

DECOMPOSITION OF COMPLETE MULTIGRAPHS INTO STARS AND CYCLES

FAIROUZ BEGGAS, MOHAMMED HADDAD

AND

HAMAMACHE KHEDDOUCI

*LIRIS UMR 5205, CNRS, University of Lyon,
Claude Bernard Lyon 1 University
43 Bd du 11 Novembre 1918, F-69622, Villeurbanne, France.*

e-mail: fairouz.beggas@liris.cnrs.fr
mohammed.haddad@liris.cnrs.fr
hamamache.kheddouci@liris.cnrs.fr

Abstract

Let k be a positive integer, S_k and C_k denote, respectively, a star and a cycle of k edges. λK_n is the usual notation for the complete multigraph on n vertices and in which every edge is taken λ times. In this paper, we investigate necessary and sufficient conditions for the existence of the decomposition of λK_n into edges disjoint of stars S_k 's and cycles C_k 's.

Keywords: graph decomposition, complete multigraph, stars, cycles.

2010 Mathematics Subject Classification: 05C70.

1. INTRODUCTION

All graphs considered in this paper are finite and undirected, with no loops. Let G , H and F be three graphs. An H -decomposition of G is a partition of the edge set of G into copies of H . If G has an H -decomposition, we say that G is H -decomposable. An (H, F) -decomposition of G is a partition of the edge set of G into copies of H and F using at least one copy of each. If G has an (H, F) -decomposition, we say that G is (H, F) -decomposable (or (H, F) -multidecomposable).

In [20], Wilson stated his fundamental theorem on the existence of an H -decomposition of the complete graph K_n for any fixed H as long as the number

of edges of K_n is divisible by the number of edges of H and n is large enough. Since then, decomposition problems became an active research area. There have been several important research papers relating to various decompositions of different graphs. For example, the problem of the H -decomposition has been widely studied such as the decomposition of bipartite graphs into closed trails [8] and also the decomposition of complete multigraphs into crowns [10], paths [19], or cycles [7]. Moreover, the multidecomposition problems were also considered by several studies such as the multidecomposition of complete graph into cycles and stars [15] or paths and cycles [14, 13]. Another multidecomposition of bipartite graphs into subgraphs was considered in [16, 9].

Let K_n be a complete graph of order n and let λ be a positive integer. We denote by λK_n the complete multigraph obtained by replacing each edge of K_n by λ parallel edges that have the same end-nodes. In [1, 2], Abueida and Daven gave necessary and sufficient conditions for decomposing K_n into cycles of k edges and stars of $k - 1$ edges, for $k = 4$ and $k = 5$. Abueida and O'Neil [3] extended this decomposition for the complete multigraph λK_n when $k = 3, 4, 5$, and they conjectured the result for any integer $k \geq 3$ and $n \geq k$. In [11], Priyadharsini and Muthusamy showed the above conjecture to be true for $n = k$.

More recently, Abueida and Lian [4] gave necessary and sufficient conditions for decomposing K_n into cycles and stars of k edges, for $n \geq 4k$ and k even or n odd. In our paper, we improve results on this decomposition and we extend it for the complete multigraph λK_n . Thus, we present necessary and sufficient conditions for different cases as follows:

- k is prime,
- k divides either $n - 1$, n or λ ,
- $n \geq 2k$ and λ is even or $\gcd(\lambda, k) = 1$,
- $n \geq 4k$, independently of the parity of n or k , thus improving the result of Abueida and Lian [4].

2. PRELIMINARIES

2.1. Related works

We introduce here some results on a C_k -decomposition and an S_k -decomposition that are useful for our proofs.

Theorem 1 [21]. *A necessary and sufficient condition for the existence of an S_k -decomposition of λK_n is that:*

- $\lambda n(n - 1) \equiv 0 [2k]$,
- $n \geq 2k$ for $\lambda = 1$,

- $n \geq k + 1$ for even λ ,
- $n \geq k + 1 + k/\lambda$ for odd $\lambda \geq 3$.

Theorem 2 [6]. *Let λ, n and k be integers with $n, k \geq 3$ and $\lambda \geq 1$. There exists a decomposition of λK_n into cycles of k edges if and only if $k \leq n$, $\lambda(n-1)$ is even and k divides $\lambda n(n-1)/2$. There exists a decomposition of λK_n into cycles of k edges and a perfect matching if and only if $k \leq n$, $\lambda(n-1)$ is odd and k divides $\lambda n(n-1)/2 - (n/2)$.*

Theorem 3 ([5],[12]). *Let n and k be positive integers. K_n has a C_k -decomposition if and only if n is odd, $3 \leq k \leq n$, and $n(n-1) \equiv 0 [2k]$.*

Theorem 4 [21]. *Let m and n be integers with $m \geq n \geq 1$. Then $K_{m,n}$ is S_k -decomposable if and only if $m \geq k$ and $m \equiv 0 [k]$ if $n < k$, $mn \equiv 0 [k]$ if $n \geq k$.*

Theorem 5 [17]. *For positive integers m, n , and k , the graph $K_{m,n}$ is C_k -decomposable if and only if m, n , and k are even, $k \geq 4$, $\min\{m, n\} \geq k/2$, and $mn \equiv 0 [k]$.*

2.2. Introductory results

Let G be a graph. The order of G is the cardinality of its vertex set and the size of the graph G is the cardinality of its edge set. We begin with the following lemma to prove the necessary conditions when λK_n is (S_k, C_k) -decomposable.

Lemma 6. *Let $n \geq 3$ and $\lambda > 1$ be positive integers. If λK_n is (S_k, C_k) -decomposable, then $2 \leq k \leq n - 1$ and $\lambda n(n - 1) \equiv 0 [2k]$.*

Proof. Since the minimum length of a cycle and the maximum size of a star in λK_n are, respectively, 2 and $n - 1$, so $2 \leq k \leq n - 1$ is necessary. Since λK_n has $\lambda n(n - 1)/2$ edges and each subgraph in a (C_k, S_k) -decomposition has k edges, k has to divide $\lambda n(n - 1)/2$. ■

As an introduction result, we show in the next proposition that the necessary conditions in Lemma 6 of the (C_k, S_k) -decomposition of λK_n are also sufficient in the special case when $k = 4$.

Proposition 7. *Let $n > 4$ and $\lambda > 1$ be positive integers. There exists a (C_4, S_4) -decomposition if and only if $\lambda n(n - 1)/2 \equiv 0 [4]$.*

Proof. We distinguish two cases according to the parity of λ .

Case 1. λ is odd. Since $\lambda n(n - 1)/2 \equiv 0 [4]$ and λ is odd by assumption, $n(n - 1) \equiv 0 [8]$. We have two subcases.

Subcase 1a. n is even. Since $n(n-1) \equiv 0 [8]$ and n is even, we obtain $n \equiv 0 [8]$. Let $n = 8\alpha$ with $\alpha \geq 1$. Then λK_n can be decomposed into disjoint union of α copies of λK_8 and disjoint union of $\alpha(\alpha-1)/2$ copies of $\lambda K_{8,8}$. Every $\lambda K_{8,8}$ can be decomposed into S_4 using Theorem 4. We now decompose each λK_8 into C_4 's and S_4 's as follows. Note that $\lambda K_8 = K_8 \cup (\lambda-1)K_8$. Since Theorem 1 implies that K_8 is S_4 -decomposable and Theorem 2 guarantees that $(\lambda-1)K_8$ is C_4 -decomposable, we have λK_8 is (C_4, S_4) -decomposable. Thus, λK_n is (C_4, S_4) -decomposable.

Subcase 1b. n is odd. Since n is odd and $n(n-1) \equiv 0 [8]$ by assumption, $n-1 \equiv 0 [8]$. Let $n-1 = 8\alpha$. Since the degree of each vertex of λK_n equals to $\lambda(n-1)$ and is divisible by 4, we take one vertex and decompose all its incident edges into $2\lambda\alpha$ stars of 4 edges. The remaining graph is λK_{n-1} with $n-1 = 8\alpha$. In this case, we use the same method as in the previous Subcase 1a for λK_n with $n = 8\alpha$.

Case 2. λ is even. Recall that $n > 4$. We give the (C_4, S_4) -decomposition of λK_n as follows according to values of n .

$n = 5$: Note that $\lambda K_5 = \lambda S_4 \cup \lambda K_4$. Since λ is even we decompose λK_4 into C_4 , by Theorem 2. Thus, λK_5 is (C_4, S_4) -decomposable.

$n = 6$ or $n = 7$: We have $n(n-1) \equiv 0 [2]$ and $\lambda n(n-1) \equiv 0 [8]$ by assumption. Consequently, $\lambda \equiv 0 [4]$. Then we take incident edges of one vertex and decompose them into S_4 's. The remaining graph is either λK_5 when $n = 6$ or λK_6 when $n = 7$. Both remaining graphs are C_4 -decomposable using Theorem 2.

$n = 8$: Since λ is even, λK_8 can be written as the disjoint union of $2K_8$'s. Now we give the (C_4, S_4) -decomposition of $2K_8$. Each $2K_4$ is decomposed into C_4 's by Theorem 2 and $2K_{4,4}$ is decomposed into S_4 's using Theorem 4. Since each $2K_8$ is (C_4, S_4) -decomposable we have λK_8 is also (C_4, S_4) -decomposable.

$n \geq 9$: Note that $\lambda K_n = \lambda K_4 \cup \lambda K_{n-4} \cup \lambda K_{4,n-4}$. Observe that $|E(\lambda K_4)|$ and $|E(\lambda K_{4,n-4})|$ are divisible by 4. By assumption $|E(K_n)|$ is a multiple of 4, so $|E(\lambda K_{n-4})|$ is also a multiple of 4. We decompose λK_4 into cycles of 4 edges using Theorem 2 with λ even. $\lambda K_{4,n-4}$ is S_4 -decomposable using Theorem 4. Since λ is even, we decompose λK_{n-4} into C_4 using Theorem 2. Thus, we conclude that λK_n is (S_4, C_4) -decomposable. ■

3. DECOMPOSITION OF λK_n WHEN $n \geq 4k$ OR $n \geq 2k$ AND λ EVEN

In this section, we prove some lemmas and theorems, each of them treating a special case of decomposition of λK_n into S_k 's and C_k 's.

The next proposition proves that λK_n is (S_k, C_k) -decomposable for all $n \geq 4k$ and $\lambda = 1$, so we complete the missing cases in [4] when $n \geq 4k$.

Proposition 8. *Let n and k be positive integers such that $n \geq 4k$ and $n(n - 1)/2 \equiv 0 [k]$. Then the graph K_n is (S_k, C_k) -decomposable.*

Proof. Let $n = qk + r$, where q and r are integers with $0 \leq r < k$ and $q \geq 4$. Note that $K_n = K_{qk+r} = K_{2k} \cup K_{(q-2)k+r} \cup K_{2k,(q-2)k+r}$.

Clearly, $|E(K_{2k})|$ and $|E(K_{2k,(q-2)k+r})|$ are multiples of k . Thus $((q - 2)k + r)((q - 2)k + r - 1)/2$ is also a multiple of k . We distinguish two cases according to the parity of k .

Case 1. k is odd. It follows that $K_{(q-2)k+r}$ is S_k -decomposable by Theorem 1, since $(q - 2)k + r \geq 2k$, and $K_{2k,(q-2)k+r}$ is also S_k -decomposable by Theorem 4.

We write $K_{2k} = K_k \cup K_k \cup K_{k,k}$. Now, it is clear that each copy of K_k is C_k -decomposable when k is odd by Theorem 3, and $K_{k,k}$ is S_k -decomposable by Theorem 4.

Case 2. k is even. In this case, K_{2k} is S_k -decomposable by Theorem 1. If n is even, then $(q - 2)k + r$ is even. So, we can decompose $K_{2k,(q-2)k+r}$ into C_k using Theorem 5. Since $q \geq 4$, $(q - 2)k + r \geq 2k$. Consequently, $K_{(q-2)k+r}$ is S_k -decomposable by Theorem 1. Conversely, if n is odd, then $(q - 2)k + r$ is odd. Using Theorem 3, $K_{(q-2)k+r}$ can be decomposed into cycles of k edges, and $K_{2k,(q-2)k+r}$ is S_k -decomposable by Theorem 4. Thus, we conclude that λK_n is (S_k, C_k) -decomposable when $\lambda = 1$. ■

In the rest of this section, we will focus on complete multigraph λK_n , where $\lambda > 1$. The following lemma gives sufficient conditions for decomposing λK_n into C_k 's and S_k 's, where $\lambda > 1$ is odd and $n \geq 4k$.

Lemma 9. *Let n , k and $\lambda > 1$ be positive integers such that $n \geq 4k$ and λ is odd. If $\lambda n(n - 1)/2 \equiv 0 [k]$, then λK_n is (C_k, S_k) -decomposable.*

Proof. Let $n = qk + r$, where q and r are integers with $0 \leq r < k$ and $q \geq 4$. Note that

$$\begin{aligned} \lambda K_n &= \lambda K_{qk+r} = \lambda K_{2k} \cup \lambda K_{(q-2)k+r} \cup \lambda K_{2k,(q-2)k+r} \\ &= (\lambda - 1)K_{2k} \cup K_{2k} \cup \lambda K_{(q-2)k+r} \cup \lambda K_{2k,(q-2)k+r}. \end{aligned}$$

$|E(\lambda K_{2k})|$ and $|E(\lambda K_{2k,(q-2)k+r})|$ are multiples of k . Using argument that $|E(\lambda K_n)|$ is a multiple of k , i.e., $\lambda n(n - 1)$ is divisible by k , we obtain $\lambda((q - 2)k + r)((q - 2)k + r - 1)/2 \equiv 0 [k]$. Since $(\lambda - 1)(2k - 1)$ is even and $2k \geq k$ we have $(\lambda - 1)K_{2k}$ is C_k -decomposable by Theorem 2. Theorem 1 for K_{2k} with $\lambda = 1$ implies that K_{2k} is S_k -decomposable. We now decompose $\lambda K_{(q-2)k+r}$.

We have $q \geq 4$. Then $(q - 2)k + r \geq 2k + r$ implies that $(q - 2)k + r \geq 2k \geq 3k/2 + 1$ for any $k \geq 2$. Given that $\lambda \geq 2$ we obtain $3k/2 + 1 \geq k + 1 + k/\lambda$, so $(q - 2)k + r \geq k + 1 + k/\lambda$. Using Theorem 1 when λ is odd, since $(q - 2)k + r \geq k +$

$1 + k/\lambda$, we have $\lambda K_{(q-2)k+r}$ is S_k -decomposable. Note that $\lambda K_{2k,(q-2)k+r}$ can be decomposed into λ copies of $K_{2k,(q-2)k+r}$. Since $K_{2k,(q-2)k+r}$ is S_k -decomposable by Theorem 4, so is $\lambda K_{2k,(q-2)k+r}$. Thus λK_n is (C_k, S_k) -decomposable. ■

In the following lemmas, we will give sufficient conditions of the decomposition of λK_n into C_k 's and S_k 's, where $n \geq 2k$ and λ is even or $\gcd(\lambda, k) = 1$.

Lemma 10. *Let n, k and λ be positive integers such that λ is even. For all $n \geq 2k$, if $\lambda n(n - 1)/2 \equiv 0 [k]$, then λK_n is (C_k, S_k) -decomposable.*

Proof. Let $n = qk + r$, where q and r are integers with $0 \leq r < k$ and $q \geq 2$. Note that $\lambda K_n = \lambda K_{qk+r} = \lambda K_{(q-1)k} \cup \lambda K_{k+r} \cup \lambda K_{(q-1)k,k+r}$.

Obviously, $|E(\lambda K_{(q-1)k})|$ and $|E(\lambda K_{(q-1)k,k+r})|$ are multiples of k . Thus, $\lambda(k + r)(k + r - 1)/2 \equiv 0 [k]$ from the assumption that $\lambda n(n - 1)/2$ is divisible by k . $\lambda K_{(q-1)k}$ and λK_{k+r} are C_k -decomposable by Theorem 2 because λ is even, $(q - 1)k \geq k$ and $k + r \geq k$ by assumption. Note that $\lambda K_{(q-1)k,k+r}$ can be decomposed into λ copies of $K_{(q-1)k,k+r}$. Since $K_{(q-1)k,k+r}$ is S_k -decomposable by Theorem 4, so is $\lambda K_{(q-1)k,k+r}$. Thus, λK_n is (C_k, S_k) -decomposable. ■

Lemma 11. *Let n, k and $\lambda > 1$ be positive integers such that $\gcd(\lambda, k) = 1$. For all $n \geq 2k$, if $\lambda n(n - 1)/2 \equiv 0 [k]$, then λK_n is (C_k, S_k) -decomposable.*

Proof. From the previous lemma, we only have to examine the case when λ is odd. We can decompose λK_n as an edge disjoint union of $(\lambda - 1)K_n$ and K_n . Since $\gcd(\lambda, k) = 1$, we have $|E(K_n)| \equiv 0 [k]$. It is clear that $(\lambda - 1)K_n$ has a (C_k, S_k) -decomposition by Lemma 10. Now we decompose K_n into stars of size k by Theorem 1, since $n \geq 2k$. Thus λK_n is (C_k, S_k) -decomposable. ■

Using Proposition 8 and Lemmas 9, 10 and 11, we obtain the following theorem.

Theorem 12. *Let n, k and λ be positive integers. If $\lambda n(n - 1)/2 \equiv 0 [k]$ and*

- $n \geq 4k$, or
- $n \geq 2k$ and $\lambda > 1$ is even or $\gcd(\lambda, k) = 1$,

then λK_n is (C_k, S_k) -decomposable.

4. DECOMPOSITION OF λK_n WHEN k IS PRIME OR DIVIDES EITHER $n - 1, n$ OR λ

One can easily check that λK_n is (C_2, S_2) -decomposable if and only if $n > 2$, $\lambda > 1$ and $\lambda n(n - 1) \equiv 0 [4]$. Thus, we admit the following lemma without proof.

Lemma 13. *Let $n > 2$ and $\lambda > 1$ be positive integers. There exists a decomposition of λK_n into copies of S_2 and copies of C_2 if and only if $\lambda n(n - 1)/2$ is even.*

In Lemmas 14–16, we will show the sufficient conditions of the decomposition of λK_n into C_k 's and S_k 's when $n = k + 1$, $n = 2k + 1$ and $n = 3k + 1$, respectively, with $k \geq 3$.

Lemma 14. *Let $n = k + 1$, $\lambda > 1$ and $k \geq 3$ be positive integers. There exists a decomposition of λK_n into copies of S_k and C_k if and only if $\lambda k(k - 1)/2 \equiv 0 [k]$.*

Proof. We split the proof into two cases as follows.

Case 1. k is odd or λ is even. By assumption, $n = k + 1$ and the degree of each vertex of λK_n is λk . We use one vertex in order to construct λ stars of k edges. The remaining graph is λK_{n-1} . Since k is odd or λ is even and we have $n - 1 = k$, we obtain $\lambda(n - 2) = \lambda(k - 1)$ is always even and $\lambda k(k - 1)/2 \equiv 0 [k]$, so by Theorem 2 λK_{n-1} is C_k -decomposable. Thus, λK_n is (S_k, C_k) -decomposable.

Case 2. k is even and λ is odd. This subcase does not exist because by assumption $\lambda k(k - 1)/2 \equiv 0 [k]$, which implies $\lambda(k - 1)$ to be even, a contradiction. The opposite implication is easy to prove. ■

Lemma 15. *Let $n = 2k + 1$ and $\lambda > 1$ be positive integers, and let k be a positive integer, $k \geq 3$. There exists a decomposition of λK_n into copies of S_k and C_k for any k .*

Proof. The number of edges in λK_{2k+1} , $\lambda k(2k + 1)$, is a multiple of k . We decompose λK_{2k+1} as follows : $\lambda K_{2k+1} = (\lambda - 1)K_{2k+1} \cup K_{2k+1}$. Clearly, $|E((\lambda - 1)K_{2k+1})|$ and $|E(K_{2k+1})|$ are multiples of k . We decompose $(\lambda - 1)K_{2k+1}$ into C_k 's and K_{2k+1} into S_k 's. Hence λK_{2k+1} is (S_k, C_k) -decomposable. ■

Lemma 16. *Let $n = 3k + 1$, $\lambda > 1$ and $k \geq 3$ be positive integers. There exists a decomposition of λK_n into copies of S_k and C_k if and only if $3\lambda k(3k - 1)/2 \equiv 0 [k]$.*

Proof. We split the proof into two cases as follows:

Case 1. λ is even. This case is solved by Lemma 10.

Case 2. λ is odd. If k is odd, then $\lambda K_{3k+1} = \lambda K_{2k+1} \cup \lambda K_k \cup \lambda K_{2k+1,k}$. By Lemma 15, λK_{2k+1} is (S_k, C_k) -decomposable. λK_k can be decomposed into C_k 's, and $\lambda K_{2k+1,k}$ is S_k -decomposable.

If k is even, then $3\lambda(3k + 1)$ is not even, so this case cannot exist. The opposite implication is easy to prove. ■

In the following proposition, we prove that for any k that divides n or $n - 1$, λK_n is (S_k, C_k) -decomposable.

Proposition 17. *For integers k, n and λ with $\lambda > 1$ and $2 \leq k \leq n + 1$, if $n \equiv 0, 1 [k]$ and $\lambda n(n - 1)/2 \equiv 0 [k]$, then λK_n is (S_k, C_k) -decomposable.*

Proof. In the case when $n = k + 1$, $n = 2k + 1$ and $n = 3k + 1$ we use Lemmas 13, 14, 15 and 16, respectively.

By Theorem 12, if $n = \alpha k + 1$ or $n = \alpha k$ with $\alpha \geq 4$, then λK_n is (S_k, C_k) -decomposable. To complete the proof, we study the cases when $n = 2k$ and $n = 3k$.

$n = 2k$: When λ is even, λK_n is (S_k, C_k) -decomposable by Lemma 10. When λ is odd, observe that $\lambda K_{2k} = (\lambda - 1)K_{2k} \cup K_{2k}$. $(\lambda - 1)K_{2k}$ is C_k -decomposable by Theorem 2 and K_{2k} is S_k -decomposable by Theorem 1.

$n = 3k$: If λ is even, then we have λK_n is (S_k, C_k) -decomposable by Lemma 10. If λ is odd and k is odd, then $\lambda K_{3k} = (\lambda - 1)K_{3k} \cup K_{3k}$, since $|E(K_{3k})|$ and $|E((\lambda - 1)K_{3k})|$ are multiples of k . Thus, $(\lambda - 1)K_{3k}$ is C_k -decomposable by Theorem 2, and K_{3k} is S_k -decomposable by Theorem 1. On the other hand, if λ is odd and k is even, then it is sufficient to show that $\lambda 3k(3k - 1) \equiv 0 [2k]$ is not true in this case. So, when λ is odd, k must be also odd. ■

In the following proposition, we will show the decomposition of λK_n into S_k 's and C_k 's when λ is a multiple of k .

Proposition 18. *For integers k and n with $2 \leq k \leq n - 1$, if $\lambda \equiv 0 [k]$, then λK_n is (S_k, C_k) -decomposable.*

Proof. Since $n \geq k + 1$, we distinguish two cases.

Case 1. $n \geq k + 2$. $\lambda \equiv 0 [k]$ implies that the degree of each vertex of λK_n is multiple of k . Thus, we can construct stars S_k using each vertex of the multigraph. First we decompose incident edges of some vertex into S_k 's in a circular manner as illustrated in Example 19. This process is repeated until the remaining graph is a λK_m , where $m = k + 1$ if k is even, and $m = k$ if k is odd.

If k is odd, then the remaining graph is λK_k and $\lambda k(k - 1)/2 \equiv 0 [k]$, which implies that λK_k can be decomposed into cycles of size k by Theorem 2. If k is even, then the remaining graph is λK_{k+1} , which has $\lambda k(k + 1)/2$ edges. Thus the number of edges is divisible by k . Since λk is even, the graph λK_{k+1} can be decomposed into cycles of size k by Theorem 2. Hence, λK_n is (S_k, C_k) -decomposable.

Case 2. $n = k + 1$. Since the degree of each vertex is λk , we decompose the incident edges of one vertex into λ copies of S_k . The remaining graph is λK_k . By assumption, λK_k has number of edges divisible by k , which implies that $\lambda k(k - 1)/2 \equiv 0 [k]$. Since $\lambda(k - 1)$ is even, we decompose λK_k into copies of C_k using Theorem 2. ■

Example 19, illustrated by Figure 1, shows how Proposition 18 is applied to a graph $3K_5$.

Example 19. (S_3, C_3) -decomposition of a graph λK_n with $n = 5$ and $\lambda = 3$ is as follows.

- Consider the graph $3K_5$. Since $\lambda \equiv 0 [3]$ we have $|E(3K_5)| \equiv 0 [k]$.
- Taking on a vertex of $3K_5$ called v , we decompose the graph into $\lambda(n - 1)/k = 4$ stars by rotation. This rotation is applied to all the incident edges of the considered node v (Figure 1 illustrates rotation construction).
- The remaining graph is $3K_4$. The same rotation construction is applied to finding $\lambda(n - 2)/k = 3$ stars. This rotation construction is applied until the remaining graph is $3K_k(k = 3)$.
- The remaining graph $3K_3$ can be decomposed into 3 copies of C_3 .

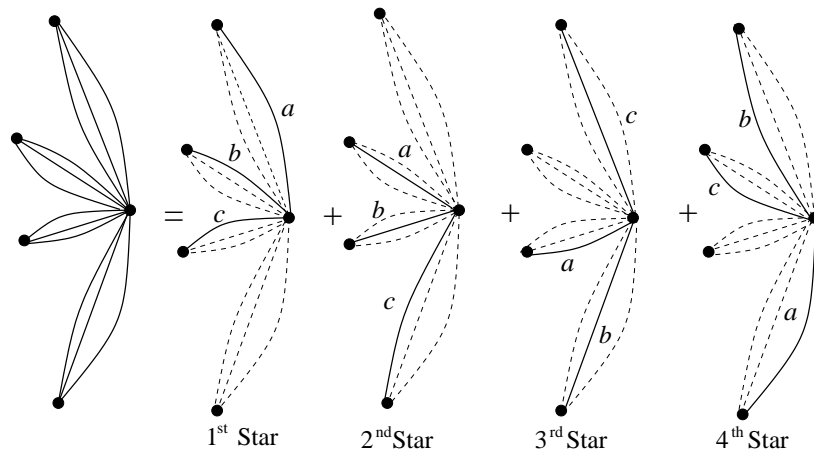


Figure 1. Rotation construction of stars. The edges of a star are labeled by a , b and c .

In the following corollary, we will investigate the problem of decomposing λK_n into S_k 's and C_k 's for each prime number k .

Corollary 20. *Let n and $\lambda > 1$ be positive integers, and let k be a positive prime number. There exists a (C_k, S_k) -decomposition of λK_n if and only if $n \geq k + 1$ and $\lambda n(n - 1)/2 \equiv 0 [k]$.*

Proof. We show that the necessary conditions given in Lemma 6 are also sufficient. $\lambda n(n - 1)/2$ is a multiple of k and k is a prime number, so we distinguish three cases according to the multiplicity of n , $n - 1$ and λ .

When k divides n or k divides $n - 1$, these cases are proved in Proposition 17. When k divides λ , this case is proved in Proposition 18. ■

The following theorem is a direct consequence of Propositions 17 and 18, and Corollary 20.

Theorem 21. *Let n , k and $\lambda > 1$ be positive integers. Then λK_n is (S_k, C_k) -decomposable if $\lambda n(n-1)/2 \equiv 0 [k]$ and*

- k is prime, or
- k divides either $n-1$, n or λ .

Acknowledgements

This work is partially supported by P2GE Rhone-Alpes Region project.

REFERENCES

- [1] A.A. Abueida and M. Daven, *Multidesigns for graph-pairs of order 4 and 5*, Graphs Combin. **19** (2003) 433–447.
doi:10.1007/s00373-003-0530-3
- [2] A.A. Abueida and M. Daven, *Multidecompositions of the complete graph*, Ars Combin. **72** (2004) 17–22.
- [3] A.A. Abueida and T. O’Neil, *Multidecomposition of λK_m into small cycles and claws*, Bull. Inst. Combin. Appl. **49** (2007) 32–40.
- [4] A.A. Abueida and C. Lian, *On the decompositions of complete graphs into cycles and stars on the same number of edges*, Discuss. Math. Graph Theory **34** (2014) 113–125.
doi:10.7151/dmgt.1719
- [5] B. Alspach and H. Gavlas, *Cycle decompositions of K_n and $K_n - I$* , J. Combin. Theory, Ser. B **81** (2001) 77–99.
doi:10.1006/jctb.2000.1996
- [6] D. Bryant, D. Horsley, B. Maenhaut and B.R. Smith, *Cycle decompositions of complete multigraphs*, J. Combin. Des. **19** (2011) 42–69.
doi:10.1002/jcd.20263
- [7] V. Chitra and A. Muthusamy, *Symmetric Hamilton cycle decompositions of complete multigraphs*, Discuss. Math. Graph Theory **33** (2013) 695–707.
doi:10.7151/dmgt.1687
- [8] S. Cichacz, *Decomposition of complete bipartite digraphs and even complete bipartite multigraphs into closed trails*, Discuss. Math. Graph Theory **27** (2007) 241–249.
doi:10.7151/dmgt.1358
- [9] H.-C. Lee and J.-J. Lin, *Decomposition of the complete bipartite graph with a 1-factor removed into cycles and stars*, Discrete Math. **313** (2013) 2354–2358.
doi:10.1016/j.disc.2013.06.014

- [10] Z. Liang and J. Guo, *Decomposition of complete multigraphs into crown graphs*, J. Appl. Math. Comput. **32** (2010) 507–517.
doi:10.1007/s12190-009-0267-0
- [11] H.M. Priyadharsini and A. Muthusamy, (G_m, H_m) -multifactorization of λK_m , J. Combin. Math. Combin. Comput. **69** (2009) 145–150.
- [12] M. Šajna, *Cycle decompositions III: Complete graphs and fixed length cycles*, J. Combin. Des. **10** (2002) 27–78.
doi:10.1002/jcd.1027
- [13] T.-W. Shyu, *Decompositions of complete graphs into paths and cycles*, Ars Combin. **97** (2010) 257–270.
- [14] T.-W. Shyu, *Decomposition of complete graphs into paths of length three and triangles*, Ars Combin. **107** (2012) 209–224.
- [15] T.-W. Shyu, *Decomposition of complete graphs into cycles and stars*, Graphs Combin. **29** (2013) 301–313.
doi:10.1007/s00373-011-1105-3
- [16] T.-W. Shyu, *Decomposition of complete bipartite graphs into paths and stars with same number of edges*, Discrete Math. **313** (2013) 865–871.
doi:10.1016/j.disc.2012.12.020
- [17] D. Sotteau, *Decomposition of $K_{m,n}$ ($K_{m,n}^{(*)}$) into cycles (circuits) of length $2k$* , J. Combin. Theory, Ser. B **30** (1981) 75–81.
doi:10.1016/0095-8956(81)90093-9
- [18] M. Tarsi, *Decomposition of complete multigraphs into stars*, Discrete Math. **26** (1979) 273–278.
doi:10.1016/0012-365X(79)90034-7
- [19] M. Tarsi, *Decomposition of a complete multigraph into simple paths: Nonbalanced handcuffed designs*, J. Combin. Theory, Ser. A **34** (1983) 60–70.
doi:10.1016/0097-3165(83)90040-7
- [20] R.M. Wilson, *Decomposition of complete graphs into subgraphs isomorphic to a given graph*, in: Proceedings of the 5th British Combinatorial Conference, Util. Math., Winnipeg, Congr. Numer. **15** (1976) 647–659.
- [21] S. Yamamoto, H. Ikeda, S. Shige-eda, K. Ushio and N. Hamada, *On claw-decomposition of complete graphs and complete bigraphs*, Hiroshima Math. J. **5** (1975) 33–42.

Received 9 september 2014

Revised 23 December 2014

Accepted 23 December 2014