

HAMILTON DECOMPOSITIONS OF LINE GRAPHS OF SOME BIPARTITE GRAPHS

DAVID A. PIKE*

Department of Mathematics and Statistics
Memorial University of Newfoundland
St. John's, Newfoundland, Canada, A1C 5S7

Abstract

Some bipartite Hamilton decomposable graphs that are regular of degree $\delta \equiv 2 \pmod{4}$ are shown to have Hamilton decomposable line graphs. One consequence is that every bipartite Hamilton decomposable graph G with connectivity $\kappa(G) = 2$ has a Hamilton decomposable line graph $L(G)$.

Keywords: Hamilton cycles, graph decompositions, line graphs.

2000 Mathematics Subject Classification: 05C70, 05C45.

1. Introduction

The *line graph*, denoted by $L(G)$, of a graph G having vertex set $V(G)$ and edge set $E(G)$ is the graph with vertex set $E(G)$, where two vertices of $L(G)$ are adjacent in $L(G)$ if and only if the corresponding edges in G are incident with a common vertex in G .

A *Hamilton decomposition* of a δ -regular graph G consists of a set of Hamilton cycles (plus a 1-factor if δ is odd) of G such that these cycles (and the 1-factor when δ is odd) partition the edges of G . If G has a Hamilton decomposition, it is said to be *Hamilton decomposable*.

Investigating Hamilton decompositions of line graphs has been largely motivated by the following conjecture of Bermond [1]:

Conjecture 1. *If G is Hamilton decomposable, then $L(G)$ is Hamilton decomposable.*

*Research supported by NSERC (Canada).

Bermond's conjecture has been shown to hold when G is a Hamilton decomposable graph satisfying any of the following criteria [3, 4, 5, 6, 7, 8, 9, 10, 11]:

1. $\delta \leq 5$,
2. $\delta \equiv 0 \pmod{4}$,
3. δ is odd and G is bipartite,
4. δ is even and G has a perfect 1-factorisation,
5. $G = K_n$, or
6. $G = K_{n,n}$.

In the case where G is a Hamilton decomposable graph that is regular of degree $\delta \equiv 2 \pmod{4}$, it is known that $L(G)$ can be decomposed into $\delta - 2$ Hamilton cycles plus a 2-factor [7, 12]. However, aside from when G is either complete or else has a perfect 1-factorisation, it is not generally known whether $L(G)$ is Hamilton decomposable.

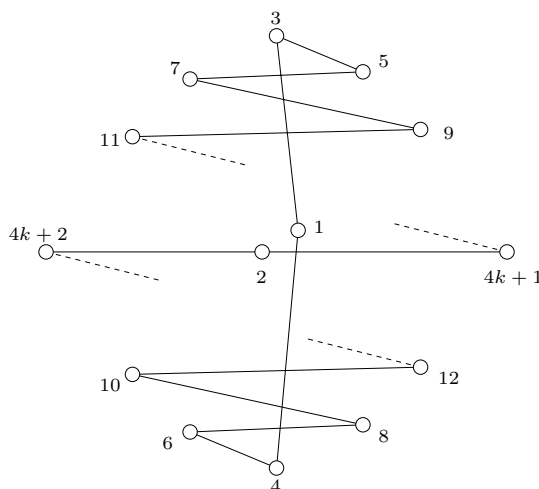
As our main result, we show that $L(G)$ is Hamilton decomposable for every bipartite graph G with $\delta \equiv 2 \pmod{4}$ that has a Hamilton decomposition H such that $\kappa(G - H_1) = 2$ for some Hamilton cycle H_1 of H . An immediate consequence of this result is that every bipartite Hamilton decomposable graph G with connectivity $\kappa(G) = 2$ has a Hamilton decomposable line graph.

2. Preliminary Results

Let \mathcal{H}_1 denote the Hamilton cycle $(1, 3, 5, \dots, 4k+1, 2, 4k+2, 4k, \dots, 6, 4, 1)$ of K_{4k+2} , where $V(K_{4k+2}) = \{1, 2, \dots, 4k+2\}$, and let \mathcal{F} denote the 1-factor of K_{4k+2} having the edges $\{2i-1, 2i\}$ for $i = 1, \dots, 2k+1$. \mathcal{H}_1 is illustrated in Figure 1. A double-centred Walecki construction described by Zhan [12] produces the following Hamilton decomposition of K_{4k+2} :

Lemma 1. *K_{4k+2} has a Hamilton decomposition in which \mathcal{H}_1 is one of the Hamilton cycles and \mathcal{F} is the 1-factor.*

Proof. For each $i = 2, 3, \dots, 2k$, let $\mathcal{H}_i = \sigma^{i-1}(\mathcal{H}_1)$ where σ is the permutation $(1)(2)(3, 5, 9, \dots, 4k+1, 4k, \dots, 12, 8, 4, 6, 10, \dots, 4k+2, 4k-1, \dots, 11, 7)$. Then the Hamilton cycles $\mathcal{H}_1, \mathcal{H}_2, \dots, \mathcal{H}_{2k}$ and the 1-factor \mathcal{F} form a Hamilton decomposition of K_{4k+2} . ■

Figure 1. The Hamilton cycle \mathcal{H}_1 .

In [9] a *stroll* was defined as an alternating sequence of vertices and edges, $v_0 e_0 v_1 e_1 \cdots v_{n-1} e_{n-1} v_n$, such that v_i and v_{i+1} (which are not necessarily distinct) are each end-vertices of the edge e_i , for $0 \leq i \leq n-1$. For closed strolls (in which $v_0 = v_n$), it suffices to state only the sequence of edges. An *Euler stroll* is any closed stroll in a graph G that uses each edge of G exactly once. Two Euler strolls are said to be *compatible* if no pair of adjacent edges (i.e., no 2-path) is contained in both.

Note that an Euler stroll in a graph G naturally corresponds to a Hamilton cycle in $L(G)$, and that any set of pairwise compatible Euler strolls in G corresponds to a set of edge-disjoint Hamilton cycles in $L(G)$.

3. Main Results

Theorem 1. *Let G be a bipartite graph that is regular of degree $\delta = 4k+2$. If there exists a Hamilton decomposition H of G such that, for some Hamilton cycle H_1 of H , $\kappa(G - H_1) = 2$, then $L(G)$ is Hamilton decomposable.*

Proof. Let H be a Hamilton decomposition of G , consisting of the Hamilton cycles H_1, \dots, H_{2k+1} , such that $((G - H_1) - \{u, v\})$ is disconnected for some pair of vertices u and v . Fix a bipartite colouring of the vertices of G using the colours red and blue, such that vertex u is coloured red.

Alternately colour the edges of H_1 with the colours 1 and 2. Since $\{u, v\}$ is a vertex cut in $(G - H_1)$, then there are two components, say \mathcal{C} and \mathcal{C}' , in $((G - H_1) - \{u, v\})$.

For each $i = 2, \dots, 2k + 1$, alternately colour the edges of H_i with the colours $(2i - 1)$ and $2i$ so that the edge from vertex u into \mathcal{C} has colour $(2i - 1)$. Let P_i be the sequence of edges along the cycle H_i of G , beginning with the edge from u to \mathcal{C} , ending with the edge from v to \mathcal{C}' , and including all edges coloured either $(2i - 1)$ or $2i$ that are contained in \mathcal{C} . Similarly, let P'_i be the sequence of edges along the cycle H_i , beginning with the edge from \mathcal{C} to u , ending with the edge from \mathcal{C}' to v , and including all edges coloured either $(2i - 1)$ or $2i$ that are contained in \mathcal{C}' . Together, P_i and P'_i contain all of the edges of H_i (with 2 edges of H_i being contained in $P_i \cap P'_i$).

Let $\mathcal{H}_1, \dots, \mathcal{H}_{2k}$ be the Hamilton cycles of the Hamilton decomposition of K_{4k+2} described in Lemma 1. These cycles will be used to generate $4k$ mutually compatible Euler strolls in G , and hence $4k$ edge-disjoint Hamilton cycles in $L(G)$.

For each $i = 1, \dots, 2k$, we wish to use H_1 and \mathcal{H}_i to generate 2 strolls in G . This can be done by noting that \mathcal{H}_i can be broken into two equal-length paths, each going from vertex 1 to vertex 2 of K_{4k+2} . For \mathcal{H}_1 , let \mathcal{P}_1 (resp. \mathcal{P}'_1) denote the path with internal vertices having odd (resp. even) labels, so that $\mathcal{P}_1 = (1, 3, 5, 7, 9, 11, \dots, 4k+1, 2)$ and $\mathcal{P}'_1 = (1, 4, 6, 8, 10, \dots, 4k+2, 2)$. For $i = 2, 3, \dots, 2k$, let $\mathcal{P}_i = \sigma^{i-1}(\mathcal{P}_1)$ and $\mathcal{P}'_i = \sigma^{i-1}(\mathcal{P}'_1)$, where σ is the permutation presented in Lemma 1.

For the first stroll generated by \mathcal{H}_i , where $i \in \{1, 2, \dots, 2k\}$, we use path \mathcal{P}_i (resp. \mathcal{P}'_i) at each vertex of H_1 that is coloured red (resp. blue) and for the second stroll we use path \mathcal{P}_i (resp. \mathcal{P}'_i) at each vertex that is coloured blue (resp. red). We use the paths \mathcal{P}_i and \mathcal{P}'_i to describe how to replace each edge sequence (e, e') of H_1 with an edge sequence $(e, e_1, e_2, \dots, e_{2k}, e')$ where each of the edges e_1, \dots, e_{2k} is incident with the vertex of G that is common to e and e' . Specifically, we wish the edge colours of the edges in the sequence $(e, e_1, e_2, \dots, e_{2k}, e')$ to be the same as the vertex labels along the path \mathcal{P}_i or \mathcal{P}'_i as appropriate. So, for example, for the first stroll generated by \mathcal{H}_1 , we would replace each 2-path in H_1 from an edge of colour 2 to an edge of colour 1 and having a blue internal vertex with a stroll consisting of edges incident with this blue vertex and having edge colours $(2, 4k+2, \dots, 10, 8, 6, 4, 1)$, whereas for the second stroll generated by \mathcal{H}_1 each such 2-path of H_1 would be replaced by a stroll whose edges are coloured $(2, 4k+1, \dots, 11, 9, 7, 5, 3, 1)$.

The $4k$ Euler strolls which are generated in this manner will be mutually compatible, and hence correspond to $4k$ edge-disjoint Hamilton cycles in $L(G)$. Let B_{2i-1} and B_{2i} denote the two Hamilton cycles in $L(G)$ that are generated from \mathcal{H}_i , for each $i = 1, \dots, 2k$.

If we were to remove the Hamilton cycles B_1, \dots, B_{4k} from $L(G)$ we would then have a 2-factor consisting of $(2k + 1)$ disjoint cycles of length $|V(G)|$. Let A_1, \dots, A_{2k+1} denote these $(2k + 1)$ cycles in $L(G)$. Note that for each $i = 1, \dots, 2k + 1$, there exists a natural correspondence between the cycle A_i in $L(G)$ and the Hamilton cycle H_i of G . With the vertices of $L(G)$ inheriting colours from the edges of G , it follows that the vertices of A_i are alternately coloured with the colours $(2i - 1)$ and $2i$.

To achieve a Hamilton decomposition of $L(G)$ we now show that the subgraph of $L(G)$ that is formed from the union of B_1 and A_1, \dots, A_{2k+1} is itself Hamilton decomposable. The structure formed by $B_1 \cup A_1$ is particularly important at this point, and is illustrated in Figure 2, where the outer cycle is B_1 and the inner cycle is A_1 .

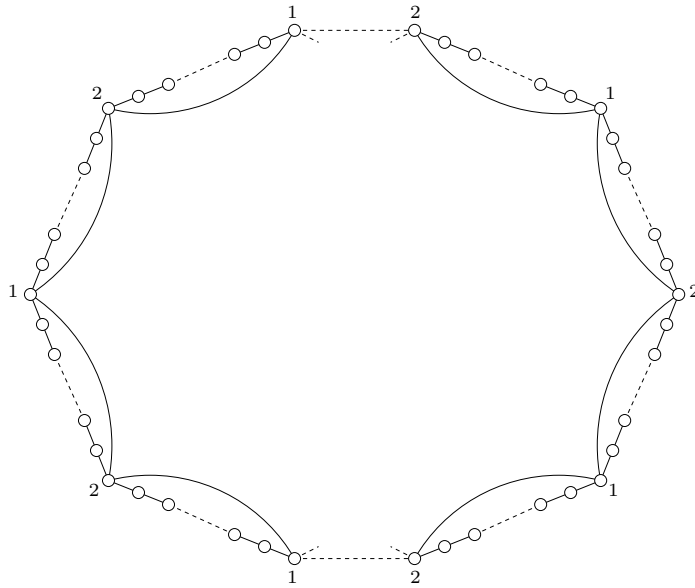


Figure 2. $B_1 \cup A_1$

Note that between each consecutive pair of vertices having colours 1 and 2 is a sequence of vertices whose colours match the labels of the vertices of either \mathcal{P}_1 or \mathcal{P}'_1 . Also, each segment of $B_1 \cup A_1$ (i.e., each set of vertices

that is between a consecutive pair of vertices having colours 1 and 2) is a subgraph of a clique of $L(G)$ that was generated by the δ edges incident with a common vertex, say x , of G . We will call this segment (resp. clique) the x segment (resp. x clique) of $B_1 \cup A_1$ (resp. $L(G)$).

Observe now that the edge sequences P_2, \dots, P_{2k+1} in G correspond to a set of $2k$ paths in $L(G)$, say $L(P_2), \dots, L(P_{2k+1})$. Moreover, since each sequence P_i in G begins at an edge incident with u and ends at an edge incident with v , the corresponding path $L(P_i)$ in $L(G)$ will begin in the u segment and finish in the v segment. The internal edges of the sequence P_i pass through the component \mathcal{C} of $((G - H_1) - \{u, v\})$, and so it follows that the set of segments of $B_1 \cup A_1$ through which the path $L(P_2)$ travels is the same set of segments as for each of the paths $L(P_3), \dots, L(P_{2k+1})$.

Similarly, the paths $L(P'_2), \dots, L(P'_{2k+1})$ in $L(G)$ start and end in the u and v segments, and go through a common set of segments of $B_1 \cup A_1$ that is the complement of those used by the internal vertices of $L(P_2), \dots, L(P_{2k+1})$.

We now construct a Hamilton cycle C_1 in $L(G)$, using only edges of $B_1 \cup A_1 \cup \dots \cup A_{2k}$. Include in C_1 the $(k+1)$ edges that form a maximum matching in the B_1 portion of the u segment of $B_1 \cup A_1$. Also include in C_1 the maximum matching in the v segment of $B_1 \cup A_1$ that contains the edge from A_1 . Add to C_1 all of the edges in each of $L(P_2), \dots, L(P_{2k+1})$. Figure 3 now illustrates the portion of C_1 that we have so far constructed. (Note that there are two cases, depending on whether u and v are in the same part of the bipartition of G .)

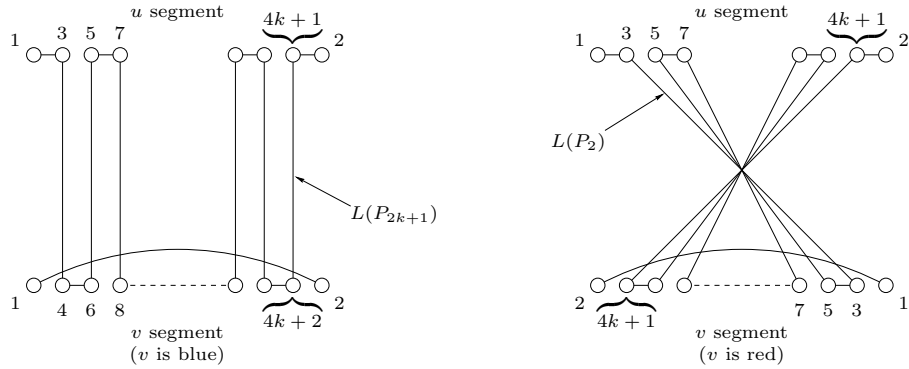


Figure 3. Some of the edges of the Hamilton cycle C_1 in $L(G)$.

Now, in each segment of $B_1 \cup A_1$ that is used by an internal vertex of $L(P_2)$, include in C_1 the edge from A_1 . In each segment of $B_1 \cup A_1$ not used by any vertices of $L(P_2)$, include in C_1 all $(2k+1)$ edges from B_1 . At this point we find that C_1 is a Hamilton cycle of $L(G)$.

The edges which remain when C_1 is removed from the union of B_1 and A_1, \dots, A_{2k+1} form a second Hamilton cycle, C_2 . C_1 and C_2 , together with B_2, \dots, B_{4k} , constitute the $(4k+1)$ Hamilton cycles of a Hamilton decomposition of $L(G)$. ■

It follows from Theorem 1 that if G is a bipartite Hamilton decomposable graph with $\delta \equiv 2 \pmod{4}$ and connectivity $\kappa(G) = 2$, then $L(G)$ is Hamilton decomposable. Combined with known results [7, 9], we conclude that every bipartite Hamilton decomposable graph G with $\kappa(G) = 2$ has a Hamilton decomposable line graph.

References

- [1] J.C. Bermond, *Problem 97*, Discrete Math. **71** (1988) 275.
- [2] J.A. Bondy and U.S.R. Murty, Graph Theory with Applications (North-Holland Publishing Company, New York, 1979).
- [3] K. Heinrich and H. Verrall, *A Construction of a perfect set of Euler tours of K_{2k+1}* , J. Combin. Designs **5** (1997) 215–230.
- [4] F. Jaeger, *The 1-factorization of some line-graphs*, Discrete Math. **46** (1983) 89–92.
- [5] A. Kotzig, *Z teorie konečných pravidelných grafov tretieho a štvrtého stupňa*, Časopis Pěst. Mat. **82** (1957) 76–92.
- [6] P. Martin, *Cycles Hamiltoniens dans les graphes 4-réguliers 4-connexes*, Aequationes Math. **14** (1976) 37–40.
- [7] A. Muthusamy and P. Paulraja, *Hamilton cycle decompositions of line graphs and a conjecture of Bermond*, J. Combin. Theory (B) **64** (1995) 1–16.
- [8] B.R. Myers, *Hamiltonian factorization of the product of a complete graph with itself*, Networks **2** (1972) 1–9.
- [9] D.A. Pike, *Hamilton decompositions of some line graphs*, J. Graph Theory **20** (1995) 473–479.
- [10] D.A. Pike, *Hamilton decompositions of line graphs of perfectly 1-factorisable graphs of even degree*, Australasian J. Combin. **12** (1995) 291–294.

- [11] H. Verrall, *A Construction of a perfect set of Euler tours of $K_{2k}+I$* , J. Combin. Designs **6** (1998) 183–211.
- [12] S. Zhan, *Circuits and Cycle Decompositions* (Ph.D. thesis, Simon Fraser University, 1992).

Received 3 February 2004