GENERALIZED CONNECTED DOMINATION IN GRAPHS

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Generalized connected domination in graphs

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As a generalization of connected domination in a graph $G$ we consider domination by sets having at most $k$ components. The order $\gamma^c_k(G)$ of such a smallest set we relate to $\gamma(G)$, the order of a smallest connected dominating set. For a tree $T$ we give bounds on $\gamma^c_k(T)$ in terms of minimum valency and diameter. For trees the inequality $\gamma^c_k(T) \leq n - k - 1$ is known to hold, we determine the class of trees, for which equality holds.

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1 Introduction

We consider simple non-oriented graphs. The largest valency in $G$ is denoted by $\Delta(G) = \Delta$, the smallest by $\delta(G) = \delta$. $P_n$ is a path on $n$ vertices and $C_n$ is a circuit on $n$ vertices. In a graph a leaf or pendent vertex is a vertex of valency one and a stem is a vertex adjacent to at least one leaf. In $K_2$ a vertex is both a leaf and a stem. The set of leaves in $T$ is denoted by $\Omega(T)$. By $K_{1,k}$ we denote a star with one central vertex joined to $k$ other vertices. A subdivided star is a star with a subdivision vertex on each edge. A graph $G$ is called a corona graph if each vertex of $G$ is a leaf or a stem adjacent to exactly one leaf. For
a corona graph we write $G = H \circ K_1$, where $H$ is the subgraph in $G$ spanned by all stems in $G$. If $H$ is a tree we obtain a corona tree $T = H \circ K_1$.

The eccentricity $e(x)$ of a vertex $x$ is the distance to a vertex at maximum distance from it, $e(x) = \max\{d(x, y)\} y \in V(G)$. The diameter of $G$ is $\text{diam}(G) = \max\{e(x)\} x \in V(G)$. Let $D \subseteq V(G)$, then $N(D)$ is the set of vertices which have a neighbour in $D$ and $\overline{N}(D)$ is the set of vertices which are in $D$ or have a neighbour in $D$. $N[D] = D \cup N(D)$. A set $D \subseteq V(G)$ dominates $G$ if $V(G) \subseteq N[D]$, i.e., each vertex not in $D$ is adjacent to a vertex in $D$. The domination number $\gamma(G)$ is the cardinality of a smallest dominating set in $G$.

Ore (1962) proved the inequality below and Payan and Xuong (1982), Fink et al. (1985) determined its extremal graphs.

**Theorem (Ore, Payan, Xuong).** Let $G$ be a connected graph with $n$ vertices, $n \geq 2$. Then $\gamma(G) \leq \frac{n}{2}$ and equality holds if and only if $G$ is either a corona graph or a 4-circuit.

If a tree $T$ has $\gamma(T) = \frac{n}{2}$, then $n$ is even and this Theorem implies that $T$ is a corona tree.

**Definition** For a positive integer $k$ and a graph $G$ with at most $k$ components we define

$$\gamma_k^*(G) = \min \{|D|; D \subseteq V(G), D \text{ has at most } k \text{ components and } D \text{ dominates } G\}.$$

A set $D$ attaining the minimum above is called a $\gamma_k^*$-set for $G$.

**Example**

$$\gamma_k^*(C_n) = \begin{cases} n - 2k & \text{for } n \geq 3k \\ \frac{n}{3} & \text{for } 1 \leq n \leq 3k \end{cases}$$

For $k = 1$ we have that $\gamma_k^*$ is the usual connected domination number, $\gamma_k^*(G) = \gamma_c(G)$.

For $G$ connected and $k \geq 1$, obviously, $\gamma(G) \leq \gamma_k^*(G) \leq \gamma_c(G)$.

## 2 General graphs

Let $G$ be a connected graph with $n$ vertices and $k$ a positive integer. Let $\varepsilon_F(G)$ be the maximum number of leaves among all spanning forests of $G$, let $\varepsilon_T(G)$ be the maximum number of leaves among all spanning trees of $G$. Then Niemen (1974) proved statement (i) below about $\gamma$ and (Hedetniemi and Laskar (1984) generalized it to statement (ii) about $\gamma_k^*$

(i) $\gamma(G) = n - \varepsilon_F(G)$,

(ii) $\gamma_c(G) = n - \varepsilon_T(G)$.

We extend these results to $\gamma_k^*$.

**Theorem 1** Let $G$ be a connected graph with $n$ vertices and $k$ a positive integer. Let $\varepsilon_{F_k}(G)$ be the maximum number of leaves among all spanning forests of $G$ with at most $k$ trees. Then $\gamma_k^*(G) = n - \varepsilon_{F_k}(G)$. 

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Proof: In any spanning forest $F$ with at most $k$ trees the leaves will be dominated by their stems, so $\gamma_c^k(G) \leq n - |\Omega(F)|$ and hence $\gamma_c^k(G) \leq n - \varepsilon_k(G)$.

Conversely, let $D = D_1 \cup D_2 \cup \ldots \cup D_t$, $1 \leq t \leq k$, be a $\gamma_c^k$-set for $G$. Choose for each $D_i$ a spanning tree $T_i$, $1 \leq i \leq t$. For each vertex in $V(G) - D$ choose one edge to $D$. We have constructed a spanning forest $F$ with $t$ components and at least $n - |D| = n - \gamma_c^k(G)$ leaves. Therefore $\varepsilon_k(G) \geq n - \gamma_c^k(G)$ and Theorem 1 is proven. □

Theorem 2 Let $k$ be a positive integer and $G$ a connected graph. Then

$$\gamma_c^k(G) = \min \left\{ \gamma_c^k(F_k) \mid F_k \text{ is a spanning forest of } G \text{ with at most } k \text{ trees} \right\}$$

$$= \min \left\{ \gamma_c^k(T) \mid T \text{ is a spanning tree of } G \right\}$$

Proof: Let $F_k$ be a spanning forest of $G$ with at most $k$ trees. Clearly $\gamma_c^k(G) \leq \gamma_c^k(F_k)$ since a set which dominates $F_k$ also dominates in $G$. Conversely, we can in $G$ find a spanning forest $F_k$ with at most $k$ components such that $\gamma_c^k(G) = \gamma_c^k(F_k)$: As was also done in the proofs of (i) and (ii) above we construct $F_k$ from a $\gamma_c^k$-set $D = D_1 \cup D_2 \cup \ldots \cup D_t$, $1 \leq t \leq k$, by choosing a spanning tree $T_i$ in each connected subgraph $D_i$ and joining each vertex in $V(G) - D$ to precisely one vertex in $D$. Obviously, $\gamma_c^k(F_k) \leq |D| = \gamma_c^k(G)$. This proves the first equality. For the second equality we observe that the first minimum is chosen among a larger set, so that $\min \gamma_c^k(F_k) \leq \min \gamma_c^k(T)$, and secondly that any $F_k$ by addition of edges renders a tree $T$ with $\gamma_c^k(T) \leq \gamma_c^k(F_k)$. □

Hartnell and Vestergaard (2003a) proved the following result.

Theorem (Hartnell, Vestergaard). For $k \geq 1$ and $G$ connected

$$\gamma_c(G) - 2(k - 1) \leq \gamma_c^k(G) \leq \gamma_c(G).$$

From this theorem we can easily derive the following classical result proven by Duchet and Meyniel (1982).

Corollary (Duchet, Meyniel) For any connected graph $G$, $\gamma_c(G) \leq 3\gamma(G) - 2$.

Proof: Let $G$ be a connected graph with domination number $\gamma(G)$. Choose $k = \gamma(G)$, then $\gamma_c^k(G) = \gamma(G)$. Substituting into Hartnell’s and Vestergaard’s theorem above we obtain $\gamma_c(G) - 2(k - 1) \leq \gamma(G)$ and that proves the corollary. □

2.1 Other bounds on $\gamma_c^k$

Theorem 3 For a positive integer $k$ and a connected graph $G$ with maximum valency $\Delta$ we have

(A) $\gamma_c(G) \leq n - \Delta$ and for trees $T$ equality holds if and only if $T$ has at most one vertex of valency $\geq 3$.

(B) $\gamma_c^k(G) \leq n - \frac{(D - 1)(\delta - 2)}{3} - 2k$ if $G$ has diameter $D \geq 3k - 1$ and the minimum valency $\delta = \delta(G)$ is at least 3.

(C) If $G$ is a connected graph with two vertices of valency $\Delta$ at distance $d$ apart, $d \geq 3$, then $\gamma_c^k(G) \leq$
\( n - 2(\Delta - 1) - 2 \min(k - 1, \frac{d - 2}{3}) \).

(D) Let \( x \in V(G) \) have valency \( d(x) \) and eccentricity \( e(x) \). Then \( \gamma'(G) \leq n - d(x) - 2 \min(k - 1, \frac{e(x) - 2}{3}) \).

Proof: (A). Let \( T \) be a spanning tree of \( G \) with \( \Delta(T) = \Delta(G) = \Delta \). \( T \) has at least \( \Delta \) leaves, and hence \( \gamma_c(G) \leq \gamma_c(T) \leq n - \Delta \).

If \( T \) has two vertices of valency \( \geq 3 \), the number of leaves in \( T \) will be larger than \( \Delta \), and we get strict inequality in (A). Clearly, a tree \( T \) with exactly one vertex of valency \( \Delta \geq 3 \) has equality in (A) and for \( \Delta = 2 \), \( \gamma_c(P_3) = n - 2 \).

(B). Let \( P = v_1 v_2 v_3 \ldots v_{3k+u} \), \( k \leq t, 0 \leq u \leq 2 \), be a diagonal path in \( G \). \( P \) has length \( D = 3t + u - 1 \). For \( i = 1, \ldots, t \) let \( v_{3i-1} \) have neighbours \( v_{3i-2}, v_{3i} \) and \( a_{ij}, j = 1, \ldots, j \geq \delta - 2 \geq 1 \). In \( G - \{ v_{3i+1} \mid 1 \leq i \leq k - 1 \} \) consider the \( k - 1 \) disjoint stars with center \( v_{3i-1} \) and neighbours \( N(v_{3i-1}), 1 \leq i \leq k - 1 \), and the tree consisting of the path \( v_{3k-2} v_{3k-1} v_{3k} \ldots v_{3k+u} \) and leaves \( v_{3i-1} a_{3j-1}, j = 1, \ldots \) from vertices \( v_{3i-1}, k \leq i \leq t \).

Extend this forest of \( k \) trees to a spanning forest \( F \) with \( k \) trees in \( G - \{ v_{3i+1} \mid 1 \leq i \leq k - 1 \} \). The number of leaves in \( F \) is at least \( t(\delta - 2) + 2k \) and hence \( \gamma'_c(G) \leq n - t(\delta - 2) - 2k \). From \( t = \frac{D + 1 - u}{3} \)

\[ \frac{D - 1}{3} \leq n - \frac{(D - 1)(\delta - 2)}{3} - 2k. \]

(C). Let \( d(v_1) = d(v_2) = \Delta \) and let \( P = v_1 v_2 \ldots v_s \) be a shortest \( v_1 v_2 \)-path, \( s = 3t + 1 + u, t \geq 1, 0 \leq u \leq 2 \). \( t \geq k - 1 \). In \( G - \{ v_{3i-1} v_{3i} \mid 1 \leq i \leq k - 2 \} \) we extend the \( k \) trees below to a spanning forest \( F \) of \( G \),

1. The star consisting of \( v_1 \) joined to all its neighbours,
2. the \( k - 2 \) paths of length two \( v_{3i+1} v_{3i+2}, 1 \leq i \leq k - 2 \),
3. the path \( v_{3k-3} v_{3k-2} \ldots v_s \) together with all \( \Delta - 1 \) neighbours of \( v_s \) outside of \( P \).

\( F \) will have at least \( 2(\Delta - 1) + 2(k - 1) \) leaves.

\[ t \leq k - 2; s = 3t + 1 + u, d = d(v_1, v_2) = s - 1 = 3t + u, t - 1 = \frac{d - u}{3} - 1 \geq \frac{d - 2}{3} - 1. \] As before, we can find a spanning forest \( F \) whose number of leaves is at least \( 2\Delta + 2(t - 1) \geq 2(\Delta - 1) + \frac{2d - 2}{3} \) and consequently \( \gamma'_c(G) \leq n - 2(\Delta - 1) - 2 \frac{d - 2}{3} \). The proof of (D) is similar. \( \square \)

3 Trees

For trees Hartnell and Vestergaard (2003a) found

**Theorem (Hartnell, Vestergaard).** Let \( k \) be a positive integer and \( T \) a tree with \( |V(T)| = n, n \geq 2k + 1 \). Then \( \gamma'_c(T) \leq n - k - 1 \).

This inequality is best possible. For \( k = 1 \) the extremal trees are paths \( P_n \) and for \( k \geq 2 \) extremal trees will be described in the following Theorem 4.

A tree is of type \( A \) if \( T \) contains a vertex \( x_0 \) such that \( T - x_0 \) is a forest of trees \( T_1, T_2, \ldots, T_\alpha, \alpha \geq 1 \), such that each tree \( T_i \) is a corona tree and \( x_0 \) is joined to a stem in each of the trees \( T_i, 1 \leq i \leq \alpha \). We note that a subdivision of a star is a tree of type \( A \).
A tree is of type B if \( T \) contains a path \( uvw \) such that \( T - \{ u, v, w \} \) is a forest of corona trees \( T_1, T_2, \ldots, T_s, T_{s+1}, \ldots, T_0, s \geq 2, 1 \leq s < \alpha \) and \( u \) is joined to a stem in each of the trees \( T_1, T_2, \ldots, T_s \), while \( w \) is joined to a stem in each of the trees \( T_{s+1}, \ldots, T_0 \).

The theorem below was proven by Randerath and Volkmann (1998) and Baogen et al. (2000).

**Theorem (Randerath, Volkmann, Baogen, Cockayne, et al.).** If \( T \) is a tree with \( n \) vertices, \( n \) odd, and \( \gamma(T) = \left\lfloor \frac{n}{2} \right\rfloor \) then \( T \) is a tree of type A or B.

We shall now determine the trees extremal for Hartnell, Vestergaard’s Theorem.

**Theorem 4.** Let \( k \geq 2 \) be a positive integer and \( T \) a tree with \( n \) vertices, \( n \geq 2k + 1 \). Then \( \gamma^c(T) = n - k - 1 \) if and only if one of cases (i)-(iii) below occur.

(i) \( k = \frac{n - 1}{2}, \gamma^c(T) = \gamma(T) = \frac{n - 1}{2} \) and \( T \) is of type A or B.

(ii) \( k = \frac{n - 2}{2}, \gamma^c(T) = \gamma(T) = \frac{n}{2} \) and \( T \) is a corona tree.

(iii) \( k = \frac{n - 3}{2}, \gamma^c(T) = \frac{n + 1}{2}, \gamma(T) = \frac{n - 1}{2} \) and \( T \) is a star \( K_{1,k+1} \) with a subdivision vertex on each edge.

**Proof:** Let \( k \geq 2 \) and a tree \( T \) of order \( n \) be given such that \( n \geq 2k + 1 \) and \( \gamma^c(T) = n - k - 1 \). We shall prove that one of cases (i)-(iii) must occur.

We note that \( \gamma(T) \leq k \) as well as \( \gamma^c(T) \leq k \) implies \( \gamma^c(T) = \gamma(T) \). We also note that for \( k \geq 1 \) and a tree \( T \) of order \( n \geq 2 \) we either have \( n \geq 2k + 1 \) and then \( \gamma^c(T) \leq \gamma(T) = n - k - 1 \) by Hartnell, Vestergaard’s Theorem or \( 2 \leq n \leq 2k \) and \( \gamma^c(T) = \gamma(T) \) by Ore, Payan, Xuong’s Theorem.

If \( n = 2k + 1 \) we have \( \gamma^c(T) = n - k - 1 = k \). By the remark above \( \gamma(T) = k = \frac{n}{2} \) and from the Theorem by Randerath et al. we see that \( T \) is a tree of type A or B, so (i) occurs. If \( n = 2k + 2 \) we have \( \gamma^c(T) = n - k - 1 = k + 1 \) and \( \gamma(T) = \gamma^c(T) = \frac{n}{2} \), so \( T \) by Ore, Payan, Xuong’s Theorem is a corona tree and (ii) occurs. We may now assume \( n \geq 2 + 3 \).

Let \( v_1, v_2, \ldots, v_n \) be a longest path in \( T \). Since \( \gamma^c(T) = n - k - 1 \geq k + 2 \geq 4 \), \( T \) is neither a star nor a bistar, so \( \alpha \geq 5 \). We have \( d_T(v_2) = 2 \). Otherwise \( d_T(v_2) \geq 3 \) and we could from \( T \) delete three leaves adjacent to \( v_2 \) if \( d_T(v_2) \geq 4 \) and in case \( d_T(v_2) = 3 \) we could delete \( v_2 \) and two leaves adjacent to it obtaining in both cases a tree \( T' \) of order \( n - 3 \geq 2(k - 1) + 1 \) which by Harthnell, Vestergaard’s Theorem has \( \gamma^c(T') \leq (n - 3) - (k - 1) - 1 \leq n - k - 3 \). Adding \( v_2 \) to a \( \gamma^c(T') \)-set we would obtain \( \gamma^c(T) \leq n - k - 2, \) a contradiction so \( d_T(v_2) = 2 \). No leaf is adjacent to \( v_3 \) because, if \( c \) were a leaf adjacent to \( v_3 \) let \( d \) denote either another leaf adjacent to \( v_3 \) or \( d = v_3 \) if no other leaf exists. Consider \( T' = T - \{ v_1, v_2, c, d \} \). \( T' \) has order \( n - 4 \geq 2(k - 1) + 1 \) and by Harthnell, Vestergaard’s Theorem \( \gamma^c(T') \leq n - k - 2, \) a contradiction, so \( v_3 \) is not a stem. On the other hand \( d_T(v_3) \geq 3 \), for assume \( d_T(v_3) = 2 \), then \( T' = T - \{ v_1, v_2, v_3 \} \) has \( \gamma^c(T') \leq n - k - 3 \) and addition of \( v_2 \) gives \( \gamma^c(T) \leq n - k - 2, \) a contradiction. Assume therefore that \( v_2 \) besides \( v_3 \) is adjacent to \( a_1, a_2, \ldots, a_t \), \( t \geq 1 \), where each \( a_i \) has valency two and is adjacent to the leaf \( b_1, 1 \leq i \leq t \). We have \( k - 1 \geq 1 \) because \( V(T) - \{ v_1, b_1, b_2, \ldots, b_t, v_3 \} \) is a connected subgraph with \( n - t - 2 \) vertices which dominate \( T \), so that \( n - k - 1 = \gamma^c(T) \leq n - t - 2 \) giving \( k - t \geq 1 \). Consider the tree \( T' = T - \{ v_1, v_3, a_1, \ldots, a_t, b_1, b_2, \ldots, b_t, v_3 \} \) of order \( n - 2t - 3 \). If \( n - 2t - 3 \geq 2(k - t) + 1 \) we obtain by Harthnell, Vestergaard’s Theorem that \( \gamma^c(T') \leq (n - 2t - 3) - (k - t) - 1 \leq n - k - 4 \), and adding \( t + 2 \) vertices \( \{ v_2, v_3, a_1, a_2, \ldots, a_t \} \), forming one component, to a \( \gamma^c(T') \)-set we obtain \( \gamma^c(T) \leq n - k - 2, \)
a contradiction. So we have 
\[ n - 2t - 3 \leq 2(k-t) \] 
and by an earlier remark \( \gamma_{k-1}(T') \leq \frac{n-2t-3}{2} \). That implies
\[ n - k - 1 = \gamma_k(T) \leq \frac{n-2t-3}{2} + t + 2 = \frac{n+1}{2} \] or \( n \leq 2k + 3 \). Together with the assumption \( n \geq 2k + 3 \) we get \( n = 2k + 3 \). Then \( \gamma_k(T) = k + 2 \) and we have \( \gamma(T) \leq k + 1 \) by Ore, Payan, Xuong's change Theorem. Thus \( \gamma(T) = k + 1 \) and any \( \gamma(T) \)-set consists of \( k + 1 \) isolated vertices. As \( \gamma(T) = \left\lfloor \frac{n}{k} \right\rfloor \) the tree \( T \) is of type A or B. But \( T \) cannot be of type B, for assume \( T \) is of type B. Then \( T \) consists of a \( 3 \)-path \( uuv \), with each of its ends joined to stems of corona trees, and since we have just seen that \( v_1, v_{k-2} \) are neither stems nor leaves, they must play the role of \( u, w \), so \( \alpha = 7 \) and \( T \) consists of two subdivided stars centered at \( u = v_3 \) and \( w = v_5 \) and a vertex \( v = v_4 \) joined to \( u \) and \( w \). This graph \( T \) has a \( \gamma \)-set with two adjacent vertices \( v_2 \) and \( v_3 \), a contradiction, so \( T \) is of type A. Using, in analogy to \( v_2, v_3 \), that \( d_{T}(v_{k-1}) = 2 \) and that \( v_{k-2} \) is not a stem, we get that \( \alpha = 5 \) and \( T \) is a subdivided star so that (iii) occurs.

Conversely, it is easy to see that if (i), (ii) or (iii) holds then \( \gamma_k(T) = \gamma(T) = n - k + 1 \). This proves Theorem 4.

\[ \Box \]

References


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