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Short Note

On coalition graphs and coalition count of graphs

Swathi Shetty[†], **Sayinath Udupa N V**[*], **Rakshith B R**[‡]

Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, India
[†]`swathi.dscmpl2022@learner.manipal.edu`
[*]`sayinath.udupa@manipal.edu`
[‡]`ranmsc08@yahoo.co.in`; `rakshith.br@manipal.edu`.

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Abstract: Let G be graph with vertex set $V(G)$ and order n. A set $S \subseteq V(G)$ is a dominating set of a graph G if every vertex in $V(G)\backslash S$ is adjacent to at least one vertex in S. A coalition in a graph G consists of two disjoint sets of vertices V_1 and V_2, neither of which is a dominating set but whose union $V_1 \cup V_2$ is a dominating set. A coalition partition, abbreviated c-partition, in a graph G is a vertex partition $\pi = \{V_1, V_2, \ldots, V_k\}$ such that every set V_i of π is either a singleton dominating set, or is not a dominating set but forms a coalition with another set V_j in π. The sets V_i and V_j are coalition partners in G. The coalition number $C(G)$ equals the maximum order k of a c-partition of G. For any graph G with a c-partition $\pi = \{V_1, V_2, \ldots, V_k\}$, the coalition graph $CG(G, \pi)$ of G is a graph with vertex set $V_1, V_2, \ldots, V_k$, corresponding one-to-one with the set π, and two vertices V_i and V_j are adjacent in $CG(G, \pi)$ if and only if the sets V_i and V_j are coalition partners in π. In [T.W. Haynes, J.T. Hedetniemi, S.T. Hedetniemi, A.A. McRae, and R. Mohan, Coalition graphs, Commun. Comb. Optim. 8 (2023), 423-430], authors proved that for every graph G there exist a graph H and c-partition π such that $CG(H, \pi) \cong G$, and raised the question: Does there exist a graph H^* of smaller order n^* and size m^* with a c-partition π^* such that $CG(H^*, \pi^*) \cong G$? In this paper, we constructed a graph H^* of small order and size and a c-partition π^* such that $CG(H^*, \pi^*) \cong G$. Recently, Haynes et al. [Introduction to coalitions in graphs, AKCE Int. J. Graphs Comb. 17 (2020), 653-659] defined the coalition count $c(G)$ of a graph G as the maximum number of different coalition in any c-partition of G. We characterize all graphs G with $c(G) = 1$. Further, imposing some suitable conditions on coalition number, we study the properties of coalition count of graph.

Keywords: dominating set, coalition partition, coalition number.

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[*] *Corresponding Author*

1. Introduction

Let $G = (V(G), E(G))$ be a graph with vertex set $V(G)$, edge set $E(G)$, order $n(G) = |V(G)|$, and size $m(G) = |E(G)|$. A set $S \subseteq V(G)$ is a *dominating set* of a graph G if every vertex in $V(G)\backslash S$ is adjacent to at least one vertex in S. A detailed account of domination in graphs is presented in the recent books on domination theory [8, 9]. In a graph G of order n, a vertex of degree one is a *pendant vertex* and a vertex of degree $n-1$ is called a *full vertex*. A subset V_i is called a *singleton set* if $|V_i| = 1$. Note that any full vertex forms a singleton dominating set. The open neighborhood $N(v)$ of a vertex v in G is the set of vertices adjacent to v, while the closed neighborhood of v is the set $N[v] = \{v\} \cup N(v)$. The *domatic partition* is a partition of the vertex set into dominating sets. The *domatic number* $d(G)$ is equal to the maximum order k of the vertex partition, called domatic partition, $P = \{V_1, V_2, \dots, V_k\}$, such that every set V_i is a dominating set in G. For more details on the domatic number refer [13, 14].

The concept of coalitions in graphs was introduced by Haynes et.al. [4] in 2020 as follows. A *coalition* in a graph G consists of two disjoint sets of vertices V_1 and V_2, neither of which is a dominating set but whose union $V_1 \cup V_2$ is a dominating set. A *coalition partition*, henceforth called a c-partition, in a graph G is a vertex partition $\pi = \{V_1, V_2, \dots, V_k\}$ such that every set V_i of π is either a singleton dominating set, or is not a dominating set but forms a coalition with another set V_j in π. The *coalition number* $C(G)$ equals the maximum order k of a c-partition of G, and a c-partition of G having order $C(G)$ is called a *$C(G)$-partition*. In [5], Haynes et al. established upper bounds on the coalition number in terms of the minimum and maximum degree. In [6], they proved that every graph is the coalition graph of some graph, while in [7], they investigated coalition graphs of trees, paths, and cycles. Furthermore, in [4], the authors posed the open problem of characterizing all graphs G of order n with coalition number $C(G) = n$. This problem was partially addressed by Bakhshesh et al. [3], where the authors characterized all graphs of order n with $\delta(G) \leq 1$ that satisfy $C(G) = n$, and identified all trees whose coalition number equals $n-1$, which was later fully solved by Yang et al. in [12]. In addition, several variants of coalition have been introduced and studied in [1, 2, 10, 11].

In the paper [4] while introducing coalitions, the authors suggest several related areas for future study, one of which is coalition count of G defined as follows. The coalition count $c(G)$ of a graph G is equal to the maximum number of different coalition in any c-partition of G.
Let us give an example to illustrate the coalition count.

Example 1. Consider the cycle $C_4 = (v_1, v_2, v_3, v_4)$.
The partition $\pi_1 = \{\{v_1\}, \{v_2\}, \{v_3\}, \{v_4\}\}$ is a c-partition of C_4. No individual set in π_1 is a dominating set. However the following different coalition exist:

- The set $\{v_1\}$ forms coalition with $\{v_2\}$, $\{v_3\}$ and $\{v_4\}$.
- The set $\{v_2\}$ forms coalition with $\{v_3\}$ and $\{v_4\}$.

- The set $\{v_3\}$ form coalition with $\{v_4\}$.

Thus, every set in π_1 forms a coalition with at least one other set. Hence, $C(C_4) = 4$, and π_1 is a $C(C_4)$-coalition partition. But, the total number of different possible coalitions is 6, thus $c(C_4) = 6$.

2. Coalition graphs

In [6], Haynes et al. defined coalition graph of G as follows. Let G be a graph with a c-partition $\pi = \{V_1, V_2, \ldots, V_k\}$. The coalition graph $CG(G, \pi)$ of G is a graph with vertex set $V_1, V_2, \ldots, V_k$, and two vertices V_i and V_j are adjacent in $CG(G, \pi)$ if and only if the sets V_i and V_j are coalition partners in π. In [6], Haynes et.al proved that, for every graph G, there is a graph H and some c-partition π of H, such that $CG(H, \pi) \cong G$, that is, for every graph $G = (V, E)$ having n non-isolated vertices and t isolated vertices with $|E| = m$, they constructed a graph H of order $n + m + \binom{n}{2} + t$ and size $m = \binom{n}{2} + 2m(n-1) + \overline{m}(n-2) + t(n(H) - 1)$, where $n(H)$ is order of H, and the c-partition π such that $CG(H, \pi) \cong G$.

Further, they raised the following question: Does there exist a graph H^* of smaller order n^* and size m^* with a c-partition π^* such that $CG(H^*, \pi^*) \cong G$?

Theorem 1. *For every graph G, there exist a graph H^* and c-partition π^* such that $CG(H^*, \pi^*) \cong G$.*

Proof. Let G be a graph with vertex set $V(G) = \{v_1, v_2, \ldots, v_n\} \cup \{w_1, w_2, \ldots, w_t\}$, where each v_i has degree at least one and each w_i is an isolate. Let $G' = G - \{w_1, \ldots, w_t\}$. Then $|E(G)| = |E(G')| = m$ and $|E(\overline{G'})| = \overline{m}_{G'}$, where $m + \overline{m}_{G'} = \binom{n}{2}$. To construct H^*, we begin with a complete graph K_n on vertices $\{v_1, \ldots, v_n\}$, corresponding to the non-isolates of G. If n is even, partition these vertices into $\frac{n}{2}$ disjoint pairs and delete the edge within each pair; if n is odd, form $\frac{n-1}{2}$ such pairs and delete the edge within each pair and retain all edges incident with v_n. These n vertices are referred to as the base vertices of H^*. The partition π^* is initially taken as the singleton partitions $V_i = \{v_i\}$, $1 \leq i \leq n$. We will add to the sets in the partition as we build H^*.

Now we consider the following cases:

Case 1: Let $G \cong K_n \cup tK_1$. If n is even and $t \neq 0$, we construct H^* by adding each isolate vertex $w_i \in V(G)$ to H^* and connecting w_i to every other vertex of H^*. Then, the partition π^* is extended by adding singleton sets $W_i = \{w_i\}$ for $n \leq i \leq t$. In this construction, no set V_i in π^* is a dominating set, but every pair of sets V_i in π^* forms a coalition. Therefore, the coalition graph satisfies $CG(H^*, \pi^*) \cong K_n \cup tK_1$, where n is even.

If n is odd and $t \neq 0$, we first extend H^* by introducing a new vertex u_n associated with vertex v_n, such that u_n is adjacent to all base vertices except v_n. The vertex u_n is assigned to a set V_k in π^*, where $k \neq n$, and the edge $u_n v_k$ is removed from

H^*. Next, for every isolate $w_i \in V(G)$, we add w_i to H^* and connect it to every other vertex of H^*. The partition π^* is then extended by singleton sets $W_i = \{w_i\}$ for $n \leq i \leq t$. Further, none of the sets V_i is a dominating set, but every pair of sets V_i in π^* forms a coalition. Thus, $CG(H^*, \pi^*) \cong K_n \cup tK_1$, where n is odd.

Case 2: If $G \cong G' \cup tK_1$, where $G' \ncong K_n$, then without loss of generality, we assume that v_n is not a full vertex in G. For each edge $v_j v_k \in E(\overline{G'})$, introduce a new vertex v_{jk} adjacent to every base vertex except v_j and v_k, and place v_{jk} into some set of π^* other than V_j or V_k and then remove edges between the vertices in the same set V_i in π^*. Here it is important to note that none of the base vertices of H^* is a full vertex. Finally, add each isolate $w_i \in V(G)$ to H^* and insert an edge from w_i to every other vertices of H^*. Now, extend π^* by a singleton sets $W_i = \{w_i\}$, $1 \leq i \leq n$.

In the resulting graph, every edge of H^* is incident with either a base vertex or a dominating vertex, and no set V_j of π^* is itself a dominating set. For any edge $v_j v_k \in E(G)$. Since v_j and v_k collectively dominate every vertex in H^*, $V_j \cup V_k$ is a coalition in H^*. Further, if $v_j v_k \notin E(G)$, then $V_j \cup V_k$ is not a dominating set as there is no vertex in $V_j \cup V_k$ that will dominate the vertex v_{jk}. Each w_i is dominating vertex in H^*, so w_i is an isolate in G. Hence the partition $\pi^* = \{V_1, \ldots, V_n, W_1, \ldots, W_t\}$ is a c-partition of H^* satisfying $CG(H^*, \pi^*) \cong G$. □

Properties of graph H^* constructed above

Graph G	$n(H^*)$	$m(H^*)$
$G \cong K_n \cup tK_1$, n is even	$n + t$	$\binom{n}{2} - \frac{n}{2} + t(n(H^*) - 1)$
$G \cong K_n \cup tK_1$, n is odd	$n + t + 1$	$\binom{n}{2} - \frac{n-1}{2} + n - 2 + t(n(H^*) - 1)$
$G \cong G' \cup tK_1$, where $G' \ncong K_n$	$n + \overline{m}_{G'} + t$	$\binom{n}{2} - \lfloor \frac{n}{2} \rfloor + \overline{m}_{G'}(n-3) + t(n(H^*) - 1)$

3. Properties of coalition count $c(G)$ of graph G

The following observations on coalition count $c(G)$ of graph G motivated us to study the properties of $c(G)$.

1. The coalition number $C(G)$ and coalition count $c(G)$ of graph G are not comparable. For example, Consider complete graph K_n, $C(K_n) = n > 0 = c(K_n)$, but for C_4, $c(C_4) = 6 > C(C_4) = 4$ and for P_4, $c(P_4) = C(P_4) = 4$.

2. The c-partition used to count the coalition number and coalition count need not be unique. For example, consider $P_6 = \{v_1, v_2, v_3, v_4, v_5, v_6\}$. The partition $\pi_2 = \{\{v_2\}, \{v_4\}, \{v_1, v_6\}, \{v_3\}, \{v_5\}\}$ is a c-partition of P_6. Thus, $C(P_6) = 5$ but the total number of different possible coalitions is 3. Now, consider $\pi_3 = \{\{v_2, v_4\}, \{v_6\}, \{v_1, v_3\}, \{v_5\}\}$ is a c-partition of P_6, where $c(G) = 5$.

3. The maximum number of edges among all the graphs $CG(G, \pi)$ is the coalition count of G.

We next establish a relationship between the coalition count and the domatic number.

Theorem 2. *For any graph G with no isolated vertices and f full vertices, $c(G) \geq d(G) - f$.*

Proof. Assume $P = \{V_1, V_2, \ldots, V_k\}$ is a domatic partition of G with $k = d(G)$. Without loss of generality, suppose that $V_1, V_2, \ldots, V_{k-1}$ are minimal dominating sets. If any V_i (for $1 \leq i \leq k-1$) is not minimal, we replace it with a minimal dominating set $V_i' \subseteq V_i$, and add the vertices in $V_i \setminus V_i'$ to V_k. Since G has f full vertices, there will be f singleton dominating sets. Now, consider a domatic-partition $P_1 = \left\{ \underbrace{V_1', \ldots, V_f'}_{f \text{ full vertices}}, \underbrace{V_{f+1}', \ldots, V_{k-1}'}_{\text{minimal dominating sets}}, V_k' \right\}$. Then each of $k - f - 1$ minimal dominating sets can be partitioned into two non-empty, non-dominating subsets $V_{i,1}$ and $V_{i,2}$, where $i = f+1, \ldots, k-1$, whose union is dominating. Thus, these minimal dominating sets contribute at least $k - f - 1$ coalitions.

Consider the vertex partition $P_2 = \left\{ V_1', \ldots, V_f', V_{f+1,1}, V_{f+2,2}, \ldots, V_{k-1,1}, V_{k-2,2}, V_k' \right\}$. Further, if V_k' is also a minimal dominating set, then V_k' can be partitioned into two non-empty, non-dominating subsets whose union is dominating. Therefore, by replacing $\{V_k'\}$ in P_2 using these two sets, we get a c-partition of G. Thus, $c(G) \geq k - f - 1 + 1 = k - f$.

Suppose V_k' is not a minimal dominating set. Let $V_k'' \subseteq V_k'$ be a minimal dominating set, and let $V_k'' = V_{k,1} \cup V_{k,2}$, where $V_{k,1}$ and $V_{k,2}$ are non-empty, non-dominating sets that together form a coalition. Define $W = V_k' \setminus V_k''$. If W is a dominating set, then there exist at least $k+1$ disjoint dominating sets in G, contradicting $d(G) = k$. Thus, W is not a dominating set in G. Now, by replacing V_k' in P_2 by $V_{k,1}, V_{k,2}$ and W, we obtain a c-partition of G. If W can form a coalition with another non-dominating set then $c(G) \geq k - f + 1$. If W does not form a coalition with any set, then consider the union $V_{k,2} \cup W$ as a set in c-partition. This set remains non-dominating but forms a coalition with $V_{k,1}$. Thus, $c(G) \geq k - f$. Therefore, $c(G) \geq k - f = d(G) - f$. $\square$

The bound of Theorem 2 is sharp for stars $K_{1,n-1}$, for $n \geq 3$, as $c(K_{1,n-1}) = 1$, $d(G) = 2$ and $f = 1$. Also, the bound is sharp for complete graph, where $c(K_n) = 0$ and $d(K_n) = f = n$.

An *independent set* is a set of vertices in G such that no two vertices in the set are adjacent. The *independence number* $\alpha(G)$ of a graph G is the cardinality of the largest independent set in G.
In next theorem, we characterize the graphs whose coalition count is exactly one.

Theorem 3. *Let G be a graph with f full vertices. Then $c(G) = 1$ if and only if $\alpha(G) = n - f$.*

Proof. Consider a graph G with f full vertices $U = \{v_1, v_2, \dots, v_f\}$ and $c(G) = 1$. Then there exist exactly two sets V_i and V_j which are not dominating sets, but $V_i \cup V_j$ is a dominating set. Since V_i is not a dominating set, there exists a vertex $x \in V_j$, such that $(N[x] \backslash U) \cap V_i = \phi$.

Claim: $N(x) \backslash U = \phi$.
Suppose $N(x) \backslash U \neq \phi$. Then by adding the vertices in $V_j \backslash (N[x])$ to V_i, it follows that the set V_i is not a dominating set and $V_j = N[x]$. Now consider the sets $V_{j_1} = \{x\}$ and $V_{j_2} = N(x)$. We note that the set V_i form coalition with the sets $\{x\}$ and $N(x)$. Thus, $c(G) \geq 2$, a contradiction. In similar way one can prove that if there exist a vertex in $y \in V_i$ such that $N(y) \backslash U \neq \phi$, then $c(G) \geq 2$. Thus, $N(x) \backslash U = \phi$. Therefore, $\alpha(G) = n - f$.

Conversely, suppose G has f full vertices and $\alpha(G) = n - f$. Then, there are $n - f$ vertices which are not adjacent to each other, and all these $n - f$ vertices is of degree f. Thus, in order to form a coalition partition, these $n - f$ vertices must be divided into exactly two sets V_i and V_j which are not dominating sets but $V_i \cup V_j$ is a dominating set. If we partition these $n - f$ vertices into at least three sets V_i, V_j and V_k. Then clearly, V_i do not form coalition with V_j as there is no vertices either in V_i or in V_j which can dominate the vertices of V_k. Similarly, V_i cannot form coalition with V_k. Thus, $c(G) = 1$. ☐

The union of two graphs G_1 and G_2 is the graph with vertex set $V(G_1) \cup V(G_2)$ and edge set $E(G_1) \cup E(G_2)$. It is denoted by $G_1 \cup G_2$. The join of two graphs G_1 and G_2 is the graph obtained by taking the union of G_1 and G_2, and adding edges between every vertex of G_1 and every vertex of G_2. It is denoted by $G_1 + G_2$.
Using Theorem 3, we deduce the following result:

Corollary 1. *Let G be a graph of order n with f full vertices. Then $c(G) = 1$ if and only if $G \cong (K_f + pK_1) \cup qK_1$, where $f + p + q = n$.*

Theorem 4. *Let G be a graph with exactly one full vertex and $\delta(G) = 1$. If $C(G) = s (s \geq 2)$, then $c(G) = s - 2$. Further, $CG(G, \pi) \cong K_1 \cup K_{1,s-2}$.*

Proof. Consider a graph G with $\delta(G) = 1$ and a full vertex u_1. For $s = 2, 3$, clearly result holds. For $s \geq 4$, let $u_2, u_3, \dots, u_p$ are pendant vertices attached to u_1. Then $\pi = \{\{u_1\}, W\}$, where $W = \{V_1, V_2, \dots, V_{s-1}\}$ is the partition of the $V(G) \backslash \{u_1\}$ such that every V_i is not a dominating set but forms coalition with some other set V_j in π. Here it is important to note that the pendant vertices must form a single set otherwise, it is impossible to form coalition with other sets as they are independent to each other. Without loss of generality let $\{u_2, u_3, \dots, u_p\} \subseteq V_1$. Therefore, all other sets in W must form coalition with the unique set V_1. If not, then there exist no vertex other than u_1 that will dominate the vertices $u_2, u_3, \dots, u_p$. Since $\{u_1\}$ is a dominating set, it do not form coalition with any set in W. Thus, $c(G) = s - 2$. Since G has only one full vertex and $\delta(G) = 1$, the coalition graph $CG(G, \pi)$ will have exactly two components. Further, as $CG(G,\pi)$ has s vertices out of which the vertex corresponding to the set $\{u_1\}$ do not form coalition with any other vertices, it will be an isolated vertex in $CG(G,\pi)$. Let H be the another component of $CG(G,\pi)$. Then the remaining $s-1$ vertices out of which one vertex corresponding to the set $\{u_2,u_3,\ldots,u_p\}$ form coalition with all $s-2$ vertices and as $c(G)=s-2$, $H\cong K_{1,s-2}$. Thus, $CG(G,\pi)\cong K_1\cup K_{1,s-2}$. $\square$

A coalition partition π of G is a singleton coalition partition if every set in π consists of a single vertex. If a graph G has a singleton coalition partition, then G is referred to as a singleton-partition graph (SP-graph).

Next, we relate coalition number $C(G)$ of graph G with coalition count of G. We omit the proof as it is straight forward.

Remark 1. For any graph G with f full vertices having coalition number $C(G)$ and coalition count $c(G)$, $c(G)\geq\lceil\frac{C(G)-f}{2}\rceil$.

Theorem 5. *For any SP-graph G of order n with no full vertices, $c(G)\geq\alpha(G)$.*

Proof. Let G is a singleton-partition graph. Then $\pi=\{\{v_1\},\{v_2\},\ldots,\{v_n\}\}$ is a c-partition. Since G has no full vertex, each set V_i must form a coalition with some set V_j, $1\leq i<j\leq n$. By remark 1, $c(G)\geq\lceil\frac{n}{2}\rceil$. If $\alpha(G)\leq\lceil\frac{n}{2}\rceil$, then clearly result holds. Suppose $\alpha(G)\geq\lceil\frac{n}{2}\rceil+1$. Then there are at least $\lceil\frac{n}{2}\rceil+1$ vertices in G are independent. Let $I=\{v_1,v_2,\ldots,v_\alpha\}$ is the maximum independent set. Further, it is easy to observe that any set in π corresponding to the vertices of I will form coalition with the set corresponding to the vertex not in I. Thus, there will be at least α coalitions. Therefore, $\alpha(G)\leq c(G)$. $\square$

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