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Article

# Generalized Domination and Cardinality in Hop Fuzzy Graphs

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**Abstract:** This paper outlines the Hop Fuzzy Graph (HFG) as an extension of fuzzy graph models. Each vertex and edge is characterized by mem-bership, non-membership, hop membership and hop non-membership functions. The concepts of cardinality and domination are redefined in this framework. Applications to graphs such as the Moser spin-dle, cricket and Diamond graph demonstrate that hop-based analysis reduces domination size and provides a more comprehensive model structure.

**Keywords:** Hop Fuzzy1Graph, Graph Cardinality, Hop Domination Number, Moser Spindle Graph, Intuitionistic Fuzzy Graph, etc.

## 1. Introduction

Graph theory constitutes a fundamental domain within discrete mathematics [4] offering a robust framework for modelling and analyzing relational structures among entities. A graph comprising a set of vertices and edges serves as an essential mathematical abstraction for representing complex systems such as communication networks, transportation infrastructures, biological interactions, and social relationships .The inception of fuzzy set theory by Lotfi A. [14] Zadeh in 1965 marked a paradigm shift in handling uncertainty beyond the limitations of classical binary logic. Unlike traditional set the-ory where elements are strictly classified as either members or non-members fuzzy set theory permits partial membership characterized by values in the interval . This flexibility enables a more realistic representation of ambiguous and imprecise information, which is prevalent in numerous practical applica-tions. For instance the strength of interpersonal relationships, the reliability of network connections and the degree of similarity between biological enti-ties cannot be adequately captured using crisp classifications. Subsequently, [9] fuzzy graph theory emerged as a natural extension of fuzzy sets, wherein vertices and edges are associated with membership values that quantify their significance and relational strength, respectively. This framework has proven to be highly effective in modeling systems with inherent uncertainty. Fur-ther refinement of this concept led to the development of intuitionistic fuzzy graphs, which incorporate both membership and non-membership functions, thereby providing a more comprehensive depiction of uncertainty along with an implicit degree of hesitation. In order to address this shortcoming, the present study introduces the concept of a Hop Fuzzy Graph (HFG). The proposed Hop Fuzzy Graph framework extends conventional fuzzy and in-tuitionistic fuzzy graph models by incorporating such indirect interactions, thereby facilitating a more holistic analysis of network structures. Within the Hop Fuzzy Graph paradigm, each vertex and edge is characterized by four distinct parameters: membership, non-membership, hop membership, and hop nonmembership functions. While the membership and non-membership values encapsulate the direct attributes of vertices and edges, the hop mem-bership and hop non-membership values quantify the influence arising from indirect relationships. This enriched representation significantly enhances the descriptive and analytical capabilities of the graph model. One of the primary motivations for introducing Hop Fuzzy Graphs lies in the refinement of the concept of domination in graphs[9]. Domination constitutes a pivotal notion in graph theory wherein a subset of vertices is said to dominate the graph if every vertex is either contained within the subset or is adjacent to at least one vertex in it[11]. This concept finds extensive applications in areas such as network monitoring facility location optimization, and resource al-location. However, when indirect relationships are taken into consideration, the traditional definition of domination can be generalized to include vertices that are within a distance of two thereby yielding more efficient and practi-cally viable solutions. Another critical aspect of graph analysis pertains to the concept of cardinality, which serves as a quantitative measure of the size or structural intensity of a graph. In classical graph theory, cardinality is simply defined in terms of the number of vertices and edges. In fuzzy and intuitionistic fuzzy graphs this notion is extended by incorporating member-ship and non-membership values. The Hop Fuzzy Graph further generalizes this concept by including hop membership and hop non-membership parame-ters. In the present work, the proposed Hop Fuzzy Graph model is applied to several notable graph structures, including the Moser spindle, the Diamond graph and the Cricket graph. These graphs have been selected due to their distinctive topological characteristics and their relevance in theoretical and applied contexts.

## 2. Preliminaries

In this section, we present some basic definitions related to fuzzy graphs and hop fuzzy graphs.

Definition: 2.1

A graph $G = (V, \mu)$ is said to be a fuzzy graph if it satisfies the following conditions:

(i) The function $\mu : V \to [0, 1]$ is a fuzzy subset of a non-empty set $V$.

(ii) The function $\sigma : V \times V \to [0, 1]$ is a symmetric fuzzy relation on $V$ such that

$$\sigma(v_i, v_j) \le \min\{\mu(v_i), \mu(v_j)\},$$

for all $v_i, v_j \in V$.

Definition: 2.2

The hop graph $H(G)$ of a graph $G$ is the graph obtained from $G$ by taking [ V(H(G)) = V(G) ] and joining two vertices $(u, v)$ in $H(G)$ if they are at a distance 2 in $G$.

Definition: 2.3

A Hop Fuzzy Graph (HFG) is a graph [ G=(V,E), ] where $V$ is the vertex set and $E$ is the edge set. Let

[ $\sigma_A, \ \mu_A, \ \rho_{HA}, \ \lambda_{HA} : V \to [0, 1]$]

represent the degree of Membership (MS), Non-Membership (NMS), Hop Membership (HMS), and Hop Non-Membership (HNMS), respectively, of a vertex $v \in V$.

$$\rho_{HA}(V) \le \min\{d(\sigma_A(u, v)) = 2\}$$

$$\lambda_{HA}(V) \ge \max\{d(\mu_A(u, v)) = 2\},$$

$$0 \le \sigma_A(V) + \mu_A(V) + \rho_{HA}(V) + \lambda_{HA}(V) \le 1 \quad (1)$$

$$\sigma_B, \mu_B, \rho_{HB}, \lambda_{HB} : V \times V \to [0, 1]$$

represent the degree of MS, NMS, HMS and HNMS of

$$x = (u, v) \in V \times V$$

$$\sigma_B(x) \le \min\{\sigma_A(u), \sigma_A(v)\} \quad (2)$$

$$\mu_B(x) \ge \max\{\mu_B(u), \mu_B(v)\} \quad (3)$$

$$\rho_{HB}(V) \le \min\{\rho_{HA}(u), \rho_{HA}(v)\} \quad (4)$$

$$\lambda_{HB}(V) \le \max\{\lambda_{HA}(u), \lambda_{HA}(v)\} \quad (5)$$

$$0 \le \sigma_B(x) + \mu_B(x) + \rho_{HB}(x) + \lambda_{HB}(x) \le 1 \quad (6)$$

Definition: 2.4

The Moser spindle is a unit distance graph consisting of 7 vertices and 11 edges arranged in plane such that every edge has equal length.

Definition: 2.5

The cricket graph is also called as campstool graph, it is a small planar undirected graph with 5 vertices and 5 edges. Its structure as a triangle $k3$ with two disjoint pendant vertices attached to one vertices.

Definition: 2.6

A diamond graph is a simple undirected graph formed by removing one edge from the complete graph $k4$. It consists of four vertices and five edges, cresting two triangular faces that share a common edges.

Definition: 2.7

Let $G = (V, E)$ be an HFG. Then the cardinality of $G$ is defined to be

$$|G| = \sum_{v_i \in V} \frac{1 + \sigma_A(v) - \mu_A(v) + \rho_{H_A}(v) - \lambda_{H_A}(v)}{2} \cdot \sum_{(u,v)\in E} \frac{1 + \sigma_B(u,v) - \mu_B(u,v) + \rho_{H_B}(u,v) - \lambda_{H_B}(u,v)}{2}.$$

Definition: 2.8

A subset $H$ of $V$ is called a dominating set in $G$ if for every $v \in V - H$, there exists $u \in H$ such that $u$ dominates $v$.

## 3. Main Results

### *THEOREM : 3.1*

If $G = (V, E)$ be a Hop Fuzzy Moser spindle graph, then Fuzzy domina-tion number of $G$ is

$$\gamma(G) = 2.$$

Proof.

Let us consider the set $D = \{a, d\}$. From the structure of the given Moser spindle graph (Fig. 3.1), vertex $a$ is directly adjacent to the vertices $b$, $c$, $f$ ,

and $g$. Thus, these vertices are directly dominated by $a$.

Now consider the remaining vertices. The vertex $e$ is connected to $a$ through the path $d \to f \to g$. The vertex $d$ is connected to $a$ through the path $b \to c \to e$ and it has minimum degree value of Membership (MS), Non-Membership (NMS), Hop Membership (HMS) and Hop Non-Membership

(HNMS).

Thus, every vertex in $V$ is directly dominated by $(a, d)$. Hence, $D = \{a, d\}$

is a dominating set, we obtain

$\gamma(G) = 2$.

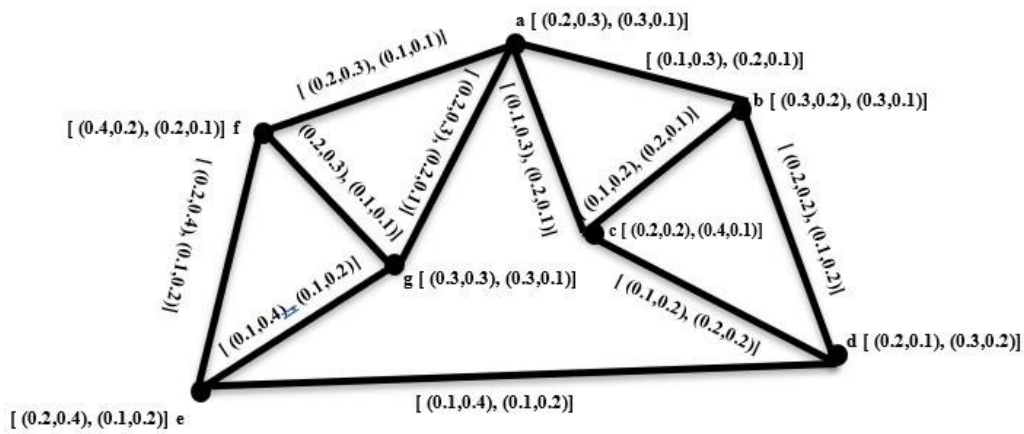


Figure 1: Generalized Domination and Cardinality in Hop Fuzzy Graphs

## *THEOREM : 3.2*

Domination number of the hop fuzzy diamond graph is 1.

Proof:

Let $G = (V, E)$ be a Hop Fuzzy Graph defined on a diamond graph with vertex set

$$V = \{a, b, c, d\}.$$

Let us assess the set $D = \{d\}$ all vertices are dominates by $d$. The Hop Fuzzy domination number is

$$\gamma(G) = 1.$$

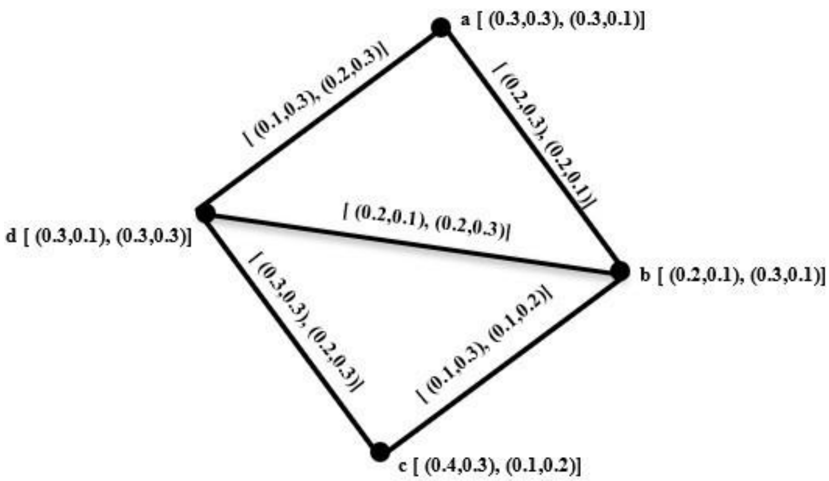


Figure 2: Hop Fuzzy Diamond Graph

## *THEOREM: 3.3*

If $G = (V, E)$ be a Hop Fuzzy cricket Graph, Then the Hop Fuzzy domi-nation number is

$$\gamma(G) = 1.$$

Proof:

A cricket graph consists of five vertices and five edges, where one vertex has degree four, two vertices has degree two and two vertices have degree one. Let $G$ be a hop fuzzy graph defined on the vertex set

$$V = \{a, b, c, d, e\}.$$

with fuzzy vertex membership values:

$$a = [(0.2, 0.1), (0.3, 0.2)], \quad b = [(0.2, 0.2), (0.1, 0.2)], \quad c = [(0.2, 0.3), (0.2, 0.2)],$$

$$d = [(0.3, 0.1), (0.3, 0.2)], \quad e = [(0.3, 0.1), (0.2, 0.2)].$$

and fuzzy edge membership values:

$$(a, c) = [(0.1, 0.3), (0.2, 0.2)],$$

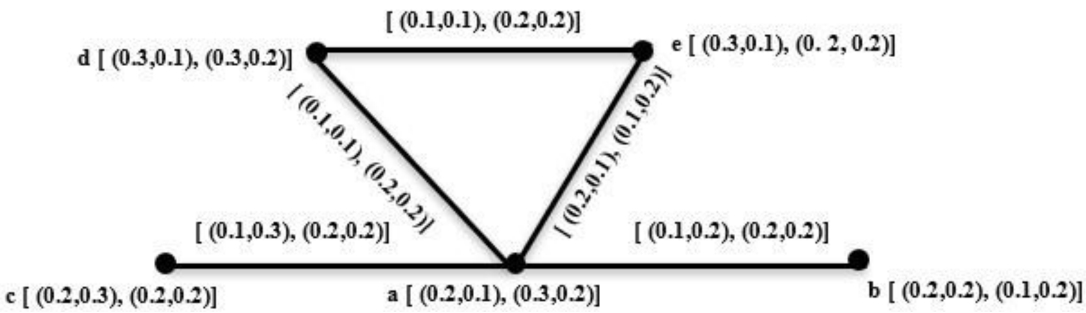


Figure 3: Hop Fuzzy Cricket Graph

$$(a, b) = [(0.1, 0.2), (0.2, 0.2)],$$

$$(a, d) = [(0.1, 0.1), (0.2, 0.2)],$$

$$(a, e) = [(0.2, 0.1), (0.1, 0.2)],$$

$$(d, e) = [(0.1, 0.1), (0.2, 0.2)].$$

Let consider the set $D = \{a\}$, where $a$ is the central vertex of the graph. From the structure of the graph, vertex $a$ is directly connected to all vertices.

Hence domination number of $G$ is

$$\gamma(G) = 1.$$

and fuzzy edge membership values:

$$(a, c) = [(0.1, 0.3), (0.2, 0.2)], \qquad (a, b) = [(0.1, 0.2), (0.2, 0.2)],$$

$$(a, d) = [(0.1, 0.1), (0.2, 0.2)],$$

$$(a, e) = [(0.2, 0.1), (0.1, 0.2)], \quad (d, e) = [(0.1, 0.1), (0.2, 0.2)].$$

Let Consider the set $D = \{a\}$. Where $a$ is the central vertex of the graph. From the structure of the graph, Vertex $a$ is directly connected to all vertices.

Hence domination number of $G$ is

$$\gamma(G) = 1.$$

## 4. Cardinality Relationship Between Hop Fuzzy Graph and Removing of Vertices in Hop Fuzzy Graph

Definition: 4.1

If removing of a vertex in a graph often denoted as $(G - v)$, is the oper-ations of subtract a specific vertex along with all its incident edges from a graph $G$.

*THEOREM : 4.1*

The graph $G$ is hop fuzzy Moser spindle graph, if subtract a vertex then the cardinality of

$$|HFG(G - v)| < |HFG(G)|.$$

Proof:

A Moser spindle graph is a finite undirected graph

$$G = (V, E).$$

It consists of 7 vertices and 11 edges. By definition, the cardinality of a Hop Fuzzy Graph is given by

$$|G| = \sum_{v_i \in V} \frac{1 + \sigma_A(v) - \mu_A(v) + \rho_{H_A}(v) - \lambda_{H_A}(v)}{2} + \sum_{(u,v) \in E} \frac{1 + \sigma_B(u,v) - \mu_B(u,v) + \rho_{H_B}(u,v) - \lambda_{H_B}(u,v)}{2}.$$

And fuzzy edge membership values:

$(a, b) = [(0.1, 0.3), (0.2, 0.1)]$, $(a, c) = [(0.1, 0.3), (0.2, 0.1)]$,

$(a, f) = [(0.2, 0.3), (0.1, 0.1)]$, $(a, g) = [(0.2, 0.3), (0.2, 0.1)]$,

$(f, g) = [(0.2, 0.3), (0.1, 0.1)]$, $(f, e) = [(0.2, 0.4), (0.1, 0.2)]$,

$(e, d) = [(0.1, 0.4), (0.1, 0.2)]$, $(c, d) = [(0.1, 0.2), (0.2, 0.2)]$,

$(b, d) = [(0.2, 0.2), (0.4, 0.1)]$, $(b, c) = [(0.1, 0.2), (0.2, 0.1)]$,

$(g, e) = [(0.1, 0.4), (0.1, 0.2)]$.

Then, the total contribution from all vertices is calculated as

$$|V| = \sum_{v_i \in V} \frac{1 + \sigma_A(v) - \mu_A(v) + \rho_{H_A}(v) - \lambda_{H_A}(v)}{2}.$$

$$a = \frac{1 + 0.2 - 0.3 + 0.3 - 0.1}{2} = 0.55, \qquad b = \frac{1 + 0.3 - 0.2 + 0.3 - 0.1}{2} = 0.65.$$

$$c = \frac{1 + 0.2 - 0.2 + 0.4 - 0.1}{2} = 0.65, \qquad g = \frac{1 + 0.3 - 0.3 + 0.3 - 0.1}{2} = 0.60.$$

$$\Rightarrow |V| = 4.05.$$

Then the total contribution from all edges is calculated as

$$|E| = \sum_{(u,v) \in E} \frac{1 + \sigma_B(u,v) - \mu_B(u,v) + \rho_{H_B}(u,v) - \lambda_{H_B}(u,v)}{2}.$$

Therefore, the cardinality of the graph is

$$|E| = 4.95.$$

The cardinality of

$$|G_H| = 4.05 + 4.95 = 9.$$

Hence, the Moser spindle Hop Fuzzy Graph admits a single vertex dom-inating set $\gamma(G) = 1$ and its total cardinality is equal to 9.

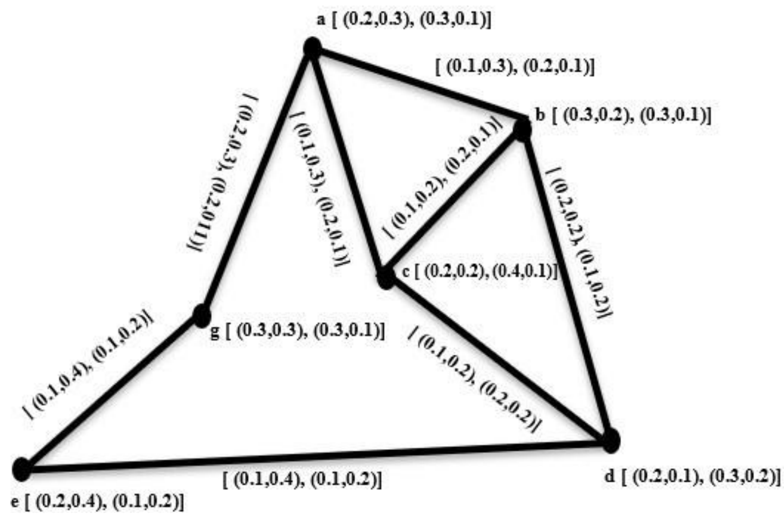


Figure 4: Hop Fuzzy Moser Spindle Graph after Vertex Removal

By removing a degree minimum with high membership value vertex in hop fuzzy Moser spindle graph we have 6 vertices and 8 edges.

The cardinality of a Hop Fuzzy Graph is given by

$$|G| = \sum_{v_i \in V} \frac{1+\sigma_A(v)-\mu_A(v)+\rho_{H_A}(v)-\lambda_{H_A}(v)}{2} + \sum_{(u,v)\in E} \frac{1+\sigma_B(u,v)-\mu_B(u,v)+\rho_{H_B}(u,v)-\lambda_{H_B}(u,v)}{2}.$$

The fuzzy vertex membership values:

$a$ = [(0.2, 0.3), (0.3, 0.1)], $b$ = [(0.3, 0.2), (0.3, 0.1)],

$c$ = [(0.2, 0.2), (0.4, 0.1)], $d$ = [(0.2, 0.1), (0.3, 0.2)],

$e$ = [(0.2, 0.4), (0.1, 0.2)], $g$ = [(0.3, 0.3), (0.3, 0.1)].

And fuzzy edge membership values:

$(a, b)$ = [(0.1, 0.3), (0.2, 0.1)], $(a, c)$ = [(0.1, 0.3), (0.2, 0.1)],

$(a, g)$ = [(0.2, 0.3), (0.2, 0.1)], $(e, d)$ = [(0.1, 0.4), (0.1, 0.2)],

$(c, d)$ = [(0.1, 0.2), (0.2, 0.2)], $(b, d)$ = [(0.2, 0.2), (0.4, 0.1)],

$(b, c)$ = [(0.1, 0.2), (0.2, 0.1)], $(g, e)$ = [(0.1, 0.4), (0.1, 0.2)].

The total contribution from all vertices is calculated as

$$|V| = \sum_{v_i \in V} \frac{1+\sigma_A(v)-\mu_A(v)+\rho_{H_A}(v)-\lambda_{H_A}(v)}{2} = 3.4.$$

Then the total contribution from all edges is calculated as

$$|E| = \sum_{(u,v)\in E} \frac{1 + \sigma_B(u,v) - \mu_B(u,v) + \rho_{H_B}(u,v) - \lambda_{H_B}(u,v)}{2} = 3.7.$$

Therefore, the cardinality of

$$|G| = 3.4 + 3.7 = 7.1.$$

Hence, by comparing both we get the cardinality of

$|HFG(G - v)| < |HFG(G)|$.

## *THEOREM : 4.2*

The cardinality of hop fuzzy diamond graph

$$|HFG(G - v)| < |HFG(G)|.$$

Proof:

Let $G = (V, E)$ be a Hop Fuzzy Graph defined on a diamond graph with vertex set

$$V = \{a, b, c, d\}.$$

By definition, the cardinality of a Hop Fuzzy Graph is given by

$$|G| = \sum_{v_i\in V} \frac{1 + \sigma_A(v) - \mu_A(v) + \rho_{H_A}(v) - \lambda_{H_A}(v)}{2} + \sum_{(u,v)\in E} \frac{1 + \sigma_B(u,v) - \mu_B(u,v) + \rho_{H_B}(u,v) - \lambda_{H_B}(u,v)}{2}.$$

From Fig. 3.2, the total contribution from all vertices is calculated as

$$|V| = \sum_{v_i\in V} \frac{1 + \sigma_A(v) - \mu_A(v) + \rho_{H_A}(v) - \lambda_{H_A}(v)}{2} = 3.7$$

and then the total contribution from all edges is calculated as

$$|E| = \sum_{(u,v)\in E} \frac{1 + \sigma_B(u,v) - \mu_B(u,v) + \rho_{H_B}(u,v) - \lambda_{H_B}(u,v)}{2} = 4.3.$$

Therefore, the cardinality of

$$|G| = 3.7 + 4.3 = 8.$$

Hence, the diamond Hop Fuzzy Graph admits a dominating set $\gamma(G) = 1$ and its total cardinality is equal to 8.

If removing of a vertex with minimum degree and maximum value of membership, the graph has 3 vertices and 3 edges.

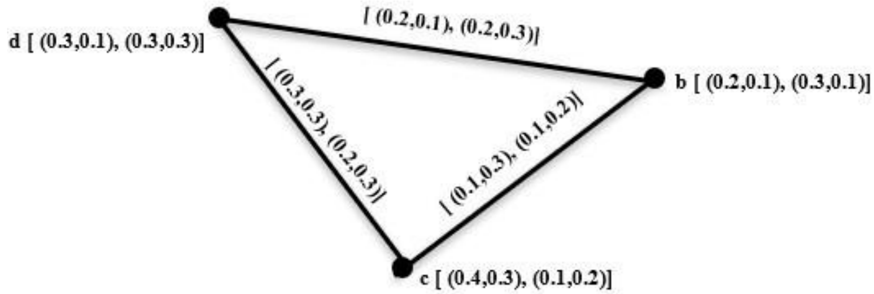


Figure 5: Hop Fuzzy Diamond Graph after Vertex Removal

$$|V| = \sum_{v_i \in V} \frac{1 + \sigma_A(v) - \mu_A(v) + \rho_{H_A}(v) - \lambda_{H_A}(v)}{2} = 1.75$$

and then the edges is calculated as

$$|E| = \sum_{(u,v) \in E} \frac{1 + \sigma_B(u,v) - \mu_B(u,v) + \rho_{H_B}(u,v) - \lambda_{H_B}(u,v)}{2} = 1.45.$$

Therefore, the cardinality of

$$|G| = \begin{array}{l} \displaystyle\sum_{v_i \in V} \frac{1 + \sigma_A(v) - \mu_A(v) + \rho_{H_A}(v) - \lambda_{H_A}(v)}{2} \\ \cdot \displaystyle\sum_{(u,v) \in E} \frac{1 + \sigma_B(u,v) - \mu_B(u,v) + \rho_{H_B}(u,v) - \lambda_{H_B}(u,v)}{2} \end{array}$$

$$= |1.75 + 1.45| = 3.2.$$

Therefore,

$$|3.2| < 8|.$$

Hence it proves our statement

$$|HFG(G - v)| < |HFG(G)|.$$

## *THEOREM : 4.3*

If the graph $G$ is hop fuzzy cricket graph, if subtract a vertex then the cardinality of $|HFG(G - v)| < |HFG(G)|$.

Proof:

The value of Fig. 3.3, all vertices is calculated as

$$|V| = \sum_{v_i \in V} \frac{1 + \sigma_A(v) - \mu_A(v) + \rho_{H_A}(v) - \lambda_{H_A}(v)}{2} = 2.75$$

and then the total contribution from all edges is calculated as

$$|E| = \sum_{(u,v)\in E} \frac{1 + \sigma_B(u,v) - \mu_B(u,v) + \rho_{H_B}(u,v) - \lambda_{H_B}(u,v)}{2} = 2.5.$$

Therefore, the cardinality of

$$|G| = 2.75 + 2.5 = 5.25.$$

Hence, the cricket Hop Fuzzy Graph admits a dominating set $\gamma(G) = 1$ and its total cardinality is equal to 5.25.

Let $(G - v)$ be a hop fuzzy graph subtract vertex $b$. It has minimum degree and maximum membership value and the vertex set is

$$V = \{a, c, d, e\}$$

with fuzzy vertex membership values:

$$a = [(0.2, 0.1), (0.3, 0.2)], \quad c = [(0.2, 0.3), (0.2, 0.2)],$$

$$d = [(0.3, 0.1), (0.3, 0.2)], \quad e = [(0.3, 0.1), (0.2, 0.2)].$$

and fuzzy edge membership values:

$$(a, c) = [(0.1, 0.3), (0.2, 0.2)], \quad (a, d) = [(0.1, 0.1), (0.2, 0.2)],$$

$$(a, e) = [(0.2, 0.1), (0.1, 0.2)], \quad (d, e) = [(0.1, 0.1), (0.2, 0.2)].$$

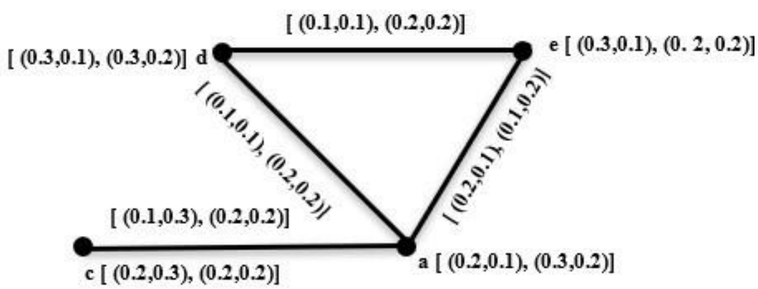


Figure 6: Hop Fuzzy Cricket Graph after Removing Vertex *b*

$$|V| = 2.3$$

and then the edges is calculated as

$$|E| = 2.05.$$

Therefore, the cardinality of

$$|G| = \sum_{v_i\in V} \frac{1 + \sigma_A(v) - \mu_A(v) + \rho_{H_A}(v) - \lambda_{H_A}(v)}{2} \cdot \sum_{(u,v)\in E} \frac{1 + \sigma_B(u,v) - \mu_B(u,v) + \rho_{H_B}(u,v) - \lambda_{H_B}(u,v)}{2}.$$

$$= |2.3 + 2.05| = 4.35.$$

Therefore,

$$4.35 < 5.25.$$

Hence it validates our statement

$$|HFG(G - v)| < |HFG(G)|.$$

## 5. Conclusion

This paper proposes Hop Fuzzy Graphs as a sophisticated generalization of fuzzy graph theory by incorporating indirect interactions through hop-based parameters. The framework refines the notions of domination and cardinality yielding a more comprehensive and nuanced structural representation.

The examination of Moser spindle, diamond, and cricket graphs reveals that a single vertex suffices to dominate the entire network within this paradigm. Furthermore, the cardinality formulation integrates both direct and indirect influences with greater precision.

It is also established that vertex removal results in a strict diminution of cardinality affirming structural coherence. Hence, Hop Fuzzy Graphs consti-tute a robust model for complex uncertain systems.

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