for any pair of communicating VCs that belong to two different ASNs. Each VC has a CH, which serves as the center and the coordinator of the VC. The CNS of a ASN is used to coordinate all routing issues and to store all routing information that are related to the associated ASN, including both Intra-ASN and Inter-ASN routing information. The proposed routing protocol effectively solves the following problems of a large-scale network: area-based WCDS formation, WCDS virtual cluster formation, VC-based Intra-VC and Inter-VC routing, and Inter-ASN end-to-end communication. We use the concept of bounded diameter to determine a reasonable size of a sub-area. From Fig. 5 and Fig. 7, we observe that the total number of network nodes deployed in an ASN with VC hop-count bounded by 5 to 6 is about 100~120. In the ABRP protocol, an end-to-end ABRP routing path may traverse

several ASNs, but each one of these ASNs (the source ASN, the intermediate ASNs, the destination ASN) is responsible only for the VC path that goes through its district. The main advantages of the proposed protocol are as follows. First, it provides the network with reliability. Second, it enables the routing protocol more scalable by making the complexity of the routing protocol reduced and not related to the network size. Third, it improves the robustness of large-scale networks.

B. Flexibility

The proposed routing protocol is flexible to adapt to the route selection changes in the network. First, route selection changes in an Intra-VC routing will not affect the Inter-VC routing within an ASN. Second, route selection changes within intermediate ASNs on an ABRP routing path will not affect the ABRP routing table. This is because only border-to-border information (VC hop-count) of an intermediate ASN is needed by the ABRP protocol. It is not necessary for the ABRP routing protocol to know the VC-to-VC routing paths that is managed by the associated intermediate ASNs. The ABRP routing table has to be updated only when the VC hop-count of a border-to-border routing path within an intermediate ASN is changed. Third, every ABRP VC-to-VC communication has alternative path selections, when a routing path with higher priority is not available. This increases the reliability and robustness of WCDS-induced routing in large-scale WSN/WMNs.

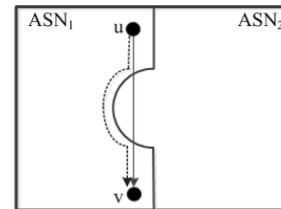


Fig. 10. An apparent concave-convex borderline between two ASNs.

C. Problems and Mitigation

The ABRP protocol should avoid having apparently concave-convex boundary between two adjacent ASNs. As shown in Fig. 10, the shortest path between nodes u and v has to go through ASN₂, but both nodes are resided within the same ASN₁. The proposed protocol will use the spanning tree method to build the shortest Intra-ASN routing path between u and v , but will not regard it as an Inter-ASN routing. Another crucial factor that will strongly affect the performance of the cluster-based routing protocol is the node's transmission radius. The variation of this factor will change the results of WCDS formation and the VC formation, and thus affect the effectiveness of the proposed routing protocol.

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