Enhancing the Performance of Routing in Mobile Ad Hoc Networks using Connected Dominating Sets

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ABSTRACT
Connected Dominating Sets (CDS) are very useful in improving the routing for Mobile Ad Hoc Networks (MANETs). A CDS will act as a virtual backbone for communication in the ad hoc networks. Due to the importance of the CDS in routing, formation and selection of the CDS will have significance impact on routing and performance of the network. In the literature number of metrics was proposed to select and form a CDS in a network. In this paper, we studied and analyzed algorithms to construct CDS based on different metrics. The algorithms examined include Minimum Velocity-based CDS (MinV-CDS), Maximum Density CDS (MaxD-CDS), Node ID-based CDS (ID-CDS), Node Stability Index-based (NSI-CDS) and Strong-Neighborhood based CDS (SN-CDS). The performance metrics for the CDS are its Node size, Edge size, Lifetime, Hop count per path, Diameter and Energy index.

Keywords
Connected Dominating Sets, Mobile Ad Hoc Networks, Routing, Stability, Density, Strong neighborhood.

1. INTRODUCTION
Ad hoc network is an autonomous system consisting of mobile hosts connected by wireless links. Unlike wired networks or cellular networks, no central administration and no physical backbone infrastructure is installed in ad hoc networks. Every host can move to any direction at any speed and any time. Communication is achieved either through a single-hop if the communication nodes are close enough, or through relaying by intermediate nodes otherwise. If two hosts are not located in each other's transmission range, intermediate hosts will act as routers to build communication paths. This is the *multi-hop* characteristic of the ad hoc wireless network. Wireless mobiles are usually light-weight and battery-powered. Compared with wired lines, wireless links have much less available bandwidth. The features viz., *dynamic topology, multi-hop communication, wireless interference, frequent connectivity changes and strict resource limitation* make routing as a challenging problem in ad hoc wireless network.

Ad hoc Networking has been a focus of research in recent years due to its tremendous potential in sensing, disaster relief, battle-field operations, community networking, etc. The traditional routing algorithms for wired networks are not applicable to ad hoc networks since the nodes are mobile and the network topology is dynamic. In wired networks, the network structure is mostly static and link failure is not frequent. In contrast, ad hoc networks allow higher mobility which permits rapid topology changes. Thus, pre-calculated routing information can become stale quickly. A Mobile Ad Hoc Network (MANET) [1][2] is a decentralized group of mobile nodes which exchange information using wireless transmission. Researchers have done lot of work on routing protocols on MANET. These protocols are classified into three generations these are based on their working principles and performances.

The first generation of routing schemes for MANETs concentrates on data collection. Protocols of this generation are again classified into two types – reactive and proactive routing protocols [3][4]. The Proactive protocols, such as Destination Sequenced Distance Vector (DSDV) [4][5] and Optimized Link State Routing (OLSR) protocols [6], maintain up-to-date routing information from each node to every other node in the network. In Reactive protocols viz., Dynamic Source Routing (DSR) [7][8] protocol and Ad-hoc On-demand Distance Vector Routing (AODV) [9][10] protocols, routes from source to destination are constructed only when they required to transmit message. These protocols requires network with large bandwidth and energy due to flooding problem.

The second generation of routing protocol uses coordinator-based identifier [11][12][13] to locate nodes and perform the searching and routing process. Greedy Perimeter Stateless Routing (GPSR) [11] and Beacon Vector Routing protocol (BVR) [12] belong to this category. These are efficient and smart as they use the geographic information to get the accurate address of the destination and use this information to forward packets.

The third generation routing uses *virtual backbone* and these belongs to Connected Dominating Set (CDS) routing. With the virtual backbone structure, packets do not need to go through every node in the network to a destination node. A virtual structure is created to support the necessary network services and optimize the resource usage. This is said to be virtual as it is not the direct result of the physical dedicated network components. Nodes in the virtual backbone act as a *connected skeleton* for the entire network and frequently exchange local routing information such as current traffic/mobility conditions, neighborhood information, etc. so that other routing protocols can be implemented efficiently on top of the virtual backbone. In [14], Lin et al. proposed four problems that should be studied before designing a virtual backbone algorithm. In [15] Basagni stated that a backbone should *"first and foremost be small. Additionally it should have other characteristics such as robustness to node failure low stretch, i.e. routes in the backbone should not be much longer than the shortest routes"*.

The paper is organized as the next section describes about the Connected Dominating Sets (CDS). In the Section 2 basic definitions and the terminologies related to the CDS are discussed. The Section 3 describes about the work related to the CDS. Section 5 focuses on the performance metrics for evaluating the routing protocols based on CDS. Section 6 is conclusion.

2. BASIC DEFINITIONS AND TERMINILOGIES

The dominating set problem arose in the 1850's, well before the advent of wireless networks [16]. The objective of the five queens problem is to find the minimum number of queens that can be placed on a chessboard such that all squares are either attacked or occupied by a queen. This problem was formulated as a dominating set of a graph *G* (*V*,*E*), with the vertices corresponding to squares on the chessboard, and $(u, v) \in E$ if and only if a queen can move from the square corresponding to *u* to the square corresponding to *v*.

Most of the MANET broadcast route discoveries have been implemented using flooding. Even though flooding ensures that every node gets the broadcast message, it incurs significant overhead due to multiple redundant transmissions and the resulting energy and bandwidth consumption is quite high [17]. Due to this, researchers have proposed the idea of *Connected Dominating Sets* (CDS) from graph theory. CDS based virtual backbone techniques aims at creating a structure with the characteristics of a connected dominating set. This notion is a connected variation of the dominating set, i.e. a set of nodes covering a whole graph. Creating such a backbone is suitable as all devices may either be in the backbone or have at least a one-hop neighbor in the backbone.

A MANET can be represented by a graph *G* (*V*, *E*) comprised of a set of vertices *V* and time-varying edges *E*. For each pair of vertices $u, v \in V$, $(u; v) \in E$ if and only if the nodes *u* and *v* are within communication range.

Definition 1: An *Independent Set*, is a subset of V such that no two vertices within the set are adjacent in V.

Definition 2: A *Maximal Independent Set*, is an independent set such that adding any vertex not in the set breaks the independence property of the set. Thus, any vertex outside of the maximal independent set must be adjacent to some node in the set.

Definition 3: A *dominating set* of a graph G = (*V*,*E*) is a vertex subset $S \subseteq V$, such that every vertex $v \in V$ is either in S or adjacent to a vertex of *S*. A vertex of *S* is said to dominate itself and all adjacent vertices. A dominating set can also be independent, called *independent dominating set*, in which no two vertices are adjacent. Every Maximal Independent Set (MIS) is a dominating set.

Definition 4: A *connected dominating set* of a graph is a sub graph comprising of a subset of the vertices in the original graph, such that any vertex in the graph is either in the CDS or connected to a vertex in the CDS [18].

In the Figure 1, bold nodes represent *dominators* and the *dominator number* is two, where dominator number is the number of nodes in the smallest of dominating sets. In this figure {A,B} and {B,D} are dominating sets, where as {A,B} is the connected dominating set.

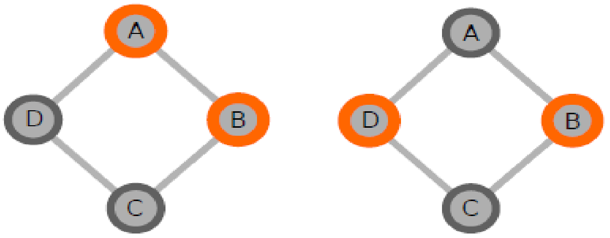

Figure 1. Two solutions for the Dominating Set problem

Definition 5: A *Minimum Connected Dominating Set* (MCDS) is the CDS with minimum cardinality. Finding minimum sized dominating set is NP-Hard problem, so that finding the MCDS is also NP-Hard.

Definition 6: A *Weakly Connected Dominated Set* (WCDS), *S*, is a dominating set such that N[S] induces a connected sub graph of *G*. In other words, the sub graph weakly induced by *S* is the graph induced by the vertex set containing *S* and its neighbors. Given a connected graph *G*, all of the dominating sets of *G* are weakly connected. Computing a minimum WCDS is NP-Hard.

Among the routing techniques proposed for MANETs, routing based on a CDS has been recognized as a suitable approach for adapting quickly to unpredictable fast changing topologies. As long as topological changes do not affect the CDS, there is no need to reconfigure the CDS; the routing tables in the CDS would still be valid.

3. RELEATED WORK

From the literature, it was observed that the CDS construction problem can be broadly classified into three categories based on the network information they use — *centralized algorithms, localized algorithms* and *distributed algorithms.*

Guha and Khullar [31] have proposed two centralized greedy algorithms for CDS construction in general graphs which contains two greedy heuristic algorithms with bounded performance guarantees. In the first algorithm, the CDS is grown from one node outward. In the second algorithm, a WCDS is constructed, and then intermediate nodes are selected to create a CDS. The centralized algorithms in [31, 32] require global information of the complete network, making them unsuitable for wireless networks which do not have centralized control.

Alzoubi *et. al.* [33] proposed a real localized 2-phase algorithm which is good at maintenance. An MIS is generated in a distributed fashion without building a tree or selecting a leader. In a localized algorithm for CDS construction, Adjih [34] proposed an approach based on multipoint relays (MPR). Based on the MPR approach several extensions have been reported leading to localized MPR based CDS construction. Wu [16] and Wu and Li [35] proposed a localized algorithm that can quickly determine a CDS in ad hoc networks. This approach uses a marking process where hosts interact with others in the neighborhood. Specifically, each host is marked true if it has two unconnected neighbors. It is shown that, collectively, these hosts achieve a desired global objective—a set of marked hosts forms a small CDS.

For sensor networks and MANETs, distributed CDS construction is more effective due to the lack of a centralized administration. Distributed algorithms can be based on a single leader or multiple leaders. In the algorithm reported in [35], Wu and Li first constructed a trivial CDS and then redundant nodes are deleted based on two sets of pruning rules. The algorithm requires that each node should know its 2-hop neighbors. The performance ratio of Wu and Li's algorithm is O(n), n being the network size. The performance ratio of distributed algorithms reported by Stojmenovic et al. in [36] is also O(n) while that of Das et al. in [32, 37] is O(logn). Thus none of the above distributed algorithms can guarantee to generate a CDS of small size. The algorithms also incur high message and time complexities. In recent works related to distributed CDS construction, it has been popular to construct a CDS by first selecting an independent dominating set, also known as a maximal independent set (MIS) and then connect the nodes in the MIS. Among all the approximation algorithms for distributed CDS construction, the best known approximation factor is (4.8+ln5)|opt|+1.2, achieved by Li's S-MIS algorithm in [38] and collaborative cover heuristic in [39]. Both the approaches first construct an MIS and then tap the MIS nodes through a Steiner tree construction. In [39], the MIS is constructed using effective coverage as a metric. However, the collaborative cover heuristic [39] has a high message complexity of $O(n\Delta^2)$ and time complexity of O(n).

According to Ephremedis *et al.*, a CDS can create a virtual network backbone for packet routing and control [19]. Messages can be routed from the source 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. This is termed *dominating set based routing* [20], or *Backbone based routing* [21], or *spine based routing* [22]. A CDS is also useful for *location-based routing*, where messages are forwarded based on the geographical coordinates of the hosts [23]. The efficiency of *multicast/broadcast routing* can also be improved through the CDS. The CDS can eliminate most of the redundant broadcasts [24, 25, 26, 27] and can solve the *broadcast storm problem* [28] also.

Nodes in a wireless network often have a limited energy supply. CDS play an important role in power management. They have been used to increase the number of nodes that can be in an sleep mode, while still preserving the ability of the network to forward messages [29]. They have also been used to balance the network management requirements to conserve energy among nodes [25, 26, 27]. In *large-scale dense sensor networks*, sensor topology information extraction can be handled by CDS construction [30].

4. CDS BASED ALGORITHMS

From the above section, it is clear that there are many ways to form a CDS within a given MANET, and the algorithm used for CDS formation will affect the performance and lifetime of the CDS and the MANET. A minimum connected dominating set (MCDS) is the smallest possible CDS in a MANET. Reducing the size of the CDS will reduce the number of unnecessary transmissions. Among the CDS based algorithms the minimum velocity-based CDS (MinV-CDS) [40] and the Node Stability Index-based CDS (NSI-CDS) [41] represents the *stability-driven CDS* algorithms; maximum density-based CDS (MaxD-CDS) [42] and Node ID-based CDS (IDCDS) [45] represents the *minimum node size-based CDS* algorithms.

4.1 Data Structures

The CDS based algorithms uses the following data structures:

(i) *MinV-CDS-Node-List* – includes all the nodes that are part of the minimum-velocity based CDS.

(ii) *Covered-Nodes-List* – includes nodes that either in the *MinV-CDS-Node-List* or covered by a node in the *MinVCDS-Node-List*

(iii) *Uncovered-Nodes-List* – includes all the nodes that are not covered by a node in the *MinV-CDS-Node-List*

(iv) *Priority-Queue* – includes nodes that are in the *Covered-Nodes-List* and are probable candidates for addition to the *MinV-CDS-Node-List*. This list is sorted in the decreasing order of the velocity of the nodes. A dequeue operation returns the node with the lowest velocity.

4.2 Minimum Velocity-based Connected Dominating Set (MinV-CDS)

In [40] the author has proposed MinV-CDS algorithm that choose nodes with lower velocity to include in the CDS. This algorithm starts with the inclusion of the node having the lowest velocity, into the CDS. Once a node is added to the CDS, all its neighbors are said to be covered. The covered nodes are considered in the increasing order of their velocity. If a node has lower velocity and is the next candidate node to be considered for inclusion in the CDS, it is added to the CDS if it has at least one uncovered neighbor. This procedure is repeated until all the nodes in the network are covered.

In the MinV-CDS algorithm, the *Priority-Queue* stores the covered non-CDS nodes in the increasing order of the node velocities and have at least one uncovered neighbor node, the node with the lowest velocity and having the at least one uncovered neighbor node is in the front of the queue. The *Start Node* is the first node added to the *MinV-CDS-Node-List*. All the neighbors of the *Start Node* are said to be covered, removed from the *Uncovered-Nodes-List* and added to the *Covered-Nodes-List* and to the *Priority-Queue*. If both the *Uncovered-Nodes-List* and the *Priority-Queue* are not empty, dequeue the *Priority-Queue* to extract a node *s* that has the lowest velocity and is not yet in the *MinV-CDS-Node-List*. If there is at least one neighbor node *u* of node *s* that is yet to be covered, all such nodes *u* are removed from the *Uncovered-Nodes-List* and added to the *Covered-Nodes-List* and to the *Priority-Queue*; node *s* is also added to the *MinV-CDS-Node-List*. If all neighbors of node *s* are already covered, then node *s* is not added to the *MinV-CDSNode-List*. This is repeated until the *Priority-Queue* becomes empty or the *Uncovered-Nodes-List* becomes empty. If the *Uncovered-Nodes-List* becomes empty, then all the nodes in the network are covered. If the *Priority-Queue* becomes empty and the *Uncovered-Nodes-List* has at least one node, then the underlying network is considered to be disconnected.

The complexity of the MinV-CDS algorithm is $O(|E| + |V|\log|V|)$ where $|V|$ and $|E|$ are the number of nodes and edges in the snapshot of the ad hoc network graph. The above time complexity is achieved only when the *Priority-Queue* is implemented as a *binary heap*. A CDS is used as long as it exists and if it is failed, the MinV-CDS algorithm is initiated to determine a new CDS.

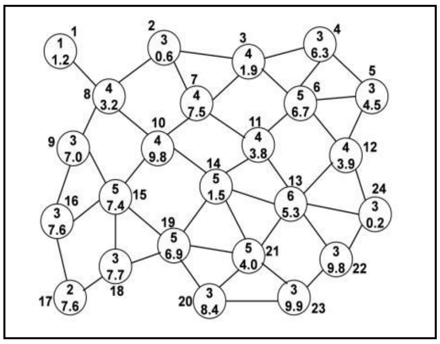

Figure 2 Initial Network

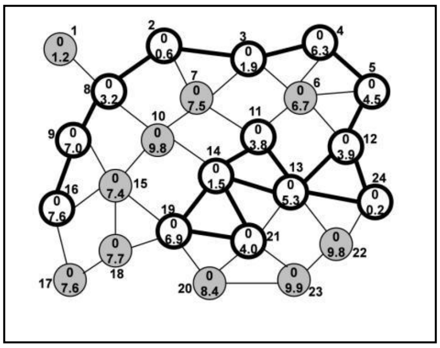

Figure 3 Final MinV-CDS edges with 14 nodes, 16 edges

Figure 2 shows the initial network. In this, a circle represents a node, integer outside the circle represents the node ID, the integer inside the circle represents the number of uncovered neighbors of the corresponding node and the real-number inside the circle represents the velocity (in m/s) of the node. In the Figure 3 the nodes that are part of the CDS have their circles bold. The shaded circles are covered, but are not part of the CDS. The MinV-CDS includes 14 nodes and 16 edges.

4.3 Node Stability Index-based Connected Dominating Set (NSI-CDS)

The idea of Node Stability Index-based algorithms is to select a node with large NSI value into the CDS. The NSI of a node is defined as the sum of the predicted expiration times of the links (LETs) with the neighbor nodes that are not yet covered by a CDS node i.e., uncovered neighbor nodes. According to [41] every node in the network maintains a LET-table having the estimated LET values to each of its neighbor node of a link $i - j$ between two nodes i and j, at (X_i, Y_i) and (X_j, Y_j), moving with velocities v_i and v_j in directions θ_i and θ_j is calculated using the following formula proposed in [47]

$$LET(i, j) = \frac{-(ab+cd)+\sqrt{(a^2+c^2)R^2-(ad-bc)^2}}{a^2+c^2}$$

Where $a = v_i*cos\theta_i - vj*cos\theta_j$; $b = X_i - X_j$;
$c = v_i*sin\theta_i - v_j*sin\theta_j$; $d = Y_i - Y_j$

The Figure 3.1 and 3.2 demonstrate the construction of CDS based on the NSI algorithm.

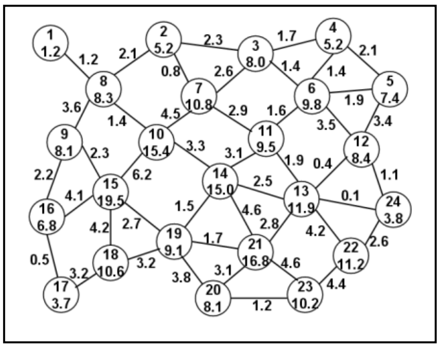

Figure 4 Initial Network graph

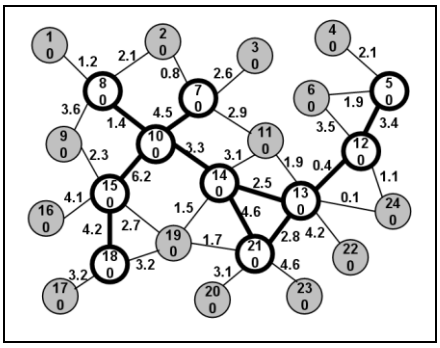

Figure 5 NSI-CDS sub graph with 10 nodes and 10 edges

The Figure 4 shows the initial network with each circle representing the node. The integer value inside the node represents the node ID and the real number represents the sum of the LETs of the edges incident on the node. The real number on the edge represents the LET of the edge. The Figure 5 shows the NSI-CDS graph. Comparing to the CDS obtained with MinV-CDS the NSI-CDS graph is having fewer CDS nodes and CDS edges. This is because the node into the NSI-CDS is decided by the number of uncovered neighbors of the node and the LETs of the links to the uncovered neighbors. The important characteristic of NSI-CDS is, nodes that have larger number of uncovered neighbors are more likely to have a larger NSI value and hence have greater chances for inclusion into the NSI-CDS.

4.4 Maximum Density based Connected Dominating Set (MaxD-CDS)

In [43] [44] several heuristics have been proposed to approximate the MCDS for MANETs. A common thread among these heuristics is to give the preference to nodes that have high neighborhood density. The MaxD-CDS heuristic [45] is one such heuristic.

In MaxD-CDS algorithm the criteria for inclusion of a node into the CDS is the number of uncovered neighbors i.e., *density*. The algorithm uses *CDS-Node-List* and *Covered-Node-List* data structures. The first node to be included in the *CDS-Node-List* is the node with the maximum number of uncovered neighbors. The node is considered as "covered" and is also added to the Covered-Nodes-List. All nodes that are adjacent to a CDS member are also said to be covered and are added to the *Covered-Node-List*. To choose the next node to be added to the *CDS-Node-List*, the criteria for CDS membership selection are: the node cannot be a member of *CDS-Node-List*, the node must be in the *Covered-Nodes-List*, and the node must have at least one uncovered neighbor. Amongst the nodes that meet these criteria, select the node with the largest density (i.e., the largest number of uncovered neighbors) will be the next member of the CDS. This process is repeated until all nodes in the network are included in the *Covered-Nodes-List*. Once all nodes in the network are considered to be "covered", the CDS has been formed and the algorithm returns *CDS-Node-List* as list of the members in the resultant MaxD-CDS.

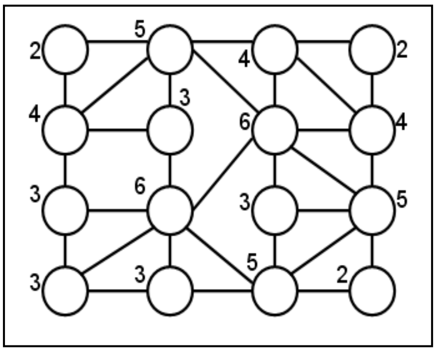

Figure 6 Initial Network graph

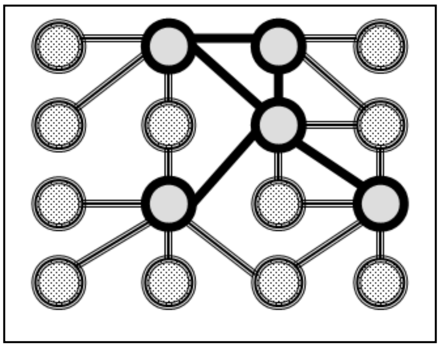

Figure 7 MaxD-CDS sub graph with 5 nodes and 5 edges

The Figure 6 and Figure 7 shows the example for MaxD-CDS algorithm, where Figure 6 shows the initial network with nodes labeled with their density. MaxD-CDS sub graph. The Figure 7 is the MaxD-CDS nodes represented with a thick black-bordered circle and gray-shaded inside; covered nodes are represented with a thick gray-bordered circles and black dots inside the circle.

4.5 Node-ID based Connected Dominating Set (ID-CDS)

The idea of the ID-CDS approach is to select nodes with larger node IDs for inclusion in the CDS, whereas the MaxD-CDS approach prefers nodes with a larger number of uncovered neighbors (a larger density) for CDS selection. Compared to MaxD-CDS, the ID-CDS method may include a slightly larger number of nodes in the CDS, but the advantage can be better connectivity and stability.

The algorithm proposed in [46] takes an input graph representing a snapshot of the MANET at a particular instance and outputs a list of nodes that are part of the CDS. The algorithm uses *CDS-Node-List* and *Covered-Node-List* data structures. The node with largest ID in the network is added to the *CDS-Node-List* as the first node and is considered as *covered*; it is also added to *Covered-Node-List*. The nodes that are adjacent to the covered node are also considered as *covered* and are added to the *Covered-Node-List*. The criteria for inclusion into the ID-based CDS are same as the criteria for inclusion into the MaxD-CDS. Amongst all the nodes of the network that meet these criteria, select the node with the largest node ID as the next member of the CDS. This process is repeated until all the nodes in the network are included in the *Covered-Nodes-List*. Once all the nodes in the network are considered to be "covered", the CDS has been formed and the algorithm returns *CDS-Node-List* as a list of members in the resultant IDCDS.

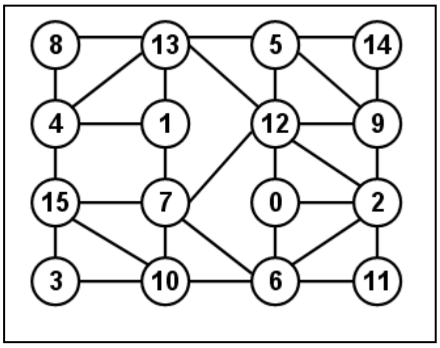

Figure 8 Initial Network graph

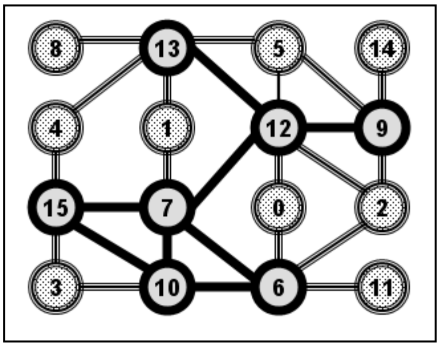

Figure 9 ID-CDS sub graph with 7 nodes and 8 edges

The Figure 8 and Figure 9 illustrate the example for ID-based CDS algorithm. The Figure 8 is the initial network with an integer in side the circle representing the ID of the node and Figure 9 shows the resultant ID-CDS sub graph with selected nodes and edges.

5. PERFORMANCE METRICS

The following performance metrics are used to measure and to evaluate the CDS based algorithms discussed in the above section.

CDS Node Size – The time-averaged value of the number of nodes in the CDS during the entire simulation time.

CDS Edge Size – The time-averaged value of the number of edges connecting nodes that are part of the CDS during the entire simulation time.

CDS Life Time – The average of the duration of existence of a CDS during the entire simulation time.

Hop count per path – The time-averaged hop count of the source-destination (s-d) paths, averaged across all s-d paths during the entire simulation time.

CDS Diameter – This is the maximum of the minimum number of hops between any two CDS nodes in the CDS-induced sub graphs containing only the edges between any two CDS nodes.

CDS Energy Index – This is a measure of the potential energy consumption that will be incurred if a CDS is used for network-wide broadcasting.

6. CONCLUSION

In this paper we have studied few of the most recent routing algorithms for MANETs based on Connected Dominating Sets. Among the two Minimum node size based CDS algorithms, the ID-based CDS is more stable than MaxD-CDS. The ID-based algorithm can form a CDS with longer average lifetime than the CDS generated by Max-CDS algorithm but with a larger node size. Under the Stability driven CDS algorithms, Node Stability Index based CDS (NSI-CDS) can be considered the best choice than the MinV-CDS, as it has a significantly lower tradeoff ratio and lower hop count per path and does not incur a significantly larger Node Size. The NSI-CDS is also the most preferred from the points of view of optimal energy consumption, delay per path, bandwidth and fairness of node usage.

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