Domination in intersecting hypergraphs

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Abstract

A matching in a hypergraph $H$ is a set of pairwise disjoint hyperedges. The matching number $\alpha'(H)$ of $H$ is the size of a maximum matching in $H$. A subset $D$ of vertices of $H$ is a dominating set of $H$ if for every $v \in V \setminus D$ there exists $u \in D$ such that $u$ and $v$ lie in an hyperedge of $H$. The cardinality of a minimum dominating set of $H$ is called the domination number of $H$, denoted by $\gamma(H)$. It is known that for a intersecting hypergraph $H$ with rank $r$, $\gamma(H) \leq r - 1$. In this paper we present structural properties on intersecting hypergraphs with rank $r$ satisfying the equality $\gamma(H) = r - 1$. By applying the properties we show that all linear intersecting hypergraphs $H$ with rank 4 satisfying $\gamma(H) = r - 1$ can be constructed by the well-known Fano plane.

Keywords: Hypergraph; Intersecting hypergraph; Domination; Matching; Linear hypergraph

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1 Introduction

Hypergraphs are a natural generalization of undirected graphs in which “edges” may consist of more than 2 vertices. More precisely, a (finite) hypergraph $H = (V(H), E(H))$ consists of a (finite) set $V(H)$ and a collection $E(H)$ of non-empty subsets of $V(H)$. The elements of $V(H)$ are called vertices and the elements of $E(H)$ are called hyperedges, or simply edges of the hypergraph. An $r$-edge is an edge containing exactly $r$ vertices. The rank of $H$, denoted by $r(H)$, is the maximum size of an edge in $H$. Specially, An $r$-uniform hypergraph $H$ is a hypergraph such that all edges are $r$-edges. A hypergraph is called linear if any two edges of the hypergraph intersect in at most one vertex. Obviously, every (simple) graph is a linear

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2-uniform hypergraph. Throughout this paper, we only consider hypergraphs of rank \( r \geq 2 \) without multiple edges and all edges have size at least 2.

The degree of a vertex \( v \) in \( H \), denoted by \( d_H(v) \), is the number of edges of \( H \) containing the vertex \( v \). A vertex of degree zero is called an isolated vertex. A vertex of degree \( k \) is called a degree-\( k \) vertex. The minimum and maximum degree among the vertices of \( H \) are denoted by \( \delta(H) \) and \( \Delta(H) \), respectively. The quasidegree of \( v \) in \( H \), denoted \( qd_H(v) \), is the maximum number of edges of \( H \) whose pairwise intersection is only \( v \). Two vertices \( u \) and \( v \) in \( H \) are adjacent if there is an edge \( e \) of \( H \) such that \( \{u, v\} \subseteq e \). The open neighborhood of a vertex \( v \) in \( H \), denoted \( N_H(v) \), is the set of all vertices different from \( v \) that are adjacent to \( v \). If \( H \) is clear from the context, we denote \( d_H(v) \), \( qd_H(v) \) and \( N_H(v) \) by \( d(v) \), \( qd(v) \) and \( N(v) \), respectively.

Two edges in \( H \) are said to be overlapping if they intersect in at least two vertices.

A partial hypergraph \( H' = (V(H'), E(H')) \) of \( H = (V(H), E(H)) \), denoted by \( H' \subseteq H \), is a hypergraph such that \( V(H') \subseteq V(H) \) and \( E(H') \subseteq E(H) \). In the class of graphs, partial hypergraphs are called subgraphs. In particular, if \( V(H') = V(H) \), \( H' \) is called a spanning partial hypergraph of \( H \).

For a hypergraph \( H \) and \( X \subseteq V(H) \), \( H - X \) denotes the hypergraph obtained by removing the vertices \( X \) from \( H \) and removing all edges that intersect \( X \). For a subset \( E' \subseteq E(H) \) of edges in \( H \), we define \( H - E' \) to be the hypergraph obtained from \( H \) by deleting the edges in \( E' \) and resulting isolated vertices, if any. If \( E' = \{e\} \), then we write \( H - E' \) simply as \( H - e \). For \( e \in E(H) \) and \( v \in e \), if we remove the vertex \( v \) from the edge \( e \), we say that the resulting edge is obtained by \( v \)-shrinking the edge \( e \).

### 1.1 Domination, matchings and transversals in hypergraphs

A dominating set in a hypergraph \( H \) is a subset \( D \) of vertices of \( H \) such that for every vertex \( v \in V(H) \setminus D \) there exists an edge \( e \in E(H) \) for which \( v \in e \) and \( e \cap D \neq \emptyset \). Equivalently, every vertex \( v \in V(H) \setminus D \) is adjacent to a vertex in \( D \). The minimum cardinality of a dominating set in \( H \) is called its domination number, denoted by \( \gamma(H) \). A matching in \( H \) is a set of disjoint edges. The maximum cardinality of a matching in \( H \) is called the matching number, denoted by \( \alpha'(H) \). A subset \( T \) of vertices in \( H \) is a transversal (also called cover) if \( T \) has a nonempty intersection with each edge of \( H \). The transversal number, \( \tau(H) \), is the minimum size of a transversal of \( H \). Transversals and matchings in hypergraphs are well studied in the literature (see e.g. \[4, 7, 9, 12, 15, 16, 17, 18\]) and elsewhere. Domination in hypergraphs, was introduced by Acharya \[1\] and studied further in \[2, 5, 6, 15, 27, 28\].

For a hypergraph \( H \) of rank \( r \), when \( r = 2 \), \( H \) is a graph, Haynes et al. \[14\] observed that
When \( r \geq 3 \), by definitions, clearly \( \gamma(H) \leq \tau(H) \) and \( \alpha'(H) \leq \tau(H) \) still hold. The extremal graphs, i.e., linear 2-uniform hypergraphs achieving \( \gamma(G) \leq \tau(G) \) were studied in [5, 23, 25, 29]. Recently, Arumugam et al. [5] investigated the hypergraphs of rank \( r \geq 3 \) satisfying \( \gamma(H) = \tau(H) \), and proved that their recognition problem is NP-hard on the class of linear hypergraphs of rank 3.

In [21] we observed that the inequality \( \gamma(H) \leq \alpha'(H) \) does not hold for a hypergraph \( H \) of rank \( r \geq 3 \), and the difference \( \gamma(H) - \alpha'(H) \) can be arbitrarily large. Further, we obtained the following inequality.

**Theorem 1.1.** ([21]) If \( H \) is a hypergraph of rank \( r \geq 2 \) without isolated vertex, then \( \gamma(H) \leq (r - 1)\alpha'(H) \) and this bound is sharp.

In particular, if \( r = 2 \) in Theorem 1.1, as Haynes et al. [14] observed, \( \gamma(H) \leq \alpha'(H) \).

For extremal hypergraphs of rank \( r \) satisfying \( \gamma(H) = (r - 1)\alpha'(H) \), Randerath et al. [26] gave a characterization of graphs (hypergraphs of rank \( r = 2 \)) with minimum degree two. In 2010, Kano et al. [22] provided a complete characterization of graphs with minimum degree one. For the case when rank \( r = 3 \), we give a complete characterization of hypergraphs \( H \) in [28]. For the case when \( r \geq 4 \), a constructive characterization of hypergraphs with \( \gamma(H) = (r - 1)\alpha'(H) \) seems difficult to obtain. Thus we restrict our attention to intersecting hypergraphs.

A hypergraph is intersecting if any two edges have nonempty intersection. Clearly, \( H \) is intersecting if and only if \( \alpha'(H) = 1 \). Intersecting hypergraphs are well studied in the literature (see, for example, [3, 8, 10, 11, 13, 19, 20, 24]). For an intersecting hypergraph \( H \) of rank \( r \), we immediately have \( \gamma(H) \leq r - 1 \).

In this paper we first give some structural properties on the intersecting hypergraphs of rank \( r \) achieving the equality \( \gamma(H) = r - 1 \). By applying the properties and Fano plane, we provides a complete characterization of linear intersecting hypergraphs \( H \) of rank 4 satisfying \( \gamma(H) = r - 1 \).

## 2 The intersecting hypergraphs of rank \( r \) with \( \gamma(H) = r - 1 \)

In this section we give some structural properties on intersecting hypergraphs of rank \( r \) satisfying \( \gamma(H) = r - 1 \). The properties play an important role in the characterization of intersecting hypergraphs of rank 4 with \( \gamma(H) = r - 1 \).

Let \( \mathcal{H}_r \) be a family of intersecting hypergraphs of rank \( r \) in which each hypergraph \( H \) satisfies \( \gamma(H) = r - 1 \).
**Lemma 2.1.** For every $H \in \mathcal{H}_r$, there exists an $r$-uniform spanning partial hypergraph $H^*$ of $H$ such that every edge in $H^*$ contains exactly one degree-1 vertex.

**Proof.** Let $H_0 = H$. We define recursively the hypergraph $H_i$ by $H_{i-1}$. If there exists an edge $e_{i-1} \in E(H_{i-1})$ such that $d_{H_{i-1}}(v) \geq 2$ for each vertex $v$ in $e_{i-1}$, then set $H_i := H_{i-1} - e_{i-1}$ for $i \geq 1$. By repeating this process until every edge which remains contains at least one degree-1 vertex, we obtain a spanning partial hypergraph of $H$. Assume that the above process stops when $i = k$. Let $H^* = H_k$. Then $H^*$ is a spanning partial hypergraph of $H$. Clearly, every edge in $H^*$ contains at least one degree-1 vertex and $H^*$ is still intersecting.

We claim that each edge in $H^*$ contains exactly one degree-1 vertex. Suppose not. Then there exists an edge $e$ containing at least two degree-1 vertices. Let $D = \{v \in e \mid d_H(v) \geq 2\}$. Then $|D| \leq r - 2$. Since $H^*$ is intersecting, $D$ is a transversal of $H^*$, so $\gamma(H^*) \leq \tau(H^*) \leq |D| \leq r - 2$. Since $H^*$ is a spanning partial hypergraph of $H$, we have $\gamma(H) \leq \gamma(H^*) \leq r - 2$, contradicting the assumption that $\gamma(H) = r - 1$. Further, we show that $H^*$ is $r$-uniform. Suppose not. Let $e^*$ be an edge of $H^*$ such that $|e^*| \leq r - 1$ and $u$ the unique degree-1 vertex of $e^*$. Since $H^*$ is intersecting, $e^* \setminus \{u\}$ is a dominating set of $H^*$. Thus $\gamma(H) \leq \gamma(H^*) \leq r - 2$, contradicting $\gamma(H) = r - 1$ again. □

For each $H \in \mathcal{H}_r$, let $H^*$ be the $r$-uniform spanning partial hypergraph of $H$ in Lemma 2.1. Further, let $H'$ be the hypergraph obtained from $H^*$ by shrinking every edge to $(r - 1)$-edge by removing the degree-1 vertex from each edge of $H^*$ and deleting multiple edges, if any. Obviously, $H'$ is an $(r - 1)$-uniform intersecting hypergraph.

**Lemma 2.2.** For every $H \in \mathcal{H}_r$, $\gamma(H) = \gamma(H^*) = \tau(H^*) = \tau(H') = r - 1$.

**Proof.** Let $e \in E(H^*)$ and $u$ be the unique degree-1 vertex in $e$. Since $H^*$ is intersecting, $e \setminus \{u\}$ is a transversal of $H^*$, so $\gamma(H^*) \leq \tau(H^*) \leq r - 1$. On the other hand, note that $\gamma(H^*) \geq \gamma(H) = r - 1$. Hence $\gamma(H^*) = \tau(H^*) = \gamma(H) = r - 1$. By the construction of $H'$, clearly any transversal of $H'$ is a transversal of $H^*$ and $e \setminus \{u\}$ is also a transversal of $H'$. Hence $\tau(H') = \tau(H^*)$. The equality chain follow. □

**Lemma 2.3.** For $r \geq 3$ and every vertex $v$ in $H'$, $2 \leq qd_{H'}(v) \leq r - 1$.

**Proof.** Suppose, to the contrary, that there exists a vertex $v \in V(H')$ such that $qd_{H'}(v) \leq 1$ or $qd_{H'}(v) \geq r$.

Suppose that $qd_{H'}(v) \leq 1$. Note that every vertex $H'$ has degree at least 2, so $qd_{H'}(v) \neq 1$. Hence $qd_{H'}(v) = 0$. Let $e$ be an edge containing $v$. Since $H'$ is intersecting, $e \cap f \neq \emptyset$ for any $f \in E(H') \setminus \{e\}$. In particular, if $v \in e \cap f$, then $|e \cap f| \geq 2$ since $d_{H'}(v) \geq 2$ and $qd_{H'}(v) = 0$. Thus $e \setminus \{v\}$ would be a transversal of $H'$, contradicting the fact in Lemma 2.2. □
Suppose that \( qd_{H'}(v) \geq r \). Let \( e_1, \ldots, e_r \) be the edges whose pairwise intersection is only \( v \). By Lemma 2.2 and \( r \geq 3 \), we have \( \tau(H') = r - 1 \geq 2 \). This implies that there exists an edge \( g \) such that \( v \not\in g \). Since \( H' \) is intersecting, \( |g \cap e_i| \geq 1 \) for each \( i = 1, 2, \ldots, r \). But then \( |g| \geq r \), contracting the fact that \( H' \) is \((r-1)\)-uniform.

**Lemma 2.4.** Let \( H \in \mathcal{H}_r \) \((r \geq 3)\). If \( H \) is linear, then every edge of \( H' \) has at most one degree-2 vertex and \( \Delta(H') = r - 1 \).

**Proof.** If \( H \) is linear, so is \( H' \). First, we show that every edge of \( H' \) has at most one degree-2 vertex. Suppose not, and let \( e \) be an edge of \( H' \) with two degree-2 vertices. Suppose not, let \( v \in V(H') \) such that \( d_{H'}(v) = 2 \). Then \( |V(H')| \leq (r-1)(r-a) \). Let \( v \in V(H') \) such that \( d_{H'}(v) = r-a \). Then \( |N_{H'}(v)| = (r-2)(r-a) \). Note that \( V(H') \setminus N_{H'}(v) \) is a transversal of \( H' \). But \( |V(H') \setminus N_{H'}(v)| \leq (r-1)(r-a) - (r-2)(r-a) = r-a \leq r-2 \). Thus \( \tau(H') \leq r-2 \), contradicting that \( \tau(H') = r-1 \).

Next we show that \( \Delta(H') = r - 1 \). Suppose not, let \( \Delta(H') = r-a \) where \( a \geq 2 \). As we have seen, \( H' \) is a linear intersecting \((r-1)\)-uniform hypergraph with \( \tau(H') = r-1 \). Then \( |V(H')| \leq (r-1)(r-a) \). Let \( v \in V(H') \) such that \( d_{H'}(v) = r-a \). Then \( |N_{H'}(v)| = (r-2)(r-a) \). Note that \( V(H') \setminus N_{H'}(v) \) is a transversal of \( H' \). But \( |V(H') \setminus N_{H'}(v)| \leq (r-1)(r-a) - (r-2)(r-a) = r-a \leq r-2 \). Thus \( \tau(H') \leq r-2 \), contradicting that \( \tau(H') = r-1 \).

**Lemma 2.5.** Let \( H \in \mathcal{H}_r \) \((r \geq 3)\). If \( H \) is linear, then \( 3(r-2) \leq |E(H')| \leq (r-1)^2 - (r-1) + 1 \), \( n(H') = (r-1)^2 - (r-1) + 1 \), and so \( \gamma(H') = 1 \).

**Proof.** Since \( H' \) is a linear intersecting \((r-1)\)-uniform hypergraph, \( |E(H')| = \sum_{v \in e} d_{H'}(v) - (r-2) \) for any edge \( e \in E(H') \). By Lemma 2.4, we immediately have \( 3(r-2) \leq |E(H')| \leq (r-1)^2 - (r-1) + 1 \).

We now show that \( n(H') = (r-1)^2 - (r-1) + 1 \). Let \( v \in V(H') \) such that \( d_{H'}(v) = \Delta(H') = r-1 \). Then \( |n(H')| \geq |N_{H'}(v) \cup \{v\}| = (r-1)(r-2) + 1 = (r-1)^2 - (r-1) + 1 \). Suppose that \( |n(H')| \geq (r-1)^2 - (r-1) + 2 \). Then there exists \( u \in V(H') \) such that \( u \not\in N_{H'}(v) \cup \{v\} \). By Lemma 2.3, \( d_{H'}(u) \geq 2 \), so there exist two edges \( e_1 \) and \( e_2 \) such that \( u \in e_1 \cap e_2 \). Clearly, \( v \not\in e_1 \) and \( v \not\in e_2 \). Since \( H' \) is linear intersecting, \( e_1 \) intersects each one of the edges that contains \( v \), implying that \( |e_1| \geq 5 \). This contradicts that \( H' \) is an \((r-1)\)-uniform hypergraph. Therefore, \( n(H') = (r-1)^2 - (r-1) + 1 \), that is, \( n(H') = |N_{H'}(v) \cup \{v\}| \). This implies that \( \{v\} \) is a dominating set of \( H' \), so \( \gamma(H') = 1 \).
3 Linear intersecting hypergraphs $H$ of rank 4 with $\gamma(H) = 3$

In the section we give a complete characterization of linear intersecting hypergraphs $H$ of rank 4 with $\gamma(H) = r - 1$. For this purpose, let $F$ be the Fano Plane and let $F^-$ be the hypergraph obtained from $F$ by deleting any edge of $F$. The two hypergraphs $F$ and $F^-$ are shown in Fig. 1.

![Figure 1: The Fano Plane $F$ and the hypergraph $F^-$](image)

**Lemma 3.1.** Let $H \in \mathcal{H}_4$ and $H'$ be the hypergraph as defined in the above section. If $H$ is linear, then $H' = F$ or $H' = F^-$.  

**Proof.** By Lemma 2.5, we have $6 \leq |E(H')| \leq 7$ and $n(H') = 7$ for $r = 4$. Note that $H'$ is a linear intersecting 3-uniform hypergraph. If $|E(H')| = 7$, then $H'$ must be the Fano plane $F$. If $|E(H')| = 6$, then $H'$ is the hypergraph $F^-$ (see Fig. 1). \qed

To complete our characterization, we let $F_1$ ($F_1^-$) be the hypergraph obtained from $F$ ($F^-$) by adding a new vertex to each edge of $F$ ($F^-$), respectively. Let $F_2$ be the hypergraph obtained from $F_1$ by shrinking one edge to 3-edge by removing the degree-1 vertex in the edge. Let $F_3$ be the hypergraph obtained from $F_1^-$ by adding a new edge $f = \{x_{i_1}, x_{i_2}, x_{i_3}, x_{i_4}\}$ where $x_{i_1}, x_{i_2}, x_{i_3}$ and $x_{i_4}$ lie in distinct edges of $F_1^-$ and $d_{F_1^-}(x_{i_1}) = d_{F_1^-}(x_{i_2}) = 2$, $d_{F_1^-}(x_{i_3}) = d_{F_1^-}(x_{i_4}) = 1$. We define $\mathcal{L} = \{F_1, F_1^-, F_2, F_3\}$ (see Fig. 2). Clearly, every hypergraph in $\mathcal{L}$ is a linear intersecting hypergraph of rank 4.

**Theorem 3.1.** For a linear intersecting hypergraph $H$ of rank 4, $\gamma(H) = 3$ if and only if $H \in \mathcal{L}$.  

**Proof.** First, suppose that $H \in \mathcal{L}$, and let $e$ be an arbitrary edge of $H$ containing four vertices and $v$ the degree-1 vertex. Then it is easy to check that $D = e \setminus \{e\}$ is a minimum dominating set of $H$. Thus $\gamma(H) = 3$.  

6
Conversely, suppose that \( \gamma(H) = 3 \), we show that \( H \in \mathcal{L} \). Let \( H^* \) and \( H' \) be the hypergraphs corresponding to \( H \) as defined in above section. By Lemma \[3.1\] \( H' = F \) or \( H' = F^- \), so \( H^* = F_1 \) or \( H^* = F^-_1 \).

Case 1. \( H^* = F_1 \). In this case, we claim that \( H = H^* = F_1 \). It suffices to show that \( E(H) \setminus E(H^*) = \emptyset \). Suppose not. Let \( e \in E(H) \setminus E(F_1) \). Then \( |e \cap f| = 1 \) for any \( f \in E(F_1) \). By the construction of \( F_1 \), \( V(F_1) = V(F) \cup I \) where \( I \) consists of seven degree-1 vertices in \( F_1 \). Note that any two vertices of \( F \) lie in exactly one common edge of \( F_1 \), so \( |e \cap V(F)| \leq 1 \). This implies that \( |e| \geq 5 \), since \( H \) is linear and intersecting. This contradicts that \( r(H) = 4 \).

Case 2. \( H^* = F^-_1 \). In this case, we show that \( H \in \{ F^-_1, F_2, F_3 \} \). It suffices to show that \( H = F_3 \) if \( H \neq F^-_1 \) and \( H \neq F_2 \). Let \( V(F^-_1) = V_1 \cup V_2 \cup V_3 \) where \( V_i \) is the set of degree-\( i \) vertices in \( F^-_1 \). Then \( |V_1| = 6, |V_2| = 3 \) and \( |V_3| = 4 \). Suppose now that \( H \neq F^-_1 \) and \( H \neq F_2 \). Then \( E(H) \setminus E(F^-_1) \neq \emptyset \). Let \( e \in E(H) \setminus E(F^-_1) \). Suppose that \( e \cap V_3 \neq \emptyset \). Since \( H \) is linear and intersecting, \( |e \cap f| = 1 \) for any \( f \in E(F^-_1) \). Note that any two vertices of \( V_3 \) lie in exactly one common edge of \( F^-_1 \), so \( |e \cap V_3| = 1 \). Let \( e \cap V_3 = \{x_i\} \). This implies that \( e \supseteq V_1 \cup V(H - x_i) \). But then \( x_i \) is a dominating set of \( H \), contradicting that \( \gamma(H) = 3 \). Hence \( e \cap V_3 = \emptyset \), and thus \( e \subseteq V_1 \cup V_2 \). Suppose that \( |e \cap V_2| \leq 1 \). Then \( |e \cap V_1| \geq 4 \). Hence \( |e| \geq 5 \), a contradiction. So \( |e \cap V_2| = 2 \) since \( H \neq F_2 \). It immediately follows that \( E(H) \setminus E(F^-_1) = \{e\} \). Therefore, \( H = F_3 \).

\[\Box\]

4 Conclusions

In this paper we present the propositions of the intersecting hypergraphs that achieve the equality \( \gamma(H) = r - 1 \). Especially, we provide a complete characterization of the linear intersecting hypergraphs with rank \( r = 4 \) satisfying \( \gamma(H) = 3 \). One is interested in characterizing the extremal intersecting hypergraphs with rank \( r = 4 \) satisfying \( \gamma(H) = 3 \).

![Figure 2: The hypergraphs \( F_1, F^-_1, F_2 \) and \( F_3 \)](image)
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