Smallest defining number of r-regular k-chromatic graphs: $r \neq k$

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Abstract

In a given graph G, a set S of vertices with an assignment of colors is a defining set of the vertex coloring of G, if there exists a unique extension of the colors of S to a $\chi(G)$-coloring of the vertices of G. A defining set with minimum cardinality is called a smallest defining set (of vertex coloring) and its cardinality, the defining number, is denoted by $d(G, \chi)$. Let $d(n, r, \chi = k)$ be the smallest defining number of all r-regular k-chromatic graphs with n vertices. Mahmoodian and Mendelsohn (1999) proved that for each n and each $r \geq 4$, $d(n, r, \chi = 3) = 2$. They raised the following question: Is it true that for every k, there exist $n_0(k)$ and $r_0(k)$, such that for all $n \geq n_0(k)$ and $r \geq r_0(k)$ we have $d(n, r, \chi = k) = k - 1$? We show that the answer to this question is positive, and we prove that for a given k and for all $n \geq 3k$, if $r \geq 2(k-1)$ then $d(n, r, \chi = k) = k - 1$.

Keywords: regular graphs, defining sets, uniquely extendible colorings.

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1 Introduction

We follow the concept of graphs defined in standard textbooks. For the definitions and notations not defined here we refer the reader to texts, such as [7]. A k-coloring of a graph G is an assignment of k different colors to the vertices of G such that no two adjacent vertices receive the same color. The (vertex) chromatic number of a graph G, denoted by $\chi(G)$, is the smallest number k, for which there exists a k-coloring for G. A graph G with $\chi(G) = k$ is called k–chromatic. In a given graph G, a set of vertices S with an assignment of colors is called a defining set of vertex coloring, if there exists a unique extension of the colors of S to a $\chi(G)$ -coloring of the vertices of G. A defining set with minimum cardinality is called a smallest defining set (of a vertex coloring) and its cardinality is the defining number (of a vertex coloring), denoted by $d(G, \chi)$. There are some results on defining numbers in [4] (see also [1], and [2]). Here we study the smallest defining number of regular graphs. Let $d(n, r, \chi = k)$ be the smallest value of $d(G, \chi)$ for all r-regular graphs with n vertices and the chromatic number equal to k. By Brooks's Theorem, if G is a connected r-regular k-chromatic graph which is not a complete graph or an odd cycle, then $k \leq r$. Mahmoodian and Mendelsohn in [3] studied $d(n, r, \chi = k)$ and raised two questions. The first one was on $d(n, k, \chi = k)$ which is answered by Mahmoodian and Soltankhah in [5]. For the case of $r > k$, they proved in [3], that for each n, and for each $r \geq 4$ we have $d(n, r, \chi = 3) = 2$, and asked the following question:

Question. *Is it true that for every k, there exist $n_0(k)$ and $r_0(k)$, such that for all $n \geq n_0(k)$ and $r \geq r_0(k)$ we have $d(n, r, \chi = k) = k - 1$?*

We show that the answer to this question is positive. In fact we prove that:

Theorem. *Let k be a positive integer. For each $n \geq 3k$, if $r \geq 2(k-1)$ then $d(n, r, \chi = k) = k - 1$.*

2 Preliminaries

In this section, we state some known results and definitions which will be used in the sequel. Throughout, n, k, l, r, s and such denote positive integers.

Definition 1 [3]. *Let G and H be two vertex disjoint graphs each with a given proper k-coloring say c_G and c_H (respectively). Then the* chromatic join *of G and H, denoted by* $G \overset{\chi}{\vee} H$ *is a graph where* $V(G \overset{\chi}{\vee} H)$ *is* $V(G) \cup V(H)$, *and* $E(G \overset{\chi}{\vee} H)$ *is* $E(G) \cup E(H)$, *together with the set* $\{xy \mid x \in V(G),\ y \in V(H)$ such that $c_G(x) \neq c_H(y)\}$.

Theorem A [3]. *Let n be a multiple of k, say* $n = kl$ $(l \geq 2)$; *then*

$$d(kl, 2(k-1),\ \chi = k) = k - 1.$$

To prove this theorem Mahmoodian and Mendelsohn constructed a $2(k-1)$-regular k-chromatic graph with $n = kl$ vertices as follows. Let $G_1, G_2, \ldots, G_l$ be vertex disjoint graphs such that G_1 and G_l are two copies of K_k and if $l \geq 3$, $G_2, \ldots, G_{l-1}$ are copies of $\overline{K}_k$. Color each G_i with k colors $1, 2, \ldots, k$. Then construct a graph G with kl vertices by taking the union of $G_1 \cup G_2 \cup \cdots \cup G_l$, and by making a chromatic join between G_i and G_{i+1}; for $i = 1, 2, \ldots, l-1$. This is the desired graph. We denote such a graph by $G_{l(k)}$ and use this construction in Section 3.

Theorem B [3]. *For each n and each* $r \geq 4$, *we have* $d(n, r,\ \chi = 3) = 2$.

The following lemma from [6] is straightforward.

Lemma A [6]. *Let H be a subgraph of G such that* $\chi(G) = \chi(H)$. *If* $V(H)$ *with any coloring is a defining set for G, then any defining set of H is also a defining set for G.*

Definition 2 [5]. Let G be a k-chromatic graph and let S be a defining set for G. Then a set $F(S)$ of edges is called nonessential edges, if the chromatic number of $G - F(S)$, the graph obtained from G by removing the edges in $F(S)$, is still k, and S is also a defining set for $G - F(S)$.

Definition 3. Let G be a graph with a given proper coloring c with k colors. Then the chromatic complement of G, denoted by $\tilde{G}_c$ or simply by $\tilde{G}$ if there is no danger of confusion, is a spanning subgraph of $\overline{G}$ (complement of G) such that $E(\tilde{G}_c) = E(\overline{G}) - \{uv \mid c(u) = c(v)\}$.

3 Main results

In the following three theorems we prove our main result, which was mentioned at the end of Section 1.

Theorem 1. *For each $k \geq 3$, and each $n \geq 3k$, we have*

$$d(n, 2(k-1),\ \chi = k) = k - 1.$$

Proof. By Theorem A the statement is true when n is a multiple of k. For $n = kl + s$ ($l \geq 3$), $s = 1, \ldots, k-1$, we construct a $2(k-1)$-regular k-chromatic graph H with n vertices and $d(H,\ \chi) = k - 1$ as follows.

Consider the graph $G_{l(k)}$ as constructed in Theorem A. From now on in $G_{l(k)}$, we let $V(G_1) = \{u_1, \ldots, u_k\}$, $V(G_{l-1}) = \{v_1, \ldots, v_k\}$, and $V(G_l) = \{w_1, \ldots, w_k\}$. Also assume that $c(u_i) = c(v_i) = c(w_i) = i$, for $i = 1, 2, \ldots, k$. It is obvious that the set $S = \{u_1, u_2, \ldots, u_{k-1}\}$ is a defining set for $G_{l(k)}$. And the following set

$$\begin{aligned} F(S) = \ & \{u_i u_j, 1 \leq i < j \leq k-1\} \cup \{v_i w_j, 1 \leq i < j \leq k-1\} \\ & \cup \{z_i w_k,\ i = 1, \ldots, k-1\}; \end{aligned}$$

where for each i, either $z_i = v_i$ or w_i, is a set of nonessential edges in $G_{l(k)}$.
Now to construct H we add s new vertices $x_1, \ldots, x_s$ to $G_{l(k)}$, delete some suitable nonessential edges, and join the new vertices to the vertices from which the edges were deleted, as follows. There are two cases to be considered.

Case 1. k is odd.

The induced subgraph $< S >$ of $G_{l(k)}$ is a complete graph K_{k-1}. This graph is 1-factorable. We denote its 1-factors by $F_1, \ldots, F_{k-2}$. From now on, any 1-factorizations of complete graphs which are used in this paper are considered to be "standard" factorizations. I.e. for K_n, n even, suppose the vertex set to be $\{1, 2, \ldots, n\}$, and we arrange the vertices $2, \ldots, n$ in a regular $(n-1)$-gon, and place the vertex 1 in the center. Join every two vertices by a straight line segment. For $i = 2, \ldots, n$, define the edge set of the factor F_{i-1} to be the edge $1i$ together with all those edges perpendicular to $1i$.

If $s \leq k-2$, then for each i ($1 \leq i \leq s$) we join the added vertices x_i to all of the vertices of S, and delete all of the edges of F_i. Also with respect to each edge $u_a u_b \in F_i$ ($a < b$), we delete $v_a w_b$ and join x_i to the vertices v_a and w_b. Now it can be easily seen that $\deg(x_i) = 2(k-1)$. Note that colors of vertices of $G_{l(k)}$ force the colors of all new vertices to be k.

If $s = k-1$, then for x_i ($1 \leq i \leq k-2$) we proceed as before and for x_{k-1}, first we delete the edge $w_1 w_k$ and join x_{k-1} to w_1 and w_k. Since each x_i, is joined to a v_j (which was obtained by deleting the edge $v_j w_{k-1}$), we delete the edges x_iv_j and join x_{k-1} to x_i and v_j for $i, j = 1, \ldots, k-2$. We have $\deg(x_{k-1}) = 2(k-1)$ and $c(x_{k-1}) = k-1$. Because the neighbors of x_{k-1} have colors $1, 2, \ldots, k-2, k$.

Case 2. k is even.

In this case we consider the induced subgraph $< S \cup \{u_k\} >$ of $G_{l(k)}$ which is a complete graph K_k of even order. This graph is 1-factorable. Let $F_1, \ldots, F_{k-1}$ be a factorization such that $u_iu_k \in F_i$. For each i $(1 \leq i \leq s)$ we join x_i to all of the vertices of F_i, except to u_i and u_k, and delete all of the edges of F_i, except u_iu_k. Now as in the Case 1, with respect to each $u_au_b \in F_i \backslash \{u_iu_k\}$, we delete the edges v_aw_b and join x_i to the ends of these deleted edges. Finally for each i, $1 \leq i \leq s, i \neq k-2$ we delete the edge $w_{i+1 (\mathrm{mod}\ k-1)}w_k$ and join x_i to the ends of this edge. Note that since we assumed F_i, $(1 \leq i \leq k-1)$ is a standard factorization, x_i was not joined to $w_{i+1 (\mathrm{mod}\ k-1)}$ before. Then we delete the edge $v_{k-1}w_k$ and join x_{k-2} to the ends of this edge. It is obvious that $\deg(x_i) = 2(k-1)$ and the color of x_i is forced to be i. ■

To illustrate the construction shown in the proof of Theorem 1, we provide the following two examples.

Example 1. Let $k = 5$. For $n = 3k + s$, $1 \leq s \leq 4$, we construct an 8-regular 5-chromatic graph of order n with a defining set of size 4. For $n = 15 + s$, $1 \leq s \leq 4$, we add s new vertices to the graph $G_{3(5)}$ and delete some nonessential edges as explained in the proof of Theorem 1 (Case 1). Table 1 shows all the deleted edges corresponding to newly added vertices. In Figure 1, we show an 8-regular 5-chromatic graph of order 16 ($s = 1$) with a defining set of size 4. The vertices of the defining set are shown by the filled circles.

New vertices	x_1	x_2	x_3	x_4
Deleted edges	u_1u_4	u_2u_4	u_3u_4	w_1w_5
	u_2u_3	u_1u_3	u_1u_2	x_1v_1
	v_1w_4	v_2w_4	v_3w_4	x_2v_2
	v_2w_3	v_1w_3	v_1w_2	x_3v_3

Table 1: New vertices and corresponding deleted edges.

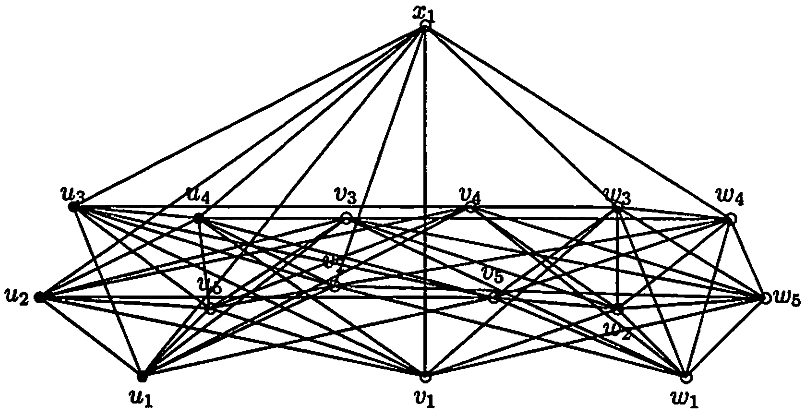

Figure 1: $d(H, \chi = 5) = 4$.

Example 2. Let $k = 4$. For $n = 3k + s$, $1 \leq s \leq 3$, we construct a 6-regular 4-chromatic graph of order n with a defining set of size 3. For $n = 12 + s$, $1 \leq s \leq 3$, we add s new vertices to the graph $G_{3(4)}$ and delete some nonessential edges as explained in the proof of Theorem 1 (Case 2). Table 2 shows all the deleted edges corresponding the newly added vertices. In Figure 2, a 6-regular 4-chromatic graph of order 13 ($s = 1$) with a defining set of size 3 is shown. In this figure also the vertices of the defining set are shown by the filled circles.

New vertices	x_1	x_2	x_3
Deleted edges	u_2u_3	u_1u_3	u_1u_2
	v_2w_3	v_1w_3	v_1w_2
	w_2w_4	v_3w_4	w_1w_4

Table 2: New vertices and corresponding deleted edges.

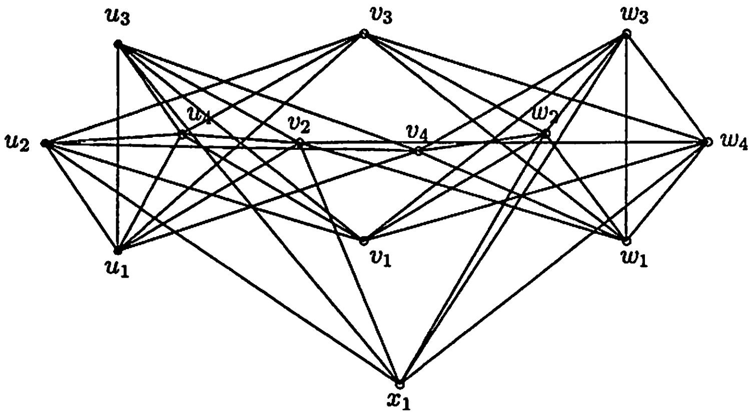

Figure 2: $d(H, \chi = 4) = 3$.

Remark 1. If G is an r-regular k-chromatic graph on n vertices then each chromatic class in G has at most $n-r$ vertices. Therefore $n \leq k(n-r)$. This implies $\frac{n}{k} \geq \frac{r}{k-1}$. Note that for each n, r, and k such that $\frac{n}{k} \geq \frac{r}{k-1}$, only one of the following holds: (i) $\lfloor\frac{n}{k}\rfloor \geq \lceil\frac{r}{k-1}\rceil$ or (ii) $\lfloor\frac{n}{k}\rfloor = \lfloor\frac{r}{k-1}\rfloor \neq \frac{r}{k-1}$.

Next we generalize the statement of Theorem 1 to $r > 2(k-1)$. This is done in the following two theorems.

Theorem 2. *For each $k \geq 3$, $n \geq 3k$, and $r > 2(k-1)$, such that $\lfloor\frac{n}{k}\rfloor \geq \lceil\frac{r}{k-1}\rceil$, we have $d(n, r, \chi = k) = k - 1$.*

Proof. We prove the statement in two cases.

Case 1. $n = kl$.

Consider $G_{l(k)}$, and let $\tilde{G}_{l(k)}$ be the chromatic complement of $G_{l(k)}$ (see Definition 3). Note that $\tilde{G}_{l(k)}$ is an $(l-2)(k-1)$-regular graph. For each r by adding suitable edges of $\tilde{G}_{l(k)}$ to $G_{l(k)}$ we will construct an r-regular k-chromatic graph H_r such that $d(H_r, \chi) = k-1$. We explain the procedure according to the parities of k and r.

If k is even then the complete graph K_k is 1-factorable. Since $\tilde{G}_{l(k)}$ is a k-partite graph, a 1-factor of K_k corresponds to a union of $\frac{k}{2}$ bipartite subgraphs of $\tilde{G}_{l(k)}$, each of which is $(l-2)$-regular; this union is obviously 1-factorable. Thus $\tilde{G}_{l(k)}$ is 1-factorable. By adding the edges of $r-2(k-1)$ disjoint 1-factors of $\tilde{G}_{l(k)}$ to $G_{l(k)}$, we obtain an r-regular k-chromatic graph H_r with $d(H_r, \chi) = k-1$.

If k is odd then $\tilde{G}_{l(k)}$ is a regular graph of even degree, therefore by a theorem of Petersen (see [7], page 125) is 2-factorable. For r even, H_r can be obtained by adding the edges of $\frac{r-2(k-1)}{2}$ disjoint 2-factors of $\tilde{G}_{l(k)}$ to $G_{l(k)}$. For r odd, $n = kl$ is even, thus l is even. In this case, $\tilde{G}_{l(k)}$ contains $\frac{l}{2}$, disjoint bipartite subgraphs, each of which is $(k-1)$-regular. Also, since k is odd, each of these $(k-1)$-regular bipartite graph is 2-factorable. Note that each 2-factor is a union of edge-disjoint cycles. Since we consider bipartite graph, there is no odd cycle. Therefore, we can find a 2-factorization in which, of 2-factors say F, can be chosen to be a union of edge-disjoint even cycles. The alternate edges in F are two edge-disjoint 1-factors. Hence, F is a union of two 1-factors say F_1 and F_2. By adding the edges of F_1 to $G_{l(k)}$ as well as the edges of $\frac{r-2(k-1)-1}{2}$ of other disjoint 2-factors of $\tilde{G}_{l(k)}$ to $G_{l(k)}$, we obtain H_r. By Lemma A, $d(H_r, \chi) = k-1$.

Case 2. $n = kl + s$, $1 \leq s \leq k-1$.

We will use the following procedure to construct an r-regular k-chromatic graph on n vertices with defining number equal to $k-1$. We take the graph H_r, constructed in Case 1, and recognize some nonessential edges in it. Then we add s new vertices $x_1, \ldots, x_s$ to H_r, delete some suitable nonessential edges, and join the new vertices to the ends of the deleted edges. Let $P_1, P_2, \ldots, P_k$ denote the parts of k-partite graph H_r, and assume that all of the vertices in P_i are colored i $(i = 1, 2, \ldots, k)$. Note that for each i, $|P_i| = l$. Throughout the proof we let $m = \lfloor \frac{r}{k-1} \rfloor$ $(m \geq 2)$. In the construction given in Case 1 it is obvious that H_r contains $H_{m(k-1)}$ as a subgraph. The graph $H_{m(k-1)} \backslash G_{l(k)}$ is an $(m-2)(k-1)$-regular k-partite graph. Each induced subgraph $< P_i \cup P_j >$ of $H_{m(k-1)} \backslash G_{l(k)}$ is an $(m-2)$-regular bipartite graph. If $m = 2$ then $H_r \backslash G_{l(k)}$ is an $(r-2(k-1))$-regular graph. For convenience we let $r - 2(k-1) = t$. All of the edges in $H_r \backslash G_{l(k)}$ are nonessential. There are two cases to be considered.

Case 2.1. k is even.

Let $F'_1, \ldots, F'_{k-1}$ be a standard 1-factorization of K_k with the vertex set $\{1,\dots,k\}$, such that $ik \in F'_i$. Let F_{ab} be a 1-factor in the induced subgraph $< P_a \cup P_b >$ of $H_{m(k-1)} \backslash G_{l(k)}$ when $m > 2$, or $H_r \backslash G_{l(k)}$ when $m = 2$. Then $F_i = \cup_{ab \in F'_i} F_{ab}$, $i = 1,\dots,k-1$, are $k-1$ mutually disjoint 1-factors of $H_{m(k-1)} \backslash G_{l(k)}$ when $m > 2$. If $m = 2$ then F_i, $i = 1,\dots,t$, are t mutually disjoint 1-factors of $H_r \backslash G_{l(k)}$.

Case 2.1.1. r is even.

If $m > 2$ then for each x_i, $i = 1,\dots,s$, at the first step, from each F_{ab} other than F_{ik} and F_{pq}, where p and q are arbitrary and $F_{ab} \subset F_i$, we delete m edges. Then in the second step we delete $\lfloor \frac{m}{2} \rfloor$ disjoint edges from each of the 1-factors F_{pk}, F_{qk}, and F_{pq}. Since $m < l$, at least one edge has remained undeleted in each F_{ab}, and at the third step we delete $\frac{r-2m(\frac{k}{2}-2)-6(\lfloor \frac{m}{2} \rfloor)}{2}$ edges from the rest of the edges in some arbitrary F_{ab}, where $F_{ab} \subset F_i \backslash F_{ik}$. Finally we join x_i to the ends of all deleted edges.

For $m = 2$, if $s \le t$ then for each x_i $(1 \le i \le s)$ at the first step we delete 2 edges from each $F_{ab} \subset F_i \backslash F_{ik}$. In the second step we delete an edge $v_p w_k$ from the nonessential edges in $G_{l(k)}$ (see Theorem 1), for an arbitrary p such that v_p is not the end of deleted edges in the first step. At the third step we delete $\lfloor \frac{r-4(\frac{k}{2}-1)-2}{2} \rfloor = \lfloor \frac{t}{2} \rfloor$ edges from the rest of the edges in some arbitrary $F_{ab} \subset F_i \backslash F_{ik}$. If $l = 3$ and $t = k-2$, then there are $\frac{t}{2} - 1$ edges remaining in each $F_{ab} \subset F_i \backslash F_{ik}$. In this case we delete one edge of 1-factor F_{qk} where $F_{pq} \subset F_i$; we are sure that such an edge exists, since t is even, forcing $t \ge 2$.
For $s > t$, first we add the edges of t disjoint 1-factors of K_s in the case of s even, or the edges of $\frac{t}{2}$ disjoint 2-factors of K_s in the case of s odd, to $x_1, x_2, \dots, x_s$. Then for each x_i we delete $k-1$ edges of nonessential edges of $G_{l(k)} \subset H_r$ as explained in Theorem 1 and join x_i to the end vertices of them.

Case 2.1.2. r is odd.

Note that in this case s must be even. If $m > 2$ then for each x_i, $i = 1,\dots,s$, by an argument similar as above, we join $2m(\frac{k}{2}-2)+6(\lfloor \frac{m}{2} \rfloor)$ vertices to x_i in the first and second steps. So we delete $\lfloor \frac{r-m(k-1)}{2} \rfloor$ edges from the rest of the edges of some arbitrary $F_{ab} \subset F_i \backslash F_{ik}$, and join x_i to the ends of all deleted edges. Note that the difference $\alpha = r - 2(m(\frac{k}{2} - 2) + 3\lfloor \frac{m}{2} \rfloor + \lfloor \frac{r-m(k-1)}{2} \rfloor)$ is equal to 1 or 3. If $\alpha = 1$ then we join x_i to x_{i+1}, for $i = 1,3,5,\dots,s-1$. If $\alpha = 3$ let $F_{pq} \subset F_i$ and $F_{p'q'} \subset F_{i+1}$ be the corresponding 1-factors to x_i and x_{i+1}, respectively, which

are chosen in step 1. Assume $y_{p'}y_k \in F_{p'k}$, $y_{q'}y_k \in F_{q'k}$, and $y_py_q \in F_{pq}$ are undeleted edges. We delete the edges $\{y_{p'}y_k, y_{q'}y_k, y_py_q\}$ and for each i, $i = 1,3,5,\ldots,s-1$, join x_i to the vertices $\{y_p, y_q, y_k\}$ and x_{i+1} to $\{y_{p'}, y_{q'}, y_k\}$. Since x_i is not joined to any vertex in part P_i it can be seen that in each case $c(x_i) = i$ and $\deg(x_i) = r$, for $i = 1,2,\ldots,s$.
If $m = 2$ we deal with it as we did in Case 2.1.1. Moreover if $s \leq t$ then we join x_i to x_{i+1}, for $i = 1,3,5,\ldots,s-1$.

Case 2.2. k is odd.

Let $F'_1,\ldots,F'_{k-2}$ be a standard 1-factorization for the complete graph K_{k-1}, whose vertex set is $\{1,\ldots,k-1\}$, such that $\{i,(k-1)\} \in F'_i$. If $m > 2$, it is clear that $F_i = \cup_{ab\in F'_i} F_{ab}$, $i = 1,\ldots,k-2$, are disjoint maximal matchings of $H_{m(k-1)}\backslash G_{l(k)}$, and if $m = 2$ then F_i, $i = 1,2,\ldots,t-1$, are disjoint maximal matchings of $H_r\backslash G_{l(k)}$.

Case 2.2.1. r is even.

If $s \leq k-2$ (for $m = 2$, $s \leq t-1$) then for each x_i, $i = 1,\ldots,s$, we delete m edges of each F_{ab}, where $F_{ab} \subset F_i$. Also we delete $\frac{r-m(k-1)}{2}$ edges from the rest of the edges in some arbitrary $F_{ab} \subset F_i$. Now we join x_i to the ends of all deleted edges.

If $s = k-1$ then we deal with x_i, for $i = 1,\ldots,k-2$, as we did before. For x_{k-1} we delete m edges of 1-factor F_{1k}. Note that if $m \geq 4$ then each induced subgraph
$< P_i \cup P_j >$ of $H_{m(k-1)}\backslash G_{l(k)}$ has more than one 1-factor. We delete m edges of another 1-factor from each of $< P_2 \cup P_{k-1} >, < P_3 \cup P_{k-2} >$ $,\ldots,$ and $< P_{\frac{k-1}{2}} \cup P_{\frac{k-1}{2}+2} >$. Finally we delete $\frac{r-m(k-1)}{2}$ edges from the rest of the edges in some of the above 1-factors, and join x_{k-1} to the ends of all deleted edges. It is obvious that in this case $c(x_{k-1}) = \frac{k+1}{2}$.

If $m = 3$, then we delete the edges x_iy_i for $i = 2,\ldots,k-2$ which were obtained by deleting an edge of $F_{i(k-1)} \subset F_i$, such that y_i is not a vertex in G_1, and joining x_{k-1} to x_i and to y_i. Also we delete the edges of a 1-factor of induced subgraph $< u_2,\ldots,u_{k-2} > \subset G_1$ and join x_{k-1} to the ends of these deleted edges. If $\frac{r-m(k-1)}{2} > 0$ then $l \geq 4$, and we can assume that y_i is not a vertex in G_1, G_{l-1}, or G_l. We delete $\frac{r-m(k-1)}{2}$ disjoint edges from the nonessential edge set $\{v_iw_j \mid 2 \leq i < j \leq k-2\}$ (see Theorem 1) and join x_{k-1} to the ends of these deleted edges. It is obvious that $\deg(x_{k-1}) = r$ and $c(x_{k-1}) = k-1$.
For $m = 2$, if $s \geq t$ then for x_i $(i \leq t-1)$ we could deal as before. For

x_i $(t \le i \le s)$ we delete $2(k-1)$ edges from the set of nonessential edges in $G_{l(k)}$, just as we did in Theorem 1. We join x_i to the ends of deleted edges. Then we delete $\frac{t}{2}$ edges from the rest of the edges in $\cup_{i=1}^{t-1} F_i$, which are suitably chosen and join x_i to the ends of these deleted edges.

Case 2.2.2. r is odd.

Here $n = kl + s$ must be even, so l and s have the same parity. We consider two subcases.

Case 2.2.2.1. l and s are even.

With an argument similar to that for even r, we join each $x_i, i = 1, \dots, s$ (for $m = 2$, $s \le t-1$) to $m(k-1)$ vertices. So we delete $\lfloor \frac{r-m(k-1)}{2} \rfloor$ edges from the remaining edges in some of 1-factors above. Now we join x_i to the ends of all deleted edges.
Finally for each $i = 1, 3, 5, \dots, s-1$, we choose an undeleted edge $y_a y_b \in F_i$ such that there exists an undeleted edge $y_j y_b \in F_{i+1}$. We delete the edge $y_a y_b$ and join x_i to y_a and x_{i+1} to y_b. For $m = 2$, if $s \ge t$ then we deal with x_i as before for $i \le t-1$. For x_i $(t \le i \le s)$ we delete $2(k-1)$ edges from the set of nonessential edges in $G_{l(k)}$ as we did in Theorem 1. Also we delete $\frac{(s-t+1)t}{2}$ edges from the rest of the edges in $\cup_{i=1}^{t-1} F_i$, and join each x_i $(t \le i \le s)$ to the t ends of these deleted edges which are suitably chosen.

Case 2.2.2.2. l and s are odd.

Note that in this case the graph H_r with $n = kl$ vertices does not exist. Here first we consider an $m(k-1)$-regular k-chromatic graph on $n = kl + s$, $1 \le s \le k-1$, vertices, the same as in the case of r even, and denote this graph by H'.
Note that the construction of H' is not dependent on l and it is the same as construction of $m(k-1)$-regular graph on $n = k(l-1) + s$ vertices. Therefore the graph $\tilde{G}_{l(k)} \backslash \tilde{H}'$ contains $\tilde{G}_2 = K_k$ as a subgraph, and $\frac{l-1}{2}$ disjoint $(k-1)$-regular bipartite subgraphs, which were constructed on the vertex sets $V(G_i)$, $i \ne 2$.
Since k is odd we know that the complete graph K_k with the vertex set, say $\{1, \dots, k\}$, has k disjoint maximal matchings. We denote these matchings by $F_1, \dots,$
F_k, so that the vertex $i \notin V(F_i)$.
Now we add $r - m(k-1)$ maximal matchings $F_1, \dots, F_{r-m(k-1)}$ of $\tilde{G}_2 = K_k$ to H'. In $\tilde{G}_{l(k)} \backslash \tilde{H}'$ there are $(k-1)$-regular bipartite subgraphs. Adjoint

to H', $r-m(k-1)$ 1-factors of $\frac{l-1}{2}$ of these subgraphs.
If $s \leq r-m(k-1)$ then for each x_i $(1 \leq i \leq s)$ we delete $\lfloor \frac{r-m(k-1)}{2} \rfloor$ edges of F_i. And we join x_i to the (isolated) vertex i and to the ends of all deleted edges. Since $\beta = r-m(k-1)-s$ is even, we can partition the vertices $s+1, s+2, \ldots, s+\beta$ into disjoint pairs of nonadjacent vertices. Now by joining these pairs of vertices, we obtain a graph of the kind we need.
If $s > r-m(k-1)$ then for each x_i, $i \leq r-m(k-1)$, we use similar method as in the above, and then we delete $\frac{(s-r+m(k-1))(r-m(k-1))}{2}$ edges from the rest of the edges in $\cup_{i=1}^{r-m(k-1)} F_i$, and join each x_i, $i = r-m(k-1)+1, \ldots, s$, to the $r-m(k-1)$ ends of these deleted edges which are suitably chosen. It can be easily seen that $\deg(x_i) = r$ and $c(x_i) = k$, for $i = 1, \ldots, s$. ∎

Theorem 3. *For each $k \geq 3$, $n \geq 3k$, and $r > 2(k-1)$, such that $\lfloor \frac{n}{k} \rfloor = \lfloor \frac{r}{k-1} \rfloor \neq \frac{r}{k-1}$, we have $d(n, r, \chi = k) = k-1$.*

Proof. Let $n = kl+s$, $0 \leq s \leq k-1$, and $r = (k-1)l+t$, $1 \leq t \leq k-2$. By Remark 1, if an r-regular k-chromatic graph with n vertices exists, then $s > t$. First we show that there does not exist such a graph for $t = k-2$. For, if there exists one, say G, since $s > t$, then $s = k-1$. Also we know that each chromatic class consists of at most $n-r = l+1$ vertices. On the other hand since $n = kl+k-1$, G must have $k-1$ chromatic classes of size $l+1$ and one chromatic class of size l. And each vertex in a chromatic class of size $l+1$ must be adjacent to all the vertices in the other parts. This implies that the degree of each vertex in the chromatic class with l vertices is $(l+1)(k-1) = r+1$ which contradicts the r-regularity of the graph G.

Now by a recursive method we construct an r-regular k-chromatic graph $G^\star$ with n vertices so that $d(G^\star, \chi) = k-1$. Let $n_1 = n-(n-r) = r$ and $r_1 = r-(n-r) = 2r-n$.
If there exists an r_1-regular, $(k-1)$-chromatic graph G_1 with n_1 vertices and $d(G_1, \chi) = k-2$, then by adding $n-r$ new vertices to G_1 and joining each of these new vertices to all of n_1 vertices of G_1, we obtain the desired graph $G^\star$.
If not, then we continue this procedure and let $n_i = (k-i)l+it-(i-1)s$ and $r_i = (k-i-1)l+(i+1)t-is$. If for some i there exists an r_i-regular, $(k-i)$-chromatic graph G_i with n_i vertices and $d(G_i, \chi) = k-i-1$, then we can construct $G^\star$ similarly, by constructing the graphs $G_{i-1}, G_{i-2}, \ldots, G_1$. But note that for $i = \lceil \frac{t}{s-t} \rceil$ such a graph exists. For, $\frac{n_i}{k-i} = l + \frac{i(t-s)+s}{k-i}$ and $\frac{r_i}{k-i-1} = l + \frac{i(t-s)+t}{k-i-1}$. Thus for $i = \lceil \frac{t}{s-t} \rceil$ we have $\frac{t}{s-t} \leq i \leq \frac{t}{s-t}+1 = \frac{s}{s-t}$. Therefore, $\frac{r_i}{k-i-1} \leq l \leq \frac{n_i}{k-i}$. And this implies that $\lceil \frac{r_i}{k-i-1} \rceil \leq \lfloor \frac{n_i}{k-i} \rfloor$. Now

by Theorem 2 for this i there exists an r_i-regular, $(k-i)$-chromatic graph G_i with n_i vertices and $d(G_i,\ \chi) = k - i - 1$. ∎

Remark 2. Concerning this work there are two questions to be investigated. The first is the determination of $d(n, r,\ \chi = k)$ for admissible n such that $n < 3k$ and $r \geq 2(k-1)$. The second is to determine $d(n, r,\ \chi = k)$ for the remaining values of r $(k + 1 \leq r < 2(k-1))$.

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