The circular flow number of a 6-edge connected graph is less than four

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Abstract

We show that every 6-edge connected graph admits a circulation whose range lies in the interval $[1, 3)$.

KEYWORDS: *nowhere zero flow, circular flow number, star flow number, circulation, eulerian graph, cogirth even, T-join.*

The *circular flow number* $\phi_c(G)$ of a (finite) graph G is defined by

$$\phi_c(G) = \inf\{r \in \mathbb{R} : \text{ some orientation } \vec{G} \text{ admits a circulation } f : E(\vec{G}) \to [1, r-1]\}.$$

This parameter is a refinement of the well studied *flow number* $\phi(G) := \lceil \phi_c(G) \rceil$, which was introduced by Tutte as a dual to the chromatic number. Since $\phi_c(G) \geq 2$ with equality if and only if G is eulerian, the circular flow number may be regarded as a measure of how close a graph is to being eulerian. The following results and conjectures can be found in [4].

- THEOREM (Seymour, 1979) Every 2-edge connected graph G has $\phi_c(G) \leq 6$.
- CONJECTURE (Tutte, 1954) Every 2-edge connected graph G has $\phi_c(G) \leq 5$.
- THEOREM (Jaeger, 1975) Every 4-edge connected graph G has $\phi_c(G) \leq 4$.
- CONJECTURE (Tutte, 1966) Every 4-edge connected graph G has $\phi_c(G) \leq 3$.

This list suggests that the circular flow number might decrease as edge connectivity increases. For this and other reasons, the following has been asked [1].

QUESTION 1 *Is it true that* $\sup\{\phi_c(G) : G \text{ is } k\text{-edge connected}\} \to 2$ *as* $k \to \infty$*?*

The answer is "yes" for graphs of bounded genus [5], but little progress has been made for general graphs. In this note we present a refinement of Jaeger's result.

THEOREM 2 *Every* 6*-edge connected graph* G *has* $\phi_c(G) < 4$.

*Supported by NATO-CNR Fellowship; this work was done while the author was visiting the Dept. of Mathematics and Statistics at Simon Fraser University, Canada;

†Supported by a National Sciences and Engineering Research Council Research Grant

It suits our purpose to use the following "Minty-like" formula for ϕ_c which arises directly from Hoffman's circulation condition (see [2]). If $G=(V,E)$ is finite and 2-edge connected, then

$$\phi_c(G) = \min_{\vec{G}} \max_{\emptyset \neq X \subset V} \frac{|\delta X|}{|\delta^+ X|} \tag{1}$$

where $\vec{G}$ ranges over the strong orientations of G. (Here δ^+X denotes the set of arcs from X to $V-X$, and $\delta X = \delta^+ X \cup \delta^+(V-X)$.)

Let $T \subseteq V(G)$. A *T-join* in G is a subset $J \subseteq E(G)$ such that T is the set of odd-degree vertices in the induced subgraph $G[J]$. An $\emptyset$-join is usually called a *cycle* or *even subgraph* of G. We use two standard results regarding trees and T-joins. The first is folklore, and the second was first proved by Nash-Williams [3].

LEMMA 3 *Any tree H contains a T-join, for any $T \subseteq V(H)$ of even cardinality.*

LEMMA 4 *Any $2k$-edge connected graph contains k edge-disjoint spanning trees.*

LEMMA 5 *Let H_1 and H_2 be edge-disjoint spanning trees of a graph G and let T be an even subset of $V(G)$. Then $H_1 \cup H_2$ contains a T-join which is spanning and connected.*

PROOF: Let V_1 be the set of odd-degree vertices in H_1. The symmetric difference $V_1 \Delta T$ has even cardinality so by Lemma 3, H_2 contains a $(V_1\Delta T)$-join J_2. Let $F = H_1 \cup J_2$. Since H_1 and J_2 are edge disjoint, F is a T-join. Furthermore $E(H_1) \subseteq F$ so F spans G and is connected. ∎

LEMMA 6 *Consider the polyhedron $P = \{x \in \mathbb{R}^8 : Ax = b,\ x \geq 0\}$ where*

$$[A|b] = \left[\begin{array}{cccccccc|c} 1 & 1 & 1 & 0 & -1 & -1 & -1 & 0 & 0 \\ 1 & 0 & -1 & 1 & -1 & 0 & 1 & -1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{array}\right].$$

Then the linear program $z^* = \min\{[1\ 1\ 1\ 1\ 0\ 0\ 0\ 0]x : x \in P\}$ has a unique optimum solution $x^* = \left[\frac{1}{4}\ 0\ 0\ 0\ 0\ 0\ \frac{1}{4}\ \frac{1}{2}\right]^T$ with value $z^* = \frac{1}{4}$.

PROOF: It is routine to check that x^* is P-feasible and that the vector $y^* = \left[\frac{1}{2}\ \frac{1}{4}\ \frac{1}{4}\right]$ is a feasible solution to the dual linear program $\max\{y[0\ 0\ 1]^T : yA \leq [1\ 1\ 1\ 1\ 0\ 0\ 0\ 0]\}$. Both objective values equal $\frac{1}{4}$ so (x^*, y^*) is an optimal dual pair. To show uniqueness we demonstrate that the primal objective vector is in the strict interior of a full dimensional cone generated by normals of active (tight) constraints at x^*. Writing $x = [x_1\ x_2\ \ldots\ x_8]^T$, the active constraints are the three equations $Ax = b$ and the five equations $x_i = 0$, $i = 2,3,4,5,6$. Indeed we have the positive linear combination

$$[1\ 1\ 1\ 1\ 0\ 0\ 0\ 0] = \left[\frac{1}{2}\ \frac{1}{4}\ \frac{1}{4}\right] A + \frac{1}{4}e_2 + \frac{1}{2}e_3 + \frac{1}{2}e_4 + \frac{1}{2}e_5 + \frac{1}{4}e_6$$

where e_i is the i-th standard unit vector in $\mathbb{R}^8$. The cone is full dimensional since the first, seventh and eighth columns of A are linearly independent. ∎

PROOF OF THEOREM 2. Let V_1 be the vertices of odd degree in G. By Lemma 4, G has three edge disjoint spanning trees. So by Lemmas 3 and 5, G has two edge-disjoint V_1-joins, J_1, J_2, such that

J_2 spans G and is connected. Let $\vec{C_1}$ and $\vec{C_2}$ be eulerian orientations of the complementary cycles $C_1 = E - J_1$ and $C_2 = E - J_2$. Note that $C_1 \cup C_2 = E(G)$. Let $\vec{G}$ be the *lexicographic orientation* of G induced by $(\vec{C_1}, \vec{C_2})$. That is, we orient each edge $e \in E(G) \cap C_1$ as it is oriented in $\vec{C_1}$, and we orient each $e \in E(G) - C_1$ as it is oriented in $\vec{C_2}$.

Let X be a proper nonempty subset of $V(\vec{G})$. We shall show that $\frac{|\delta^+ X|}{|\delta X|} > \frac{1}{4}$ and the result follows from (1). We associate with every edge $e \in \delta X$ an ordered pair $\sigma\tau \in \{+, -, 0\}^2$ where

$$\sigma = \begin{cases} + & \text{if } \vec{C_1} \text{ traverses } e \text{ from } X \text{ to } V - X \\ - & \text{if } \vec{C_1} \text{ traverses } e \text{ from } V - X \text{ to } X \\ 0 & \text{if } e \notin C_1 \end{cases}$$

and where τ is defined similarly using C_2 in place of C_1. The pair $\sigma\tau$ is called the *type* of e.

Let $x_{\sigma\tau}$ denote the proportion of edges in δX having type $\sigma\tau$. Since $C_1 \cup C_2 = E(G)$, no edge has type 00. We consider the 8-dimensional column vector

$$x = [x_{++}\ x_{+0}\ x_{+-}\ x_{0+}\ x_{--}\ x_{-0}\ x_{-+}\ x_{0-}]^T.$$

Since each $\vec{C_i}$ traverses δX the same number of times in each direction, x is a feasible point in the polyhedron P of Lemma 6. Because $\vec{G}$ is defined lexicographically, we have

$$\frac{|\delta^+ X|}{|\delta X|} = [1\ 1\ 1\ 1\ 0\ 0\ 0\ 0]x$$

so this ratio is bounded below by the optimum value of the linear program of Lemma 6. By that lemma, the unique optimum solution is $x^* = \left[\frac{1}{4}\ 0\ 0\ 0\ 0\ 0\ \frac{1}{4}\ \frac{1}{2}\right]^T$ with value $z^* = \frac{1}{4}$. Since J_2 is spanning and connected, we have $\delta X - C_2 \neq \emptyset$, so $x_{+0} + x_{-0} > 0$. Thus $x \neq x^*$ and $[1\ 1\ 1\ 1\ 0\ 0\ 0\ 0]x > \frac{1}{4}$ as claimed. ∎

REMARK: We have not proved that $\sup\{\phi_c(G) : G \text{ is } k\text{-edge connected }\} < 4$ for any value of k. To do so by our method would require finding disjoint V_1-joins J_1, J_2 such that $|J_1 \cap \delta X| \geq c|\delta X|$ for all $X \subseteq V$ and some $c > 0$. Using only Lemmas 3 and 4, the best we can ensure is $|J_1 \cap \delta X| \geq \lfloor \frac{k-4}{2} \rfloor$.

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