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# On three domination-based identification problems in block graphs\*

Dipayan Chakraborty<sup>†</sup> Florent Foucaud<sup>†</sup> Aline Parreau<sup>‡</sup> Annegret Wagler<sup>†</sup>

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## Abstract

The problems of determining the minimum-size *identifying*, *locating-dominating* and *open locating-dominating codes* of an input graph are special search problems that are challenging from both the theoretical and computational viewpoints. In these problems, one selects a dominating set  $C$  from the vertex set  $V(G)$  of a graph  $G$  such that the vertices of a chosen subset of  $V(G)$  (i.e. either  $V(G) \setminus C$  or  $V(G)$  itself) are uniquely determined by their neighborhoods in  $C$ . A typical line of attack for these problems is to determine tight bounds for the minimum codes in various graphs classes. In this work, we present tight lower and upper bounds for all three types of codes for *block graphs* (i.e. diamond-free chordal graphs). Our bounds are in terms of the number of maximal cliques (or *blocks*) of the block graph and the order of the graph. Two of our upper bounds verify conjectures from the literature — with one of them being now proven for block graphs in this article. As for the lower bounds, we prove them to be linear in terms of both the number of blocks and the order of the block graph. For each of our bounds, we provide examples of families of block graphs whose minimum codes attain these bounds, thus showing each bound to be tight.

**Keywords**— identifying code, locating-dominating, domination number, block graph, maximal clique, order of a graph, articulation

## 1 Introduction

For a graph (or network)  $G$  that models a facility or a multiprocessor network, detection devices can be placed at its vertices to locate an intruder (like a faulty processor, a fire or a thief). Depending on the features of the detection devices, different types of dominating sets can be used to determine the optimum distributions of these devices across the vertices of  $G$ . In this article, we study three problems arising in this context, namely the three types of dominating sets — called the *identifying codes*, *locating-dominating codes* and *open locating-dominating codes* — of a given graph. Each of these problems has been extensively studied during the last decades (see the bibliography maintained by Lobstein [29]). These three types of codes are among the most prominent notions within the larger research area of identification problems in discrete structures pioneered by Rényi [34], with numerous applications in fault-diagnosis [33], biological testing [30] or machine learning [12].

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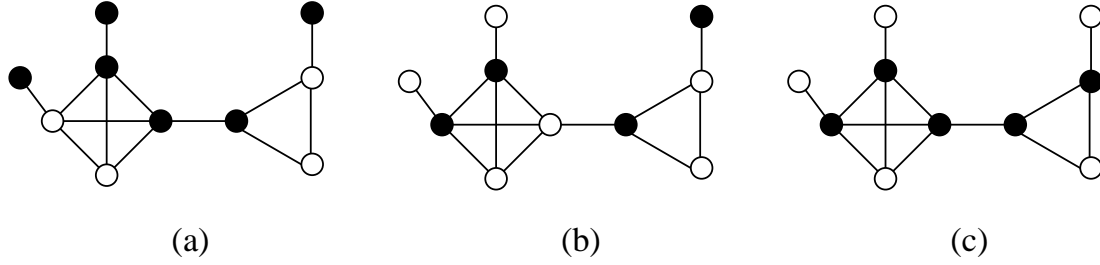


Figure 1: Examples of (a) an ID-code, (b) an LD-code and (c) an OLD-code. The set of black vertices in each of the three graphs constitute the respective code of the graph.

Let  $G = (V(G), E(G))$  be a graph, where  $V(G)$  and  $E(G)$  denote the set of vertices (also called the *vertex set*) and the set of edges (also called the *edge set*), respectively, of  $G$ . The (*open*) *neighborhood* of a vertex  $u \in V(G)$  is the set  $N_G(u)$  of all vertices of  $G$  adjacent to  $u$ ; and the set  $N_G[u] = \{u\} \cup N_G(u)$  is called the *closed neighborhood* of  $u$ . A subset  $C \subseteq V(G)$  is called an *identifying code* [28] (or an *ID-code* for short) of  $G$  if

- $N_G[u] \cap C \neq \emptyset$  for all vertices  $u \in V(G)$  (i.e.  $C$  is said to be a *dominating set* of  $G$ , or is said to possess the property of *domination* in  $G$ ); and
- $N_G[u] \cap C \neq N_G[v] \cap C$  for all distinct vertices  $u, v \in V(G)$  (i.e.  $C$  is called a *closed-separating set* of  $G$ , or is said to possess the property of *closed-separation* in  $G$ ).

See Figure 1a for an example of an ID-code. A graph  $G$  admits an ID-code if and only if  $G$  has no *closed-twins* (i.e. a pair of distinct vertices  $u, v \in V$  with  $N_G[u] = N_G[v]$ ). Said differently, a graph  $G$  admits an ID-code if and only if  $G$  is *closed-twin-free*.

A subset  $C \subseteq V(G)$  is called a *locating-dominating code* [36, 37] (or an *LD-code* for short) of  $G$  if

- $N_G[u] \cap C \neq \emptyset$  for all vertices  $u \in V(G)$  (i.e.  $C$  is a dominating set of  $G$ ); and
- $N_G(u) \cap C \neq N_G(v) \cap C$  for all distinct vertices  $u, v \in V(G) \setminus C$  (i.e.  $C$  is called a *locating set* of  $G$ , or is said to possess the property of *location* in  $G$ ).

See Figure 1b for an example of an LD-code. Note that every graph has an LD-code.

Finally, a subset  $C \subseteq V(G)$  is called an *open locating-dominating code* [35] (or an *OLD-code* for short) of  $G$  if

- $N_G(u) \cap C \neq \emptyset$  for all vertices  $u \in V(G)$  (i.e.  $C$  is called an *open-dominating set* of  $G$ , or is said to possess the property of *open-domination* in  $G$ )<sup>1</sup>; and
- $N_G(u) \cap C \neq N_G(v) \cap C$  for all distinct vertices  $u, v \in V(G)$  (i.e.  $C$  is called an *open-separating set* of  $G$ , or is said to possess the property of *open-separation* in  $G$ ).

See Figure 1c for an example of an OLD-code. A graph  $G$  admits an OLD-code if and only if  $G$  has neither isolated vertices nor *open-twins* (i.e. a pair of distinct vertices  $u, v \in V(G)$  such that  $N_G(u) = N_G(v)$ ). Again, said differently, a graph  $G$  admits an OLD-code if and only if  $G$  has no isolated vertices and is *open-twin-free*.

A graph with neither open- nor closed-twins is simply referred to as *twin-free*.

For the rest of this article, we often simply use the word *code* to mean any of the above three ID-, LD- or OLD-codes without distinction. Given a graph  $G$ , the *identifying code number*  $\gamma^{ID}(G)$  (or *ID-number* for short), the *locating-dominating number*  $\gamma^{LD}(G)$  (or *LD-number* for short) and the *open locating-dominating number*  $\gamma^{OLD}(G)$  (or *OLD-number* for short) of a graph  $G$  are the minimum cardinalities among all ID-codes, LD-codes and OLD-codes, respectively, of  $G$ . In other words, for simplicity, for any

<sup>1</sup>The property of open-domination is often called that of *total-domination* in the literature. See for example ??

symbol  $X \in \{\text{ID}, \text{LD}, \text{OLD}\}$ , we have the X-number:  $\gamma^X(G) = \min\{|C| : C \text{ is an X-code of } G\}$ . In the case that all three codes are addressed together as one unit anywhere in the text, i.e. any specific symbol for  $X \in \{\text{ID}, \text{LD}, \text{OLD}\}$  is irrelevant to the context, we then simply refer to the X-numbers as the *code numbers* of  $G$ .

Given two sets  $A$  and  $B$ , the set  $A \Delta B = (A \setminus B) \cup (B \setminus A)$  is called the *symmetric difference* of  $A$  and  $B$ . For a subset  $C \subset V(G)$  and distinct vertices  $u, v \in V(G)$ , if there exists a vertex  $w \in (N_G(u) \cap C) \Delta (N_G(v) \cap C)$  (resp.  $(N_G[u] \cap C) \Delta (N_G[v] \cap C)$ ), then  $C$  is said to *open-separate* (resp. *closed-separate*) the vertices  $u$  and  $v$  in  $G$ . Moreover, the vertex  $w$  is said to *open-separate* (resp. *closed-separate*) the vertices  $u$  and  $v$  in  $C$ .

## 1.1 Known results

Given a graph  $G$ , determining  $\gamma^{\text{ID}}(G)$  or  $\gamma^{\text{LD}}(G)$  is, in general, NP-hard [11] and remains so for several graph classes where other hard problems become easy to solve. These include bipartite graphs [11] and two subclasses of chordal graphs, namely split graphs and interval graphs [21]. In fact, for both bipartite and split graphs, it is NP-hard to even approximate the ID-number and LD-number within a factor of  $\log |V(G)|$  [14]. Determining  $\gamma^{\text{OLD}}(G)$  is also, in general, NP-hard [35] and remains so for perfect elimination bipartite graphs [31] and interval graphs [21]. On the other hand, determining  $\gamma^{\text{OLD}}(G)$  becomes APX-complete for chordal graphs with maximum degree 4 [31].

As these problems are computationally very hard, a typical line of attack is to determine bounds on the code numbers for specific graph classes. Closed formulas for these parameters have so far been found only for restricted graph families (e.g. for paths and cycles [8, 37, 35], for stars [24], for complete multipartite graphs [3, 5] and for some subclasses of split graphs including thin headless spiders [4]). Lower bounds for all three code numbers for several graph classes like interval graphs, permutation graphs, cographs [20] and lower bounds for ID-numbers for trees [9], line graphs [16], planar graphs [32] and many others of bounded VC-dimension [10] have been determined. As far as upper bounds for the code numbers are concerned, for certain graph classes, upper bounds for ID-codes (See [6, 19, 22]), LD-codes (see [6, 18, 23]) and OLD-codes (see [26]) have been obtained.

## 1.2 Our work

In this paper, we consider the family of block graphs, defined by Harary in [25], see also [27] for equivalent characterizations. A *block graph* is a graph in which every maximal 2-connected subgraph (or *block*) is complete. Equivalently, block graphs are diamond-free chordal graphs [7]. Linear-time algorithms to compute all three code numbers in block graphs have been presented in [2]. In this paper, we complement these results by determining tight lower and upper bounds for all three code numbers for block graphs. We give bounds using (i) the number of vertices, i.e. the order of a graph, as has been done for several other classes of graphs; and (ii) the number of blocks of a block graph, a quantity equally relevant to block graphs. In doing so, we also prove the following conjecture.

**Conjecture 1.1** ([1, Conjecture 1]). The ID-number of a closed-twin-free block graph is bounded above by the number of blocks in the graph.

In addressing LD-codes for twin-free block graphs, we prove (for block graphs) the following conjecture posed by Garijo et al. [23] and reformulated in a slightly stronger form by Foucaud et al. [18].

**Conjecture 1.2** ([18, Conjecture 2]). Every twin-free graph  $G$  with no isolated vertices satisfies  $\gamma^{\text{LD}}(G) \leq \frac{|V(G)|}{2}$ .

## 1.3 Notations

For a block graph  $G$ , we let  $\mathcal{K}(G)$  denote the set of all blocks of  $G$ , i.e. the set of all maximal cliques of  $G$ . Noting that any two distinct blocks  $K$  and  $K'$  of  $G$  intersect at at most a single vertex, any vertex  $x \in V(G)$  such that  $\{x\} = V(K) \cap V(K')$  is called an *articulation vertex* of both  $K$  and  $K'$ . We define  $\text{art}(K)$  to be the set of all articulation vertices of a block  $K \in \mathcal{K}(G)$ . For a connected block graph, we fix

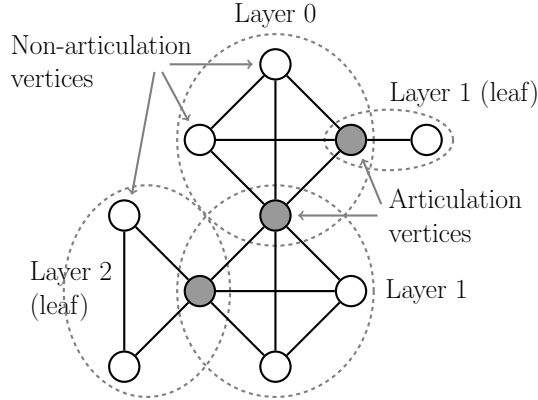


Figure 2: Example of different layer numbers, articulation vertices (grey) and non-articulation vertices (white) of a connected block graph.

a root block  $K_0 \in \mathcal{K}(G)$  and define a system of assigning numbers to every block of  $G$  depending on “how far” the latter is from  $K_0$ . So, define a *layer function*  $f : \mathcal{K}(G) \rightarrow \mathbb{Z}$  on  $G$  by:  $f(K_0) = 0$ , and for any other  $K (\neq K_0) \in \mathcal{K}(G)$  (also called a *non-root* block), define inductively  $f(K) = i$  if  $V(K) \cap V(K') \neq \emptyset$  for some block  $K' (\neq K) \in \mathcal{K}(G)$  such that  $f(K') = i - 1$ . For a pair of blocks  $K, K' \in \mathcal{K}(G)$  such that  $f(K) = f(K') + 1$ , define  $art^-(K) = V(K) \cap V(K')$ ; and for the root block  $K_0$ , define  $art^-(K_0) = \emptyset$ . Note that for a block  $K \in \mathcal{K}(G)$  such that  $f(K) \geq 1$ , we have  $|art^-(K)| = 1$ , and the only vertex in  $art^-(K)$  is called the *negative articulation* vertex of the block  $K$ . In contrast to the negative articulation vertices of  $G$ , define  $art^+(K) = art(K) \setminus art^-(K)$  to be the set of all *positive articulation* vertices of the block  $K$  and  $\overline{art}(K) = V(K) \setminus art(K)$  to be the set of all *non-articulation* vertices of  $K$ . Any block  $K$  with  $|art(K)| = 1$  is called a *leaf block* and all blocks that are not leaf blocks are called *non-leaf blocks*. For simplicity, we also denote the set  $f^{-1}(\{i\})$  by  $f^{-1}(i)$ . Then, for each  $i \geq 0$ ,  $f^{-1}(i)$  is called the  *$i$ -th layer* of  $G$  and each block  $K \in f^{-1}(i)$  is said to be *in the  $i$ -th layer* of  $G$ . See Figure 2 for an illustration of the layers and the related concepts in a connected block graph.

## 1.4 Structure of the paper

Our results on the upper bounds for the code numbers are contained in Section 2 of this paper, whereas Section 3 is dedicated to the lower bounds for the code numbers. Section 2 is further subdivided into three subsections with each of the latter containing the results for a particular code. We conclude in Section 4.

## 2 Upper bounds

In this section, we establish upper bounds on the ID-, LD- and OLD-numbers for block graphs. Two of these upper bounds are in fact proving Conjectures 1.1 and 1.2. All our results in this section are for *connected* block graphs. However, applying the results to each connected component of a block graph, the results of Theorem 2.1, 2.2 and 2.4 hold equally well for all block graphs.

### 2.1 Identifying codes

The number of blocks is, structurally speaking, as relevant a quantity for block graphs as is the number of vertices for trees. In the next result, we prove Conjecture 1.1 to provide an upper bound for  $\gamma^{ID}(G)$  for a block graph  $G$  in terms of its number of blocks.

**Theorem 2.1.** Let  $G$  be a connected closed-twin-free block graph and let  $\mathcal{K}(G)$  be the set of all blocks of  $G$ . Then  $\gamma^{ID}(G) \leq |\mathcal{K}(G)|$ .

*Proof.* Assume by contradiction that there is a closed-twin-free block graph  $G$  of minimum order such that  $\gamma^{ID}(G) > |\mathcal{K}(G)|$ . We also assume that  $G$  has at least four vertices since it can be easily checked that the theorem is true for block graphs with at most three vertices. Suppose that  $K \in \mathcal{K}(G)$  is a leaf-block of  $G$ . Due to the closed-twin-free property of  $G$ , one can assume that  $V(K) = \{x, y\}$  and, without loss of generality, that  $x$  and  $y$  are the non-articulation and the negative articulation vertices, respectively, of  $K$ . Let  $G' = G - x$  be the graph obtained by deleting the vertex  $x \in V(G)$  (and the edge incident on  $x$ ) from  $G$ . Then  $G'$  is a block graph with  $|\mathcal{K}(G')| = |\mathcal{K}(G)| - 1$ . We now consider the following two cases.

**Case 1** ( $G'$  is closed-twin-free). By the minimality of the order of  $G$ , there is an ID-code  $C'$  of  $G'$  such that  $|C'| \leq |\mathcal{K}(G')| = |\mathcal{K}(G)| - 1$ . First, assume that  $y \notin C'$ . Then by the property of domination of  $C'$ , there exists a vertex  $z \in V(G')$  such that  $z \in N_{G'}(y) \cap C'$ . We claim that  $C = C' \cup \{x\}$  is an ID-code of  $G$ . First of all, that  $C$  is a dominating set of  $G$  is clear from the fact that  $C'$  is a dominating set of  $G'$ . To prove that  $C$  is a closed-separating set of  $G$ , we see that  $x$  is closed-separated in  $C$  from all vertices in  $V(G') \setminus \{y\}$  by itself and is closed-separated in  $C$  from  $y$  by the vertex  $z \in C'$ . Moreover, all other pairs of distinct vertices closed-separated by  $C'$  and are also closed-separated by  $C$ . Thus,  $C$ , indeed, is an ID-code of  $G$ . This implies that  $\gamma^{ID}(G) \leq |C| \leq |\mathcal{K}(G)|$ , contrary to our assumption.

We therefore assume that  $y \in C'$ . If again, there exists a vertex  $z \in N_{G'}(y) \cap C'$ , then by the same reasoning as above,  $C = C' \cup \{x\}$  is an ID-code of  $G$ . Otherwise, we have  $N[y] \cap C' = \{y\}$ . Now, since  $G$  is connected, we have  $deg_G(y) > 1$  and therefore, there exists a vertex  $w \in N_G(y) \setminus \{x\}$ . Then  $C = C' \cup \{w\}$  is an ID-code of  $G$ . This is because, first of all,  $C$  still closed-separates every pair of distinct vertices in  $V(G')$ . Also,  $x$  is closed-separated in  $C$  from all vertices in  $V(G') \setminus \{y, w\}$  by  $y$ , from  $y$  by the vertex  $w \in C$  and from  $w$  by  $w$  itself. Moreover,  $C$  is clearly also a dominating set of  $G$ . Hence, this leads to the same contradiction as before.

**Case 2** ( $G'$  has closed-twins). Assume that vertices  $u, v \in V(G')$  are a pair of closed-twins of  $G'$ . Since  $u$  and  $v$  were not closed-twins in  $G$ , it means that  $x$  is adjacent to  $u$ , say, without loss of generality. This implies that  $u = y$ . Note that  $v$  is then unique with respect to being a closed-twin with  $y$  in  $G'$ . This is because, if  $u$  and some vertex  $v' (\neq v) \in V(G')$  were also closed-twins in  $G'$ , then it would mean that  $v$  and  $v'$  were closed-twins in  $G$ , contrary to our assumption. Now, let  $G'' = G' - v$ . We claim the following.

**Claim 2A.**  $G''$  is closed-twin-free.

*Proof of Claim 2A.* Toward a contradiction, if vertices  $z, w \in V(G'')$  were a pair of closed-twins in  $G''$ , it would then mean that the vertex  $z \in N_{G'}(v)$ , without loss of generality. This would, in turn, imply that  $z \in N_{G'}(y)$  (since the vertices  $z$  and  $w$  are closed-twins in  $G'$ ). Or, in other words,  $y \in N_{G''}(z)$ . Now, since  $z$  and  $w$  are closed-twins in  $G''$ , we have  $y \in N_{G''}(w)$ , i.e.  $w \in N_{G'}(y)$ . Again, by virtue of  $y$  and  $v$  being closed-twins in  $G'$ , we have  $w \in N_{G'}(v)$ . This implies that  $z$  and  $w$  are closed-twins in  $G$  which is a contradiction to our assumption.  $\blacklozenge$

We also note here that the vertices  $y$  and  $v$  must be from the same block for them to be closed-twins in  $G'$ . Thus,  $G''$  is a connected closed-twin-free block graph. Therefore, by the minimality of the order of  $G$ , there is an ID-code  $C''$  of  $G''$  such that  $|C''| \leq |\mathcal{K}(G'')| < |\mathcal{K}(G)|$ . If  $y \notin C''$ , then we claim that  $C = C'' \cup \{x\}$  is an identifying code of  $G$ . This is true because, firstly,  $C$  is a dominating set of  $G$  (note that, by the property of domination of  $C''$  in  $G''$ , there exists a vertex  $z \in N_{G''}(y) \cap C''$ ; and since  $y$  and  $v$  are closed-twins in  $G'$ , we have  $z \in N_G(v) \cap C$ ). Moreover,  $x$  is closed-separated in  $C$  from every other vertex in  $V(G) \setminus \{y\}$  by  $x$  itself; vertices  $x$  and  $y$  are closed-separated in  $C$  by some vertex in  $N_{G''}(y) \cap C''$  that dominates the vertex  $y$ ; the vertices  $y$  and  $v$  are closed-separated in  $C$  by  $x$ ; the vertex  $y$  is closed-separated in  $C$  from all vertices in  $V(G'') \setminus \{y\}$  and so is  $v$ , since  $y$  and  $v$  have the same closed neighborhood in  $G'$ . Finally, every pair of distinct vertices closed-separated by  $C''$  still remain so by  $C$ . Thus,  $C$ , indeed, is an ID-code of  $G$ . This implies that  $\gamma^{ID}(G) \leq |C| \leq |\mathcal{K}(G)|$ ; again a contradiction.

Let us, therefore, assume that  $y \in C''$ . This time, we claim that  $C = (C'' \setminus \{y\}) \cup \{x, v\}$  is an ID-code of  $G$ . That  $C$  is a dominating set of  $G$  is clear. So, as for the closed-separating property of  $C$  is concerned, as before,  $x$  is closed-separated in  $C$  from every other vertex in  $V(G) \setminus \{y\}$  by  $x$  itself; vertices  $x$  and  $y$  are closed-separated in  $C$  by  $v$ ; the vertices  $y$  and  $v$  are closed-separated in  $C$  by  $x$  and the vertices  $v$  and  $x$  are closed-separated in  $C$  by  $v$ . Since  $y$  and  $v$  have the same closed neighbourhood in  $G'$  and since  $y$  is closed-separated in  $C''$  from every other vertex in  $V(G'')$ , both  $v$  and  $y$  are also each closed-separated

in  $C$  from every vertex in  $V(G'') \setminus \{v, y\}$ . Finally, every pair of distinct vertices of  $G''$  closed-separated by  $C''$  still remain so by  $C$ . This proves that  $C$  is an ID-code of  $G$  and hence, again, we are led to the contradiction that  $\gamma^{LD}(G) \leq |C| \leq |\mathcal{K}(G)|$ .

This proves the theorem.  $\square$

Note that, besides for stars [24], the upper bound in Theorem 2.1 is attained by the ID-numbers of thin headless spiders [4] which, therefore, serve as examples of cases where the bound in Theorem 2.1 is tight. Note further that this bound does not even hold for chordal graphs, let alone for general graphs. A counterexample to the bound in Theorem 2.1 for chordal graphs is the graph  $P_{2k}^{k-1}$  (the graph obtained from a path on  $2k$  vertices with edges introduced between all pairs of vertices  $u, v \in V(P_{2k})$  such that  $d_{P_{2k}}(u, v) \leq k - 1$ ) which is closed-twin-free, has only two maximal cliques, but needs  $2k - 1$  vertices in any identifying code [17].

## 2.2 Locating-dominating codes

In this subsection, we prove two results on upper bounds for the LD-numbers of block graphs. The first result is a more general one in which the upper bound is in terms of the number of blocks and other quantities arising out of the structural properties of a block graph. On the other hand, the second result is proving Conjecture 1.2 for block graphs. We begin with the more general result.

**Theorem 2.2.** Let  $G$  be a connected block graph,  $\mathcal{K}(G)$  be the set of blocks in  $G$  and  $\mathcal{S}_G = \{S \subset K \in \mathcal{K} : S \text{ is a maximum set of pairwise closed-twins in } G\}$ . Then  $\gamma^{LD}(G) \leq |\mathcal{K}(G)| + \sum_{S \in \mathcal{S}_G} (|S| - 2)$ .

*Proof.* We define a set  $C \subset V(G)$  by the following rules.

Rule 1: For every block  $K \in \mathcal{K}(G)$  which does not contain any closed-twins, i.e. with at most one non-articulation vertex, pick any one vertex from  $V(K) \setminus \text{art}^-(K)$  in  $C$ .

Rule 2: For every block  $K \in \mathcal{K}(G)$  which contains closed-twins, i.e. with at least two non-articulation vertices, pick any  $|\overline{\text{art}}(K)| - 1$  vertices from  $\overline{\text{art}}(K)$  in  $C$ .

Note that the vertices added in  $C$  by the above rules are all distinct. Therefore, the following is the size of  $C$ .

$$|C| = \left| \{K \in \mathcal{K}(G) : |\overline{\text{art}}(K)| \leq 1\} \right| + \sum_{\substack{K \in \mathcal{K}(G), \\ |\overline{\text{art}}(K)| \geq 2}} (|\overline{\text{art}}(K)| - 1) = |\mathcal{K}(G)| + \sum_{\substack{K \in \mathcal{K}(G), \\ |\overline{\text{art}}(K)| \geq 2}} (|\overline{\text{art}}(K)| - 2)$$

which is the same as the right-hand side of the inequation in the statement of the theorem, since the size of the maximum set of closed-twins in any block  $K \in \mathcal{K}(G)$  with  $|\overline{\text{art}}(K)| \geq 2$  is  $|\overline{\text{art}}(K)|$  itself. The result, therefore, follows from proving that  $C$  is an LD-code of  $G$ .

First of all, we notice that, by the construction of  $C$ , for every block  $K \in \mathcal{K}(G)$ , there exists a vertex  $v_K \in V(K) \cap C$ . Therefore,  $C$  is a dominating set of  $G$ . We now show that  $C$  is also a locating set of  $G$ . So assume that  $u, v \in V(G) \setminus C$  are distinct vertices of  $G$ . Then, by the construction of  $C$ , we must have  $u \in V(K)$  and  $v \in V(K')$  for a distinct pair of blocks  $K, K' \in \mathcal{K}(G)$ . Now, there exist vertices  $v_K \in V(K) \cap C$  and  $v_{K'} \in V(K') \cap C$  such that  $v_K \neq v_{K'}$ . This is because, if not, then either  $v_K \in \text{art}^-(K)$  or  $v_{K'} \in \text{art}^-(K')$  which would be a contradiction to our construction of  $C$ . This implies that at least one of  $v_K$  and  $v_{K'}$  must open-separate  $u$  and  $v$  in  $C$  and, hence,  $C$  is a locating set of  $G$ .  $\square$

There are an infinite number of arbitrarily large connected block graphs whose LD-numbers attain the upper bound in Theorem 2.2. One such subclass of block graphs is the following. For positive integers  $t, m_1, m_2, \dots, m_t$ , we define a class of graphs  $S_t(m_1, m_2, \dots, m_t)$  by the following rule: Assume that  $X$  is a copy of the complete graph on  $t$  vertices and name its vertices  $v_1, v_2, \dots, v_t$ . Also, for all  $1 \leq i \leq t$ , suppose that  $Y_i$  is a copy of the complete graph on  $m_i$  vertices. Let  $S_t(m_1, m_2, \dots, m_t)$  be the block graph obtained by identifying a vertex of  $Y_i$  with  $v_i$  of  $X$  for every  $1 \leq i \leq t$ . For brevity, we continue to call the identified vertices resulting in  $S_t(m_1, m_2, \dots, m_t)$  by the same names of  $v_1, v_2, \dots, v_t$  as before. See Figure 3 for an example of the graph  $S_t(m_1, m_2, \dots, m_t)$  constructed with  $t = 5$ , and  $m_1 = m_3 = 4$ ,  $m_2 = m_5 = 3$  and  $m_4 = 5$ . We then show the following.

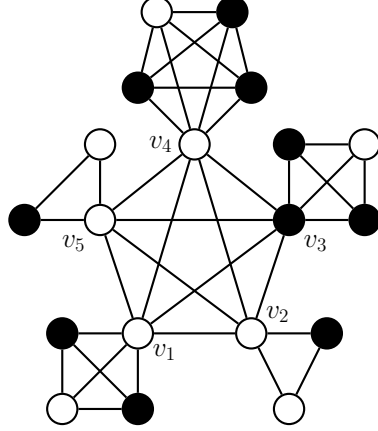


Figure 3: Graph  $S_5(4, 3, 4, 5, 3)$  whose LD-number attains the upper bound in Theorem 2.2. The black vertices represent those included in the LD-code  $C$  of  $G$  as described in the proof of Theorem 2.2.

**Proposition 2.3.** For  $t \geq 2$ , and  $m_1, m_2, \dots, m_t$  such that  $m_i \geq 3$  for all  $1 \leq i \leq t$ , we have

$$\gamma^{LD}(S_t(m_1, m_2, \dots, m_t)) = |\mathcal{K}(S_t(m_1, m_2, \dots, m_t))| + \sum_{S \in \mathcal{S}_{S_t(m_1, m_2, \dots, m_t)}} (|S| - 2).$$

*Proof.* Let  $G = S_t(m_1, m_2, \dots, m_t)$ . We note here that the number of blocks in  $G$  is  $t + 1$ ; and the only blocks  $K \in \mathcal{K}(G)$  with  $|\overline{\text{art}}(K)| \geq 2$  are  $Y_1, Y_2, \dots, Y_t$  (as per the notations used in the preceding discussion). Moreover, for each  $1 \leq i \leq t$ , we have  $|\overline{\text{art}}(Y_i)| = m_i - 1$ . So, the upper bound for the LD-number of  $G$  by Theorem 2.2 is  $t + 1 + \sum_{i=1}^t (m_i - 3) = 1 - 2t + \sum_{i=1}^t m_i$ .

Now, assume that  $C$  is a minimum LD-code of  $G$ . Then, we have  $|V(Y_i) \cap C| \geq m_i - 2$ . Moreover,  $V(Y_i) \setminus \{v_i\} \not\subset C$  for every  $1 \leq i \leq n$ , or else, for  $t \geq 2$ , we would have  $|C| \geq -t + \sum_{i=1}^t m_i > 1 - 2t + \sum_{i=1}^t m_i$ , the upper bound by Theorem 2.2 resulting in a contradiction. So, without loss of generality, assume that  $y_1 \in (V(Y_1) \setminus \{v_1\}) \setminus C$ . Now, if  $v_i \notin C$  for all  $1 \leq i \leq t$ , then  $C$  does not open-separate  $v_1$  and  $y_1$  which is a contradiction. Therefore,  $v_i \in C$  for some  $1 \leq i \leq t$ . Hence,  $|C| \geq |\{v_i\}| + \sum_{i=1}^t |V(Y_i) \cap C| \geq 1 - 2t + \sum_{i=1}^t m_i = |\mathcal{K}(G)| + \sum_{S \in \mathcal{S}_G} (|S| - 2)$ .  $\square$

Imposing additional structural constraints on a block graph, one could still limit the number of vertices one needs to choose from each of its blocks in order to form an LD-code of the graph. Our next result shows exactly that.

**Theorem 2.4.** Let  $G$  be a connected twin-free block graph. Then  $\gamma^{LD}(G) \leq \frac{|V(G)|}{2}$ .

*Proof.* To prove the theorem, we partition the vertex set of  $G$  into two special subsets  $C^*$  and  $D^*$ .

Assume that  $K_0 \in \mathcal{K}(G)$  is a leaf block of  $G$ . Then,  $|V(K_0)| = 2$ , as  $G$  is twin-free. Assign  $K_0$  to be the root block of  $G$ , i.e. define a layer function  $f : \mathcal{K}(G) \rightarrow \mathbb{Z}$  on  $G$  such that  $f(K_0) = 0$ . We then construct the sets  $C^*$  and  $D^*$  by the following rules applied inductively on  $i \in f(\mathcal{K}(G))$ . See Figure 4 for a demonstration of this construction.

Rule 1: Pick the (positive) articulation vertex of the root block  $K_0$  in  $D^*$  (i.e. let  $\text{art}^+(K_0) \subset D^*$ ) and pick the (other) non-articulation vertex of  $K_0$  in  $C^*$  (i.e. let  $\overline{\text{art}}(K_0) \subset C^*$ ). See Figure 4a for an example.

Rule 2: For every non-root block  $K \in \mathcal{K}(G)$  with at least one non-articulation vertex (i.e.  $\overline{\text{art}}(K) \neq \emptyset$ ) and whose negative articulation vertex is in  $D^*$  (i.e.  $\text{art}^-(K) \subset D^*$ ), pick all non-articulation vertices of  $K$  in  $C^*$  (i.e. let  $\overline{\text{art}}(K) \subset C^*$ ); and all positive articulation vertices of  $K$  in  $D^*$  (i.e. let  $\text{art}^+(K) \subset D^*$ ). See Figure 4b for an example.



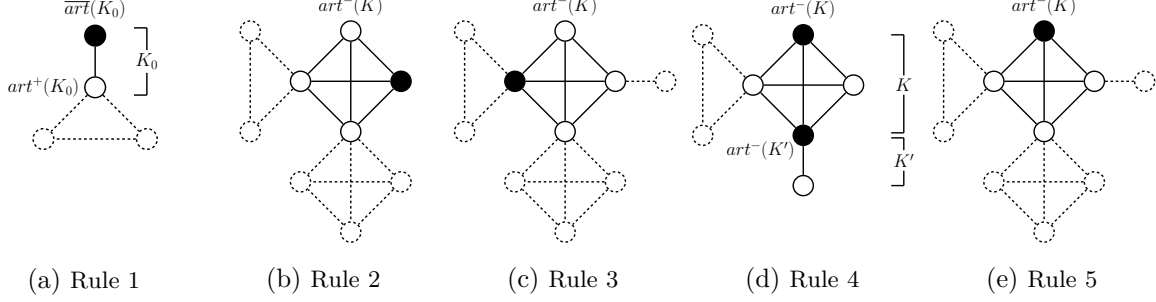


Figure 4: Example of each rule in the proof of Theorem 2.4 for the construction of the sets  $C^*$  or  $D^*$ . In each example, the black vertices represent those picked in  $C^*$  and the white vertices represent those picked in  $D^*$ . The blocks with solid edges represent those blocks (in  $i$ -th layer, say) from which vertices are chosen either in  $C^*$  or  $D^*$ . The blocks with dashed edges represent those blocks in the next layer (the  $(i+1)$ -th) which, inductively, are yet to be analysed for their choices of vertices in  $C^*$  and  $D^*$ ; but whose presence in the figure is necessary to determine the positive, negative and the non-articulation vertices of the block in  $i$ -th layer.

Rule 3: For any non-root block  $K \in \mathcal{K}(G)$  with no articulation vertices (i.e.  $\overline{\text{art}}(K) = \emptyset$ ) and whose negative articulation vertex is in  $D^*$  (i.e.  $\text{art}^-(K) \subset D^*$ ), pick *one* positive articulation vertex, say,  $w$  of  $K$  in  $C^*$  and the rest of the positive articulation vertices in  $D^*$  (i.e. let  $\text{art}^+(K) \setminus \{w\} \subset D^*$ ). See Figure 4c for one such case.

Rule 4: For every non-root block  $K \in \mathcal{K}(G)$  with at least one non-articulation vertex (i.e.  $\overline{\text{art}}(K) \neq \emptyset$ ) and whose negative articulation vertex is in  $C^*$  (i.e.  $\text{art}^-(K) \subset C^*$ ), pick *one* positive articulation vertex (if available), say,  $w$  of  $K$  in  $C^*$ ; and pick all other vertices in  $V(K)$ , except the vertex  $w$  and the negative articulation vertex of  $K$ , in  $D^*$  (i.e. let  $V(K) \setminus (\text{art}^-(K) \cup \{w\}) \subset D^*$ ). See Figure 4d for both examples of when articulation vertices are available (block  $K$ ) and when they are not, i.e. in the case of leaf blocks (block  $K'$ ).

Rule 5: For every non-root block  $K \in \mathcal{K}(G)$  with no non-articulation vertices (i.e.  $\overline{\text{art}}(K) = \emptyset$ ) and whose negative articulation vertex is in  $C^*$  (i.e.  $\text{art}^-(K) \subset C^*$ ), pick all positive articulation vertices of  $K$  in  $D^*$  (i.e.  $\text{art}^+(K) \subset D^*$ ). See Figure 4e for an illustration.

From the construction,  $C^*$  and  $D^*$  are complements of each other in  $V(G)$ . We claim that both  $C^*$  and  $D^*$  are LD-codes of  $G$ . We first show that both are dominating sets of  $G$ .

**Claim A.** Both  $C^*$  and  $D^*$  are dominating sets of  $G$ .

*Proof of Claim A.* To prove that both  $C^*$  and  $D^*$  are dominating sets of  $G$ , it is enough to show that, for every block  $K \in \mathcal{K}(G)$ , both  $V(K) \cap C^* \neq \emptyset$  and  $V(K) \cap D^* \neq \emptyset$ . By Rule 1, the claim is true for the root block  $K_0$ . So, assume  $K \in \mathcal{K}(G)$  to be a non-root block. First, suppose that the negative articulation vertex of  $K$  belongs to  $D^*$ . Then, by Rules 2 and 3, we have  $V(K) \cap C^* \neq \emptyset$ . Next, suppose that the negative articulation vertex of  $K$  belongs to  $C^*$ . Then, by Rules 4 and 5, we have  $V(K) \cap D^* \neq \emptyset$ .  $\blacklozenge$

We now show that both  $C^*$  and  $D^*$  are also locating sets of  $G$ . We start with  $C^*$ .

**Claim B.**  $C^*$  is a locating set of  $G$ .

*Proof of Claim B.* Assume that  $u, v \in D^*$  are distinct vertices of  $G$ . Since  $G$  is twin-free, there exist a pair of distinct blocks  $K, K' \in \mathcal{K}(G)$  such that  $u \in V(K)$  and  $v \in V(K')$ . By the proof of Claim A, there exist vertices  $v_K \in V(K) \cap C^*$  and  $v_{K'} \in V(K') \cap C^*$ . If  $v_K \neq v_{K'}$ , then either one of  $v_K$  and  $v_{K'}$  must locate  $u$  and  $v$  in  $C^*$ . So, let us assume that no such pairs of distinct vertices  $v_K \in V(K) \cap C^*$  and  $v_{K'} \in V(K') \cap C^*$  exist, i.e.  $V(K) \cap V(K') \subset C^*$  and that  $V(K) \Delta V(K') \subset D^*$ .

We now claim that either  $u$  is an articulation vertex of  $K$  or  $v$  is an articulation vertex of  $K'$ . So, toward contradiction, assume that both  $u$  and  $v$  are non-articulation vertices of  $K$  and  $K'$ , respectively. Then the following two cases arise.

**Case 1** ( $K$  and  $K'$  belong to different layers). Without loss of generality, assume that  $f(K') = f(K) + 1$ . Then,  $K \neq K_0$ , or else, by Rule 1,  $u$ , being a non-articulation vertex of  $K$ , must belong to  $C^*$ , contrary to our assumption. Therefore,  $K$  is a non-leaf block. Now,  $V(K)\Delta V(K') \subset D^*$  implies that the negative articulation vertex of  $K$  belongs to  $D^*$ . Since  $u$  is a non-articulation vertex of  $K$ , by Rule 2,  $u \in C^*$  which is a contradiction to our assumption.

**Case 2** ( $K$  and  $K'$  belong to the same layer). In this case,  $K$  and  $K'$  cannot both be leaf blocks, or else,  $G$  would have twins. So, without loss of generality, suppose that  $K$  is a non-leaf block. Now, the negative articulation vertex of  $K$  belongs to  $C^*$ . Since  $K$  is a non-leaf block, there exists a positive articulation vertex of  $K$  and, hence, by Rule 4,  $art^+(K) \cap C^* \neq \emptyset$  which contradicts the fact that  $V(K)\Delta V(K') \subset D^*$ .

This proves our claim that either  $u$  is an articulation vertex of  $K$  or  $v$  is an articulation vertex of  $K'$ . So if, without loss of generality, we assume that  $u$  is an articulation vertex of  $K$ , then  $\{u\} = V(K) \cap V(K'')$  for some block  $K'' (\neq K, K') \in \mathcal{K}(G)$  and so, some vertex in  $V(K'') \cap C^*$  (which exists due to the proof of Claim A) must locate  $u$  and  $v$  in  $C^*$ . This proves our current claim.  $\blacklozenge$

We now prove the same for  $D^*$ .

**Claim C.**  $D^*$  is a locating set of  $G$ .

*Proof of Claim C.* Assume that  $u, v \in C^*$  are distinct vertices of  $G$ . Since  $G$  is twin-free, there exist a pair of distinct blocks  $K, K' \in \mathcal{K}(G)$  such that  $u \in V(K)$  and  $v \in V(K')$ . By the proof of Claim A, there exist vertices  $v_K \in V(K) \cap D^*$  and  $v_{K'} \in V(K') \cap D^*$ . If  $v_K \neq v_{K'}$ , then either one of  $v_K$  and  $v_{K'}$  must open-separate  $u$  and  $v$  in  $D^*$ . So, let us assume that no such pairs of distinct vertices  $v_K \in V(K) \cap D^*$  and  $v_{K'} \in V(K') \cap D^*$  exist, i.e.  $V(K) \cap V(K') \subset D^*$  and that  $V(K)\Delta V(K') \subset C^*$ .

We now claim that either  $u$  is an articulation vertex of  $K$  or  $v$  is an articulation vertex of  $K'$ . So, toward contradiction, assume that both  $u$  and  $v$  are non-articulation vertices of  $K$  and  $K'$ , respectively. Then the following two cases arise.

**Case 1** ( $K$  and  $K'$  belong to different layers). Without loss of generality, assume that  $f(K') = f(K) + 1$ . If  $|V(K')| \geq 3$ , since  $G$  is twin-free and since  $v$  is a non-articulation vertex of  $K'$ , then  $K'$  contains exactly one non-articulation vertex and thus  $art^+(K') \cap D^* \neq \emptyset$ . This, however, is a contradiction to the fact that  $V(K)\Delta V(K') \subset C^*$ . So, assume that  $|V(K')| = 2$ , in which case,  $K'$  is a leaf block (since, again,  $v$  is a non-articulation vertex of  $K'$ ). This implies that  $K$  is a non-leaf block, or else,  $G$  would have twins. So, in particular,  $K \neq K_0$ , the root block of  $G$ . Moreover,  $V(K)\Delta V(K') \subset C^*$  implies that the negative articulation vertex of  $K$  belongs to  $C^*$ . Therefore, since  $u$  is a non-articulation vertex of  $K$ , by Rule 4,  $u \in D^*$  which is a contradiction to our assumption.

**Case 2** ( $K$  and  $K'$  belong to the same layer). In this case,  $K$  and  $K'$  cannot both be leaf blocks, or else,  $G$  would have twins. So, without loss of generality, assume  $K$  to be a non-leaf block. Therefore,  $|V(K)| \geq 3$ , or else,  $u$  would be an articulation vertex of  $K$ , contrary to our assumption. The negative articulation vertex of  $K$  belongs to  $D^*$ . Therefore, by Rule 2,  $art^+(K) \cap D^* \neq \emptyset$  which contradicts  $V(K)\Delta V(K') \subset C^*$ .

This, therefore, proves our claim that either  $u$  is an articulation vertex of  $K$  or  $v$  is an articulation vertex of  $K'$ . If, without loss of generality,  $u$  is an articulation vertex of  $K$ , then  $\{u\} = V(K) \cap V(K'')$  for some block  $K'' (\neq K) \in \mathcal{K}(G)$  and so, some vertex in  $V(K'') \cap D^*$  (which exists due to the proof of Claim A) must open-separate  $u$  and  $v$  in  $D^*$ . This, again, proves our current claim.  $\blacklozenge$

Combining Claims A, B and C, we find that  $C^*$  and  $D^*$  are both LD-codes of the twin-free block graph  $G$  with no isolated vertices. Moreover, since  $C^*$  and  $D^*$  are complements of each other in  $V(G)$ , at least one of them must have cardinality of at most half the order of  $G$ . This proves the theorem.  $\square$

Theorem 2.4 therefore proves Conjecture 1.2 for block graphs.

**Corollary 2.5.** Let  $G$  be a twin-free block graph without isolated vertices. Then  $\gamma^{LD}(G) \leq \frac{|V(G)|}{2}$ .

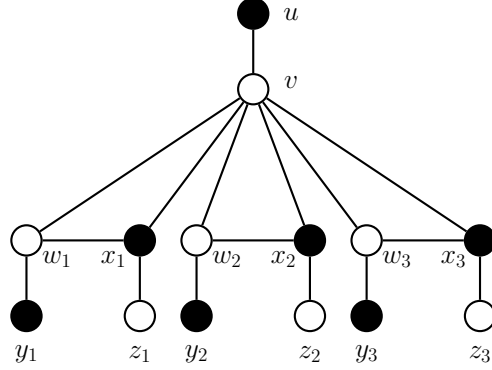


Figure 5: Graph  $H_3$  whose LD-number attains the upper bound in Theorem 2.4. The black vertices represent those included in the LD-code  $C^*$  of  $G$  described in the proof of Theorem 2.4.

The trees attaining the bound of Theorem 2.4 were characterized in [18]. There are also arbitrarily large twin-free block graphs that are not trees and whose LD-numbers attain the bound given in Theorem 2.4. To demonstrate this attainment, we look at the following subclass of block graphs which we denote by  $H_t$ : For a fixed integer  $t \geq 1$ , assume that  $T_1, T_2, \dots, T_t$  are  $t$  copies of  $K_3$ , the complete graph on three vertices. Suppose that  $V(T_i) = \{v_i, w_i, x_i\}$  for each  $1 \leq i \leq t$ . Assume  $R, R_1, R_2, \dots, R_t, R'_1, R'_2, \dots, R'_t$  to be  $2t + 1$  copies of  $P_2$ , the path on two vertices. Also, let  $V(R) = \{u, v\}$  and for all  $1 \leq i, i' \leq t$ , let  $V(R_i) = \{y'_i, y_i\}$  and  $V(R'_{i'}) = \{z'_{i'}, z_{i'}\}$ . We then identify the vertices  $v, v_1, v_2, \dots, v_t$  to a single vertex which we continue to call  $v$ ; and, for each  $1 \leq i \leq t$ , we identify the vertices  $w_i$  and  $y'_i$  to a single vertex and the vertices  $x_i$  and  $z'_i$  to a single vertex. In the latter two cases, we continue to call the identified vertices  $w_i$  and  $x_i$ , respectively. The new resulting graph is what we call  $H_t$ . See Figure 5 for an example of  $H_t$  with  $t = 3$ . With that, we now prove the following.

**Proposition 2.6.** For each integer  $t \geq 1$ ,  $\gamma^{LD}(H_t) = \frac{|V(H_t)|}{2}$ .

*Proof.* Since  $|V(H_t)| = 4t + 2$ , we therefore have from Theorem 2.4 that  $\gamma^{LD}(H_t) \leq 2t + 1$ .

We now prove that  $\gamma^{LD}(H_t) \geq 2t + 1$ . Since each of the  $2t + 1$  edges  $uv, w_i y_i, x_i z_i$  (for  $1 \leq i \leq t$ ) of  $H_t$  contains a vertex of degree 1, therefore any LD-code of  $H_t$ , by its the property of domination, must contain at least one endpoint of each of these edges. Since the above edges are all pairwise disjoint, any LD-code of  $H_t$  must contain at least  $2t + 1$  vertices of  $H_t$ .  $\square$

### 2.3 Open locating-dominating codes

We now focus our attention on upper bounds for OLD-numbers for block graphs. Before we get to our results, we define the following two special graphs.

1. The *4-path* (or  $P_4$  in symbol) is a graph defined by its vertex set  $V(P_4) = \{p_1, p_2, p_3, p_4\}$  and its edge set  $E(P_4) = \{p_1 p_2, p_2 p_3, p_3 p_4\}$ .
2. The *bull graph* (or  $B_5$  in symbol) is a graph defined by its vertex set  $V(B_5) = \{b_1, b_2, b_3, b_4, b_5\}$  and its edge set  $E(B_5) = \{b_1 b_2, b_2 b_3, b_3 b_4, b_4 b_5, b_2 b_4\}$ . See Figure 7 for a depiction of a bull graph.

We note here that both  $P_4$  and  $B_5$  are block graphs with articulation vertices  $p_2$  and  $p_3$  for  $P_4$  and  $b_2$  and  $b_4$  for  $B_5$ . For  $P_4$ , the vertices  $p_1$  and  $p_4$  are called the *leaf vertices*; and for  $B_5$ , the vertices  $b_1$  and  $b_5$  are the leaf vertices. Assume  $G'$  to be any graph and  $X$  to be a graph which is either a copy of  $P_4$  or  $B_5$ . For a fixed vertex  $q \in V(G')$ , we define a new graph  $G' \triangleright_q X$  to be the graph obtained by identifying the vertex  $q$  with an articulation vertex of  $X$  (see Figures 6a and 6b for examples of  $K_4 \triangleright_q P_4$  and  $K_4 \triangleright_q B_5$ , respectively). As a matter of reference, we call the new vertex in  $G' \triangleright_q X$  — obtained as a result of identifying two vertices — as the *quotient vertex*; and continue to refer to the quotient vertex as  $q$  itself. We now turn to our results. Firstly, it is easy to establish the following.

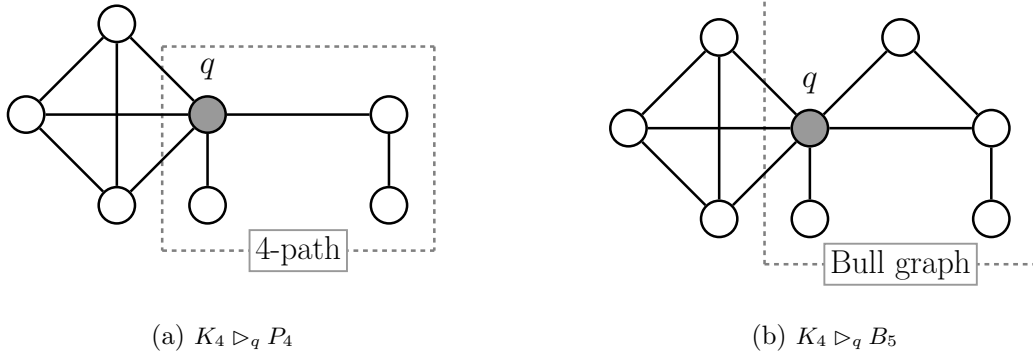


Figure 6: Examples of  $G' \triangleright_q X$ , where  $G' \cong K_4$  and  $X \in \{P_4, B_5\}$ . The vertex  $q$  (in grey) is obtained by identifying a vertex of  $G'$  and an articulation vertex of  $X$ .

**Lemma 2.7.** If  $P$  is a 4-path, then  $\gamma^{OLD}(P) = 4$ .

**Lemma 2.8.** If  $B$  is a bull graph, then  $\gamma^{OLD}(B) = 3$ .

*Proof.* Let  $V(B) = \{b_1, b_2, b_3, b_4, b_5\}$ , where  $b_2$  and  $b_4$  are the articulation vertices; and  $b_1$  and  $b_5$  are the leaf vertices of  $B$ . Then it is easy to check that  $\{b_2, b_3, b_4\}$  is an OLD-code of  $B$  and hence  $\gamma^{OLD}(B) \leq 3$ . See Figure 7 for the OLD-code demonstrated with black vertices in the figure.

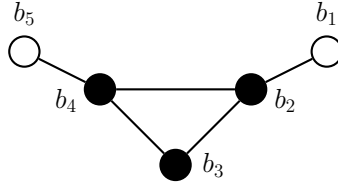


Figure 7: The Bull graph  $B_5$ . The set of black vertices constitute an OLD-code of  $B_5$ .

On the other hand, assume that  $C$  is an OLD-code of  $B$ . Since  $b_1$  and  $b_5$  are degree 1 vertices, their only neighbours, namely  $b_2$  and  $b_4$ , respectively, must be in  $C$  for the latter to be an open-dominating set of  $B$ . Moreover, at least one of  $b_1$  and  $b_3$  must be in  $C$  for  $b_2$  and  $b_5$  to be open-separated in  $C$ . Hence,  $|C| \geq 3$  and this establishes the result.  $\square$

This brings us to our result on the upper bound for OLD-numbers for block graphs.

**Theorem 2.9.** Let  $G$  be a connected open-twin-free block graph with no isolated vertices. Moreover, let  $G$  neither be a copy of  $P_2$  nor of  $P_4$ . Moreover, let  $m_Q(G)$  be the number of non-leaf blocks of  $G$  with at least one non-articulation vertex. Then  $\gamma^{OLD}(G) \leq |V(G)| - m_Q(G) - 1$ .

*Proof.* To start with, if  $G$  is a copy of the bull graph, then  $|V(G)| = 5$  and  $m_Q(G) = 1$ . Moreover, by Lemma 2.8,  $\gamma^{OLD}(G) = 3 = |V(G)| - m_Q(G) - 1$  and so, we are done. So, let us assume that  $G$  is not a copy of the bull graph.

We first choose a root block  $K_0 \in \mathcal{K}(G)$  according to the following two possibilities.

**Possibility 1:**  $G \cong G' \triangleright_q X$  for some block graph  $G'$  and some graph  $X$  that is a copy of either  $P_4$  or  $B_5$ . In such a case, assume that  $x$  is the articulation vertex of  $X$  which is identified with the vertex  $q$  of  $G'$  to form  $G$ . Then, we choose  $K_0$  to be the block of  $G$  isomorphic to a  $P_2$  with vertices  $\{x, z\}$ , where  $z$  is the leaf vertex of  $X$  adjacent to  $x$ .

**Possibility 2:**  $G \not\cong G' \triangleright_q X$  for any block graph  $G'$  and any  $X$  that is a copy of either  $P_4$  or  $B_5$ . In this case, choose  $K_0 \in \mathcal{K}(G)$  such that  $|V(K_0)| = \min\{|V(K)| : K \text{ is a leaf block of } G\}$ .

Next, we construct a set  $C \subset V(G)$  by the following rules.

Rule 1: For every non-root leaf block  $K \in \mathcal{K}(G)$ , pick all vertices of  $K$  in  $C$ .

Rule 2: For every block  $K \in \mathcal{K}(G)$  that is either the root block  $K_0$  or is a non-leaf block in  $\mathcal{K}(G) \setminus \{K_0\}$ ,  
 (i) pick all articulation vertices of  $K$  in  $C$ ; and  
 (ii) pick all but one non-articulation vertices of  $K$  in  $C$ .

To compute the size of  $C$ , we note that, for the root block and every other non-leaf block  $K$  with at least one non-articulation vertex, exactly one vertex is left out from it in  $C$ . This gives  $|C| = |V(G)| - m_Q(G) - 1$ . Thus, the upper bound for  $\gamma^{OLD}(G)$  in the theorem is established on showing that  $C$ , indeed, is an OLD-code of  $G$ ; which is what we prove next.

To show that  $C$  is an OLD-code of  $G$ , we notice first of all that, if the root block  $K_0$  is isomorphic to  $P_2$ , then the (only) non-articulation vertex of  $K_0$  is open-dominated by the articulation vertex of  $K_0$  which belongs to  $C$ . In every other case, all blocks  $K \in \mathcal{K}(G)$  have  $|V(K) \cap C| \geq 2$ . This makes  $C$  an open-dominating set of  $G$ . Now we show that  $C$  is also an open-separating set of  $V(G)$ . So, let us assume that  $u, v \in V(G)$  are distinct vertices of  $G$ . We now consider the following three cases.

**Case 1** ( $u, v \in V(K)$  for some block  $K \in \mathcal{K}(G)$ ). We note here that, by the construction of  $C$ , for every block  $K \in \mathcal{K}(G)$ , at most one vertex of  $K$  is not in  $C$ . This implies that at least one of  $u$  and  $v$ , say  $u$  without loss of generality, must be in  $C$ . Then  $u$  open-separates  $u$  and  $v$  in  $C$ .

**Case 2** ( $u \in V(K), v \in V(K')$  for distinct  $K, K' \in \mathcal{K}(G)$  and neither of  $u$  and  $v$  belong to  $V(K) \cap V(K')$ ). In this case, if  $V(K) \cap V(K') = \emptyset$ , then  $u$  and  $v$  are open-separated by the negative articulation vertex of  $K$  (which belongs to  $C$ , by construction) and so, we are done. Therefore, assume that  $V(K) \cap V(K') = \{w\}$  for some vertex  $w \in V(G)$ . Now, if either of  $V(K)$  and  $V(K')$ , say  $V(K)$  without loss of generality, has size at least 4, then  $|V(K) \cap C| \geq 3$  and so, at least one vertex in  $V(K) \setminus \{u, w\}$  belongs to  $C$  which open-separates  $u$  and  $v$  in  $C$ . So, assume that  $|V(K)| \leq 3$  and  $|V(K')| \leq 3$ . We next look at the following two subcases.

**Subcase 2.1** ( $|V(K)| = |V(K')| = 2$ ). Then, at least one of  $K$  and  $K'$  must be a non-leaf block, or else,  $G$  would have open-twins. So, without loss of generality, suppose that  $K$  is a non-leaf block. Then  $\{u\} = V(K) \cap V(K'')$  for some block  $K'' (\neq K, K') \in \mathcal{K}(G)$ . If however,  $K'$  too is a non-leaf-block, then  $\{v\} = V(K') \cap V(K''')$  for some block  $K''' (\neq K', K, K'') \in \mathcal{K}(G)$ . Now, at least one of  $K''$  and  $K'''$  is not the root block. Without loss of generality, therefore, assume that  $K''$  is not the root block. Then there is at least one vertex in  $V(K'') \setminus \{u\}$  which is in  $C$  and, hence, open-separates  $u$  and  $v$  in  $C$ . So, let us assume that  $K'$  is a leaf block, i.e.  $v$  is a non-articulation vertex of  $K'$ . Now again, if  $K''$  is not the root block, then there is at least one vertex in  $V(K'') \setminus \{u\}$  which is in  $C$  and, hence, open-separates  $u$  and  $v$  in  $C$ . So, now let us assume that  $K''$  is the root block. Since  $K'$  is a leaf block and  $|V(K')| = 2$ , by the minimality in size of the root block, we must have  $|V(K'')| = 2$ . So, assume  $z$  to be the non-articulation vertex of  $K_0$ . If  $P = G[z, u, w, v]$ , we have  $P \cong P_4$  with  $u$  and  $w$  being the articulation vertices and  $z$  and  $v$  being the leaf-vertices of  $P$ . Since  $G \not\cong P_4$ , we must have  $G \cong G' \triangleright_q P$  for some block graph  $G'$  and some vertex  $q \in \{u, w\}$  (note that both  $z$  and  $v$  are non-articulation vertices of  $G$ ). However, by the way we have chosen the root block  $K_0$ , we must have  $q = u$ . This implies that  $u$  is the negative articulation vertex  $K^*$  for some  $K^* \in \mathcal{K}(G)$  such that  $K^* \notin \{K, K_0\}$ . This, in turn, implies that  $u$  and  $v$  are open-separated in  $C$  by some vertex in  $(V(K^*) \cap C) \setminus \{u\}$ .

**Subcase 2.2** (At least one of  $V(K)$  and  $V(K')$  has size 3). Without loss of generality, let us assume that  $|V(K)| = 3$ . So, assume that  $K = G[w, u, y]$  for some vertex  $y \in V(G)$ . We must have  $y \notin C$  (otherwise  $y$  would open-separate  $u$  and  $v$ ). We first assume that  $K$  is the root block. If  $v$  is an articulation vertex of  $K'$ , then  $\{v\} = V(K') \cap V(K''')$  for some block  $K''' (\neq K') \in \mathcal{K}(G)$ . This implies that there exists a vertex in  $V(K''') \setminus \{v\}$  which open-separates  $u$  and  $v$  in  $C$ . Moreover, if  $v$  is a non-articulation vertex of  $K'$ , then we must have  $|V(K')| = 3$  (or else,  $K'$  is a leaf block of size smaller than the root block which is a contradiction). Assume that  $V(K') = \{w, v, a\}$  for some vertex  $a \in V(G)$ . If  $a$  too is a non-articulation vertex of  $K'$ , then  $K'$  is a leaf block that is not a root block and, hence,  $a \in C$ . If however,  $a$  is an

articulation vertex of  $K'$ , then too,  $a \in C$ . Thus, either way,  $a$  open-separates  $u$  from  $v$  in  $C$ . Thus, we are done in the case that  $K$  is the root block of  $G$ .

So, let us now assume that  $K$  is *not* the root block of  $G$ . Now, if  $y \in C$ , then  $y$  open-separates  $u$  and  $v$  in  $C$ . So, let us assume that  $y \notin C$ , which implies that  $y$  is a non-articulation vertex of  $K$ . This, in turn, implies that  $u$  is an articulation vertex of  $K$ , or else,  $K$  would be a leaf block of  $G$  that is not the root block and so,  $y \in C$ , contrary to our assumption. So, let  $\{u\} = V(K) \cap V(K'')$  for some block  $K'' (\neq K) \in \mathcal{K}(G)$ . If however,  $v$  too is an articulation vertex of  $K'$ , then  $\{v\} = V(K') \cap V(K''')$  for some block  $K''' (\neq K') \in \mathcal{K}(G)$ . Now, at least one of  $K''$  and  $K'''$  is not the root block. So, without loss of generality, assume that  $K''$  is not the root block. Then, there is at least one vertex in  $V(K'') \setminus \{u\}$  which is in  $C$  and, hence, open-separates  $u$  and  $v$  in  $C$ . So, let us assume that  $v$  is a non-articulation vertex of  $K'$ . Again, if  $K''$  is not the root block, then there exists at least one vertex in  $V(K'') \setminus \{u\}$  which is in  $C$  and, hence, open-separates  $u$  and  $v$  in  $C$ . So, now assume  $K''$  to be the root block. If  $|V(K'')| \geq 3$ , then there exists a vertex of  $V(K'') \setminus \{u\}$  in  $C$  and, hence, open-separates  $u$  and  $v$  in  $C$ . So, let us assume that  $|V(K'')| = 2$  and that  $z$  is the non-articulation of  $K''$ . If  $|V(K')| = 3$ , then suppose that  $V(K') = \{w, v, a\}$  for some vertex  $a \in V(G)$ . If  $a$  too is a non-articulation vertex of  $K'$ , then  $K'$  is a leaf block that is not a root block and hence,  $a \in C$ . If however,  $a$  is an articulation vertex of  $K'$ , then too,  $a \in C$ . Thus, either way,  $a$  open-separates  $u$  from  $v$  in  $C$  and we are done in the case that  $|V(K')| = 3$ . So, let us finally assume that  $|V(K')| = 2$  and that  $v \in V(K')$  is a non-articulation vertex of  $K'$ .

If  $B = G[z, u, y, w, v]$ , we have  $B \cong B_5$  with  $u$  and  $w$  being the articulation vertices and  $z$  and  $v$  being the leaf-vertices of  $B$ . Since by our assumption,  $G \not\cong B_5$ , we have  $G \cong G' \triangleright_q B$  for some block graph  $G'$  and some vertex  $q \in \{u, w\}$  (note that  $z, y$  and  $v$  are non-articulation vertices of  $G$ ). Now, by the way we have chosen the root block, this implies that we must have  $q = u$ . This further implies that  $u$  is the negative articulation vertex of  $K^*$  for some  $K^* \in \mathcal{K}(G)$  such that  $K^* \notin \{K, K_0\}$ . Hence,  $u$  and  $v$  are open-separated in  $C$  by some vertex in  $V(K^*) \cap C \setminus \{u\}$ .

This, therefore, proves that  $C$  is an OLD-code of  $G$  and with that, we prove the theorem.  $\square$

Applying Theorem 2.10 to each connected component of a block graph, one has the following general result.

**Corollary 2.10.** Let  $G$  be an open-twin-free block graph with  $k$  connected components and no isolated vertices. Moreover, let  $G$  neither be a copy of  $P_2$  nor of  $P_4$ . Also, let  $m_Q(G)$  be the number of non-leaf blocks of  $G$  with at least one non-articulation vertex. Then  $\gamma^{OLD}(G) \leq |V(G)| - m_Q(G) - k$ .

Foucaud et al. [15] have shown that, for any open-twin-free graph  $G$ ,  $\gamma^{OLD}(G) \leq |V(G)| - 1$  unless  $G$  is a special kind of bipartite graph called half-graph (a *half-graph* is a bipartite graph with both parts of the same size, where each part can be ordered so that the open neighbourhoods of consecutive vertices differ by exactly one vertex [13]). Noting that  $P_2$  and  $P_4$  are the only block graphs that are half-graphs, Theorem 2.10 can be seen as a refinement of this result for block graphs.

We now show that the upper bound given in Theorem 2.10 is tight and is attained by arbitrarily large connected block graphs. To prove so, for two non-negative integers  $k$  and  $l$  such that  $k + l \geq 1$ , let us define a subclass  $G_{k,l}$  of block graphs by the following rule: Assume that  $T_1, T_2, \dots, T_k$  are  $k$  copies of  $K_3$  with  $V(T_i) = \{u_i, v_i, w_i\}$  for each  $1 \leq i \leq k$ . Further, assume that  $A_1, A_2, \dots, A_k$  are  $k$  copies of  $P_2$  with  $V(A_i) = \{a_i, b_i\}$  for each  $1 \leq i \leq k$ , and that  $L_1, L_2, \dots, L_l$  are  $l$  copies of  $P_3$  with  $V(L_j) = \{x_j, y_j, z_j\}$  for each  $1 \leq j \leq l$ . Let  $G_{k,l}$  be the graph obtained by identifying the vertices  $v_i$  with  $b_i$  for each  $1 \leq i \leq k$  and identifying the vertices  $u_i$  and  $z_j$  for all  $1 \leq i \leq k$  and  $1 \leq j \leq l$  into a single vertex  $u$ , say. See Figure 8 for an example of a construction of  $G_{k,l}$  with  $k = 2$  and  $l = 3$ . As a matter of reference, we continue to call the vertices of  $G_{k,l}$  obtained by identifying  $v_i$  with  $b_i$ , for all  $1 \leq i \leq k$ , as  $v_i$  itself.

**Proposition 2.11.** For all positive integers  $k$  and  $l$  with  $l+k \geq 2$ ,  $\gamma^{OLD}(G_{k,l}) = |V(G_{k,l})| - m_Q(G_{k,l}) - 1$ .

*Proof.* First of all, we have  $|V(G_{k,l})| = 3k + 2l + 1$ , and  $m_Q(G_{k,l}) = k$ . Therefore, by Theorem 2.10, we have  $\gamma^{OLD}(G_{k,l}) \leq 2(k+l)$ .

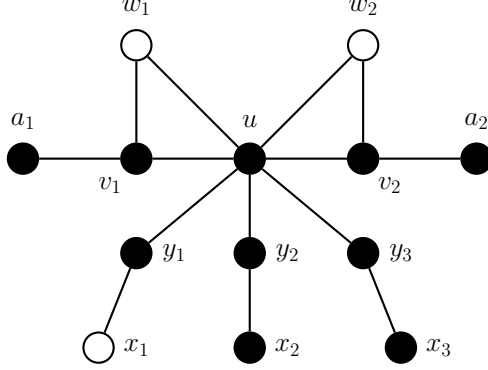


Figure 8: Graph  $G_{2,3}$  whose OLD-number attains the upper bound in Theorem 2.10. The black vertices represent those included in the OLD-code  $C$  of  $G$  as described in the proof of the Theorem 2.10.

Now, let  $C$  be an OLD-code of  $G_{k,l}$ . For  $C$  to be an open-dominating set of  $G_{k,l}$ , the only neighbours  $v_i$  and  $y_j$  of the degree 1 vertices  $a_i$  and  $x_j$ , respectively, of  $G_{k,l}$  must be in  $C$ . Moreover,  $u \in C$  for each pair of  $w_i$  and  $a_i$  to be open-separated in  $C$ . Similarly, all but one of the  $x_i$ 's must belong to  $C$  for each pair of vertices  $y_i$  and  $y_j$ , for  $1 \leq i < j \leq l$ , to be open-separated in  $C$ . Finally, for all  $1 \leq i \leq k$ , at least one of  $w_i$  and  $a_i$  must be in  $C$  for each pair of vertices  $v_i$  and  $v_j$ , for  $1 \leq i < j \leq k$ , to be open-separated in  $C$ . Adding up, therefore, we have  $|C| \geq 2(k+l)$ . □

### 3 Lower bounds

The general lower bound for the size of an identifying code using the number of vertices is  $\gamma^{ID}(G) \geq \lceil \log_2(|V(G)| + 1) \rceil$  [28]. However, to reach this bound, a graph needs to have a large VC-dimension [10] (the *VC-dimension* of a graph  $G$  is the size of a largest *shattered set*, that is, a set  $S$  of vertices such that for every subset  $S'$  of  $S$ , some closed neighbourhood in  $G$  intersects  $S$  exactly at  $S'$ ). Indeed, if a graph has VC-dimension  $c$ , then any identifying code has size at least  $O(|V(G)|^{1/c})$  [10]. The value  $1/c$  is not always tight, see for example the case of line graphs, which have VC-dimension at most 4 but for which the tight order for the lower bound is  $\Omega(|V(G)|^{1/2})$  [16]. Similar results hold for LD- and OLD-codes, by using the same techniques as in [10].

Block graphs have VC-dimension at most 2 (one can check that a shattered set of size 3 would imply the existence of an induced 4-cycle or diamond), and thus, using the result from [10], their ID-number is lower bounded by  $\Omega(|V(G)|^{1/2})$ . In this section, we improve this lower bound to a linear one, and give a tight result.

For the rest of this article, given a block graph  $G$ , by  $\mathcal{K}_{leaf}(G)$  we shall mean the set of all leaf blocks of  $G$  with at least one edge in the block. Moreover, by the symbol  $n_i(G)$ , we shall mean the number of vertices of degree  $i$  in the graph  $G$ .

**Lemma 3.1.** Let  $G$  be a connected block graph with at least one edge. Then we have

$$|\mathcal{K}(G)| \leq |V(G)| - 1 - |\mathcal{K}_{leaf}(G)| + n_1(G).$$

*Proof.* Let  $\mathcal{L}(G) = \{L \in \mathcal{K}_{leaf}(G) : L \cong K_2\}$  and  $G^*$  be a graph obtained from  $G$  by, for each  $L \in \mathcal{L}(G)$ , introducing a new vertex and making it adjacent to both elements of  $V(L)$ . Thus,  $G^*$  is a block graph in which every leaf block has at least 3 vertices. We also note here that

- (1)  $|\mathcal{L}(G)| = n_1(G)$ ,
- (2)  $|V(G^*)| = |V(G)| + |\mathcal{L}(G)| = |V(G)| + n_1(G)$ ,

(3)  $|\mathcal{K}(G)| = |\mathcal{K}(G^*)|$  and that

(4)  $|\mathcal{K}_{leaf}(G)| = |\mathcal{K}_{leaf}(G^*)|$ .

Now, let  $|\mathcal{K}(G^*)| = h$  and that  $\mathcal{K}(G^*) = \{K_1, K_2, \dots, K_h\}$ . Since each block of a connected block graph has at least one edge, assume that  $e_1 = (v_1^1 v_2^1), e_2 = (v_2^2 v_3^2), e_3 = (v_3^3 v_4^3) \dots, e_h = (v_h^h v_{h+1}^h)$  are  $h$  edges of  $G^*$  from each of  $E(K_1), E(K_2), \dots, E(K_h)$ , respectively; where  $v_j^i \in V(K_i)$  for all  $1 \leq i \leq h$  and  $1 \leq j \leq h+1$ . Since, by the structure of a block graph, for any subset  $S \subset \{v_j^i : 1 \leq i \leq h; 1 \leq j \leq h+1\}$ ,  $G^*[S]$  does not contain a cycle as a subgraph, each of the vertices  $v_1^1, v_2^1, v_3^2, \dots, v_{h+1}^h$  are distinct. Moreover, since at least one vertex in each leaf block of  $G^*$  is not any of the vertices  $v_j^i$ , we have

$$\begin{aligned} |\mathcal{K}(G)| = |\mathcal{K}(G^*)| = h &= |\{v_1^1, v_2^1, v_3^2, v_4^3, \dots, v_{h+1}^h\}| - 1 \leq |V(G^*)| - |\mathcal{K}_{leaf}(G^*)| - 1 \\ &= |V(G)| + n_1(G) - |\mathcal{K}_{leaf}(G)| - 1. \end{aligned}$$

□

**Corollary 3.2.** Let  $G$  be a block graph with  $k$  connected components. Then, we have

$$|\mathcal{K}(G)| - n_0(G) \leq |V(G)| - k - |\mathcal{K}_{leaf}(G)| + n_1(G).$$

*Proof.* Assume that  $k = p + q$  such that  $G_1, G_2, \dots, G_p$  are the connected components of  $G$ , each with at least one edge; and that  $S_1, S_2, \dots, S_q$  are the components of  $G$ , each with a single vertex. Then, we have

$$\begin{aligned} |\mathcal{K}(G)| &= \sum_{1 \leq i \leq p} |\mathcal{K}(G_i)| + \sum_{1 \leq j \leq q} |\mathcal{K}(S_j)| \\ &\leq q - p + \sum_{1 \leq i \leq p} (|V(G_i)| - |\mathcal{K}_{leaf}(G_i)| + n_1(G_i)) && \text{[using Lemma 3.1]} \\ &= |V(G)| - k - |\mathcal{K}_{leaf}(G)| + n_1(G) + n_0(G) && \text{[since } q = n_0(G)\text{]} \end{aligned}$$

□

**Corollary 3.3.** Let  $G$  be a block graph with  $k$  connected components. Then we have

$$|\mathcal{K}(G)| - n_0(G) \leq |V(G)| - k.$$

*Proof.* The result follows from Corollary 3.2 and the fact that  $n_1(G) \leq |\mathcal{K}_{leaf}(G)|$ . □

Before we come to our results, we define the following notations.

For a given code  $C$  of a connected block graph  $G$ , let us assume that  $C_1, C_2, \dots, C_k$  are the  $k$  connected components of the subgraph  $G[C]$  of  $G$  induced by  $C$ . Note that each  $C_i$  is a block graph. Then,  $V(G)$  is partitioned into the four following parts.

- (1)  $V_1 = C$ ,
- (2)  $V_2 = \{v \in V(G) \setminus V_1 : |N(v) \cap C| = 1\}$ ,
- (3)  $V_3 = \{v \in V(G) \setminus V_1 : \text{there exist distinct } i, j \leq k \text{ such that } N(v) \cap C_i \neq \emptyset \text{ and } N(v) \cap C_j \neq \emptyset\}$ ,
- (4)  $V_4 = V(G) \setminus (V_1 \cup V_2 \cup V_3)$ . Note that, for all  $v \in V_4$ ,  $N(v) \cap C \subset V(C_i)$  for some  $i$  and that  $|N(v) \cap V(C_i)| \geq 2$ .

We now prove a series of lemmas establishing upper bounds on the sizes of each of the vertex subsets  $V_1, V_2, V_3$  and  $V_4$  of a connected block graph  $G$ .

**Lemma 3.4.** Let  $G$  be a connected block graph and  $C$  be a code of  $G$ . Then following are upper bounds on the size of the vertex subset  $V_2$  of  $G$ .

- (1)  $|V_2| \leq |C| - n_0(G[C])$  if  $C$  is an ID-code.
- (2)  $|V_2| \leq |C|$  if  $C$  is an LD-code.



(3)  $|V_2| \leq |C| - n_1(G[C])$  if  $C$  is an OLD-code.

*Proof.* By definition of  $V_2$ , each vertex  $v \in V_2$  has a unique neighbor  $u$  in  $C$ , i.e.  $N(v) \cap C = \{u\}$ . Hence, there can be at most  $|C|$  vertices in  $V_2$  and this proves (2).

If  $C$  is an ID-code,  $u$  cannot be isolated in  $G[C]$  (or else,  $u$  and  $v$  will not be closed-separated in  $C$ ). Thus, there are at most  $|C| - n_0(G[C])$  vertices in  $V_2$  and this proves (1).

Finally, if  $C$  is an OLD-code and  $u$  has a neighbor  $w \in N(u) \cap C$  such that  $\deg_{G[C]}(w) = 1$ , then  $v$  and  $w$  are not open-separated. Thus, there are at most  $|C| - n_1(G[C])$  vertices in  $V_2$  and this proves (3).  $\square$

Next, given a connected block graph  $G$  and a code  $C$  of  $G$ , we define the following auxiliary graph  $F_C(G)$ . As above, let  $C_1, C_2, \dots, C_k$  be the  $k$  connected components of  $G[C]$  and that the vertex set  $V(G)$  be partitioned into the subsets  $V_1, V_2, V_3, V_4$ . Then, consider the bipartite graph  $F_C(G)$  where  $A = \{a_j : v_j \in V_3\}$  and  $B = \{u_i : C_i \text{ is a connected component of } G[C]\}$  are the two *parts* of  $V(F_C(G))$ . As for the edge set  $E(F_C(G))$ , for each vertex  $v_j$  in  $V_3$ , we add an edge between  $a_j$  and  $u_i$  if  $v_j$  is adjacent to a vertex of  $C_i$ .

**Lemma 3.5.** For a connected block graph  $G$  and a code  $C$  of  $G$ , the auxiliary graph  $F_C(G)$  is a forest.

*Proof.* If there is a cycle in  $F_C(G)$ , there would be a cycle in  $G$  involving two vertices of different connected components  $C_i$  and  $C_j$ , say. By the definition of a block graph, the latter cycle in  $G$  has to induce a complete subgraph in  $G$ . However, that would imply that  $C_i$  and  $C_j$  must be the same component of  $G[C]$  which is a contradiction. Thus,  $F_C(G)$  is cycle-free and, hence, is a forest.  $\square$

**Lemma 3.6.** Let  $G$  be a connected block graph,  $C$  be a code of  $G$  and  $C_1, C_2, \dots, C_k$  be  $k$  connected components of  $G[C]$ . Then, we have  $|V_3| \leq k - 1$ .

*Proof.* By Lemma 3.5,  $F_C(G)$  is a forest. Let  $V(F_C(G)) = A \sqcup B$  be as defined above. Then we have  $|B| = k$ . Since any vertex in the part  $A$  of  $V(F_C(G))$  is adjacent to at least two distinct vertices of  $B$ , we have  $|V_3| \leq k - 1$ .  $\square$

**Lemma 3.7.** Let  $G$  be a connected block graph and  $C$  be a code of  $G$ . Then, we have  $|V_4| \leq |C| - k$ . In particular,

- (1)  $|V_4| \leq |C| - 3k + 2n_0(G[C])$  if  $C$  is an ID-code;
- (2)  $|V_4| \leq |\mathcal{K}(G[C])| \leq |C| - 2k_1 - 3k_2 + n_1(G[C])$  if  $C$  is an OLD-code; where  $k_1 = |\{C_i : C_i \text{ is a connected component of } G[C] \text{ and } C_i \cong K_3\}|$  and  $k_2 = k - k_1$ .

*Proof.* We first prove that every vertex in  $V_4$  is adjacent to the vertices of *exactly one* block of some  $C_i$ , where  $C_i$  is a connected component of  $G[C]$ . So, consider a vertex  $v$  of  $V_4$ . Let  $C_i$  be the component of  $G[C]$  such that  $N(v) \cap C \subseteq V(C_i)$ . Since  $G[N(v) \cap C]$  is a connected subgraph of  $G$ , the vertex subset  $N[v] \cap C$  induces a 2-connected subgraph of  $G$ . By definition of a block graph, therefore,  $N[v] \cap C$  must be a clique. In particular,  $N(v) \cap C$  is a clique of  $C_i$  of size at least 2. Assume that it is not a block of  $C_i$ . Let  $u$  be a vertex in the block of  $C_i$  containing  $N(v) \cap C$  such that  $u$  is not adjacent to  $v$ . Then the set  $\{u, v\} \cup (N(v) \cap C)$  induces a 2-connected subgraph of  $G$  that is not complete, a contradiction. Thus  $N(v) \cap C$  is a block of  $C_i$ .

Also, if  $v$  and  $v'$  are two distinct elements of  $V_4$  adjacent to vertices of  $C_i$ , we must have  $N(v) \cap N(v') \cap V(C_i)$  of size at most 1 (since  $N(v) \cap C$  and  $N(v') \cap C$  are distinct). This shows that each vertex  $v \in V_4$  corresponds to a *unique* block of size at least 2 of  $G[C]$ . This implies that  $|V_4| \leq |\mathcal{K}(G[C])| - n_0(G[C]) \leq |C| - k$ , by Corollary 3. We now prove the more specific bounds for ID- and OLD-codes.

(1) First consider the case where  $C$  is an ID-code. Let  $C_i$  be a connected component of  $G[C]$  such that at least one vertex of  $V_4$  is adjacent to some vertices of  $C_i$ . In particular,  $|V(C_i)| \geq 2$  and since  $C$  is an ID-code,  $C_i$  is closed-twin-free. We first show the following.

**Claim A.** No element of  $V_4$  is adjacent to the vertices of the leaf blocks of  $C_i$ .

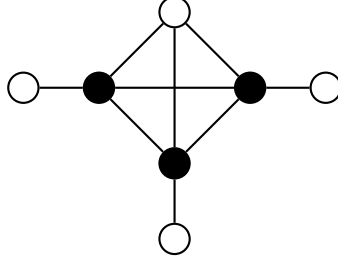


Figure 9:  $Z$ : Graph of largest size whose minimum OLD-code is a 3-clique.

*Proof of Claim A.* Suppose that  $L$  is a leaf block of  $C_i$ . Then we must have  $L \cong K_2$ , or else, at least two vertices in  $V(L)$  are not closed-separated in  $C$ . So, assume that  $V(L) = \{x, y\}$ . Then at least one of  $x$  and  $y$  must be a non-articulation vertex of  $C_i$ . Without loss of generality, suppose that  $y$  is a non-articulation vertex of  $C_i$ . If there exists a vertex  $v$  of  $V_4$  such that  $N(v) \cap C = V(L)$ , then  $v$  and  $y$  would not be closed-separated in  $C$  which is a contradiction. Hence, no element of  $V_4$  is adjacent to the vertices of the leaf blocks of  $C_i$ .  $\blacklozenge$

This implies that the number of vertices of  $V_4$  that can be adjacent to the vertices of  $C_i$  are at most  $|\mathcal{K}(C_i)| - |\mathcal{K}_{leaf}(C_i)|$ . Now, we must have the following.

**Claim B.**  $|\mathcal{K}_{leaf}(C_i)| \geq 2$

*Proof of Claim B.* If, on the contrary,  $|\mathcal{K}(C_i)| = 1$ , then  $|V(C_i)| = 1$ ; or else, all pairs of vertices of  $C_i$  are not closed-separated in  $C$ . This leads to the contradiction to the fact that  $|V(C_i)| \geq 2$ .  $\blacklozenge$

This, therefore, implies that the number of vertices of  $V_4$  adjacent to the vertices of  $C_i$  are at most  $|\mathcal{K}(C_i)| - |\mathcal{K}_{leaf}(C_i)| \leq |\mathcal{K}(C_i)| - 2 \leq |V(C_i)| - 3$  (by Corollary 3) and, hence,

$$|V_4| \leq \sum_{|V(C_i)| \geq 2} (|\mathcal{K}(C_i)| - |\mathcal{K}_{leaf}(C_i)|) = |\mathcal{K}(G[C])| - n_0(G[C]) - 2(k - n_0(G[C])) \leq |C| - 3k + 2n_0(G[C]).$$

(2) In the case that  $C$  is an OLD-code of  $G$ , we have  $n_0(G[C]) = 0$ . So, assume that  $C_i$  is a connected component of  $G[C]$  with at least one edge. Then, by Lemma 3.1, we have  $|\mathcal{K}(C_i)| \leq |V(C_i)| - 1 - |\mathcal{K}_{leaf}(C_i)| + n_1(C_i)$ . If  $C_i \cong K_3$ , then we have  $|\mathcal{K}(C_i)| = 1 = |V(C_i)| - 2$ . If however,  $C_i \not\cong K_3$ , then we have  $|\mathcal{K}(C_i)| \leq |V(C_i)| - 3 + n_1(C_i)$ . This implies that

$$\begin{aligned} |V_4| \leq |\mathcal{K}(G[C])| &= \sum_{C_i \cong K_3} |\mathcal{K}(C_i)| + \sum_{C_i \not\cong K_3} |\mathcal{K}(C_i)| \\ &\leq \sum_{C_i \cong K_3} (|V(C_i)| - 2) + \sum_{C_i \not\cong K_3} (|V(C_i)| - 3 + n_1(C_i)) \\ &= \sum_{1 \leq i \leq k} (|V(C_i)| - n_1(C_i)) - 2k_1 - 3k_2 = |C| - 2k_1 - 3k_2 + n_1(G[C]). \end{aligned}$$

$\square$

Finally, before we come to our next theorem on the lower bounds on the code-numbers of connected block graphs in terms of the order of the graph, we first define a special graph on seven vertices that is an exception to the result. We denote the special graph by  $Z$ , which is simply a graph with a three leaves each adjacent to a unique vertex of the complete graph on four vertices (see Figure 9 for a depiction). As shown in Figure 9 with the vertices marked in black, the OLD-number of  $Z$  is 3.

**Theorem 3.8.** Let  $G$  be a connected block graph. Then we have

- $\gamma^{ID}(G) \geq \frac{|V(G)|}{3} + 1$ ;

- $\gamma^{LD}(G) \geq \frac{|V(G)|+1}{3}$ .
- $\gamma^{OLD}(G) \geq \frac{|V(G)|}{3} + 1$  for all block graphs  $G$  that are not isomorphic to  $Z$

*Proof.* Assume  $C$  to be a code of  $G$  and  $C_1, C_2, \dots, C_k$  to be the  $k$  connected components of  $G[C]$ . We prove the theorem using the relation  $|V(G)| = |C| + |V_2| + |V_3| + |V_4|$  and the upper bounds for  $|V_2|$ ,  $|V_3|$  and  $|V_4|$  in Lemmas 3.4, 3.6 and 3.7, respectively.

If  $C$  is an ID-code, then we have

$$\begin{aligned} n &= |C| + |V_2| + |V_3| + |V_4| \\ &\leq |C| + |C| - n_0(G[C]) + k - 1 + |C| - 3k + 2n_0(G[C]) \\ &= 3|C| - 2k - 1 + n_0(G[C]). \end{aligned}$$

Now, there must be at least as many connected components of  $G[C]$  as there are isolated vertices in  $G[C]$ , i.e. we have  $k \geq n_0(G[C])$ . This implies that  $n \leq 3|C| - k - 1$ . Thus, for  $k \geq 2$ , the result holds. Moreover, when  $k = 1$ , we must have  $n_0(G[C]) = 0$  and so, again, the result holds.

If  $C$  is an LD-code, then

$$\begin{aligned} n &= |C| + |V_2| + |V_3| + |V_4| \\ &\leq |C| + |C| + k - 1 + |C| - k \\ &= 3|C| - 1 \end{aligned}$$

and, hence, the result holds.

Finally, if  $C$  is an OLD-code, then we have

$$\begin{aligned} n &= |C| + |V_2| + |V_3| + |V_4| \\ &\leq |C| + |C| - n_1(G[C]) + k_1 + k_2 - 1 + |C| - 2k_1 - 3k_2 + n_1(G[C]) \\ &= 3|C| - k_1 - 2k_2 - 1. \end{aligned}$$

This implies that the result holds when either  $k_1 \geq 2$  or when  $k_2 \geq 1$ .

If however,  $k_1 = 1$  and  $k_2 = 0$ , then  $G[C]$  is isomorphic to  $K_3$ . If  $n \leq 6$ , the result holds since we have  $n \leq 3|C| - 3$ . Thus  $n = 3|C| - 2 = 7$ . Since no vertex in  $V(G) \setminus C$  can be adjacent to exactly two vertices of  $C$  (otherwise the last vertex of  $C$  would not be open-separated with this vertex), the four vertices in  $V(G) \setminus C$  must each be adjacent to either exactly one vertex in  $C$  or all three vertices of  $C$ . Therefore,  $G$  is isomorphic to the graph  $Z$  in Figure 9. This implies that the result holds for all block graphs not isomorphic to  $Z$ .  $\square$

Extremal cases where these bounds are attained can be constructed as follows (see Figure 10). Consider the graph with one path on vertices  $u_1, \dots, u_k$  (the vertices in the code  $C$ ) and attach further vertices as follows.

- for an ID-code  $C$ : attach a single vertex to each  $u_i$  and vertices to the pairs  $u_i, u_{i+1}$  for  $1 < i < k-1$ ,
- for an OLD-code  $C$ : attach a single vertex to  $u_1, u_k$  and each  $u_i$  for  $2 < i < k-1$  and vertices to all the pairs  $u_i, u_{i+1}$ ,
- for an LD-code  $C$ : attach a single vertex to each  $u_i$  and vertices to all the pairs  $u_i, u_{i+1}$ .

Note that the graphs presented here are all the possible extremal cases for ID-codes, whereas further extremal graphs for OLD-codes and for LD-codes exist. If we now consider the parameter  $|\mathcal{K}(G)|$ , we can use the relation  $|V(G)| \geq |\mathcal{K}(G)| + 1$  to obtain a similar lower bound. But this lower bound can be improved as the next result shows.

**Theorem 3.9.** Let  $G$  be a connected block graph and  $\mathcal{K}(G)$  be the set of all blocks of  $G$ . Then we have

- $\gamma^{ID}(G) \geq \frac{3(|\mathcal{K}(G)|+2)}{7}$ ;
- $\gamma^{LD}(G) \geq \frac{|\mathcal{K}(G)|+2}{3}$ ; and
- $\gamma^{OLD}(G) \geq \frac{|\mathcal{K}(G)|+3}{2}$ .

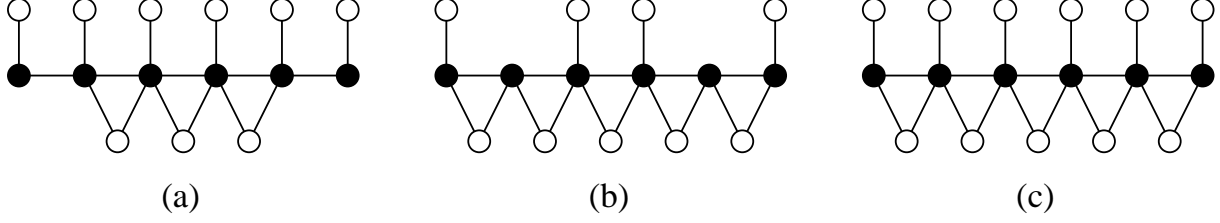


Figure 10: Extremal cases where the lower bounds are attained, black vertices form a minimum (a) ID-code, (b) OLD-code, (c) LD-code.

*Proof.* Assume  $C$  to be a code of  $G$  and that  $C_1, C_2, \dots, C_k$  are the  $k$  connected components of  $G[C]$ . First, we define an *inclusion set*  $\mathcal{I}_G(C) = \{K \in \mathcal{K}(G) : V(L) \subset V(K) \text{ for some } L \in \mathcal{K}(G[C])\}$ . Next, we define the following types of blocks of  $G$ .

1. Let  $\mathcal{K}_C(G) = \{K \in \mathcal{I}_G(C) : V(K) \subset C\}$  i.e. all blocks of  $G$  which are also blocks of the subgraph  $G[C]$  (also a block graph) of  $G$ .
2. Let  $\mathcal{K}_{\overline{C}}(G) = \mathcal{K}(G) \setminus \mathcal{I}_G(C)$ . In other words, the set  $\mathcal{K}_{\overline{C}}(G)$  includes all blocks of  $G$  which do not contain any vertices of the code  $C$ .
3. For  $i = 2, 3, 4$ , let  $\mathcal{K}_i(G) = \{K \in \mathcal{I}_G(C) : V(K) \cap V_i \neq \emptyset\}$ .

We note here that,  $\mathcal{K}(G) = \mathcal{K}_C(G) \cup \mathcal{K}_{\overline{C}}(G) \cup \mathcal{K}_2(G) \cup \mathcal{K}_3(G) \cup \mathcal{K}_4(G)$ . We now have the following bounds.

**Claim A.**  $|\mathcal{K}_2(G)| \leq |V_2|$ .

*Proof of Claim A.* Since each vertex in  $V_2$  belongs to a unique block of  $G$ , the claim is true.  $\blacklozenge$

We now invoke the auxiliary graph  $F_C(G)$  of  $G$  and assume that there are  $l$  connected components of  $F_C(G)$ . Then we have the following claim.

**Claim B.**  $|\mathcal{K}_3(G)| \leq 2(k - l)$ .

*Proof of Claim B.* Since each vertex of  $F_C(G)$  in the part  $A$  is of degree at least 2, we have  $|E(F_C(G))| \geq 2|A| = 2|V_3|$ . Combining this with the fact that  $|E(F_C(G))| = |V_3| + k - l$  (since  $F_C(G)$  is a forest by Lemma 3.5), we have  $|V_3| \leq k - l$ . Hence, we have  $|\mathcal{K}_3(G)| \leq |E(F_C(G))| \leq 2(k - l)$ .  $\blacklozenge$

**Claim C.**  $|\mathcal{K}_{\overline{C}}(G)| \leq l - 1$ .

*Proof of Claim C.* Let  $F_1, F_2, \dots, F_l$  be the  $l$  connected components of the auxiliary graph  $F_C(G)$  of  $G$ . To count  $|\mathcal{K}_{\overline{C}}(G)|$ , we first observe that, for any  $K \in \mathcal{K}_{\overline{C}}(G)$ , there exists a vertex  $v \in V(G)$  in  $K$  such that  $v$  is a positive articulation vertex of  $K$ . If  $K' \in \mathcal{K}(G)$  such that  $V(K) \cap V(K') = \{v\}$ , then there exists a vertex  $v' \in V(G)$  in  $K'$  such that  $v' \in C$ . Now, if  $v' \in V(C_i)$ , we have  $K' \in \mathcal{I}_G(C)$ . Assume that  $u_i$  is a vertex in  $B \cap F_j$  (for some  $1 \leq j \leq l$ ) of the vertex set  $V(F_C(G))$ . Then, we associate  $F_j$  with the block  $K \in \mathcal{K}_{\overline{C}}(G)$ . Moreover, we note that this association is one-to-one: if there exists another block  $K_1 \in \mathcal{K}_{\overline{C}}(G)$  also associated with  $F_j$ , i.e. if  $v_1 \in \text{art}^+(K_1)$ ,  $K'_1 \in \mathcal{K}(G)$  such that  $V(K_1) \cap V(K'_1) = \{v_1\}$  and there exists a  $v'_1 \in V(K'_1) \cap V(C_i)$ , then by virtue of both  $v \in \text{art}^+(K)$  and  $v_1 \in \text{art}^+(K_1)$ , there exists a cycle of length at least four in the block graph  $G$  which is a contradiction. This implies that  $|\mathcal{K}_{\overline{C}}(G)| \leq l - 1$  (the  $-1$  in the upper bound appears due to the fact that a block in  $\mathcal{K}_{\overline{C}}(G)$  cannot be a root block of  $G$ ).  $\blacklozenge$

**Claim D.**  $|\mathcal{K}_C(G) \cup \mathcal{K}_4(G)| \leq |\mathcal{K}(G[C])| - n_0(G[C])$ .

*Proof of Claim D.* Assume that  $K \in \mathcal{K}(G)$  is a block of  $\mathcal{K}_C(G) \cup \mathcal{K}_4(G)$ . Then,  $V(K)$  contains at least two vertices, say,  $u, v \in C$ . Therefore,  $uv \in E(G)$ . So, assume  $L \in \mathcal{K}(G[C])$  to be the block such that  $u, v \in V(L)$ . Then,  $V(L) \subset V(K)$ . Thus, every block  $K \in \mathcal{K}_C(G) \cup \mathcal{K}_4(G)$  can be associated with a block  $L \in \mathcal{K}(G[C])$  such that  $|V(L)| \geq 2$ . Moreover, by the structure of a block graph, this association is one-to-one. This implies that  $|\mathcal{K}_C(G) \cup \mathcal{K}_4(G)| \leq |\mathcal{K}(G[C])| - n_0(G[C])$ .  $\blacklozenge$

To compute  $|\mathcal{K}(G)|$  now, we have from the above Claims A, B, C and D that

$$\begin{aligned} |\mathcal{K}(G)| &\leq |\mathcal{K}_C(G) \cup \mathcal{K}_4(G)| + |\mathcal{K}_{\overline{C}}(G)| + |\mathcal{K}_2(G)| + |\mathcal{K}_3(G)| \\ &\leq |\mathcal{K}(G[C])| - n_0(G[C]) + l - 1 + |V_2| + 2(k - l). \end{aligned} \quad (1)$$

Therefore, using Equation (1), we have

For ID-codes:

$$\begin{aligned} |\mathcal{K}(G)| &\leq |\mathcal{K}(G[C])| - n_0(G[C]) + l - 1 + |V_2| + 2(k - l) \\ &= |C| - k + l - 1 + |C| - n_0(G[C]) + 2(k - l) && \text{[using Corollary 3.3 and Lemma 3.4(1)]} \\ &= 2|C| + k - l - n_0(G[C]) - 1 \\ &\leq 2|C| + k - n_0(G[C]) - 2. \end{aligned}$$

Now,  $k - n_0(G[C])$  is the total number of components of  $C$  of size at least 2. Any such component must contain at least 3 vertices of the code  $C$ . Therefore,  $3(k - n_0(G[C])) \leq |C| - n_0(G[C])$ . Therefore,  $3|\mathcal{K}(G)| \leq 7|C| - n_0(G[C]) - 6 \leq 7|C| - 6$  and, hence, the result holds.

For LD-codes:

$$\begin{aligned} |\mathcal{K}(G)| &\leq |\mathcal{K}(G[C])| - n_0(G[C]) + l - 1 + |V_2| + 2(k - l) \\ &= |C| - k + l - 1 + |C| + 2(k - l) && \text{[using Corollary 3.3 and Lemma 3.4(2)]} \\ &= 2|C| + k - l - 1 \\ &\leq 3|C| - 2. \end{aligned}$$

Finally, for OLD-codes: we assume the quantities  $k_1$  and  $k_2$  to be the same as in Claim 3.7 in the proof of Theorem 3.8. Moreover, in this case,  $n_0(G[C]) = 0$ . Hence, we have

$$\begin{aligned} |\mathcal{K}(G)| &\leq |\mathcal{K}(G[C])| + l - 1 + |V_2| + 2(k - l) \\ &= |C| - 2k_1 - 3k_2 + l - 1 + |C| + 2(k - l) && \text{[using Lemmas 3.4(3) and 3.7(2)]} \\ &= 2|C| + k_1 - k - l - 1. \end{aligned}$$

We therefore have the following two cases.

**Case 1** (Either  $k > k_1$  or  $l \geq 2$ ). In this case, we clearly have  $|\mathcal{K}(G)| \leq 2|C| - 3$  and, hence, the result holds.

**Case 2** ( $k = k_1$  and  $l = 1$ ). In this case, every block  $K \in \mathcal{K}(G)$  such that  $|V(K) \cap C| \geq 2$  must have  $|V(K) \cap C| = 3$ . We now claim the following.

**Claim 2A.** Every block  $L \in \mathcal{K}(G)$  such that  $L \cong K_2$  must be a leaf block of  $G$  with the degree 1 vertex in  $V(L)$  belonging to  $V_2$ .

*Proof of Claim 2A. (of Claim 2A).* Assume that  $V(L) \cap C = \emptyset$ . Then  $L$  cannot be a leaf block of  $G$ . However, this means that  $l \geq 2$ , contrary to our assumption. Hence,  $V(L) \cap C \neq \emptyset$ . However,  $|V(L) \cap C| = 1$ , or else,  $|V(L) \cap C| = 3$  which is not possible since  $|V(L)| = 2$ . This implies that  $L$  must be a leaf block, or else,  $l \geq 2$  again. Now, if the degree 1 vertex in  $V(L)$  is in the code  $C$ , then there exists a connected component  $C_i$  of  $C$  such that  $C_i \cong K_3$  and so,  $k > k_1$ , again contrary to our assumption. Hence, the degree 1 vertex of  $V(L)$  must belong to  $V_2$ .  $\blacklozenge$

Now, assume that a block  $K$  of  $G$  belongs to  $\mathcal{K}_2(G)$  such that a vertex  $v \in V(K) \cap V_2$  and that  $u \in V(K) \cap C$  is the only vertex of  $V(K)$  belonging to  $C$ . If there exists another vertex  $w \in V(K)$ , then

$w \notin C$ , or else,  $v \in V_4$  which is a contradiction. This implies that  $\{u\}$  is a connected component of  $C$  and so, is not isomorphic to  $K_3$ . Thus,  $k > k_1$  which is, again, the same contradiction. Hence, we must have  $K \cong K_2$  and, therefore, by Claim 2A, is a leaf block of  $G$ . This implies that  $|\mathcal{K}_2(G)| \leq n_1(G)$ . However, for the code  $C$  to have at least one connected component  $C_i \cong K_3$ , there must be at least one block of size at least 4 in  $G$ . Thus, we must have  $|C| - n_1(G) \geq 4$  (as is realised in Figure 9). This implies that  $|\mathcal{K}_2(G)| \leq n_1(G) \leq |C| - 4$ . Moreover, in a block graph  $G$  with  $k = k_1$  and  $l = 1$ , we also have  $|\mathcal{K}_{\overline{C}}(G)| = 0$ . Hence, using these bounds, we have

$$\begin{aligned} |\mathcal{K}(G)| &\leq |\mathcal{K}_C(G) \cup \mathcal{K}_4(G)| + |\mathcal{K}_2(G)| + |\mathcal{K}_3(G)| \\ &\leq |\mathcal{K}(G[C])| + |C| - 4 + 2(k_1 - 1) \\ &= |C| - 2k_1 + |C| - 4 + 2(k_1 - 1) && \text{[using Lemma 3.7(2)]} \\ &= 2|C| - 6. \end{aligned}$$

Thus, the result holds in this case as well. □

Note that, since for any tree  $G$  we have  $|\mathcal{K}(G)| = |E(G)| = |V(G)| - 1$ , the lower bounds in Theorem 3.9 are equivalent to the known lower bounds using the number of vertices (see [9] for ID-codes, [36] for LD-codes and [35] for OLD-codes). In particular, there are infinite families of trees reaching the three bounds in Theorem 3.9. Moreover, there are no such lower bounds for general graphs. For example, if we consider the split graph  $G$  with its vertex set  $V(G) = \{v_1, \dots, v_k\} \cup \{u_X : X \subseteq \{1, \dots, k\} \text{ and } X \neq \emptyset\}$ . The vertices  $v_1, \dots, v_k$  induce a clique, whereas the vertices  $u_X$  induce an independent set. Moreover, there is an edge between the vertices  $v_i$  and  $u_X$  if and only if  $i \in X$ . This graph has an identifying code of size  $2k$  (the clique with the vertices corresponding to the singletons), but the number of blocks in  $G$  is  $2^k$ .

## 4 Conclusion

Block graphs form a subclass of chordal graphs for which all three considered identification problems can be solved in linear time [2]. In this paper, we complemented this result by presenting lower and upper bounds for all three codes. We gave bounds using both the number of vertices — as it has been done for several other classes of graphs — and also using the parameter  $|\mathcal{K}(G)|$  of the number of blocks of  $G$  that is more fitting for block graphs. In particular, we verified a conjecture from [1] (Conjecture 1.1) concerning an upper bound for  $\gamma^{ID}(G)$ , and also proved the conjecture on the LD-number [23] (Conjecture 1.2) for the special case of block graphs. Moreover, we addressed the questions to find block graphs where the provided lower and upper bounds are attained.

The structural properties of block graphs have enabled us to prove interesting bounds for the three considered identification problems. It would be interesting to see whether other structured classes can be studied in a similar way. It would also be interesting to prove Conjecture 1.2 for a larger class of graphs, for example for all chordal graphs.

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