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Tiziana Calamoneri<sup>1</sup>, Saverio Caminiti<sup>1</sup>,  
Guillaume Fertin<sup>2</sup>

<sup>1</sup> Dipartimento di Informatica  
Università degli Studi di Roma "La Sapienza"  
Via Salaria 113  
00198 Roma, Italy

<sup>2</sup> LINA FRE CNRS 2729  
Université de Nantes  
2 rue de la Houssinière, BP 92208  
44322 Nantes Cedex 3, France

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Tiziana Calamoneri, Saverio Caminiti, Guillaume Fertin

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# New Bounds for the $L(h, k)$ Number of Regular Grids

Tiziana Calamoneri, Saverio Caminiti, Guillaume Fertin

calamo@di.uniroma1.it, caminiti@di.uniroma1.it, fertin@lina.univ-nantes.fr

## Abstract

For any non negative real values  $h$  and  $k$ , an  $L(h, k)$ -labeling of a graph  $G = (V, E)$  is a function  $L : V \rightarrow \mathbb{R}$  such that  $|L(u) - L(v)| \geq h$  if  $(u, v) \in E$  and  $|L(u) - L(v)| \geq k$  if there exists  $w \in V$  such that  $(u, w) \in E$  and  $(w, v) \in E$ . The *span* of an  $L(h, k)$ -labeling is the difference between the largest and the smallest value of  $L$ . We denote by  $\lambda_{h,k}(G)$  the smallest real  $\lambda$  such that graph  $G$  has an  $L(h, k)$ -labeling of span  $\lambda$ . The aim of the  $L(h, k)$ -labeling problem is to satisfy the distance constraints using the minimum span.

In this paper, we study the  $L(h, k)$ -labeling problem on regular grids of degree 3, 4, 6 and 8, solving several open problems left in the literature.

Additional Key Words and Phrases:  $L(h, k)$ -labeling, triangular grids, hexagonal grids, squared grids, octagonal grids



# 1 Introduction

For any non negative real values  $h$  and  $k$ , an  $L(h, k)$ -labeling of a graph  $G = (V, E)$  is a function  $L : V \rightarrow \mathbb{R}$  such that  $|L(u) - L(v)| \geq h$  if  $(u, v) \in E$  and  $|L(u) - L(v)| \geq k$  if there exists  $w \in V$  such that  $(u, w) \in E$  and  $(w, v) \in E$ . The *span* of an  $L(h, k)$ -labeling is the difference between the largest and the smallest value of  $L$ . Hence, it is not restrictive to assume 0 as the smallest value of  $L$ , something which will be assumed throughout this paper. We denote by  $\lambda_{h,k}(G)$  the smallest real  $\lambda$  such that graph  $G$  has an  $L(h, k)$ -labeling of span  $\lambda$ ; we call  $L(h, k)$  *number of  $G$*  this value. The aim of the  $L(h, k)$ -labeling problem is to satisfy the distance constraints using the minimum span.

Since its definition [11] as a specialization of the frequency assignment problem in wireless networks [12, 16], the  $L(h, k)$ -labeling problem has been intensively studied. Note that the  $L(h, k)$ -labeling problem is a generalization of some standard graph colorings, such as the usual (or proper) coloring when  $k = 0$ , or the 2-distance coloring (equivalent to the proper coloring of the square of the graph) when  $h = k$ . We also note that the case  $h = 2$  and  $k = 1$  (or, more generally  $h = 2k$ ), called radio-coloring or  $\lambda$ -coloring, is the most widely studied (see for instance [7, 9, 13, 14]).

The decision version of the  $L(h, k)$ -labeling problem is NP-complete even for small values of  $h$  and  $k$  [2]. This motivates seeking optimal solutions on particular classes of graphs (see for instance [3, 4, 8, 11, 17, 18, 19] and [6] for a complete survey). Concerning the more specific grid topologies, a large number of papers has been published on the subject. For instance, Makansi [15] provided an optimal  $L(0, 1)$ -labeling for squared grids. Battiti, Bertossi and Bonuccelli [1] found an optimal  $L(1, 1)$ -labeling for hexagonal, squared and triangular grids. The  $L(2, 1)$ -labeling problem of regular grids of degree  $\Delta$ , denoted  $G_\Delta$ , has been studied independently by different authors [3, 7] proving that  $\lambda_{2,1}(G_\Delta) = \Delta + 2$  by means of optimal coloring algorithms. More recently, Fertin and Raspaud [10] determined several bounds on  $\lambda_{h,k}$  for  $d$ -dimensional squared grids.

In [5] some values of  $\lambda_{h,k}$  for regular grids of degree 3, 4, and 6 are exactly computed, while in some intervals different upper and lower bounds are given; the case  $h < k$  is not considered at all.

In this paper, we study the  $L(h, k)$ -labeling problem on regular grids of degree 3, 4, and 6 for those values of  $h$  and  $k$  whose  $\lambda_{h,k}$  is either not known or not tight. Moreover, for the first time in the literature, we investigate on the problem for grids of degree 8. For all considered grids, in some cases we provide exact results, while in the other ones we give very close upper and lower bounds. A graphical representation of the four types of grids studied in this paper is given in Figure 1, while a summary of our results is depicted in Figure 2.

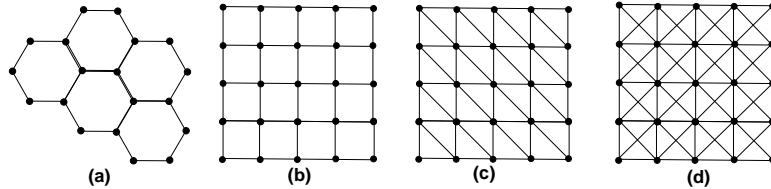


Figure 1: Grids studied in this paper: (a)  $G_3$ , (b)  $G_4$ , (c)  $G_6$  and (d)  $G_8$

## 2 Preliminaries

In this section, we show four different lemmas, which will prove to be useful in the rest of the paper. Lemmas 1 and 2 are concerned with lower bounds for the  $L(h, k)$  number, while Lemmas 3 and 4 deal with upper bounds.

**Lemma 1**  $\lambda_{h,k}(G_\Delta) \geq h + (\Delta - 1)k$  when  $h \leq k$ , for  $\Delta = 3, 4$ .

**Proof :** Consider an optimal  $L(h, k)$ -labeling of  $G_\Delta$ ,  $h \leq k$ ,  $\Delta = 3, 4$ , and let  $x$  be a node labeled 0. The smallest label among those of their neighbors must be at least  $h$ . Furthermore, the  $\Delta$  neighbors of  $x$  are all connected by a 2-length path and hence their labels must differ at least  $k$  from each other. It follows that the greatest label must be at least  $h + (\Delta - 1)k$ .  $\square$

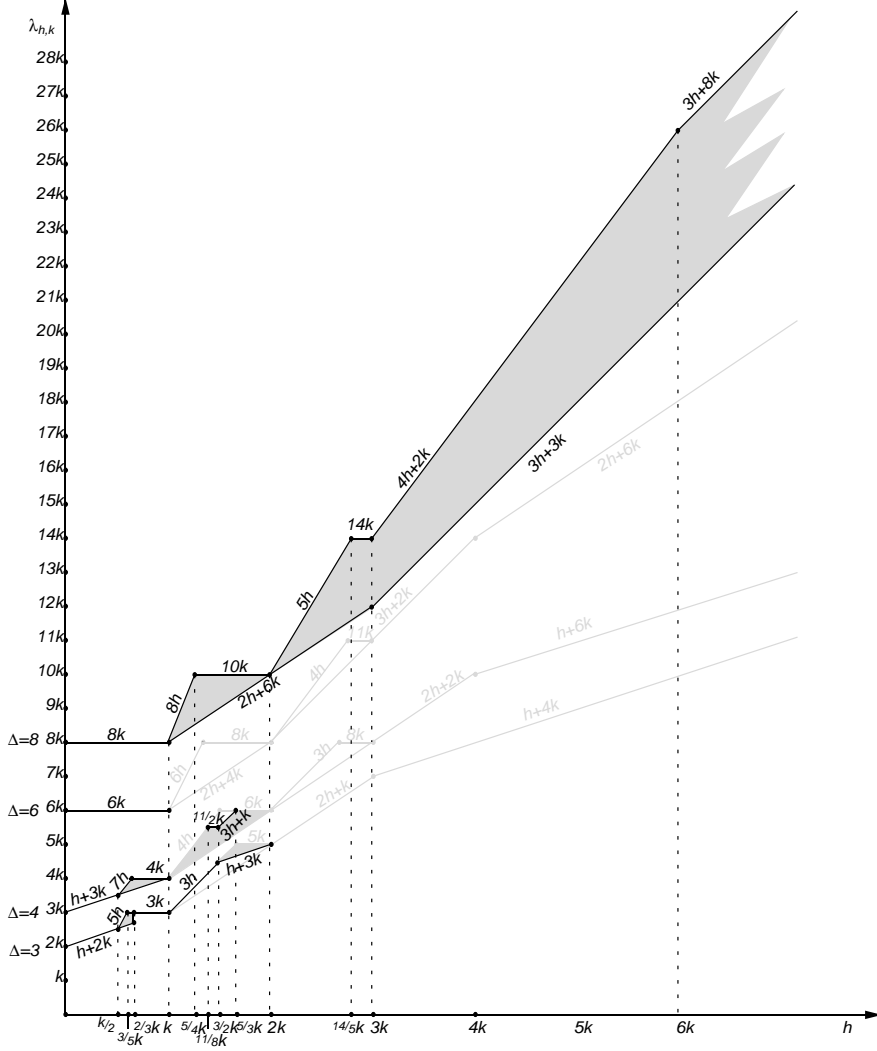


Figure 2: Summary of the results achieved in this paper: bold lines are results from this paper, while gray lines are previously known lower and upper bounds.

**Lemma 2**  $\lambda_{h,k}(G_\Delta) \geq \Delta k$  when  $h \leq k$ , for  $\Delta = 6, 8$ .

**Proof:** Observe that  $G_6$  and  $G_8$  are characterized by the property that each pair of adjacent nodes is also connected by a 2-length path. This implies that, given an optimal  $L(h, k)$ -labeling of  $G_\Delta$ ,  $h \leq k$ ,  $\Delta = 6, 8$ , starting from a node  $x$  labeled 0, the smallest label, among those of their neighbors must be at least  $k$ . With reasonings analogous to those of the previous proof, the claim follows.  $\square$

**Lemma 3** For any graph  $G$  and any  $0 \leq h \leq k$ ,  $\lambda_{h,k}(G) \leq k \cdot \lambda_{1,1}(G)$ .

**Proof:** Consider an optimal  $L(1, 1)$ -labeling, say  $\mathcal{L}$ , of  $G$ . Consider the labeling  $\mathcal{L}'$  obtained from  $\mathcal{L}$  by substituting every label  $i$  with label  $ik$  ( $i = 0, 1, \dots, \lambda_{1,1}(G)$ ). We claim that  $\mathcal{L}'$  is an  $L(h, k)$ -labeling of  $G$  with span  $k \cdot \lambda_{1,1}(G)$ , provided  $h \leq k$ . Indeed, any two neighbors, which differ by at least 1 in  $\mathcal{L}$ , differ by at least  $k \geq h$  in  $\mathcal{L}'$ ; moreover, any two nodes connected by a 2-length path, which differ by at least 2 in  $\mathcal{L}$  differ by at least  $2k \geq k$  in  $\mathcal{L}'$ .  $\square$

**Lemma 4** For any graph  $G$  and any  $h \geq \frac{k}{2}$ ,  $\lambda_{h,k}(G) \leq h \cdot \lambda_{1,2}(G)$ .

**Proof** : Analogously to proof of Lemma 3, consider an  $L(1, 2)$  labeling, say  $\mathcal{L}$ , of  $G$ . Consider the labeling  $\mathcal{L}'$  obtained from  $\mathcal{L}$  by substituting every label  $i$  with label  $ih$  ( $i = 0, 1, \dots, \lambda_{1,2}(G)$ ). Since  $h \geq \frac{k}{2}$ ,  $\mathcal{L}'$  is an  $L(h, k)$ -labeling of  $G$  with span  $h \cdot \lambda_{1,2}(G)$ . Indeed, any two neighbors, which differ by at least 1 in  $\mathcal{L}$ , differ by at least  $h$  in  $\mathcal{L}'$ ; moreover, any two nodes connected by a 2-length path, which differ by at least 2 in  $\mathcal{L}$  differ by at least  $2h \geq k$  in  $\mathcal{L}'$ .  $\square$

If no confusion arises, we will speak interchangeably, in the rest of this paper, of a node and its label.

### 3 Regular Grids of Degree 3

#### 3.1 Upper Bounds

**Proposition 1**  $\lambda_{h,k}(G_3) \leq h + 2k$  when  $h \leq \frac{k}{2}$ .

**Proof** : Consider an optimal  $L(1, 2)$ -labeling of  $G_3$  over the set of colors  $\{0, 1, \dots, 5\}$ , as shown in Figure 3(a). The idea is to substitute  $h$  to 1,  $k$  to 2,  $h+k$  to 3,  $2k$  to 4, and  $h+2k$  to 5. In that case, the labeling that is produced is a feasible  $L(h, k)$ -labeling. Indeed, each pair of consecutive labels differ by either  $h$  or  $k-h$ , but since we supposed  $h \leq \frac{k}{2}$ , we have  $k-h \geq h$  and thus any two consecutive labels differ by at least  $h$ . Similarly, any other pair of distinct labels differ by at least  $k$ . Moreover, the largest label used is  $h+2k$ , hence the result.  $\square$

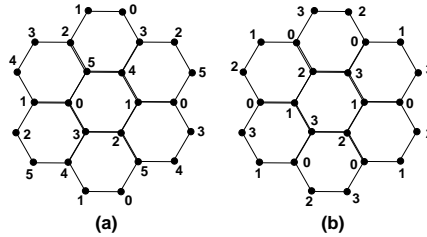


Figure 3:  $L(h, k)$ -labeling of  $G_3$ : (a)  $L(1, 2)$ -labeling ; (b)  $L(1, 1)$ -labeling

**Proposition 2**  $\lambda_{h,k}(G_3) \leq \min \{5h, 3k\}$  when  $\frac{k}{2} \leq h \leq k$ .

**Proof** : By Lemma 4, since  $\frac{k}{2} \leq h$  and since there exists an  $L(1, 2)$ -labeling of  $G_3$  that is of span 5 (as shown in Figure 3(a)), we know there exists an  $L(h, k)$ -labeling of  $G_3$  of span  $5h$ .

Analogously, since  $h \leq k$ , we obtain an  $L(h, k)$ -labeling of span  $3k$  by Lemma 3; indeed, there exists an  $L(1, 1)$ -labeling of  $G_3$  that is of span 3 (as shown in Figure 3(b)).  $\square$

#### 3.2 Lower Bounds

**Proposition 3**  $\lambda_{h,k}(G_3) \geq h + 2k$  when  $h \leq k$ .

**Proof** : This bound directly comes from Lemma 1.  $\square$

**Proposition 4**  $\lambda_{h,k}(G_3) \geq 3k$  when  $\frac{2}{3}k \leq h \leq k$ .

**Proof** : Consider an optimal  $L(h, k)$ -labeling of  $G_3$ . Suppose, by contradiction, that  $\lambda_{h,k}(G_3) < 3k$ . Let us consider a node labeled 0, and let  $x, y$ , and  $z$  be its 3 neighbors. Without loss of generality, suppose  $x < y < z$ . In view of the  $L(h, k)$ -constraints, we must have  $x \geq h, y \geq x + k \geq h + k$ , and  $z \geq y + k \geq h + 2k$ . Furthermore, from the hypothesis  $\lambda_{h,k}(G_3) < 3k$ , we have that  $z < 3k$ , hence  $y \leq z - k < 2k$ , and  $x \leq y - k < k$ . Let  $x_1$  and  $x_2, y_1$  and  $y_2, z_1$  and  $z_2$  be the not 0 neighbors of  $x, y$ , and  $z$ , respectively (see Figure 4).

Let us first prove that if  $y_m = \min\{y_1, y_2\}$  and  $y_M = \max\{y_1, y_2\}$ , then  $y_m < y < y_M$ . Indeed, if  $y < y_m$ , then  $y_m \geq y + h \geq 2h + k$ , and consequently  $y_M \geq 2h + 2k$ . However,  $2h + 2k \geq 3k$  (because we supposed  $h \leq \frac{2k}{3} \geq \frac{k}{2}$ ), a contradiction to the fact that  $\lambda < 3k$ . On the other hand, if  $y_M < y$ , then  $y \geq y_M + h$ . And



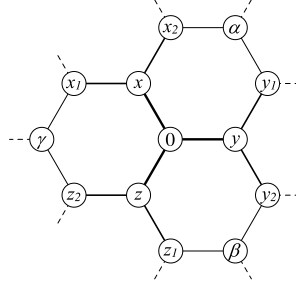


Figure 4: Neighborhood of a node labeled 0 in  $G_3$

since  $y_M \geq y_m + k \geq 2k$ , we end up with  $y \geq h + 2k$ . However, by hypothesis we know that  $y < 2k$ , a contradiction since  $3h - k \leq h + 2k$ , because we supposed  $h \leq \frac{3k}{2}$ . Thus we conclude that in all the cases, we have  $y_m < y < y_M$ .

Now, in order to prove the statement, we will show that under the hypothesis  $\lambda_{h,k}(G_3) < 3k$ , both cases  $x_1 < x_2$  and  $x_1 > x_2$  lead to a contradiction.

**Case 1:**  $x_1 < x_2$ . This implies  $x_1 \geq k$ , as  $x_1$  is connected by a 2-length path to node 0 (via  $x$ ) and  $x_2 \geq x_1 + k \geq 2k$ . If  $x_1 < x$ , then  $x \geq x_1 + h \geq k + h$ , a contradiction since  $x < k$ . Hence,  $x < x_1 < x_2$ . It follows that  $x_1 \geq x + h \geq 2h$  and  $x_2 \geq x_1 + k \geq 2h + k$ . Let us now consider  $y_1$  and  $y_2$ .

**Case 1.1:**  $y_1 < y_2$ . Hence we know that  $y_1 < y < y_2$ . In such a case  $y_1 \geq k$  and  $y_1 \leq y - h < 2k - h$ . Note that  $y_1 < x_2$  as  $y_1 < 2k - h$  and  $x_2 \geq 2k$ . Let us consider the common neighbor of  $x_2$  and  $y_1$ ,  $\alpha$ , and let us study the relative position of its label with respect to  $x_2$  and  $y_1$ .

- $\alpha < y_1 < x_2$ . Then  $\alpha \leq y - k < k$ : if  $x < \alpha$  we have  $\alpha \geq x + k \geq h + k$ , a contradiction ; on the other hand, if  $\alpha < x$  then  $\alpha \leq x - k < 0$ , a contradiction too.
- $y_1 < x_2 < \alpha$ . Then  $x_2 \leq \alpha - h < 3k - h$  ; from previous hypotheses we also have  $x_2 \geq 2h + k$ , and this leads to a contradiction as  $3k - h \leq 2h + k$  when  $h \geq \frac{2}{3}k$ .
- $y_1 < \alpha < x_2$ . We have again two cases. If  $y_1 < \alpha < y$  then  $\alpha \leq y - k < k$  and  $y_1 \leq \alpha - h < k - h$  that is a contradiction as  $y_1 \geq k$ . If  $y_1 < y < \alpha$  then  $\alpha \leq x_2 - h \leq 3k - h$ ,  $y \leq \alpha - k < 2k - h$ , and  $y_1 \leq y - h < 2k - 2h$  that is a contradiction as  $y_1 \geq k$  and  $k < 2k - 2h$  when  $h > \frac{2}{3}k$ .

**Case 1.2:**  $y_1 > y_2$ . Thus we have  $y_1 > y > y_2$ . This implies that  $y_1 \geq y + h \geq 2h + k$ . Hence,  $y_1$  lies in the interval  $[2h + k; 3k[$ . However, we also know that  $x_2$  lies in the interval  $[2h + k; 3k[$ . Since this interval is of width  $w < 2k - 2h$ , we conclude that  $w < k$  (because we supposed  $h \geq \frac{2k}{3}$  and hence  $h \geq \frac{k}{2}$ ). This leads to a contradiction because  $y_1$  and  $x_2$  must be at least  $k$  away from each other.

**Case 2:**  $x_1 > x_2$ . With considerations analogous to those done for case  $x_1 < x_2$ , we can derive  $x < x_2 < x_1$  and  $2h + k \leq x_1 < 3k$  and  $2h \leq x_2 < 2k$ . Now, let us look at  $y_1$  and  $y_2$ .

**Case 2.1:**  $y_1 < y_2$ . We thus have  $y_1 < y < y_2$ . However, this leads to a contradiction. Indeed,  $y_1 > k$  as it is connected by a 2-length path to node 0, then  $x_2 \geq y_1 + k > 2k$  and  $x_1 \geq x_2 + k > 3k$ .

**Case 2.2:**  $y_1 > y_2$ . We then have  $y_2 < y < y_1$ . This implies that  $y_1 \geq y + h \geq 2h + k$  and hence  $y_1 < x_2$  as  $x_2 < 2k$ . Now consider  $\alpha$ , the common neighbor of  $x_2$  and  $y_1$ .

- $x_2 < y_1 < \alpha$ . Then  $\alpha \geq y_1 + h \geq 3h + k \geq 3k$ , a contradiction since we supposed  $\lambda < 3k$ .
- $\alpha < x_2 < y_1$ . Then  $\alpha \leq x_2 - h < 2k - h$ . If  $\alpha > y$  then  $\alpha \geq y + k \geq h + 2k$  that is absurd ; if  $\alpha < y$  then  $\alpha \leq y - k \leq k$ . However, we know that  $x < k$  ; moreover, because  $\alpha < k$  and  $\alpha$  must lie at least  $k$  away from  $x$ , this leads to a contradiction.

- $x_2 < \alpha < y_1$ . Then  $\alpha \leq y_1 - h < 3k - h$ . If  $\alpha > y$  then  $\alpha \geq y + k \geq h + 2k$  that is greater than  $3k - h$  under the hypothesis  $h \geq \frac{2}{3}k$ ; if  $\alpha < y$  then  $\alpha \leq y - k \leq k$  that again contradicts the fact that  $\alpha$  must lie at least  $k$  away from  $x$ .

Altogether, we see that every possible case leads to a contradiction. This proves that the initial assumption,  $\lambda < 3k$ , is false, and consequently the proposition is proved.  $\square$

**Proposition 5**  $\lambda_{h,k}(G_3) \geq 3h$  when  $k \leq h \leq \frac{3}{2}k$ .

**Proof :** The proof is analogous to the previous one, i.e. by contradiction we assume that there exists a  $L(h, k)$ -labeling with span  $\lambda < 3h$ , we start from node labeled 0, we look at its neighbors and prove that neither  $x_1 < x_2$  nor  $x_1 > x_2$  can occur. Wlog, let us assume  $x < y < z$ . Hence,  $x \geq h$ ,  $y \geq h + k$  and  $z \geq h + 2k$ . From the other hand,  $z < 3h$ ,  $y < 3h - k$  and  $x < 3h - 2k$ . Let  $x_1$  and  $x_2$ ,  $y_1$  and  $y_2$ ,  $z_1$  and  $z_2$  be the not 0 neighbors of  $x$ ,  $y$ , and  $z$ , respectively (see Figure 4).

We first prove that if  $y_m = \min\{y_1, y_2\}$  and  $y_M = \max\{y_1, y_2\}$ , then  $y_m < y < y_M$ . Indeed, if  $y < y_m$ , then  $y_m \geq y + h \geq 2h + k$ , and consequently  $y_M \geq 2h + 2k$ . However,  $2h + 2k \geq 3h$  (because we supposed  $h \leq \frac{3k}{2}$ ), a contradiction to the fact that  $\lambda < 3h$ . On the other hand, if  $y_M < y$ , then  $y \geq y_M + h$ . And since  $y_M \geq y_m + k \geq 2k$ , we end up with  $y \geq h + 2k$ . However, by hypothesis we know that  $y < 3h - k$ , a contradiction since  $3h - k \leq h + 2k$ , because we supposed  $h \leq \frac{3k}{2}$ . Thus we conclude that in all the cases, we have  $y_m < y < y_M$ . Now, as in the previous proof, let us consider  $x_1$  and  $x_2$  (see Figure 4), and show that, under the hypothesis  $\lambda < 3h$ , none of the cases  $x_1 < x_2$  and  $x_1 > x_2$  can occur.

**Case 1:**  $x_1 < x_2$ . This implies  $x_1 \geq k$ , as  $x_1$  is connected by a 2-length path to node 0 (via  $x$ ). If  $x_1 < x$ , then  $x \geq x_1 + h \geq h + k$ , that is a contradiction as  $x < 3h - 2k \leq h + k$  under the hypothesis  $h \leq \frac{3}{2}k$ . Hence,  $x < x_1 < x_2$ . It follows that  $x_1 \geq x + h \geq 2h$  and  $x_2 \geq x_1 + k \geq 2h + k$ . Let us consider now  $y_1$  and  $y_2$ .

**Case 1.1:**  $y_1 < y_2$ . Then we know that  $y_1 < y < y_2$ . Note that  $y_1 < x_2$  as  $x_2 \geq 2h + k$  and  $y_1 \leq y - h \leq y_2 - 2h < 3h - 2h = h$ . Now, let us consider  $\alpha$ , common neighbor of  $y_1$  and  $x_2$ .

- $y_1 < x_2 < \alpha$ . The contradiction comes from the inequality  $\alpha \geq x_2 + h \geq 3h + k$ .
- $\alpha < y_1 < x_2$ . Then  $y_1 \geq \alpha + h \geq h$ ,  $y \geq y_1 + h \geq 2h$  and  $y_2 \geq y + h \geq 3h$ , a contradiction.
- $y_1 < \alpha < x_2$ . Since we have  $y_1 \geq k$ , this implies  $\alpha \geq y_1 + h \geq h + k$  and  $\alpha \leq x_2 - h < 2h$ . It is easy to see that the same bounds hold also for  $y$ . Hence  $y$  and  $\alpha$  both lie in the interval  $[h + k; 2h]$ , of width  $w < h - k$ , that is  $w \leq k$ . The contradiction comes from the fact that  $\alpha$  and  $y$  being connected by a 2-length path, they must lie at least  $k$  away from each other.

**Case 1.2:**  $y_1 > y_2$ . Thus, we know that  $y_1 > y > y_2$ . We know that  $x_2$  and  $y_1$  must be at least  $k$  away from each other. Moreover,  $2h + k \leq x_2 < 3h$  and  $2h + k \leq y_1 < 3h$ . Hence, both  $x_2$  and  $y_1$  lie in an interval of width  $w < h - k$ . Since we supposed  $h \leq \frac{3k}{2}$ , we conclude  $w < k$ , a contradiction.

**Case 2:**  $x_1 > x_2$ . We can easily see that in that case we must have  $x_1 > x_2 > x$ . Indeed,  $x_2 \geq k$ , since it is connected by a 2-length path to node 0. Hence, if  $x > x_2$ , then  $x \geq h + k$ . However, we know that  $x < 3h - 2k$ , a contradiction since  $h \leq \frac{3k}{2}$ . Hence we conclude that  $x_1 > x_2 > x$ , which implies  $x_2 \geq x + h \geq 2h$  and  $x_1 \geq x_2 + k \geq 2h + k$ . Now let us consider  $y_1$  and  $y_2$ .

**Case 2.1:**  $y_1 > y_2$ . Let us then consider  $\alpha$ , the common neighbor of  $y_1$  and  $x_2$ , and let us look at its relative position compared to  $x$  and  $y$ . There are three possible cases.

- $\alpha > y > x$ . We recall that we are in the case  $x_1 > x_2 > x$ , that is  $x_2 \geq x + h \geq 2h$ . If  $\alpha > x_2$  then  $\alpha \geq x_2 + h \geq 3h$ , a contradiction to the hypothesis  $\lambda < 3h$ . Now, if  $\alpha < x_2$ ,  $\alpha \leq x_2 - h$ . Since  $x_2 \leq x_1 - k < 3h - k$ , we conclude  $\alpha \leq 2h - k$ . But  $y \geq h + k$  and  $\alpha \geq y + k$ , that is  $\alpha \geq h + 2k$ . This is a contradiction since  $2h - k \leq h + 2k$ , by the hypothesis that  $h \leq \frac{3k}{2}$ .
- $y > \alpha > x$ . We then conclude that  $\alpha \leq y - k < 3h - 2k$ . On the other hand, we have  $\alpha \geq x + k \geq h + k$ . This is a contradiction since  $h + k \geq 3h - 2k$  due to the fact that we supposed  $h \leq \frac{3k}{2}$ .

- $y > x > \alpha$ . In that case, if  $\alpha < y_1$ , then  $y_1 \geq \alpha + h \geq h$ , which implies  $y \geq 2h$  and  $y_2 \geq 3h$ , a contradiction to the hypothesis  $\lambda < 3h$ . Now, if  $\alpha > y_1$ , then  $\alpha \geq h$ , which in turns means that  $x \geq h + k$  and  $y \geq h + 2k$ . However, we know that  $y < 3h - k$ , a contradiction since  $3h - k \leq h + 2k$  due to the fact that we supposed  $h \leq \frac{3k}{2}$ .

**Case 2.2:**  $y_1 > y_2$ . Here, we consider the three nodes  $z, z_1$  and  $z_2$ . We first show that if  $z_m = \min\{z_1, z_2\}$  and  $z_M = \max\{z_1, z_2\}$ , then  $z_m < z_M < z$ . Indeed, if  $z_M > z$  then  $z_M \geq z + h$ , and since we know  $z \geq h + 2k$ , we conclude  $z_M \geq 2h + 2k$ , a contradiction to the fact that  $\lambda < 3h$  since  $2h + 2k \geq 3h$ . Now let us look at the relative positions of  $z_1$  and  $z_2$ . There are two cases to consider.

- $z_1 > z_2$ . In that case, we have  $z > z_1 > z_2$ . Now let us look at  $\beta$ , common neighbor of  $z_1$  and  $y_2$ , and let us consider the relative positions of  $\beta$  and  $y$ .
  - $\beta < y$ . First, we note that  $\beta < z_1$ . Indeed,  $z_2 \geq k$  (it is connected by a 2-length path to node 0), thus  $z_1 \geq 2k$ . However,  $\beta < y$  by hypothesis, hence  $\beta \leq y - k$ , that is  $\beta < 2h - k$ . Moreover,  $2h - k \leq 2k$  since we are in the case  $h \leq \frac{3k}{2}$ , and thus we conclude that  $\beta < z_1$ . This implies  $\beta \leq z_1 - h$ , that is  $\beta \leq z - 2h$ ; and since  $z \leq \lambda < 3h$ , we get  $\beta < h$ . On the other hand,  $y_2 < y$ , thus  $y_2 \leq y - h$ . But since  $y < 2h$ , we then have  $y_2 < h$ . Hence, both  $\beta$  and  $y_2$  lie in the interval  $[0; h[$ . However, they are neighbors and thus should have labels that are at least  $h$  away, a contradiction.
  - $\beta > y$ . Then we have  $\beta \geq y + k$ , that is  $\beta \geq h + 2k$ . However, we know that  $z \geq h + 2k$  as well. Thus,  $\beta$  and  $z$  lie in the interval  $[h + 2k; \lambda[$ , where  $\lambda < 3h$  by hypothesis. Thus the width of this interval  $w$  satisfies  $w < 2h - 2k$ , and thus  $w < k$  because we supposed  $h \leq \frac{3k}{2}$ . However,  $\beta$  and  $z$  are neighbors, and thus should have labels at least differing by  $h$ , a contradiction with the fact that  $w < h$ .
- $z_2 > z_1$ . In that case, we know that  $z > z_2 > z_1$ . In particular, this means that  $z_2 < 2h$ , and  $z_1 < 2h - k$ . However,  $z_1 \geq k$  since it is connected by a 2-length path to node 0. We also have  $y \leq z - h < 2h$ , and thus  $y_2 \leq y - h < h$ ; and since  $h \geq k$ , we conclude that  $y_2 \leq 2h - k$ . Moreover,  $y_2 \geq k$  since it is connected by a 2-length path to node 0. Hence, both  $z_1$  and  $y_2$  lie in the interval  $[0; 2h - k[$ , of width  $w < 2h - 2k$ , that is  $w < k$  since we supposed  $h \leq \frac{3k}{2}$ . However,  $z_1$  and  $y_2$  are connected by a 2-length path, and thus should have labels at least differing from  $k$ , a contradiction.

Altogether, we see that every possible case leads to a contradiction. This proves that the initial assumption,  $\lambda < 3h$ , is false, and consequently the proposition is proved.  $\square$

**Proposition 6**  $\lambda_{h,k}(G_3) \geq h + 3k$  when  $\frac{3}{2}k \leq h \leq 2k$ .

**Proof :** Consider an optimal  $L(h, k)$ -labeling of  $G_3$  with span  $\lambda$ . By contradiction, suppose  $\lambda < h + 3k$ . Let us consider a node labeled 0, and let  $x, y$ , and  $z$  be its 3 neighbors. Without loss of generality, suppose  $x < y < z$ . In view of the  $L(h, k)$ -constraints, we must have  $x \geq h$ ,  $y \geq x + k \geq h + k$ , and  $z \geq y + k \geq h + 2k$ . Furthermore, for the hypothesis  $\lambda < h + 3k$ ,  $z < h + 3k$ , hence  $y \leq z - k < h + 2k$ , and  $x \leq y - k < h + k$ . Let  $x_1$  and  $x_2$ ,  $y_1$  and  $y_2$ ,  $z_1$  and  $z_2$  be the not 0 neighbors of  $x, y$ , and  $z$ , respectively (see Figure 4).

Let us first prove the following, which will be useful in the rest of the proof: if  $y_m = \min\{y_1, y_2\}$  and  $y_M = \max\{y_1, y_2\}$ , then  $y_m < y < y_M$ . Indeed, if  $y < y_m < y_M$ , we have  $y_m \geq y + h \geq 2h + k$ , and  $y_M \geq y_m + k \geq 2h + 2k$ . However, this contradicts the fact that  $\lambda < h + 3k$ , because  $2h + 2k \geq h + 3k$  (since we supposed  $h \geq \frac{3k}{2}$ ). Now suppose  $y_m < y_M < y$ . Then  $y_m \geq k$ , because it is connected by a 2-length path to node 0. Thus  $y_M \geq y_m + k \geq 2k$ , and  $y \geq y_M + h \geq h + 2k$ , which contradicts the fact that  $y < h + 2k$ . Altogether, we conclude that the only possible case is  $y_m < y < y_M$  (**1**).

In the following we show that, under the hypothesis  $\lambda < h + 3k$ , both cases  $x_1 < x_2$  and  $x_1 > x_2$  lead to a contradiction, which will prove the statement.

**Case 1:**  $x_1 < x_2$ . This implies  $x_1 \geq k$ , as  $x_1$  is connected by a 2-length path to node 0 (via  $x$ ) and  $x_2 \geq x_1 + k \geq 2k$ . If  $x_1 < x$ , then  $x \geq x_1 + h \geq k + h$ , that is a contradiction as  $x < k$ . Hence, we have  $x < x_1 < x_2$ . It follows that  $x_1 \geq x + h \geq 2h$  and  $x_2 \geq x_1 + k \geq 2h + k$ . Moreover,  $x_1 \leq x_2 - k < h + 2k$  and  $x \leq x_1 - h < 2k$ . Let us now consider  $y_1$  and  $y_2$ .

**Case 1.1:**  $y_1 < y_2$ . By (1) above, we have  $y_1 < y < y_2$ . Let us now consider  $\alpha$  (common neighbor of  $y_1$  and  $x_2$ ), and let us study its relative position compared to  $x$  and  $y$  (we recall that  $x < y$  by hypothesis).

- $\alpha > y > x$ . Hence we have  $\alpha \geq y + k \geq h + 2k$ . But  $x_2 \geq 2h + h \geq h + 2k$  as well. Hence, both  $\alpha$  and  $x_2$  lie in the interval  $[h + 2k; h + 3k[$ , of width  $w < k \leq h$ . However,  $x_2$  and  $\alpha$  are neighbors, thus they must be at least  $h$  away, a contradiction.
- $y > \alpha > x$ . In that case,  $\alpha \leq y - k < 2k$ . But we also have  $\alpha \geq x + k \geq h + k$ , a contradiction.
- $y > x > \alpha$ . Since  $x < 2k$ , we conclude that  $\alpha \leq x - k < k$ . However, we know  $y_1 \geq k$  (because it is connected by a 2-length path to node 0). Thus  $\alpha < y_1$ , hence  $y_1 \geq \alpha + h \geq h$ . But we know  $y_1 < y < y_2$ , thus  $y_1 \leq y - h$ , and  $y \leq y_2 - h < 3k$ , thus  $y_1 < 3k - h$ . But we cannot have  $y_1 \geq h$  and  $y_1 < 3k - h$ , since  $h \geq \frac{3k}{2}$ .

**Case 1.2:**  $y_2 < y_1$ . By (1) above, we have  $y_2 < y < y_1$ . Hence  $y_1 \geq y + h \geq 2h + k$ . We also know that  $x_2 \geq 2h + k$ , since  $x < x_1 < x_2$ . Thus  $y_1$  and  $x_2$  share the same interval  $[2h + k; h + 3k[$ , of width  $w < 2k - h \leq k$ . But  $y_1$  and  $x_2$  are connected by a 2-length path, and thus must be at least  $k$  away, which is impossible.

Hence, at this point we conclude that necessarily  $x_1 > x_2$ . Thus let us consider this case.

**Case 2:**  $x_2 < x_1$ . In that case, it is easily seen that actually  $x_1 > x_2 > x$ , since  $x > x_2$  would imply  $x \geq x_2 + h$ ; and since  $x_2 \geq k$  (it is connected by a 2-length path to node 0), we would have  $x \geq h + k$ , a contradiction to the fact that  $x < h + k$ . Now let us look again at the relative positions of  $y_1$  and  $y_2$ .

**Case 2.1:**  $y_1 < y_2$ . By (1) above, we have  $y_1 < y < y_2$ . This implies that  $y \leq y_2 - h < 3k$ . And since we know by hypothesis that  $x < y$ , we conclude that  $x \leq y - k < 2k$ .

- $\alpha > y > x$ . Then  $\alpha \leq x - k < k$ . However,  $y_1 \geq k$  (it is connected by a 2-length path to node 0). Thus  $y_1 > \alpha$ , which means  $y_1 \geq \alpha + h \geq h$ . But we know that  $y_1 < y$ , that is  $y_1 \leq y - h < 3k - h$ . This is a contradiction since  $h \geq 3k - h$  by hypothesis.
- $y > \alpha > x$ . Then  $\alpha \geq x + k \geq h + k$ , and  $\alpha \leq y - k < 2k$ . This is a contradiction since  $h + k \geq 2k$  by hypothesis.
- $y > x > \alpha$ . Then  $\alpha \geq y + k \geq h + 2k$ . However, we know  $x_2 < x_1$ , that is  $x_2 \leq x_1 - k < h + 2k$ , hence we conclude  $\alpha > x_2$ . Thus  $\alpha \geq x_2 + h$ , and since  $x_2 > x$  we have  $x_2 \geq x + h \geq 2h$ , we conclude  $\alpha \geq 3h$ , a contradiction to the fact that  $\lambda < h + 3k$ , since we supposed  $h \geq \frac{3k}{2}$ .

**Case 2.2:**  $y_1 > y_2$ . By (1) above, we have  $y_2 < y < y_1$ . Let us now look at the relative positions of  $z$ ,  $z_1$  and  $z_2$ . We first note that if  $z_m = \min\{z_1, z_2\}$  and  $z_M = \max\{z_1, z_2\}$ , then  $z_m < z_M < z$ . Indeed, if  $z_M > z$  then  $z_M \geq z + h$ , and since we know  $z \geq h + 2k$ , we conclude  $z_M \geq h + 3k$ , a contradiction.

- $z_1 > z_2$ . Hence  $z > z_1 > z_2$ , by the argument above. Let us derive here some inequalities that will be useful in the following. Since  $z < h + 3k$  and  $z_1 \leq z - h$ , we conclude  $z_1 < 3k$ . Moreover, we know that  $z_2 \geq k$  and  $z_1 > z_2$ , thus we conclude  $z_1 \geq z_2 + k \geq 2k$ . Finally, we recall that  $h + 2k \leq z < h + 3k$ . Now let us look at the relative positions of  $\beta$  and  $y$ .
  - $\beta < y$ . Then  $\beta \leq y - k < 2k$ . Since  $z_1 \geq 2k$ , we conclude  $\beta < z_1$ . Thus  $\beta \leq z_1 - h \leq 3k - h$ . We also know that  $y_2 \leq 3k - h$  because  $y_2 < y \leq y - h$ , and because  $y < 3k$ . Hence, both  $\beta$  and  $y_2$  are contained in the interval  $[0; 3k - h[$ , of width  $w < 3k - h$ . But  $3k - h \leq h$  by hypothesis, and since  $\beta$  and  $y_2$  must be at least  $h$  away, this is impossible.
  - $\beta > y$ . Then  $\beta \geq y + k \geq h + 2k$ . This implies that both  $\beta$  and  $z$  lie in the interval  $[h + 2k; h + 3k[$ , of width  $w < k$ . However,  $\beta$  and  $z$  must be at least  $k$  away from each other, a contradiction.
- $z_2 > z_1$ . Hence  $z > z_2 > z_1$ . In particular, we have  $k \leq z_1 < 2k$ . But we also know that  $k \leq y_2 < 3k - h \leq 2k$ . Thus  $y_2$  and  $z_1$  both lie in the interval  $[k; 2k[$ , of width  $w < k$ . But they must be at least  $k$  away, a contradiction.

Altogether, we have shown that every possible case leads to a contradiction. This proves that the initial assumption,  $\lambda < h + 3k$ , is false. This proves the proposition.  $\square$

## 4 Regular Grids of Degree 4

### 4.1 Upper Bounds

**Proposition 7**  $\lambda_{h,k}(G_4) \leq h + 3k$  when  $h \leq \frac{k}{2}$ .

**Proof :** Consider the  $L(1, 2)$ -labeling depicted in Figure 5(a). This labeling has span 7. If we now substitute labels  $0, h, k, h + k, 2k, h + 2k, 3k, h + 3k$  to labels  $0, 1, \dots, 7$ , the new labeling we obtain is an  $L(h, k)$ -labeling of  $G_4$ . Indeed, it is easy to see that when  $h \leq \frac{k}{2}$ , each pair of consecutive labels differ by at least  $h$ , while each other pair of distinct labels differ by at least  $k$ . Moreover, the largest label used is  $h + 3k$ , hence the result.  $\square$

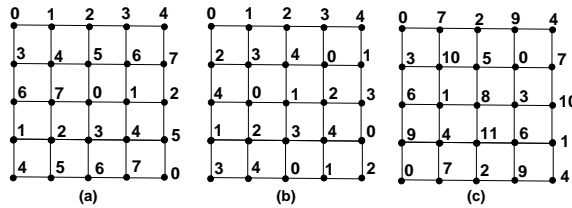


Figure 5:  $L(h, k)$ -labeling of  $G_4$ : (a)  $L(1, 2)$ ; (b)  $L(1, 1)$ ; (c)  $L(3, 2)$

**Proposition 8**  $\lambda_{h,k}(G_4) \leq \min \{7h, 4k\}$  when  $\frac{k}{2} \leq h \leq k$ .

**Proof :** By Lemma 4, since  $\frac{k}{2} \leq h$  and since there exists an  $L(1, 2)$ -labeling of  $G_4$  that is of span 7 (as shown in Figure 5(a)), we know there exists an  $L(h, k)$ -labeling of  $G_4$  of span  $7h$ .

Analogously, since  $h \leq k$ , we obtain an  $L(h, k)$ -labeling of span  $4k$  by Lemma 3; indeed, there exists an  $L(1, 1)$ -labeling of  $G_4$  that is of span 4 (as shown in Figure 5(b)).  $\square$

**Proposition 9**  $\lambda_{h,k}(G_4) \leq 3h + k$  when  $\frac{3}{2}k \leq h \leq \frac{5}{3}k$ .

**Proof :** Consider the  $L(3, 2)$ -labeling of  $G_4$  depicted in Figure 5(c). This labeling has span 11. If we now substitute labels  $0, h - k, k, h, 2h - k, h + k, 2h, 3h - k, 2h + k, 3h, 4h - k, 3h + k$  to labels  $0, 1, \dots, 11$ , the new labeling we obtain is an  $L(h, k)$ -labeling of  $G_4$ . By construction, any pair of labels that are at least 3 away in the list differ by at least  $h$ , while any pair of labels that is at least 2 away in the list differ by at least  $k$ , because we supposed  $\frac{3}{2}k \leq h$ . Moreover, the largest label used is  $3h + k$ , hence the result.  $\square$

**Proposition 10**  $\lambda_{h,k}(G_4) \leq \frac{11}{2}k$  when  $\frac{11}{8}k \leq h \leq \frac{3}{2}k$ .

**Proof :** It is known that  $\lambda_{h,k}(G_4) \leq 4h$  when  $h \geq k$ . Since  $\lambda_{h,k}$  is a non decreasing function, Proposition 9 implies that  $\lambda_{h,k}(G_4) \leq \frac{11}{2}k$  when  $\frac{11}{8}k \leq h \leq \frac{3}{2}k$ .  $\square$

### 4.2 Lower Bounds

**Proposition 11**  $\lambda_{h,k}(G_4) \geq h + 3k$  when  $h \leq k$ .

**Proof :** This bound directly comes from Lemma 1.  $\square$

## 5 Regular Grids of Degree 6

**Proposition 12**  $\lambda_{h,k}(G_6) = 6k$  when  $h \leq k$ .

**Proof :** The upper bound is proved observing that since  $h \leq k$ , we obtain an  $L(h, k)$ -labeling of span  $6k$  by Lemma 3 ; indeed, there exists an  $L(1, 1)$ -labeling of  $G_6$  of span 6, as shown in Figure 6. The lower bound directly comes from Lemma 2.  $\square$

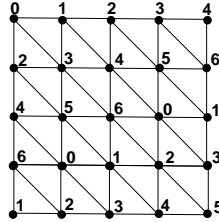


Figure 6: An  $L(1, 1)$ -labeling of  $G_6$  of span 6

## 6 Regular Grids of Degree 8

### 6.1 Upper Bounds

**Proposition 13**  $\lambda_{h,k}(G_8) \leq 8k$  when  $h \leq k$ .

**Proof :** Since  $h \leq k$ , we obtain an  $L(h, k)$ -labeling of span  $8k$  by Lemma 3 ; indeed, there exists an  $L(1, 1)$ -labeling of  $G_8$  of span 8 (as shown in Figure 7(a)).  $\square$

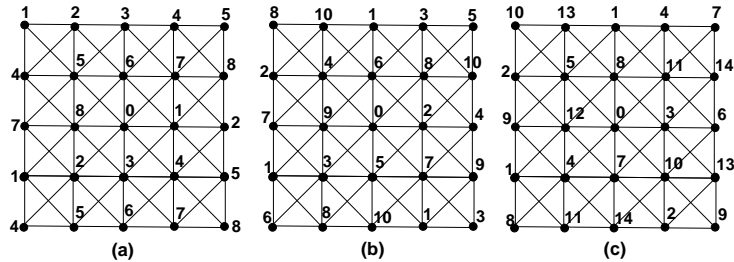


Figure 7:  $L(h, k)$ -labeling of  $G_8$ : (a)  $L(1, 1)$  ; (b)  $L(2, 1)$  ; (c)  $L(3, 1)$

**Proposition 14**  $\lambda_{h,k}(G_8) \leq \min \{8h, 10k\}$  when  $k \leq h \leq 2k$ .

**Proof :** Once again we exploit the  $L(1, 1)$ -labeling of  $G_8$  shown in Figure 7(a). If we substitute  $0, h, 2h, \dots, 8h$  to labels  $0, 1, \dots, 8$ , the new labeling we obtain is an  $L(h, k)$ -labeling of  $G_8$ . Indeed, it is easy to see that each pair of consecutive labels differ by at least  $h$ , and thus by at least  $k$  since  $k \leq h$ . Moreover, the largest label used is  $8h$ , hence the result.

The upper bound of  $10k$  comes from the  $L(2, 1)$ -labeling of  $G_8$  shown in Figure 7(b). If we substitute  $0, k, 2k, \dots, 10k$  to labels  $0, 1, \dots, 10$ , the new labeling we obtain is an  $L(h, k)$ -labeling of  $G_8$ . Indeed, it is easy to see that when  $k \leq h \leq 2k$ , each pair of non consecutive labels differ by at least  $2k \geq h$ , while any pair of distinct labels differ by at least  $k$ . Moreover, the largest label used is  $10k$ , hence the result.  $\square$

**Proposition 15**  $\lambda_{h,k}(G_8) \leq \min \{5h, 14k\}$  when  $2k \leq h \leq 3k$ .

**Proof :** Consider the  $L(2, 1)$ -labeling described in Figure 7(b). This labeling has span 10. If we now substitute  $0, k, h, h+k, 2h, 2h+k, 3h, 3h+k, 4h, 4h+k, 5h$  to labels  $0, 1, \dots, 10$ , the new labeling we obtain is an  $L(h, k)$ -labeling of  $G_8$ . Indeed, it is easy to see that each pair of non consecutive labels differ by at least  $h$ . On the other hand, since  $2k \leq h$ , any pair of distinct labels differ by at least  $k$ . Moreover, the largest label used is  $5h$ .

Analogously, the other bound is given using an  $L(3, 1)$ -labeling, such as the one shown in Figure 7(c). This labeling is of span 14. If we now substitute  $0, k, 2k, \dots, 14k$  to labels  $0, 1, \dots, 14$ , the new labeling we obtain is an  $L(h, k)$ -labeling of  $G_8$ . Indeed, when  $h \leq 3k$ , each pair of labels that are at least 3 away in the list differ by at least  $3k \geq h$ , while any pair of distinct labels differ by at least  $k$ . Moreover, the largest label used is  $14k$ , hence the result.  $\square$

**Proposition 16**  $\lambda_{h,k}(G_8) \leq 4h + 2k$  when  $3k \leq h \leq 6k$ .

**Proof :** Starting from the  $L(3, 1)$ -labeling used in the previous proof (cf. also Figure 7(c)) of span 14, we substitute labels  $0, k, 2k, h, h+k, h+2k, 2h, 2h+k, \dots, 4h, 4h+k, 4h+2k$  to labels  $0, 1, \dots, 14$ . This new labeling is also an  $L(h, k)$ -labeling of  $G_8$ . Indeed, each pair of labels that are at least 3 away in the list differ by at least  $h$  by construction, while any pair of distinct labels differ by at least  $k$  because  $h \geq 3k$ . Moreover, the largest label used is  $4h + 2k$ , hence the result.  $\square$

**Proposition 17**  $\lambda_{h,k}(G_8) \leq 3h + 8k$  when  $h \geq 6k$ .

**Proof :** Consider the labeling depicted in Figure 8(a). This labeling is an  $L(1, 1)$ -labeling of span 11, with the additional property that the only consecutive labels that can appear on neighboring nodes are of the form  $3i + 2$  and  $3(i + 1)$ . We now replace any label  $l$  of this labeling by a new label, thanks to the following rule (cf. Figure 8 (b)): any label of the form  $l = 3i + j$  ( $i = 0, 1, 2, 3, j = 0, 1, 2$ ) is replaced by  $l' = (h + 2k)i + jk$ . In this new labeling, any pair of labels of the form  $3i + 2$  and  $3(i + 1)$  are now separated by  $h$ . Moreover, the labeling we started from is an  $L(1, 1)$ -labeling, and any two differing labels in the new labeling are at least  $k$  away. Thus, this new labeling is an  $L(h, k)$ -labeling, of span  $3h + 8k$ .  $\square$

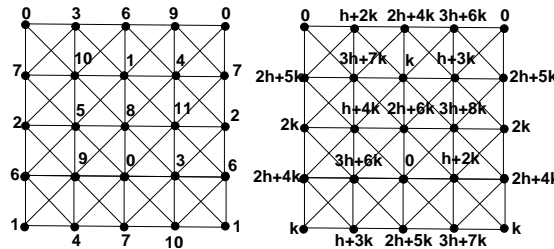


Figure 8: (a) An  $L(1, 1)$ -labeling of  $G_8$  ; (b) the  $L(h, k)$ -labeling we derive

## 6.2 Lower Bounds

**Proposition 18**  $\lambda_{h,k}(G_8) \geq 8k$  when  $h \leq k$ .

**Proof :** This bound directly comes from Lemma 2.  $\square$

**Proposition 19**  $\lambda_{h,k}(G_8) \geq 2h + 6k$  when  $k \leq h \leq 3k$ .

**Proof :** Consider any optimal  $L(h, k)$ -labeling of  $G_8$ . Let  $\lambda$  be the greatest label. Let us consider a label  $x$  which is neither 0 nor  $\lambda$  (note that there must exist one since  $G_8$  contains  $K_3$  as an induced subgraph), and consider its 8 neighbors, say  $v_1 \dots v_8$ . Then no other label than  $x$  can be used in the interval  $]x - h; x + h[$  for the  $v_i$ s. However, all the  $v_i$ s are pairwise connected by 2-length paths, so they must be at least  $k$  away from each other. If there are  $\alpha$  (resp.  $\beta$ ) labels for the  $v_i$ s in the interval  $[0; x - h]$  (resp.  $[x + h; \lambda]$ ), then we must have  $(x - h) - (\alpha - 1)k \geq 0$  and  $\lambda \geq (x + h) + (\beta - 1)k$ , with  $\alpha + \beta = 8$ . Since  $\lambda_{h,k}(G_8) = \lambda$ , we conclude that  $\lambda_{h,k}(G_8) \geq 2h + (\alpha + \beta - 2)k$ , hence the result.  $\square$

**Proposition 20**  $\lambda_{h,k}(G_8) \geq 3h + 3k$  when  $h \geq 3k$ .

**Proof** : First, observe that we have  $\lambda_{h,k}(G_8) \geq 3h + k$ . Indeed, consider an optimal  $L(h, k)$ -labeling of  $G_8$ , a node labeled 0, and the set of its neighbors (see Figure 9). Wlog, suppose  $\min\{a, b, c\} \leq \min\{e, f, g\}$ . Since  $a$ ,  $b$  and  $c$  are neighbors of 0, then we have  $\min\{a, b, c\} \geq h$ . And since any node among  $f$ ,  $g$  and  $h$  are connected by a 2-length path to any node among  $a$ ,  $b$  and  $c$ , we conclude that  $\min\{e, f, g\} \geq h + k$ . Finally, since  $e$ ,  $f$  and  $g$  induce a  $K_3$ , we have  $\max\{e, f, g\} \geq 3h + k$ .

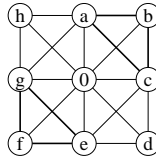


Figure 9: Neighborhood of a node labeled 0 in  $G_8$ .

However, we can derive an even better lower bound, taking into account nodes  $d$  and  $h$  as well. The result comes from an exhaustive search on the grid restricted to those nine nodes, run by computer (code available at the following URL:

<http://www.sciences.univ-nantes.fr/info/perso/permanents/fertin/Lhk/Lhk.c>. □

## 7 Concluding Remarks

In this paper, we have studied the  $L(h, k)$ -labeling problem on regular grids of degree 3, 4, 6 and 8. We observe that the definition we used imposes a condition on labels of nodes connected by a 2-length path instead of using the concept of *distance* 2, that is very common in the literature. The present formulation (supported by applications) imposes a triangle to be always labeled with three colors at least  $\max\{h, k\}$  apart from each other, although its nodes are at mutual distance 1; when  $h \geq k$ , the two definitions coincide.

An open problem arising from this paper consists in closing all the gaps between upper and lower bounds (grey zones in Figure 2).

## References

- [1] R. Battiti, A.A. Bertossi and M.A. Bonuccelli. Assigning Codes in Wireless Networks: Bounds and Scaling Properties. *Wireless Networks*, **5**:195–209, 1999.
- [2] A.A. Bertossi and M.A. Bonuccelli. Code Assignment for Hidden Terminal Interference Avoidance in Multihop Packet Radio Networks. *IEEE/ACM Trans. on Networking*, **3**:441–449, 1995.
- [3] A.A. Bertossi, C.M. Pinotti and R.B. Tan. Channel assignment with separation for interference avoidance in wireless networks. *IEEE Transactions on Parallel and Distributed Systems* **14**:222–235, 2003.
- [4] H.L. Bodlaender, T. Kloks, R.B. Tan and J. van Leeuwen.  $\lambda$ -Coloring of Graphs. In *Proc. of STACS 2000*. LNCS 1770, 395–406, 2000.
- [5] T. Calamoneri. Exact Solution of a Class of Frequency Assignment Problems in Cellular Networks and Other Regular Grids. *Proc. 8th Italian Conference on Theoretical Computer Science (ICTCS'03)*, LNCS 2841, 163–173, 2003.
- [6] T. Calamoneri. The  $L(h, k)$ -Labelling Problem: A Survey. Tech. Rep. 04/2004 Univ. of Rome “La Sapienza”, Dept. of Computer Science, 2004.
- [7] T. Calamoneri and R. Petreschi.  $L(h, 1)$ -Labeling Subclasses of Planar Graphs. *Journal on Parallel and Distributed Computing* **64**(3): 414-426, 2004.



- [8] G.J. Chang, W.-T. Ke, D. Kuo, D.D.-F. Liu and R.K. Yeh. On  $L(d, 1)$ -labelings of graphs. *Discrete Mathematics* **220**:57–66, 2002.
- [9] G.J. Chang and D. Kuo. The  $L(2, 1)$ -labeling Problem on Graphs. *SIAM J. Disc. Math.*, **9**:309–316, 1996.
- [10] G. Fertin and A. Raspaud.  $L(p, q)$  Labeling of  $d$ -Dimensional Grids. *Discrete Applied Mathematics*, to appear.
- [11] J.R. Griggs and R.K. Yeh. Labeling graphs with a Condition at Distance 2. *SIAM J. Disc. Math.*, **5**:586–595, 1992.
- [12] W.K. Hale. Frequency assignment: theory and applications. *Proc. IEEE*, **68**:1497–1514, 1980.
- [13] P.K. Jha, A. Narayanan, P. Sood, K. Sundaram and V. Sunder. On  $L(2, 1)$ -labeling of the Cartesian product of a cycle and a path. *Ars Combin.* **55**:81–89, 2000.
- [14] P.K. Jha. Optimal  $L(2, 1)$ -labeling of Cartesian products of cycles with an application to independent domination. *IEEE Trans. Circuits & Systems I: Fundamental Theory and Appl.* **47**:1531–1534, 2000.
- [15] T. Makansi. Transmitter-Oriented Code Assignment for Multihop Packet Radio. *IEEE Trans. on Comm.*, **35(12)**:1379–1382, 1987.
- [16] B.H. Metzger. Spectrum Management Technique. *In Proc. 38th National ORSA Meeting*, LNCS 1770, 395–406, 1970.
- [17] M. Molloy and M.R. Salavatipour. Frequency channel assignment on planar networks. In *Proceedings of 10th Annual European Symposium on Algorithms (ESA)*, LNCS 2461, 736–747, 2002.
- [18] D. Sakai. Labeling Chordal Graphs: Distance Two Condition. *SIAM J. Disc. Math.*, **7**:133–140, 1994.
- [19] M.A. Whittlesey, J.P. Georges and D.W. Mauro. On the  $\lambda$  number of  $Q_n$  and related graphs, *SIAM J. Discr. Math.* **8** (1995), 499-506.



# New Bounds for the $L(h, k)$ Number of Regular Grids

**Tiziana Calamoneri, Saverio Caminiti, Guillaume Fertin**

## Abstract

For any non negative real values  $h$  and  $k$ , an  $L(h, k)$ -labeling of a graph  $G = (V, E)$  is a function  $L : V \rightarrow \mathbb{R}$  such that  $|L(u) - L(v)| \geq h$  if  $(u, v) \in E$  and  $|L(u) - L(v)| \geq k$  if there exists  $w \in V$  such that  $(u, w) \in E$  and  $(w, v) \in E$ . The *span* of an  $L(h, k)$ -labeling is the difference between the largest and the smallest value of  $L$ . We denote by  $\lambda_{h,k}(G)$  the smallest real  $\lambda$  such that graph  $G$  has an  $L(h, k)$ -labeling of span  $\lambda$ . The aim of the  $L(h, k)$ -labeling problem is to satisfy the distance constraints using the minimum span.

In this paper, we study the  $L(h, k)$ -labeling problem on regular grids of degree 3, 4, 6 and 8, solving several open problems left in the literature.

Additional Key Words and Phrases:  $L(h, k)$ -labeling, triangular grids, hexagonal grids, squared grids, octagonal grids