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k-Connected *m*-Dominating Set Based Fault-Tolerant Virtual Backbone: A Survey

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Abstract – *Virtual backbone is employed to facilitate routing in ad hoc networks, which lack the physical infrastructure. In these networks, node and link failure are a common phenomenon, which makes the virtual backbone vulnerable. Even if any one of the backbone nodes fail, the virtual backbone is prone to break which ultimately breaks the network. Hence, the virtual backbone needs to have some sort of fault-tolerance capability which will help it to function even during node and link failures.k-Connected m-Dominating Set (kmCDS) has been used in the literature to construct fault-tolerant virtual backbones. kmCDS based virtual backbone structures can withstand upto k – 1 path failures and m – 1 dominator failures, and thereby the fault-tolerance capability of the network is enhanced. This paper focuses on the various kmCDS construction algorithms that have been put forth in the literature. A comparison of the major works is provided, emphasizing the technique used, k-factor and m-factor combination, performance metric used, algorithms proposed and their outcome.*

Keywords – *CDS; kmCDS; Fault-tolerant; Virtual backbone; Ad hoc networks.*

I. INTRODUCTION

An ad hoc network is a computer network with wireless communication links where each node has the capacity to forward the data to other nodes. The decision for determining what nodes are to forward the data and to whom are made dynamically based on the connectivity in the concerned network [1].

In ad hoc networks, there are no pre-designated routers and the nodes act as intermediaries (routers) to route packets among themselves. The nodes are characterized by limited energy and limited communication range. Multi-hop routing is used in such networks for the packets to reach their destinations. Due to the lack of physical infrastructure, routing in ad hoc networks becomes difficult. To overcome the difficulties in routing, virtual backbone has been proposed as a viable solution in the literature. When the virtual backbone is used, the routing path search space for each message is reduced from the whole network to the set of backbone nodes.

The virtual backbone mimics the physical infrastructure available in the wired networks. Virtual backbone has several benefits including alleviating the broadcasting storm problem, managing routing information, reducing routing related overhead, reducing wireless signal collision and interference, while increasing bandwidth efficiency and decreasing energy consumption.The concept of virtual backbone was first proposed in [2]. Conceptually, a virtual backbone is a set of nodes that can help with routing [3]. The idea of virtual backbone routing for ad hoc wireless networks is to operate routing protocols over a virtual backbone [4].

In a wireless network employing the virtual backbone, a node in the network can be either a backbone node or not. Any non-backbone node has to be adjacent to at least one backbone node. In addition, the set of backbone nodes has to be connected. Then, the routing path search space for each message is reduced from the whole network to the set of backbone nodes [5].

In virtual backbone, routing messages are not broadcasted to all the nodes. Instead, backbone nodes alone exchange the routing messages. Whenever a non-backbone node wants to communicate to a destination node, it forwards the message to a neighbour backbone node. The backbone nodes in turn send the message to the destination node. In order to decrease the protocol overhead, the virtual backbone size i.e. the number of nodes in the backbone, must be as small as possible.

A well-known approach for constructing a virtual backbone in wireless networks is Connected Dominating Set (CDS) [6]. A virtual backbone constructed using CDS usually exhibits better performance. But, in the case of networks which witness frequent node and link failures, the CDS based virtual backbone can become obsolete, thereby reducing the performance of the routing protocol. Even if any one of the backbone nodes fail, CDS is prone to break which ultimately breaks the network. Hence, the virtual backbone should be fault-tolerant,thereby having the capability to function even in the event of node and link failures. For this, *k*-Connected *m*-Dominating Set (*km*CDS) has been proposed, in the literature, as a feasible way to construct fault-tolerant virtual backbone that also provides routing flexibility and hence enhanced network performance.

In this context, the present paper focuses on the various *km*CDSbased fault-tolerant virtual backbone construction algorithms that have been proposed in the literature. The rest of the paper is organized as follows. Section 2 briefly discusses the concept of CDS, followed by *km*CDSin section 3. Section 4 elaborates the various existing research works pertaining to the construction of fault-tolerant virtual backbone using *km*CDS. Section 5 concludes the paper.

II. CONNECTED DOMINATING SET (CDS)

The history of dominating set can be tracked back to 1850's. The chess enthusiasts in Europe wanted to determine the number of queens that can be placed on a chessboard so that all squares are either attacked by a queen or are occupied by a queen. The minimum number of queens that can dominate all of the squares of an 8 x 8 chessboard turned out to be five. The five queen problem is about the placement of these five queens [7]. 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[8].

Given a graph $G= (V,E)$, a Dominating Set (DS) of G is a subset $C \subset V$ such that each node either belongs to C or is adjacent to at least one node in C[9]. In other words, a Dominating Set of a graph $G = (V,E)$ is a set of nodes V'such that $\forall(v,w) \in E$, $v \in V'$ or $w \in V'$[3].

A Dominating Set is connectedif there exist a path between any two nodes in the set and the path only consists of the nodes in the set [10]. A Connected Dominating Set of $G = (V,E)$ is a Dominating Set of G such that the subgraph of G induced by the nodes in this set is connected. The nodes in a CDS are called the dominators. The nodes other than the dominators are called the dominatees. The size of a CDS is equal to the number of dominators [3]. Each dominatee is dominated by a dominator [11]. In the CDS C, the nodes in C can communicate with any other node in the same set without using nodes in $V – C$ [12].

In CDS based routing, the dominator nodes alone maintain the routing information. A dominatee node in order to send a message to another dominatee, will send it to its dominator. Then the search space for the route is reduced to only within the CDS. When the message reaches the destination's dominator, the message is delivered to the destination via the said dominator [13].

III. *k*-CONNECTED *m*-DOMINATING SET (*km*CDS)

In the case of networks that witness frequent node and link failures, the virtual backbone structure constructed using CDS should be fault tolerant. A CDS preserves only 1-connectivity. Also many dominatees may be attached to only one dominator. Under these conditions, the failure of any one dominator results in breakage in the virtual backbone connectivity. To overcome this, the dominatee nodes need to be connected to more than one dominator node, so that the failure of dominator node(s) does not affect the reachability of the dominatee node(s). Further, multiple communication paths among the dominator nodes is essential, so that the failure of dominator node(s) does not affect the connectivity of the virtual backbone. To achieve this, *km*CDS may be utiltised to construct fault-tolerant virtual backbone.

In *km*CDS, the requirement of *k*-connectivity guarantees that, between any pair of nodes in a CDS, there exist at least k different paths. With *k*-connectivity, communication will not be disrupted even when up to $k - 1$ paths fail. *k*-connected virtual backbones also provide multi-path redundancy for load balancing and transmission error tolerance [9, 14, 15].

The requirement of *m*-domination takes care of fault-tolerance and robustness of dominatee nodes which are not part of the CDS. The *m*-domination constraint ensures that every dominatee node has at least *m*neighbour dominators in a CDS. Therefore, one dominatee node can still be connected with the CDS even when up to its $m - 1$ dominator neighbours fail [9, 14, 15]. Thus with a *km*CDS, every dominatee node can tolerate up to $m – 1$ faults on its dominators and the virtual backbone can tolerate up to $k – 1$ faults [16]. When $k= 1$ and $m= 1$ the problem is reduced to Minimum Connected Dominating Set problem [17].

Definitions:

***k*-vertex connected or *k*-connected**
A graph G is said to be *k*-vertex connected or *k*-connected if for each pair of vertices there exists at least k mutually independent paths connecting them. In other words, the graph G is still connected even after the removal of any $k – 1$ vertices from G[18].

***m*-dominating set**
An *m*-dominating set $D_m$is a set $D_m \subset V$ such that every vertex in $V \setminus D_m$ is dominated by at least m vertices in D_m[18].

***k*-Connected*m*-Dominating Set**

A set $C \subset V$ is a *k*-Connected *m*-Dominating Set (*km*CDS) of graph *G*(*V*,*E*) if the induced subgraph*G'*(*C*,*E'*) is *k*-vertex connected and the set *C* is also an *m*-dominating set of *G*[18].

IV. *km*CDSBASED FAULT-TOLERANT VIRTUAL BACKBONE CONSTRUCTION: A SURVEY

The construction of a fault-tolerant virtual backbone for wireless networks using *k*-Connected *k*-Dominating Set (*k*-CDS) was first proposed in [19]. For this, the authors have proposed four protocols to construct a *k*-CDS. All the four protocols are localized algorithms; they depend on neighbourhood information alone. The first two protocols are *k*-Gossip and *k*-Grid; both these are probabilistic schemes. The third one is an extension of a deterministic CDS algorithm. The fourth protocol is a hybrid of probabilistic and deterministic approaches that can convert many existing CDS algorithms into *k*-CDS algorithms. Here, the network is randomly partitioned into *k*subgraphs consisting of nodes with different colours (the probabilistic part). Then, for each of these subgraphs, a coloured virtual backbone is formed using a traditional CDS algorithm (the deterministic part). The authors show that, in dense wireless networks, the union of all coloured backbones forms a *k*-CDS with high probability. Further, the proposed protocols choose a small *k*-CDS with relatively low overhead.

Fault-tolerant dominating set is investigated in [20]. The authors focus on *k*-fold dominating set in two network models. They provide a distributed algorithm for general graphs and a probabilistic algorithm for a unit disk graph. Reference [21] focuses on minimum *m*-connected *k*-tuple dominating set problem. Three centralized algorithms are presented for *m*=1, 2.

*km*CDS has been studied in[22]. The authors provide two approximation algorithms: Connected Dominating Set by Maximal Independent Sets (CDSMIS) to form a 1-Connected *m*-Dominating Set (1-*m*-CDS) and Connected Dominating Set by Adding Nodes (CDSAN) to construct a *k*-CDS. Then, a general algorithm is provided for *km*CDS. To construct *km*CDS, they use CDSMIS to construct a 1-*m*-CDS and then use CDSAN to augment the 1-*m*-CDS to be a *km*CDS.

Reference [15] presents a centralized algorithm (CGA) and a distributed deterministic algorithm (DDA) to build *km*CDSfor general *k*and *m*. The authors report that, a small *km*CDS could be obtained by using CGA as compared to DDA; however, in a real network, implementing DDA is easier than CGA. Minimum *m*-connected *k*-dominating Set problem for *m*=1, 2 has been investigated in [17]. They provide two centralized approximation algorithms for the same. The authors also discuss about designing approximation algorithms for the problem with arbitrarily large *m*.

The problem of distributively constructing the *k*-dominating sets and an incremental distributed algorithm for the same has been dealt in [23]. The main idea of their algorithm is that first a 1-dominating set is formed by building a MIS. Then a MIS of the nodes that are not 2-dominated is built. When this set is added to the 1-dominating set, a 2-dominating set is obtained. The authors repeat the process until a *k*-dominating set is formed.

Reference [6] focuses on fault-tolerant CDS problem in wireless networks. An approximation algorithm for *km*CDS is presented. The algorithm achieves fault-tolerance and also minimizes the size and diameter of *km*CDS. The authors also provide two distributed algorithms for 1-connected dominating sets, viz., Basic Distributed Algorithm (BDA) and Progressive Distributed Algorithm (PDA), which could be used into the solution of the *km*CDS model.

Constructing *km*CDS for general *k* and *m* has been examined in [14]. A centralized algorithm and a distributed local decision algorithm are proposed. Further, an algorithm to construct a 1-connected *m*-dominating Set is presented, which forms a fundamental component of the proposed *km*CDS construction algorithm.

Reference [24] provides a Connecting Dominating Set Augmentation (CDSA) algorithm to form a 2-connected virtual backbone that can resist the failure of one wireless node. The key idea of their algorithm is to build a CDS first and then augment it to be 2-connected by adding new nodes to the backbone. Through simulations, the authors show that a 2-connected virtual backbone with small overhead can be constructed using CDSA.

Constructing a Connected *k*-Dominating set (1-*k*-CDS) is examined in [25]. The authors first present a distributed connected dominating set construction algorithm (DACDS) to build a 1-Connected 1-Dominating Set (1-1-CDS) which involves two steps: MIS construction and then connecting all nodes in the MIS using a Steiner tree. Based on DACDS, the authors then propose a fault-tolerant connected *k*-dominating set algorithm for the minimum 1-*k*-CDS problem. They show that the proposed algorithm has better performance ratios and low message complexity.

Reference [26] proposes a decentralized algorithm, Blackbone, for constructing 2-Connected 1-Dominating Set (2-1-CDS). It is based upon a low message complexity approach and a very high degree of localization. The authors state that the nodes require only 2-hop neighbourhood information to take decisions. The proposed algorithm gives good results for 1-connected 1-dominating set also.

2-Connected *m*-Dominating Set (2-*m*-CDS) in ad hoc networks has been studied in [27]. A decentralized algorithm, Blackbone2, is proposed. It creates a robust backbone in ad hoc networks and is adaptable to mobile environments. 2-*m*-CDS supports backbone robustness and the rules that are used depend only on 2-hop knowledge.

Reference [9] provides three algorithms to construct *km*CDS for general *k*and *m* in wireless networks. A Centralized Sequentially Augment Algorithm (CSAA) and two distributed algorithms, viz., Distributed Deterministic Algorithm (DDA) and Distributed Probabilistic Algorithm (DPA) are provided. CSAA is appropriate for small wireless networks, whereas DDA and DPA are suitable for large scale networks.

Constructing quality fault-tolerant virtual backbone in wireless networks has been examined in [28]. The authors put forward an algorithm, viz., Fault-Tolerant Connected Dominating Sets Computation Algorithm (FT-CDS-CA), to construct a smaller-size 3-Connected *m*-Dominating Set (3-*m*-CDS). Reference [29] has investigated the problem of finding small *k*-dominating sets in general graphs, which allow $k – 1$ nodes to fail and still dominate the graph. Reference [16] provides a greedy algorithm that constructs a minimum 1-*m*-CDS.

For the minimum *km*CDS problem, an integer programming formulation and an optimal algorithm to achieve routing flexibility and fault-tolerance is presented in [30]. The results indicate that their proposed optimal algorithm finds a solution within a reasonable amount of time.

Reference [31] provides an approximation algorithm for minimum 3-connected *m*-dominating set problem for $m \geq 3$ using Tutte's decomposition technique. The authors show that the proposed algorithm provides smaller 3-connected 3-dominating sets.

Some of the research studies in the area of fault-tolerant virtual backbone construction using *km*CDS are summarized in Table 1.

Table 1. Research work pertaining to fault-tolerant virtual backbone construction using kmCDS

Study	**Technique**	***k*-factor and *m*-factor**	**Performance Metric**	**Algorithm**	**Outcome**
[15]	Uses degree and energy	*k*-Connected *m*-Dominating Set (*km*CDS)	Size of CDS, Size of *km*CDS	Centralized Algorithm (CGA) and Distributed Deterministic Algorithm (DDA)	Smaller *km*CDS, robust and fault-tolerant virtual backbone
[6]	Uses size and diameter	*k*-Connected *m*-Dominating Set (*km*CDS)	Size of CDS, Diameter of CDS	Approximation algorithm, Basic Distributed Algorithm (BDA) and Progressive Distributed Algorithm (PDA)	Minimizes the size and diameter, minimizes the network latency and fault-tolerant
[25]	MIS and Steiner tree	Connected *k*-Dominating Set (1-*k*-CDS)	Size of CDS	Distributed algorithm (DACDS) and Fault-tolerant algorithm	Better performance ratios and low message complexity
[26]	Uses 2-hop neighbourhood information	2-Connected 1-Dominating Set (2-1-CDS)	Number of backbone nodes,	Blackbone, a decentralized algorithm	Low message complexity and robust backbone

Table 1. Research work pertaining to fault-tolerant virtual backbone construction using kmCDS (continued)

Study	Technique	*k*-factor and *m*-factor	Performance Metric	Algorithm	Outcome
[27]	Uses 2-hop neighbourhood information	2-Connected *m*-Dominating Set (2-*m*-CDS)	Number of backbone nodes, State changes per node	Blackbone2, a deterministic algorithm	Adaptable to mobile environments and supports backbone robustness
[24]	Augmentation	2-Connected 1-Dominating Set (2-1-CDS)	CDS size	Connecting Dominating Set Augmentation (CDSA) algorithm	Small overhead and Fault-tolerant
[9]	Augmentation	*k*-Connected *m*-Dominating Set (*km*CDS)	Size of *km*CDS, Success Ratio	Centralized Sequentially Augment Algorithm (CSAA), Distributed Deterministic Algorithm (DDA) and Distributed Probabilistic Algorithm (DPA)	High success rate
[31]	Tutte decomposition	3-Connected *m*-Dominating Set (3-*m*-CDS)	Size of CDS	Approximation algorithm	Smaller approximation factor

It is evident, from the review of literature, that distributed algorithms have been largely proposed for constructing fault-tolerant virtual backbone using *km*CDS, due to the inherent nature of lack of central administration in ad hoc networks. Most of the research works have relied upon localized neighbourhood information to form *km*CDS. The performance metric of special interest, in the various works, has been small size *km*CDS. Other metrics include minimizing the diameter of the *km*CDS, low message complexity and very high degree of localization. Some of the algorithms have used MIS based approach in the initial phases of the *km*CDS construction. Also, various combinations of *k*-factor and *m*-factor algorithms have been attempted in the literature.

V.CONCLUSION

Virtual backbone constructed using CDS is basically 1-connected 1-dominating. The failure of any one backbone node renders the virtual backbone obsolete. Particularly, in the case of networks that witness frequent node and link failures, the virtual backbone should be fault-tolerant that continues to function even in the event of such failures. Various research works have used *km*CDS to construct fault-tolerant virtual backbone. This paper presented a survey of the various *km*CDS construction algorithms. It is observed that, though various centralized and distributed algorithms have been proposed, focus has largely been on distributed algorithms. The size of the *km*CDS has been given utmost importance among the various performance metrics and most of the algorithms have used local neighbourhood information to construct *km*CDS.

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