BOUNDS ON THE DOUBLE ITALIAN DOMINATION NUMBER OF A GRAPH

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Abstract

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 $\gamma_{(R3)}(G)$. 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.

2010 Mathematics Subject Classification: 05C69.

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
v is adjacent to some vertex of S. 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 $f : V(G) \rightarrow \{0, 1, 2\}$ 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 $f : V \rightarrow \{0, 1, 2\}$ 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 $\gamma_{I\{R2\}}(G)$. A $\gamma_{I\{R2\}}(G)$-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 $f : V \rightarrow \{0, 1, 2, 3\}$ 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 $f : V \rightarrow \{0, 1, 2, 3\}$ 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 $\gamma_{I\{R3\}}(G)$. 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
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 $R3$DF for $G$, and so $\gamma_{\{R3\}}(G) \leq 2(n - \Delta - 1) + 3 = 2(n - \Delta) + 1$, as desired. \(\blacksquare\)

**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

- $V_0^3 = \{v \in V_0 : N(v) \cap V_3 \neq \emptyset\}$,
- $V_0^{12} = \{v \in V_0 \setminus V_0^3 : N(v) \cap V_1 \neq \emptyset, N(v) \cap V_2 \neq \emptyset\}$,
- $V_0^1 = \{v \in V_0 \setminus (V_0^3 \cup V_0^{12}) : N(v) \subseteq V_0 \cup V_1\}$,
- $V_0^2 = \{v \in V_0 \setminus (V_0^3 \cup V_0^{12}) : N(v) \subseteq V_0 \cup V_2\}$.
For $i = 1, 2, 3$, let $|V^i_1| = m_i$. We first present an upper bound for $|V^3_0|$ 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 $V^3_0$, and every vertex in $V_3$ with at least one neighbor in $V_1$ dominates at most $\Delta - 1$ vertices of $V^3_0$. Thus,

$$(1) \quad |V^3_0| \leq \Delta(|V_3| - m_3) + (\Delta - 1)m_3 = \Delta|V_3| - m_3.$$ 

Let $|V^1_0| = x$. We next present an upper bound for $|V^3_0|$ in terms of $|V_2|$, $x$ and $m_2$. Clearly, every vertex of $V^2_1 \cup V^2_0$ has a neighbor in $V_2$. Since $|V^2_1| = m_2$ and $|V^2_0| = x$, there are at most $\Delta|V_2| - x - m_2$ edges which have an end-point in $V_2$. Since any vertex of $V^2_0$ is adjacent to at least two vertices of $V_2$, we obtain that

$$(2) \quad |V^2_0| \leq \frac{\Delta|V_2| - x - m_2}{2}.$$ 

We next present an upper bound for $|V^1_0|$ 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 $V^1_0$ 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 $V^1_0$ is adjacent to at least three vertices of $V_1$, we obtain that

$$(3) \quad |V^1_0| \leq \frac{\Delta|V_1| - 2m_1 - m_2 - m_3 - x}{3}.$$ 

Since $|V_0| = |V^1_0| + |V^2_0| + |V^1_0| + |V^3_0|$, from (1), (2) and (3) we obtain that

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

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

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

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.

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

\[
\gamma_{(R3)}(G) \geq \frac{3n}{\Delta + 1} \geq \frac{3n}{\Delta + 1}, \text{ and so } \gamma_{(R3)}(G) \geq \left\lceil \max\left\{ \frac{3n}{\Delta + 2}, \frac{2n + \Delta}{\Delta + 1} \right\} \right\rceil + 1.
\]

Thus assume that \( |V_2| \neq 0 \). By Corollary 4, \( \gamma_{(R3)}(G) \geq \frac{3n - |V_2|}{\Delta + 1} \). Using Observation 2, we obtain

\[
|V_2| \leq \gamma_{(R3)}(G) \leq n - \Delta + \frac{1}{2},
\]

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. Thus assume that \( |V_2| = n - \Delta \). 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 \( n = v_0 + v_1 + 2v_2 + v_3 \). Since \( \Delta = n - v_2 = v_0 + v_1 + v_3 \), we obtain by a simple calculation that

\[
2v_2 = 3 - (v_1 + 3v_3) - \frac{v_1 + 3v_3}{v_0 + v_1 + v_3} < 2, \text{ a contradiction.}
\]

Thus \( v_3 \neq 0 \). If \( v_1 = 0 \), then \( 2v_2 = 3 - v_1 - \frac{v_1 + 3v_3}{v_0 + v_1 + v_3} < 0 \), a contradiction. Thus \( v_1 \neq 0 \). Then \( 2v_2 = 3 - (v_1 + 3v_3) - \frac{v_1 + 3v_3}{v_0 + v_1 + v_3} < 0 \), a contradiction. We conclude that

\[
\gamma_{(R3)}(G) \geq \frac{3n - |V_2|}{\Delta + 1}, \text{ and so } \gamma_{(R3)}(G) > \frac{3n - |V_2|}{\Delta + 1} > \frac{2n + \Delta}{\Delta + 1}, \text{ as desired.}
\]

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

\[
\frac{3n - |V_2|}{\Delta + 1} > \frac{3n}{\Delta + 2}, \text{ as desired.}
\]
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.

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 $f : V \rightarrow \{0,1,\ldots,k\}$ 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 $V_0 = V(G) \setminus (S \cup T)$, $V_1 = T$, $V_k = S$ 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

$$
\mathbb{E}(w(f)) = \mathbb{E}(k|S| + \left\lfloor \frac{k}{2} \right\rfloor |T|) = k\mathbb{E}(|S|) + \left\lfloor \frac{k}{2} \right\rfloor \mathbb{E}(|T|).
$$

Clearly, $\mathbb{E}(|S|) = np$. If $v \in T$, then $v \notin S$ and $v \notin N(S)$. Thus, $Pr(v \notin N[S]) = (1-p)^{1+\delta(v)} \leq (1-p)^{1+\delta}$. 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,

$$
\mathbb{E}(w(f)) = \mathbb{E}\left( k|S| + \left\lfloor \frac{k}{2} \right\rfloor |T| \right) \leq knp + \left\lfloor \frac{k}{2} \right\rfloor ne^{-p(1+\delta)}.
$$

(4)
Bounds on the Double Italian Domination Number of a Graph

Taking derivative of the function $g(p) = kp + \lceil \frac{k}{2} \rceil e^{-p(1+\delta)}$ and solving the equation $g'(p) = 0$, we obtain that $g(p)$ is minimized at $p = \ln \left( \frac{\lceil \frac{k}{2} \rceil (1+\delta)}{k} \right)$. Then by putting these values in (4) we obtain

$$E(w(f)) \leq nk \left( \frac{\ln \left( \frac{\lceil \frac{k}{2} \rceil (1+\delta)}{k} \right) + 1}{1 + \delta} \right) =: \alpha.$$

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

$$\gamma_{\{Rk\}}(G) \geq \frac{k(\ln \left( \frac{\lceil \frac{k}{2} \rceil}{k} \right) + \ln(1+\delta) - \ln k + 1)}{1+\delta} n(1+o(1)).$$

**Proof.** Let $H$ a complete graph with $\lceil \delta \ln \delta \rceil$ 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 $n = \lceil \delta \ln \delta \rceil + \delta$ vertices. We show that

$$\gamma_{\{Rk\}}(G) \geq \frac{k \ln \delta}{\delta} n(1+o(1)) = \frac{k \ln \delta}{\delta} (\delta \ln \delta + \delta)(1+o(1)) = k \ln^2 \delta (1+o(1)).$$

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

$$\gamma_{\{Rk\}}(G) \geq k|V_k| \geq k \ln^2 \delta - k \ln \delta \ln \ln^4 \delta = k \ln^2 \delta (1+o(1)),$$

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

$$P_r[V_k \text{ does not dominate } v_i] = \left( \frac{|V| - |V_k|}{\delta} \right)^{\delta} \geq \left( \frac{|V| - |V_k| - \delta}{|V| - \delta} \right) = \left( 1 - \frac{|V_k|}{|V| - \delta} \right)^{\delta}. $$
Using the fact that $1 - x \geq e^{-x}(1 - x^2)$ for $x \leq 1$, we find that

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

$$\geq e^{-\frac{\ln^2 \delta - \ln \delta \ln \ln 4 \delta}{\ln \delta - \delta} (1 + o_\delta(1))}$$

$$\geq e^{-\frac{\ln \delta \ln \ln 4 \delta}{1 - \frac{\ln \delta}{\ln 4 \delta} + o(1)} (1 + o_\delta(1))}$$

$$\geq e^{\ln \frac{\ln 4 \delta}{\delta} (1 + o_\delta(1)) (1 + o_\delta(1))} \geq \frac{\ln^3 \delta}{\delta}. $$

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

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

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

$$\gamma_{(Rk)}(G) \geq | \text{V}' \setminus \text{N}(\text{V}_k) | \geq \ln^3 \delta > k \ln \delta (1 + o_\delta(1)),$$

as desired. \hfill \blacksquare

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Received 30 January 2020
Revised 7 May 2020
Accepted 11 May 2020