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GENERALIZED CONNECTED DOMINATION IN GRAPHS

KOUIDER M / VESTERGAARD P

Unité Mixte de Recherche 8623
CNRS-Université Paris Sud-LRI

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CNRS – Université de Paris Sud
Centre d'Orsay
LABORATOIRE DE RECHERCHE EN INFORMATIQUE
Bâtiment 650
91405 ORSAY Cedex (France)

Generalized connected domination in graphs

Mekkia Kouider[1] and Preben Dahl Vestergaard[2]

[1] *Laboratoire de Recherche en Informatique, UMR 8623,*
Bât. 490, Université Paris Sud, 91405 Orsay, France.
E-mail: km@lri.fr
[2] *Dept. of Mathematics, Aalborg University,*
Fredrik Bajers Vej 7G, DK–9220 Aalborg Ø, Denmark.
E-mail: pdv@math.auc.dk

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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 $\gamma_c(G)$, 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 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 $N[D]$ 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

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

A set D attaining the minimum above is called a γ_c^k-set for G.

Example

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

For $k = 1$ we have that γ_c^1 is the usual connected domination number, $\gamma_c^1(G) = \gamma_c(G)$.
For G connected and $k \geq 1$, obviously, $\gamma(G) \leq \gamma_c^k(G) \leq \gamma_c(G)$.

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 γ and (Hedetniemi and Laskar (1984) generalized it to statement (ii) about γ_c.

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

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

We extend these results to γ_c^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*
$\gamma_c^k(G) = n - \varepsilon_{F_k}(G)$.

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 $\gamma_c^k(G) \leq n - \varepsilon_{F_k}(G)$.

Conversely, let $D = D_1 \cup D_2 \cup \cdots \cup D_t$, $1 \leq t \leq k$, be a γ_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 $\varepsilon_{F_k}(G) \geq n - \gamma_c^k(G)$ and Theorem 1 is proven. □

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

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

Proof: Let F_k be a spanning forest of G with at most k trees. Certainly $\gamma_c^k(G) \leq \gamma_c^k(F_k)$ since a set which dominates in 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 γ_c^k-set $D = D_1 \cup D_2 \cup \cdots \cup D_t$, $1 \leq t \leq k$, 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 γ_c^k

Theorem 3 *For a positive integer k and a connected graph G with maximum valency Δ 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 ≥ 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 Δ 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* $\gamma_c^k(G) \le n-d(x)-2\min\{k-1,\frac{e(x)-2}{3}\}$.

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

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

(B). Let $P=v_1v_2v_3\dots v_{3t+u}$, $k\le t, 0\le u\le 2$, be a diagonal path in G. P has length $D=3t+u-1$. For $i=1,\dots,t$ let v_{3i-1} have neighbours v_{3i-2}, v_{3i} and a_{ij}, $j=1,\dots,$ $j\ge\delta-2\ge 1$. In $G-\{v_{3i}v_{3i+1} | 1\le i\le k-1\}$ consider the $k-1$ disjoint stars with center v_{3i-1} and neighbours $N(v_{3i-1})$, $1\le i\le k-1$, and the tree consisting of the path $v_{3k-2}v_{3k-1}v_{3k}\dots v_{3t+u}$ and leaves $v_{3i-1}a_{3i-1,j}$, $j=1,\dots$ from vertices v_{3i-1}, $k\le i\le t$.

Extend this forest of k trees to a spanning forest F with k trees in $G-\{v_{3i}v_{3i+1} | 1\le i\le k-1\}$. The number of leaves in F is at least $t(\delta-2)+2k$ and hence $\gamma_c^k(G)\le n-t(\delta-2)-2k$. From $t=\frac{D+1-u}{3}\ge \frac{D-1}{3}$ we obtain $\gamma_c^k(G)\le n-\frac{(D-1)(\delta-2)}{3}-2k$.

(C). Let $d(v_1)=d(v_s)=\Delta$ and let $P=v_1v_2\dots v_s$ be a shortest v_1v_s-path, $s=3t+1+u, t\ge 1, 0\le u\le 2$. $\underline{t\ge k-1:}$ In $G-\{v_{3i-1}v_{3i} | 1\le i\le k-2\}$ 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 $v_{3i}v_{3i+1}v_{3i+2}, 1\le i\le k-2$,
3. the path $v_{3k-3}v_{3k-2}\dots v_s$ together with all $\Delta-1$ neighbours of v_s outside of P.

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

$\underline{t\le k-2:}$ $s=3t+1+u, d=d(v_1,v_s)=s-1=3t+u, t-1=\frac{d-u}{3}-1\ge\frac{d-2}{3}-1$. As before, we can find a spanning forest F of G whose number of leaves is at least $2\Delta+2(t-1)\ge 2(\Delta-1)+2\frac{d-2}{3}$ and consequently $\gamma_c^k(G)\le n-2(\Delta-1)-2\frac{d-2}{3}$. The proof of (D) is similar. □

3 Trees

For trees Hartnell and Vestergaard (2003a) found

Theorem (Hartnell, Vestergaard). *Let* k *be a positive integer and* T *a tree with* $|V(T)|=n, n\ge 2k+1$. *Then* $\gamma_c^k(T)\le n-k-1$.

This inequality is best possible. For $k=1$ the extremal trees are paths P_n and for $k\ge 2$ 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 $T_1,T_2,\dots,T_\alpha, \alpha\ge 1$, 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, $1\le i\le\alpha$. 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 $T_1,T_2,\dots,T_s$, $T_{s+1},,\dots,T_\alpha$, $\alpha\geq 2, 1\leq s<\alpha$ and u is joined to a stem in each of the trees $T_1,T_2,\dots,T_s$, while w is joined to a stem in each of the trees $T_{s+1},,\dots,T_\alpha$.

The t heorem 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 $\gamma(T)=\lfloor\frac{n}{2}\rfloor$ 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 $\gamma_c^k(T)=n-k-1$ if and only if one of cases (i)-(iii) below occur.*

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

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

(iii) $k=\frac{n-3}{2}$, $\gamma_c^k(T)=\frac{n+1}{2}$, $\gamma(T)=\frac{n-1}{2}$ and T is a star $K_{1,k+1}$ with a subdvision 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 $\gamma_c^k(T)=n-k-1$. We shall prove that one of cases (i)-(iii) must occur.

We note that $\gamma(T)\leq k$ as well as $\gamma_c^k(T)\leq k$ implies $\gamma_c^k(T)=\gamma(T)$. 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 $\gamma_c^k(T)\leq n-k-1$ by Hartnell, Vestergaard's Theorem or $2\leq n\leq 2k$ and $\gamma_c^k(T)=\gamma(T)\leq\frac{n}{2}$ by Ore, Payan, Xuong's Theorem.

If $n=2k+1$ we have $\gamma_c^k(T)=n-k-1=k$. By the remark above $\gamma(T)=k=\lfloor\frac{n}{2}\rfloor$ 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 $\gamma_c^k(T)=n-k-1=k+1$ and $\gamma(T)=\gamma_c^k(T)=\frac{n}{2}$, so T by Ore, Payan, Xuong's Theorem is a corona tree and (ii) occurs. We may now assume $n\geq 2k+3$.

Let $v_1v_2\dots v_\alpha$ be a longest path in T. Since $\gamma_c^k(T)=n-k-1\geq k+2\geq 4$, 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 Harntell, Vestergaard's Theorem has $\gamma_c^{k-1}(T')\leq (n-3)-(k-1)-1\leq n-k-3$. Adding v_2 to a $\gamma_c^{k-1}(T')$-set we would obtain $\gamma_c^k(T)\leq n-k-2$, 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 let $d=v_3$ 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 Hartnell, Vestergaard's Theorem $\gamma_c^{k-1}(T')\leq(n-4)-(k-1)-1$ $\leq n-k-4$. Adding v_2,v_3 to a $\gamma_c^{k-1}(T')$-set we obtain $\gamma_c^k(T)\leq n-k-2$, 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 $\gamma_c^{k-1}(T')\leq$ $n-k-3$ and addition of v_2 gives $\gamma_c^k(T)\leq n-k-2$, a contradiction. Assume therefore that v_3 besides v_2 and v_4 is adjacent to $a_1,a_2,\dots,a_t$, $t\geq 1$, where each a_i has valency two and is adjacent to the leaf $b_i, 1\leq i\leq t$. We have $k-t\geq 1$ because $V(T)-\{v_1,b_1,b_2,\dots,b_t,v_3\}$ is a connected subgraph with $n-t-2$ vertices which dominate T, so that $n-k-1=\gamma_c^k(T)\leq n-t-2$ giving $k-t\geq 1$. Consider the tree $T'=T-\{v_1,v_2,a_1,a_2,\dots,b_1,b_2,\dots,b_t,v_3\}$ of order $n-2t-3$. If $n-2t-3\geq 2(k-t)+1$ we obtain by Hartnell, Vestergaard's Theorem that $\gamma_c^{k-t}(T')\leq(n-2tk-3)-(k-t)-1\leq n-k-t-4$, and adding $t+2$ vertices $\{v_2,v_3,a_1,a_2,\dots,a_t\}$, forming one component, to a $\gamma_c^{k-t}(T')$-set we obtain $\gamma_c^k(T)\leq n-k-2$, a contradiction. So we have $n-2t-3 \leq 2(k-t)$ and by an earlier remark $\gamma_c^{k-t}(T') \leq \frac{n-2t-3}{2}$. That implies $n-k-1 = \gamma_c^k(T) \leq \frac{n-2t-3}{2} + t + 2 = \frac{n+1}{2}$ or $n \leq 2k+3$. Together with the assumption $n \geq 2k+3$ we get $n = 2k+3$. Then $\gamma_c^k(T) = k+2$ and we have $\gamma(T) \leq k+1$ by Ore, Payan, Xuong's Theorem. Thus $\gamma(T) = k+1$ and any $\gamma(T)$-set consists of $k+1$ isolated vertices. As $\gamma(T) = \lfloor \frac{n}{2} \rfloor$ 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 , uvw, with each of its ends joined to stems of corona trees, and since we have just seen that $v_3, v_{\alpha-2}$ 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 γ-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 $d_T(v_{\alpha-1}) = 2$ and that $v_{\alpha-2}$ is not a stem, we get that $\alpha = 5$ and T is a subdivided star so that (iii) occurs.

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

□

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