BOUNDS ON THE DOUBLE ITALIAN DOMINATION NUMBER OF A GRAPH

FARZANEH AZVIN AND NADER JAFARI RAD

Department of Mathematics, Shahed University, Tehran, Iran
e-mail: n.jafarirad@gmail.com

Abstract

For a graph $G$, a Roman $\{3\}$-dominating function is a function $f : V \rightarrow \{0, 1, 2, 3\}$ having the property that for every vertex $u \in V$, if $f(u) \in \{0, 1\}$, then $f(N[u]) \geq 3$. The weight of a Roman $\{3\}$-dominating function is the sum $w(f) = f(V) = \sum_{v \in V} f(v)$, and the minimum weight of a Roman $\{3\}$-dominating function is the Roman $\{3\}$-domination number, denoted by $\gamma_{(R3)}(G)$. In this paper, we present a sharp lower bound for the double Italian domination number of a graph, and improve previous bounds given in [D.A. Mojdeh and L. Volkmann, Roman $\{3\}$-domination (double Italian domination), Discrete Appl. Math. (2020), in press]. We also present a probabilistic upper bound for a generalized version of double Italian domination number of a graph, and show that the given bound is asymptotically best possible.

Keywords: Italian domination, double Italian domination, probabilistic methods.

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1. Introduction

For a (simple) graph $G = (V, E)$ with vertex set $V = V(G)$ and edge set $E = E(G)$, we denote by $|V(G)| = n(G) = n$ the order of $G$. The open neighborhood of a vertex $v$ is $N(v) = \{u \in V : uv \in E\}$ and the closed neighborhood of $v$ is $N[v] = N(v) \cup \{v\}$. For a set $S \subseteq V$, the open neighborhood of $S$ is $N(S) = \bigcup_{v \in S} N(v)$ and the closed neighborhood of $S$ is $N[S] = N(S) \cup S$. The degree of a vertex $v$ is $\deg(v) = |N(v)|$. The maximum and minimum degree among the vertices of $G$ are denoted by $\Delta(G)$ and $\delta(G)$, respectively. For a set $S \subseteq V$ in a graph $G$ and a vertex $v \in V$, we say that $S$ dominates $v$ if $v \in S$ or
A set \( S \) is called a dominating set in \( G \) if \( S \) dominates every vertex of \( G \). The domination number \( \gamma(G) \) of \( G \) is the minimum cardinality of a dominating set in \( G \). For other definitions and notations not given here we refer to [6].

Cockayne et al. [5] introduced the concept of Roman domination in graphs, although this notion was inspired by the work of ReVelle et al. in [11], and Stewart in [12]. Let \( f : V(G) \to \{0,1,2\} \) be a function having the property that for every vertex \( v \in V \) with \( f(v) = 0 \), there exists a neighbor \( u \in N(v) \) with \( f(u) = 2 \). Such a function is called a Roman dominating function or just an RDF. The weight of an RDF \( f \) is the sum \( f(V) = \sum_{v \in V} f(v) \). The minimum weight of an RDF on \( G \) is called the Roman domination number of \( G \), and is denoted by \( \gamma_R(G) \). Several varieties of Roman domination are already studied, and the reader can consult [3, 4].

A generalization of Roman domination called Italian domination (or Roman \{2\}-domination) was introduced by Chellali et al. in [2], Klostermeyer and MacGillivray [8], and Henning and Klostermeyer [7]. An Italian dominating function (IDF) on a graph \( G = (V,E) \) is a function \( f : V \to \{0,1,2\} \) satisfying the property that for every vertex \( v \in V \), with \( f(v) = 0 \), \( \sum_{u \in N(v)} f(u) \geq 2 \). The weight of an IDF \( f \) is the value \( w(f) = f(V) = \sum_{u \in V} f(u) \). The minimum weight of an IDF on a graph \( G \) is called the Italian domination number of \( G \), denoted by \( \gamma_I(G) \). This same concept was called Roman \{2\}-domination and what we called \( \gamma_I(G) \) is called \( \gamma_{IR2}(G) \). A \( \gamma_{IR2}(G) \)-function \( f \) can be represented by a triple \( f = (V_0,V_1,V_2) \) (or \( f = (V_0^f, V_1^f, V_2^f) \) to refer to \( f \)), where \( V_i = \{v \in V(G) : f(v) = i\} \) for \( i = 0, 1, 2 \).

Beeler et al. [1] introduced the concept of double Roman domination in graphs. A function \( f : V \to \{0,1,2,3\} \) is a double Roman dominating function (or just DRDF) on a graph \( G \) if the following conditions hold, where \( V_i \) denote the set of vertices assigned \( i \) under \( f \), for \( i = 0, 1, 2, 3 \): (1) If \( f(v) = 0 \), then \( v \) must have at least two neighbors in \( V_2 \) or one neighbor in \( V_3 \); (2) If \( f(v) = 1 \), then \( v \) must have at least one neighbor in \( V_2 \cup V_3 \). The weight of a DRDF \( f \) is the value \( w(f) = f(V) = \sum_{v \in V} f(v) \). The double Roman domination number, \( \gamma_{dR}(G) \), is the minimum weight of a DRDF on \( G \), and a DRDF of \( G \) with weight \( \gamma_{dR}(G) \) is called a \( \gamma_{dR} \)-function of \( G \).

Recently, Mojdeh and Volkmann [9] considered an extension of Roman \{2\}-domination as follows. For a graph \( G \), a Roman \{3\}-dominating function is a function \( f : V \to \{0,1,2,3\} \) having the property that for every vertex \( u \in V \), if \( f(u) \in \{0,1\} \), then \( f(N[u]) \geq 3 \). The weight of a Roman \{3\}-dominating function is the sum \( w(f) = f(V) = \sum_{v \in V} f(v) \), and the minimum weight of a Roman \{3\}-dominating function is the Roman \{3\}-domination number, denoted by \( \gamma_{IR3}(G) \). For a Roman \{3\}-dominating function \( f \), one can denote \( f = (V_0,V_1,V_2,V_3) \), where \( V_i = \{v \in V : f(v) = i\} \), for \( i = 0, 1, 2, 3 \). This concept was further studied...
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in [10]. Among other results, Mojdeh et al. presented the following lower bound in [9].

**Theorem 1** (Mojdeh and Volkmann [9]). If $G$ is a connected graph of order $n$ and maximum degree $\Delta$, then $\gamma_{(R3)}(G) \geq \min \left\{ \frac{3n}{\Delta + 2}, \frac{2n + \Delta}{\Delta + 1} \right\}$.  

In this paper we present upper and lower bounds for the Roman $\{3\}$-domination number of a graph. In Section 2, we present a sharp lower bound for the Roman $\{3\}$-domination number of a graph and improve the bound given in Theorem 1. In Section 3, we present a probabilistic upper bound for a generalized version of the Roman $\{3\}$-domination number, namely, the Roman $\{k\}$-domination number for every $k \geq 3$, of a graph and show that the given bound is asymptotically best possible.

In this paper, for an event $F$ we denote by $Pr(F)$ the probability that $F$ occurs. We also denote by $E(X)$ the expectation of $X$ if $X$ is a random variable.

2. Lower Bound

In this section we present a new sharp lower bound for the Roman $\{3\}$-domination number of a graph. We begin with the following observation.

**Observation 2.** For every connected graph $G$ of order $n$ and maximum degree $\Delta$, $\gamma_{(R3)}(G) \leq 2(n - \Delta) + 1$.

**Proof.** Let $v$ be a vertex of maximum degree. Let $f$ be a function defined on $V(G)$ by $f(v) = 3$, $f(x) = 0$ if $x \in N(v)$ and $f(x) = 2$ otherwise. Then $f$ is a R3DF for $G$, and so $\gamma_{(R3)}(G) \leq 2(n - \Delta - 1) + 3 = 2(n - \Delta) + 1$, as desired. ■

**Lemma 3.** If $G$ is a connected graph of maximum degree $\Delta(G) = \Delta \geq 1$ and $f = (V_0, V_1, V_2, V_3)$ is a $\gamma_{(R3)}(G)$-function, then $3|V_0| \leq (\Delta - 2)|V_1| + 2\Delta|V_2| + 3\Delta|V_3|$.  

**Proof.** Let $G$ be a connected graph of maximum degree $\Delta(G) = \Delta \geq 1$ and $f = (V_0, V_1, V_2, V_3)$ be a $\gamma_{(R3)}(G)$-function. If $\Delta = 1$, then $G = K_2$, and since $\gamma_{(R3)}(K_2) = 3$, we obtain that either $|V_0| = |V_3| = 1$ and $|V_1| = |V_2| = 0$ or $|V_0| = |V_2| = 0$ and $|V_1| = |V_3| = 1$. Thus the inequality holds.

Hence we assume that $\Delta \geq 2$. We partition $V_0$ into four sets $V_0^3, V_0^{12}, V_0^1$ and $V_0^2$, and $V_1$ into three sets $V_1^1, V_1^2$ and $V_1^3$ as follows. Let  

$$V_0^3 = \{ v \in V_0 : N(v) \cap V_3 \neq \emptyset \},$$

$$V_0^{12} = \{ v \in V_0 \setminus V_0^3 : N(v) \cap V_1 \neq \emptyset, N(v) \cap V_2 \neq \emptyset \},$$

$$V_0^1 = \{ v \in V_0 \setminus (V_0^3 \cup V_0^{12}) : N(v) \subseteq V_0 \cup V_1 \},$$

$$V_0^2 = \{ v \in V_0 \setminus (V_0^3 \cup V_0^{12}) : N(v) \subseteq V_0 \cup V_2 \}.$$
$V_1^1 = \{x \in V_1 : N(x) \cap (V_2 \cup V_3) = \emptyset\}$,
$V_1^2 = \{x \in V_1 : N(x) \cap V_2 \neq \emptyset\}$,
$V_1^3 = V_1 \setminus (V_1^1 \cup V_1^2)$.

For $i = 1, 2, 3$, let $|V_i^i| = m_i$. We first present an upper bound for $|V_0^2|$ in terms of $|V_3|$ and $m_3$. Each vertex in $V_3$ with no neighbor in $V_1$ dominates at most $\Delta$ vertices of $V_0^3$, and every vertex in $V_3$ with at least one neighbor in $V_1$ dominates at most $\Delta - 1$ vertices of $V_0^3$. Thus,

$$|V_0^2| \leq \Delta(|V_3| - m_3) + (\Delta - 1)m_3 = \Delta|V_3| - m_3. \quad (1)$$

Let $|V_0^{12}| = x$. We next present an upper bound for $|V_0^2|$ in terms of $|V_2|$, $x$ and $m_2$. Clearly, every vertex of $V_2^1 \cup V_0^{12}$ has a neighbor in $V_2$. Since $|V_2^1| = m_2$ and $|V_0^{12}| = x$, there are at most $\Delta|V_2| - x - m_2$ edges which have an end-point in $V_2$. Since any vertex of $V_0^2$ is adjacent to at least two vertices of $V_2$, we obtain that

$$|V_0^2| \leq \frac{\Delta|V_2| - x - m_2}{2}. \quad (2)$$

We next present an upper bound for $|V_0^1|$ in terms of $|V_1|$, $x$, $m_1$, $m_2$ and $m_3$. Note that every vertex of $V_1^1$ is adjacent to at least two vertices of $V_1$, every vertex of $V_1^2$ is adjacent to at least one vertex of $V_2$ and every vertex of $V_1^3$ is adjacent to at least one vertex of $V_3$. Also every vertex of $V_0^{12}$ is adjacent to a vertex in $V_1$. Thus, there are at most $\Delta|V_1| - 2m_1 - m_2 - m_3 - x$ edges which have an end-point in $V_1$. Since any vertex of $V_0^1$ is adjacent to at least three vertices of $V_1$, we obtain that

$$|V_0^1| \leq \frac{\Delta|V_1| - 2m_1 - m_2 - m_3 - x}{3}. \quad (3)$$

Since $|V_0| = |V_0^1| + |V_0^2| + |V_0^{12}| + |V_0^3|$, from (1), (2) and (3) we obtain that

$$3|V_0| \leq \Delta|V_1| - 2m_1 - m_2 - m_3 - x + \frac{3\Delta|V_2|}{2} - \frac{3x}{2} - \frac{3m_2}{2} + 3x + 3\Delta|V_3| - 3m_3.$$

Since $|V_1| = m_1 + m_2 + m_3$, we obtain that

$$3|V_0| \leq (\Delta - 2)|V_1| + 2\Delta|V_2| + 3\Delta|V_3| - \frac{m_2}{2} - 2m_3 + \frac{x}{2} - \frac{\Delta|V_2|}{2}. $$

It is evident that $x \leq \Delta|V_2|$. Thus $3|V_0| \leq (\Delta - 2)|V_1| + 2\Delta|V_2| + 3\Delta|V_3|$, as desired. 

**Corollary 4.** If $G$ is a connected graph of order $n$ with maximum degree $\Delta(G) = \Delta \geq 1$ and $f = (V_0, V_1, V_2, V_3)$ is a $\gamma_{(R3)}(G)$-function, then $\gamma_{(R3)}(G) \geq \frac{3n-|V_2|}{\Delta+1}$. 
Proof. Let $f = (V_0, V_1, V_2, V_3)$ be a $\gamma_{(R3)}(G)$-function for $G$. Then

$$(\Delta + 1)\gamma_{(R3)}(G) = (\Delta + 1)|V_1| + 2(\Delta + 1)|V_2| + 3(\Delta + 1)|V_3|$$

$$= (\Delta - 2)|V_0| + 2\Delta|V_2| + 3\Delta|V_3| + 3|V_1| + 2|V_2| + 3|V_3|$$

$$\geq 3|V_0| + 3|V_1| + 2|V_2| + 3|V_3| \quad \text{(by Lemma 3)}$$

$$= 3n - |V_2|.$$ 

Thus the result follows. \hfill \blacksquare

Now we present the main result of this section.

**Theorem 5.** If $G$ is a connected graph of order $n > 1$ and maximum degree $\Delta \geq 1$, then

$$\gamma_{(R3)}(G) \geq \left\lceil \max\left\{ \frac{3n}{\Delta + 2}, \frac{2n + \Delta}{\Delta + 1} \right\} \right\rceil + 1.$$ 

This bound is sharp.

Proof. Let $G$ be a connected graph of order $n$ and maximum degree $\Delta$ and $f = (V_0, V_1, V_2, V_3)$ be a $\gamma_{(R3)}(G)$-function for $G$. If $|V_2| = 0$, then from Corollary 4, we obtain that $\gamma_{(R3)}(G) \geq \frac{3n - |V_2|}{\Delta + 1}$. Using Observation 2, we obtain $|V_2| \leq \gamma_{(R3)}(G) \leq n - \Delta + 1$, which implies that $|V_2| \leq n - \Delta$.

We first show that $\gamma_{(R3)}(G) > \frac{2n + \Delta}{\Delta + 1}$. If $|V_2| < n - \Delta$, then we obtain that $\gamma_{(R3)}(G) \geq \frac{3n - |V_2|}{\Delta + 1} > \frac{2n + \Delta}{\Delta + 1}$, as desired. Suppose that $\gamma_{(R3)}(G) = \frac{3n - |V_2|}{\Delta + 1}$. Let $|V_i| = v_i$ for $i = 0, 1, 2, 3$. Then from $\gamma_{(R3)}(G) = \frac{3n - |V_2|}{\Delta + 1}$ we find that $(\Delta + 1)(v_1 + 2v_2 + 3v_3) = 3v_0 + 3v_1 + 2v_2 + 3v_3$, since $n = v_0 + v_1 + v_2 + v_3$. Since $\Delta = n - v_2 = v_0 + v_1 + v_3$, we obtain by a simple calculation that $v_1 + 2v_2 + 3v_3 = \frac{3v_0 + 2v_1}{n - v_2} = \frac{3v_0 + 2v_3}{n - v_2}$, and this implies that $2v_2 = 3 - (v_1 + 3v_3) - \frac{v_1 + 3v_3}{n - v_2}$. If $v_3 = 0$ and $v_1 = 0$, then $2v_2 = 3$, a contradiction. If $v_3 = 0$ and $v_1 \neq 0$, then $2v_2 = 3 - v_1 - \frac{v_1 + 3v_3}{n - v_2} < 2$, a contradiction. Thus $v_3 \neq 0$. If $v_1 = 0$, then $2v_2 = 3 - 3v_3 - \frac{3v_3}{n - v_2} < 0$, a contradiction. Thus $v_1 \neq 0$. Then $2v_2 = 3 - (v_1 + 3v_3) - \frac{v_1 + 3v_3}{n - v_2} < 0$, a contradiction. We conclude that $\gamma_{(R3)}(G) \neq \frac{3n - |V_2|}{\Delta + 1}$, and so $\gamma_{(R3)}(G) > \frac{3n - |V_2|}{\Delta + 1} > \frac{2n + \Delta}{\Delta + 1}$, as desired.

We next show that $\gamma_{(R3)}(G) > \frac{3n}{\Delta + 2}$. If $|V_2| \geq \frac{3n}{\Delta + 2}$, then $\gamma_{(R3)}(G) \geq 2|V_2| > \frac{3n}{\Delta + 2}$. Thus assume that $|V_2| < \frac{3n}{\Delta + 2}$. Then a simple calculation shows that $\gamma_{(R3)}(G) > \frac{3n}{\Delta + 2}$, as desired.
Hence, \( \gamma_{(R3)}(G) > \max \left\{ \frac{2n+\Delta}{\Delta+1}, \frac{3n}{\Delta+2} \right\} \). This completes the proof of lower bound.

To see the sharpness, consider a complete graph of order at least two. \( \blacksquare \)

We end this section by remarking that Lemma 3 holds for each R3DF. Moreover, it holds if \( \Delta = 0 \).

3. Upper Bound

In this section we present an upper bound for a generalization of the Roman \{3\}-domination number namely Roman \{k\}-domination number for every integer \( k \geq 3 \) that is defined as follows. For a graph \( G \) and an integer \( k \geq 3 \), a Roman \{k\}-dominating function is a function \( f : V \to \{0, 1, \ldots, k\} \) having the property that for every vertex \( u \in V \), if \( f(u) < \lceil \frac{k}{2} \rceil \), then \( f(N[u]) \geq k \). The weight of a Roman \{k\}-dominating function is the sum \( w(f) = f(V) = \sum_{v \in V} f(v) \), and the minimum weight of a Roman \{k\}-dominating function is the Roman \{k\}-domination number, denoted by \( \gamma_{(Rk)}(G) \). For a Roman \{k\}-dominating function \( f \), we denote \( f = (V_0, V_1, \ldots, V_k) \), where \( V_i = \{ v \in V : f(v) = i \} \), for \( i = 0, 1, \ldots, k \).

**Theorem 6.** If \( G \) is a graph of order \( n \) with minimum degree \( \delta(G) = \delta \geq 1 \), then

\[
\gamma_{(Rk)}(G) \leq \frac{k \left( \ln \left\lceil \frac{k}{2} \right\rceil + \ln(1 + \delta) - \ln k + 1 \right)}{1 + \delta} n.
\]

**Proof.** Let \( G \) be a graph of order \( n \) with minimum degree \( \delta(G) = \delta \geq 1 \). Let \( S \subseteq V(G) \) be a set obtained by choosing each vertex \( v \in V(G) \), independently, with probability \( p \in [0, 1] \), and let \( T = V(G) \setminus N[S] \). We form sets \( V_i \), \( i = 0, 1, \ldots, k \) as follows. Let \( V_0 = V(G) \setminus (S \cup T) \), \( V_{\lceil \frac{k}{2} \rceil} = T \), \( V_k = S \) and \( V_i = \emptyset \) for \( i = 1, 2, \ldots, k-1, i \neq \lceil \frac{k}{2} \rceil \). Then the function \( f = (V_0, V_1, \ldots, V_k) \) is a Roman \{k\}-dominating function for \( G \). We compute the expected value of \( w(f) \). Note that

\[
\mathbb{E}(w(f)) = \mathbb{E}(k|S| + \left\lceil \frac{k}{2} \right\rceil |T|) = k\mathbb{E}(|S|) + \left\lceil \frac{k}{2} \right\rceil \mathbb{E}(|T|).
\]

Clearly, \( \mathbb{E}(|S|) = np \). If \( v \in T \), then \( v \notin S \) and \( v \notin N(S) \). Thus, \( Pr(v \notin N[S]) = (1 - p)^{1+\deg(v)} \leq (1 - p)^{1+\delta} \). Using the fact that \( 1 - p \leq e^{-p} \) for \( p \geq 0 \), we find that \( Pr(v \in T) \leq e^{-p(1+\delta)} \), and so \( \mathbb{E}(|T|) \leq ne^{-p(1+\delta)} \). Therefore,

\[
\mathbb{E}(w(f)) = \mathbb{E} \left( k|S| + \left\lceil \frac{k}{2} \right\rceil |T| \right) \leq knp + \left\lceil \frac{k}{2} \right\rceil ne^{-p(1+\delta)}.
\]
Taking derivative of the function 
\[ g(p) = kp + \left\lceil \frac{k}{2} \right\rceil e^{-p(1+\delta)} \] and solving the equation \( g'(p) = 0 \), we obtain that \( g(p) \) is minimized at 
\[ p = \frac{\ln \left( \left\lceil \frac{k}{2} \right\rceil \frac{1+\delta}{k} \right)}{1+\delta}. \]
Then by putting these values in (4) we obtain
\[
\mathbb{E}(w(f)) \leq nk \left( \frac{\ln \left( \left\lceil \frac{k}{2} \right\rceil \frac{1+\delta}{k} + 1 \right)}{1 + \delta} \right) =: \alpha.
\]
Since the average of \( w(f) \) is not more than \( \alpha \), there is a Roman \( \{k\} \)-dominating function with weight at most \( \alpha \), i.e., \( \gamma_{\{Rk\}}(G) \leq \alpha \), as desired.

We now prove that the upper bound of Theorem 6 is asymptotically best possible.

**Theorem 7.** When \( n \) is large, there exists a graph \( G \) of order \( n \) and minimum degree \( \delta \) such that
\[ \gamma_{\{Rk\}}(G) \geq k \left( \frac{\ln \left( \frac{1+\delta}{k} \right) + \ln(1+\delta) - \ln k + 1}{1+\delta} \right)n(1+o(1)). \]

**Proof.** Let \( H \) a complete graph with \( \lfloor \delta \ln \delta \rfloor \) vertices and let \( V(H) = V \). We add a set of new vertices \( V' = \{v_1, v_2, \ldots, v_\delta\} \) and join each of them to \( \delta \) vertices of \( V(H) \) which are chosen randomly. Let \( G \) be the resulted graph. Therefore \( G \) has \( n = \lfloor \delta \ln \delta \rfloor + \delta \) vertices. We show that
\[ \gamma_{\{Rk\}}(G) \geq k \frac{\ln \delta}{\delta} n(1 + o_\delta(1)) = \frac{k \ln \delta}{\delta} (\delta \ln \delta + \delta)(1 + o_\delta(1)) = k \ln^2 \delta (1 + o_\delta(1)). \]

Let \( f = (V_0, V_1, \ldots, V_k) \) be a \( \gamma_{\{Rk\}} \)-function for \( G \). If \( |V_k| \geq \ln^2 \delta - \ln \delta \ln \ln^4 \delta \), then
\[ \gamma_{\{Rk\}}(G) \geq k |V_k| \geq k \ln^2 \delta - k \ln \delta \ln \ln^4 \delta = k \ln^2 \delta (1 + o_\delta(1)), \]
as desired. Thus assume for the next that \( |V_k| < \ln^2 \delta - \ln \delta \ln \ln^4 \delta \).

We compute the probability that \( V_k \) dominates an element of \( V' \). Note that we can assume \( V_k \subseteq V \). For a vertex \( v_i \in V' \), we have
\[
Pr[V_k \text{ does not dominate } v_i] = \left( \frac{|V| - |V_k|}{\delta} \right)^\frac{|V| - |V_k| - \delta}{|V| - \delta} \geq \left( \frac{|V| - |V_k| - \delta}{|V| - \delta} \right)^\delta = \left( 1 - \frac{|V_k|}{|V| - \delta} \right)^\delta.
\]
Using the fact that $1 - x \geq e^{-x}(1 - x^2)$ for $x \leq 1$, we find that

$$
Pr[V_k \text{ does not dominate } v_i] \geq e^{-\frac{|V_k|}{|V| - \delta}} \left(1 - \left(\frac{|V_k|}{|V| - \delta}\right)^2\right)^\delta
$$

$$
\geq e^{-\frac{\ln^2 \delta - \ln \delta \ln \ln \delta}{\delta^2} - \frac{\ln \delta \ln \ln \delta}{\delta^2}} (1 + o_\delta(1))
$$

$$
\geq e \frac{\ln \left(\frac{\ln \delta}{\delta}\right)^{1+o_\delta(1)}}{1-\frac{\ln \delta}{\delta}} (1 + o_\delta(1))
$$

$$
\geq \left(\frac{\ln \delta}{\delta}\right)^{1+o_\delta(1)} (1 + o_\delta(1)) \geq \frac{\ln^3 \delta}{\delta}.
$$

Thus $Pr[V_k \text{ dominates } v_i] \leq 1 - \frac{\ln^3 \delta}{\delta}$. Now the expected value of the random variable $|N(V_k) \cap V'|$ is bounded above as follows

$$
E\left(|N(V_k) \cap V'|\right) = \sum_{i=1}^\delta Pr[V_k \text{ dominates } v_i] \leq \delta \left(1 - \frac{\ln^3 \delta}{\delta}\right) = \delta - \ln^3 \delta.
$$

Consequently, $|V' \setminus N(V_k)| \geq \ln^3 \delta$. Since $V_k \subseteq V$, we conclude that there exists a graph $G$ for which

$$
\gamma(R_k) \geq |V' \setminus N(V_k)| \geq \ln^3 \delta > k\ln^2 \delta(1 + o_\delta(1)),
$$

as desired.

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