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FROBENIUS CIRCULANT GRAPHS OF VALENCY FOUR

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Dedicated to Cheryl Praeger for her sixtieth birthday

Abstract

A first kind Frobenius graph is a Cayley graph $\text{Cay}(K, S)$ on the Frobenius kernel of a Frobenius group $K \rtimes H$ such that $S = a^H$ for some $a \in K$ with $\langle a^H \rangle = K$, where H is of even order or a is an involution. It is known that such graphs admit ‘perfect’ routing and gossiping schemes. A circulant graph is a Cayley graph on a cyclic group of order at least three. Since circulant graphs are widely used as models for interconnection networks, it is thus highly desirable to characterize those which are Frobenius of the first kind. In this paper we first give such a characterization for connected 4-valent circulant graphs, and then describe optimal routing and gossiping schemes for those which are first kind Frobenius graphs. Examples of such graphs include the 4-valent circulant graph with a given diameter and maximum possible order.

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1. Introduction

There is a long history in searching for ‘good’ graphs to model interconnection networks. It is widely believed [1, 2, 8] that Cayley graphs, in particular circulant graphs [11, 21], are good candidates. (A *Cayley graph* on a group K is a graph $\text{Cay}(K, S)$ with vertex set K such that $x, y \in K$ are adjacent if and only if $xy^{-1} \in S$, where the *connection set* $S \subseteq K \setminus \{1\}$ is closed under taking inverse. A *circulant graph* is a Cayley graph on a cyclic group of order at least three.) In [19], Solé proved that for a certain class of graphs, called orbital-regular graphs, there exists an all-to-all shortest path routing such that the load on all edges is uniform and hence the edge-forward

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index [10] achieves the minimum. Here an *all-to-all routing* (or a routing for short) of a graph Γ is a set of oriented paths such that there is exactly one path between each ordered pair of vertices, the *load of an edge* is the number of times it is traversed by such paths in either direction, the *load of a routing* is the maximum load on an edge, and the *edge-forward index* $\pi(\Gamma)$ is [10] the minimum load over all possible all-to-all routings of Γ . The *arc-forwarding index* $\vec{\pi}$ is defined similarly by taking into account the direction when counting the number of times an arc is traversed, where an *arc* is an ordered pair of adjacent vertices. A routing is called a *shortest path routing* if all paths in it are shortest paths. The *minimal edge-* and *arc-forwarding indices* [8], π_m , $\vec{\pi}_m$, are defined by restricting to shortest path routings in the definitions of π and $\vec{\pi}$ respectively. A routing under which all edges have the same load is said to be *edge-uniform*. *Arc-uniform* routings are understood similarly.

In [7], Fang *et al.* proved that a graph is orbital-regular if and only if it is a cycle, a star, or a Frobenius graph. A group G acting transitively but not regularly on a set V such that only the identity element of G can fix two points of V is called [6, 18] a *Frobenius group*. It is well known [6, Section 3.4] that a finite Frobenius group G has a nilpotent normal subgroup K , called the *Frobenius kernel* of G , which is regular on V . Hence $G = K \rtimes H$ (semi-direct product of K by H), where H is the stabilizer of a point of V and is called a *Frobenius complement* for K in G . Since K is regular on V , we may identify V with K in such a way that K acts on itself by right multiplication, and we choose H to be the stabilizer of 1 (identity element of K) so that H acts on K by conjugation. A *G-Frobenius graph* [7] is a Cayley graph $\Gamma = \text{Cay}(K, S)$ on K , where

$$S = \begin{cases} a^H & \text{if } |H| \text{ is even or } |a| = 2, \\ a^H \cup (a^{-1})^H & \text{if } |H| \text{ is odd and } |a| \neq 2, \end{cases}$$

for some $a \in K$ satisfying $\langle a^H \rangle = K$, where $x^H = \{h^{-1}xh \mid h \in H\}$ for $x \in K$ and $|a|$ is the order of a . We call Γ a *first* or *second kind* [25] Frobenius graph, respectively, if S is as in the first or second line above. Since $\langle a^H \rangle = K$, Γ is always connected. As examples, Paley graphs are Frobenius [19], and those Hamming graphs $H(d, q)$ which are Frobenius are classified in [14], where q is a prime power. It is known that $\pi(\Gamma) = \sum_{u,v \in K} d(u, v) / |E(\Gamma)| = 2 \sum_{i=1}^d in_i$ or $\sum_{i=1}^d in_i$ [7], depending on whether Γ is of the first or second kind, where $d(u, v)$ is the distance in Γ between u and v , d is the diameter of Γ , and n_i is the number of H -orbits contained in the set of vertices at distance i from 1. $(n_1, n_2, \dots, n_d)$ is called [7] the *type* of Γ .

Besides the forwarding indices above, another important measure of performance of a network is its behavior with respect to gossiping. Here by gossiping we mean an information dissemination process for which each vertex has a distinct message to be sent to all other vertices. In this paper we consider the *store-and-forward*, *all-port* and *full-duplex* model [3]: a vertex must receive a message wholly before retransmitting it to other vertices; a vertex can exchange messages (which may be different) with all of its neighbours at each time step; messages can traverse an edge in both directions simultaneously; no two messages can transmit over the same arc at the same time;

and it takes one time step to transmit any message over an arc. A *gossiping scheme* is a procedure fulfilling the gossiping under these constraints, and the *minimum gossip time* [3] of a graph Γ , $t(\Gamma)$, is the minimum number of time steps required by such a scheme.

In [25] the second-named author devised optimal routing and gossiping schemes with attractive features for any first kind Frobenius graph. The results in [25] suggest that not only does such a graph have smallest possible forwarding indices π , $\bar{\pi}$, π_m and $\bar{\pi}_m$, but also it attains the minimum possible gossip time under the model above. In some sense, first kind Frobenius graphs admit ‘perfect’ routing and gossiping schemes, and hence they are ‘perfect’ for interconnection networks as far as routing and gossiping are concerned.

Being studied extensively, circulant graphs (or undirected multi-loop networks [11] as used in theoretical computer science) have been recognized as strong candidates for interconnection networks. It is known that some circulant graphs are first kind Frobenius graphs. For instance, in [20] the authors prove that all 6-valent circulant graphs with a given diameter and maximum possible order are Frobenius of the first kind. Because of the importance of circulant graphs (especially in the case of small valencies) in network design and very attractive properties of first kind Frobenius graphs with respect to routing and gossiping, the following problem arises naturally.

PROBLEM 1. Classify all first kind Frobenius circulant graphs.

In this paper we solve this problem in the case of valency four, and then we describe optimal routing and gossiping schemes for 4-valent first kind Frobenius circulant graphs. Let $n \geq 5$ be an integer, and let $1 \leq a, b \leq n-1$ be distinct integers such that $a, b \neq n/2$ and $a+b \neq n$. Let $\mathbb{Z}_n$ be the additive group of integers modulo n and $[x] \in \mathbb{Z}_n$ the residue class containing x . Then

$$DL_n(a, b) = \text{Cay}(\mathbb{Z}_n, S) \quad \text{where } S = \{[a], -[a], [b], -[b]\},$$

is a 4-valent circulant graph. It is connected if and only if $\gcd(a, b, n) = 1$ (see, for example, [11, 22]). In the literature $DL_n(a, b)$ is also called a double-loop network, justifying our notation, a double-loop fixed step graph [23], or a chordal ring of degree four [15]. As we will see in Lemma 5, we may assume without loss of generality that one of a, b is equal to 1.

A *complete rotation* [3, 8, 9] of a Cayley graph $\text{Cay}(K, S)$ is a group automorphism of K which fixes S setwise and induces a cyclic permutation on S . A connected graph Γ is said to be *G-arc transitive* if $G \leq \text{Aut}(\Gamma)$ is transitive on $\text{Arc}(\Gamma)$, the set of arcs of Γ . Let $\mathbb{Z}_n^* = \{[m] \mid 0 < m < n, \gcd(m, n) = 1\}$ be the multiplicative group of units of the ring $\mathbb{Z}_n$. The first result of this paper is the following theorem.

THEOREM 2. *Let $n \geq 5$ be an integer. If n is even, then there exists no first kind Frobenius circulant graph of order n and valency four. If n is odd, then the following statements are equivalent:*

- (a) *there exists $1 < h < n - 1$ such that $DL_n(1, h)$ is a first kind Frobenius graph;*
- (b) *the quadratic congruence equation $x^2 + 1 \equiv 0 \pmod n$ has a solution;*
- (c) *each prime factor of n is congruent to 1 modulo 4.*

Moreover, if one of these occurs, then the following hold:

- (d) *each solution h to $x^2 + 1 \equiv 0 \pmod n$ gives rise to a first kind Frobenius circulant graph $DL_n(1, h)$, and vice versa, and in this case $DL_n(1, h)$ is a $\mathbb{Z}_n \rtimes H$ -arc transitive $\mathbb{Z}_n \rtimes H$ -Frobenius graph which admits $[h]$ and $-[h]$ as complete rotations, where*

$$H = \langle [h] \rangle = \{[1], [h], [h^2], [h^3]\} = \{[1], [h], -[1], -[h]\} \leq \mathbb{Z}_n^*;$$

- (e) *there are exactly 2^{l-1} pairwise nonisomorphic first kind Frobenius circulant graphs with order n and valency four, where l is the number of distinct prime factors of n , and each of them is isomorphic to $DL_n(1, h)$ for some h as above.*

In particular, for any prime $p \equiv 1 \pmod 4$ and integer $e \geq 1$, there is a unique first kind Frobenius circulant graph with order p^e and valency four.

The equivalence of (b) and (c) above can be easily derived from known results in number theory. That $DL_n(1, h)$ is $\mathbb{Z}_n \rtimes H$ -arc transitive follows from a general result [25, Lemma 2.1]. The enumeration in (e) relies on known results on circulant CI-graphs (see [13] for more details and a survey). Note that H (as a set) is identical to the connection set of $DL_n(1, h)$.

A routing of a graph Γ is G -arc transitive [14] if $G \leq \text{Aut}(\Gamma)$ is transitive on $\text{Arc}(\Gamma)$ and leaves the routing invariant. The next theorem summarizes routing and gossiping properties of first kind Frobenius circulant graphs of valency four. Note that the value of $t(DL_n(1, h))$ is independent of h and that $\sum_{i=0}^r x_i(x_i + 2i + 1)$ is another form of $\sum_{u,v \in V(\Gamma)} d(u, v)/|E(\Gamma)|$, where $r, x_0, x_1, \dots, x_r$ will be defined in Section 3.

THEOREM 3. *Let $n \geq 5$ be an integer with each prime factor congruent to 1 modulo 4. Let h be a solution to $x^2 + 1 \equiv 0 \pmod n$ and $H = \{[1], [h], -[1], -[h]\}$. Then*

$$\begin{aligned} \pi(DL_n(1, h)) &= 2\tilde{\pi}(DL_n(1, h)) = 2\tilde{\pi}_m(DL_n(1, h)) = \pi_m(DL_n(1, h)) \\ &= \sum_{i=0}^r x_i(x_i + 2i + 1) \end{aligned} \tag{1}$$

$$t(DL_n(1, h)) = \frac{n-1}{4}. \tag{2}$$

Moreover, there exists a shortest path routing of $DL_n(1, h)$ which is $\mathbb{Z}_n \rtimes H$ -arc transitive, edge- and arc-uniform, and optimal for $\pi, \tilde{\pi}, \tilde{\pi}_m$ and π_m simultaneously.

Furthermore, there exists an optimal gossiping scheme for $DL_n(1, h)$ such that:

- (a) the message originating from any vertex is transmitted along shortest paths to other vertices;
- (b) for each vertex $[w]$ of $DL_n(1, h)$, at any time $t \geq 1$ precisely four arcs are used to transmit the message originating from $[w]$, and for $t \geq 2$ these four arcs form a matching of $DL_n(1, h)$;
- (c) at any time each arc of $DL_n(1, h)$ is used exactly once for message transmission.

In general, such routing and gossiping schemes are not unique, and we give a systematic way of constructing them explicitly.

The existence of these routing and gossiping schemes and the formulae above are corollaries of Theorem 2 and some general results [25, Theorems 5.1 and 6.1] for any Frobenius graph of the first kind. In this paper we thus emphasize construction of routing and gossiping with the properties above. To this end we require detailed information about the H -orbits on $\mathbb{Z}_n \setminus \{[0]\}$, and this will be derived in Section 3. With such information we then obtain the promised schemes by specifying certain procedures in [25]. Due to the importance of circulant graphs, we feel that it is necessary to include such specifications for potential practical applications. As we will see in the last section, Theorem 2 implies that the unique 4-valent circulant graph with a given diameter and maximum possible order is a first kind Frobenius graph. For this graph we recover certain known results [15, 23] as consequences of Theorems 2 and 3.

The reader is referred to [6, 18] and [4] respectively for the group- and graph-theoretic terminology used in the paper.

2. Proof of Theorem 2

It is well known (see, for example, [18, Section 5.7]) that $\text{Aut}(\mathbb{Z}_n) \cong \mathbb{Z}_n^*$. As the automorphism group of $\mathbb{Z}_n$, $\mathbb{Z}_n^*$ acts on $\mathbb{Z}_n$ by usual multiplication: $[x][m] = [xm]$, $[m] \in \mathbb{Z}_n^*$, $[x] \in \mathbb{Z}_n$. $\mathbb{Z}_n \rtimes \mathbb{Z}_n^*$ acts on $\mathbb{Z}_n$ in such a way that $\mathbb{Z}_n$ acts by addition and $\mathbb{Z}_n^*$ acts by multiplication. In other words, $[x]^{([z], [m])} = [(x + z)m]$ for $[x] \in \mathbb{Z}_n$ and $([z], [m]) \in \mathbb{Z}_n \rtimes \mathbb{Z}_n^*$, where $[z] \in \mathbb{Z}_n$ and $[m] \in \mathbb{Z}_n^*$. We identify $\mathbb{Z}_n \rtimes \text{Aut}(\mathbb{Z}_n)$ with $\mathbb{Z}_n \rtimes \mathbb{Z}_n^*$ in the following result.

LEMMA 4. A subgroup H of $\mathbb{Z}_n^*$ is semi-regular on $\mathbb{Z}_n \setminus \{[0]\}$ if and only if $[h - 1] \in \mathbb{Z}_n^*$ for all $[h] \in H \setminus \{[1]\}$.

PROOF. H is semi-regular on $\mathbb{Z}_n \setminus \{[0]\}$ if and only if for any $[x] \in \mathbb{Z}_n \setminus \{[0]\}$ and $[h] \in H$, $[hx] = [x]$ implies $[h] = [1]$. This is equivalent to $[(h - 1)x] \neq [0]$ for any $[x] \in \mathbb{Z}_n \setminus \{[0]\}$ and any $[h] \in H \setminus \{[1]\}$, which in turn is equivalent to $\gcd(h - 1, n) = 1$ for all $[h] \in H \setminus \{[1]\}$. And this holds if and only if $[h - 1] \in \mathbb{Z}_n^*$ for all $[h] \in H \setminus \{[1]\}$.

LEMMA 5. Let $n \geq 5$ be an integer. If $DL_n(a, b)$ is a first kind Frobenius graph, then the following hold:

- (a) *there exists a cyclic subgroup H of $\mathbb{Z}_n^*$ with order four such that $DL_n(a, b)$ is a $\mathbb{Z}_n \rtimes H$ -Frobenius graph;*
- (b) *at least one of a, b is coprime to n , and there exists an integer b' with $1 < b' < n - 1$ and $b' \neq n/2$ such that $DL_n(a, b) \cong DL_n(1, b')$.*

PROOF. Since $DL_n(a, b)$ is a first kind Frobenius graph, there exists a Frobenius group $G = \mathbb{Z}_n \rtimes H$ with Frobenius kernel $\mathbb{Z}_n$ such that $DL_n(a, b)$ is a first kind G -Frobenius graph. Hence S is an H -orbit (under the action of H on $\mathbb{Z}_n$), and H is regular on $S = \{[a], -[a], [b], -[b]\}$ and semi-regular on $\mathbb{Z}_n \setminus \{[0]\}$. Thus $|H| = |S| = 4$, and so either $H \cong \mathbb{Z}_4$ or $H \cong \mathbb{Z}_2 \times \mathbb{Z}_2$. Note that H is isomorphic to a subgroup of $\text{Aut}(\mathbb{Z}_n) \cong \mathbb{Z}_n^*$ and hence we may take H as a subgroup of $\mathbb{Z}_n^*$.

Since H is transitive on S , there exists an element $[m] \in H$ such that $[am] = [b]$. Note that $[m] \neq [1]$ as $[a] \neq [b]$. Since every element of $\mathbb{Z}_2 \times \mathbb{Z}_2$ other than the identity is an involution, if $H \cong \mathbb{Z}_2 \times \mathbb{Z}_2$, then $[bm] = [a]$ and hence $[(a+b)m] = [a+b]$, which is a contradiction because $[a+b] \neq [0]$, $[m] \neq [1]$ and H is semi-regular on $\mathbb{Z}_n \setminus \{[0]\}$. Therefore, $H \cong \mathbb{Z}_4$ and so $H = \{[1], [h], [h^2], [h^3]\}$ for some $[h] \in H$.

Since $DL_n(a, b)$ is a Frobenius graph, it must be connected and hence $\gcd(a, b, n) = 1$. We claim that at least one of a, b is coprime to n . Suppose otherwise, then, since S is invariant under the action of H , we have $[ha] = \pm[a]$ or $\pm[b]$. If $[ha] = -[a]$, then $[h^2a] = -[ha] = [a]$ and hence H is intransitive on S , which is a contradiction. Note that $\gcd(a, n) = d > 1$ since a is not coprime to n by our assumption. If $[ha] = [b]$, then, since $d \mid a$ and $d \mid n$, we have $d \mid b$, which contradicts $\gcd(a, b, n) = 1$. Similarly, $[ha] = -[b]$ cannot happen. If $[ha] = [a]$, then, since H is regular on S , we must have $[h] = [1]$ and so $H = \{[1]\}$, which is again a contradiction. Thus, we have proved that at least one of a, b is coprime to n . Without loss of generality, we may assume that $\gcd(a, n) = 1$. Then $[a] \in \mathbb{Z}_n^*$ and hence $DL_n(a, b) \cong DL_n(1, b')$ via the automorphism $[a]$ of $\mathbb{Z}_n$, where $[b'] = [a]^{-1}[b] \neq \pm[1]$ with $[a]^{-1}$ the inverse of $[a]$ in $\mathbb{Z}_n^*$. We may assume that $1 < b' < n - 1$. Since $DL_n(a, b)$ has valency four, we have $b' \neq n/2$. $\square$

PROOF OF THEOREM 2. Suppose that $DL_n(1, h)$ is a first kind Frobenius graph, where $1 < h < n$ and $h \neq n/2$. Then by Lemma 5(a) there exists a cyclic subgroup $H = \langle [h_0] \rangle$ of $\mathbb{Z}_n^*$ with order four such that $DL_n(1, h)$ is a $\mathbb{Z}_n \rtimes H$ -Frobenius graph. Hence H is regular on $S = \{[1], -[1], [h], -[h]\}$ and semi-regular on $\mathbb{Z}_n \setminus \{[0]\}$. Since $[1] \in S$, the regularity of H on S implies that $S = H = \{[1], [h_0], [h_0]^2, [h_0]^3\}$, and in particular $-[1] \in H$. Clearly, $-[1] \neq [h_0]$, and if $-[1] = [h_0]^3$ then $[1] = [h_0]^6 = [h_0]^2$ and so $H = \{[1], -[1]\}$, which is a contradiction. So the only possibility is that $[h_0]^2 = -[1]$, that is, h_0 is a solution to $x^2 + 1 \equiv 0 \pmod{n}$. It follows that $H = \{[1], -[1], [h_0], -[h_0]\} = S$. We may assume that $[h_0] = [h]$ for otherwise we replace h by $n - h$. Hence h is a solution to $x^2 + 1 \equiv 0 \pmod{n}$ and therefore (a) implies (b). Moreover, since H is semi-regular on $\mathbb{Z}_n \setminus \{[0]\}$, by Lemma 4 we should have $[h^2 - 1] = [-2] \in \mathbb{Z}_n^*$, which occurs only when n is odd. Thus, if n is even, then there exists no first kind Frobenius circulant graph of order n and valency four.

In the remainder of this proof we assume that $n = p_1^{e_1} p_2^{e_2} \cdots p_l^{e_l}$ is odd, where $p_1, p_2, \dots, p_l$ are distinct odd primes and $e_1, e_2, \dots, e_l$ are positive integers. Suppose that (b) holds and let h be a solution to $x^2 + 1 \equiv 0 \pmod{n}$. Then by the discussion in [16, Section 2.5] h is also a solution to the system of congruences $x^2 + 1 \equiv 0 \pmod{p_i^{e_i}}$, $1 \leq i \leq l$. Hence each p_i is a divisor of $h^2 + 1$. It follows that none of the p_i can be a divisor of h . Therefore, $\gcd(h, n) = 1$ and so $[h] \in \mathbb{Z}_n^*$. Since $h^2 \equiv -1 \pmod{n}$, it follows that $H = \langle [h] \rangle = \{[1], [h], [h]^2, [h]^3\} = \{[1], -[1], [h], -[h]\}$ is a cyclic subgroup of $\mathbb{Z}_n^*$ of order four. Consider $DL_n(1, h) = \text{Cay}(\mathbb{Z}_n, S)$, where $S = H$. Clearly, H is regular on S . Since n is odd, $[h^2 - 1] = [-2] \in \mathbb{Z}_n^*$. If $[h - 1] \notin \mathbb{Z}_n^*$, then there exists some i such that p_i is a divisor of $h - 1$, and hence p_i is a divisor of $h^2 - 1$. Since p_i is a divisor of $h^2 + 1$, it follows that p_i is a divisor of 2, which is a contradiction. Hence we must have $[h - 1] \in \mathbb{Z}_n^*$. Similarly, one can show that $[h^3 - 1] = [-h - 1] \in \mathbb{Z}_n^*$. Therefore, by Lemma 4, H is semi-regular on $\mathbb{Z}_n \setminus \{[0]\}$. Consequently, $\mathbb{Z}_n \rtimes H$ is a Frobenius group (see, for example, [17, p. 211]) and $DL_n(1, h)$ is a first kind $\mathbb{Z}_n \rtimes H$ -Frobenius graph. Thus, (b) implies (a).

For an integer $m \geq 1$, let $N(m)$ denote the number of solutions to $x^2 + 1 \equiv 0 \pmod{m}$. Then $N(n) = \prod_{i=1}^l N(p_i^{e_i})$ by [16, Theorem 2.18]. Since each p_i is odd, by [12, Proposition 4.2.3], $N(p_i^{e_i}) \geq 1$ if and only if $N(p_i) \geq 1$, which is true if and only if $p_i \equiv 1 \pmod{4}$ [16, Theorem 2.11]. Thus, $N(n) \geq 1$ if and only if each prime factor of n is congruent to 1 modulo 4. That is, (b) and (c) are equivalent for odd integers n .

Suppose that one of (a)–(c) holds, so that each p_i is congruent to 1 modulo 4. The proof above shows that every solution h to $x^2 + 1 \equiv 0 \pmod{n}$ gives rise to a first kind Frobenius circulant graph $DL_n(1, h)$, and *vice versa*, and in this case $DL_n(1, h)$ is a $\mathbb{Z}_n \rtimes H$ -Frobenius graph, where $H = \langle [h] \rangle = \{[1], -[1], [h], -[h]\} \leq \mathbb{Z}_n^*$. Clearly, $[h]$ and $-[h]$ are complete rotations of $DL_n(1, h)$. Also, $\mathbb{Z}_n \rtimes H \leq \text{Aut}(DL_n(1, h))$ and $\mathbb{Z}_n \rtimes H$ is transitive on the vertices of $DL_n(1, h)$. Let $([x], [y])$ and $([u], [v])$ be arcs of $DL_n(1, h)$. Then $[x - y], [u - v] \in S = H$. Since H is transitive on S , there exists $[m] \in H$ such that $[x - y][m] = [u - v]$. Let $[z] = [v][m]^{-1} - [y]$, where $[m]^{-1}$ is the inverse element of $[m]$ in $\mathbb{Z}_n^*$, so that $[(y + z)m] = [v]$. Then $([x], [y])^{([z], [m])} = ([x + z)m], [(y + z)m] = ([x + z)m + (u - v)], [(y + z)m] = ([u], [v])$. Therefore, $DL_n(1, h)$ is $\mathbb{Z}_n \rtimes H$ -arc transitive and (d) is established.

For each i , we have $N(p_i^{e_i}) = N(p_i) = 2$, where the first equality is from [12, Proposition 4.2.3] and the second one from [16, Corollary 2.28]. Hence $N(n) = \prod_{i=1}^l N(p_i^{e_i}) = 2^l$. By part (b) of Lemma 5, every first kind Frobenius circulant graph of order n and valency four is isomorphic to some $DL_n(1, h)$, where h is a solution to $x^2 + 1 \equiv 0 \pmod{n}$. Note that $-h$ is also a solution to this congruence equation and it gives rise to the same graph. Since $N(n) = 2^l$, it follows that there are at most 2^{l-1} pairwise nonisomorphic first kind Frobenius circulant graphs with order n and valency four. To establish (e) it remains to prove that, for distinct solutions h_1, h_2 to $x^2 + 1 \equiv 0 \pmod{n}$ such that $h_1 \not\equiv \pm h_2 \pmod{n}$, we have

$DL_n(1, h_1) \not\cong DL_n(1, h_2)$. In fact, if $DL_n(1, h_1) \cong DL_n(1, h_2)$, then since every cyclic group is a 4-CI group (see, for example, [13]), there exists $[m] \in \mathbb{Z}_n^*$ such that $S_1[m] = S_2$, where $S_1 = \{[1], -[1], [h_1], -[h_1]\}$ and $S_2 = \{[1], -[1], [h_2], -[h_2]\}$. From the proof above $H_1 = \langle [h_1] \rangle = S_1$ and $H_2 = \langle [h_2] \rangle = S_2$ are subgroups of $\mathbb{Z}_n^*$. Since $[1] \in S_2$, there exists $[x] \in S_1$ such that $[xm] = [1]$, and this implies $[m] \in H_1$. Thus, $S_2 = S_1[m] = H_1[m] = H_1 = S_1$, which contradicts the assumption that $h_1 \not\equiv \pm h_2 \pmod n$. $\square$

REMARK 6. Let $n = p_1^{e_1} p_2^{e_2} \cdots p_l^{e_l}$ be as above. All solutions to $x^2 + 1 \equiv 0 \pmod n$ can be computed by using known results in number theory. In fact, since $p_i \equiv 1 \pmod 4$, from the proof of [16, Theorem 2.11], $\prod_{j=1}^{(p_i-1)/2} j \pmod{p_i}$ and $p_i - \prod_{j=1}^{(p_i-1)/2} j \pmod{p_i}$ are the two solutions to $x^2 + 1 \equiv 0 \pmod{p_i}$. Based on these we obtain the two solutions to $x^2 + 1 \equiv 0 \pmod{p_i^{e_i}}$ by applying the procedure in the proof of [12, Proposition 4.2.3]. Using the method in the proof of [16, Theorem 2.18], we then obtain all 2^l solutions to $x^2 + 1 \equiv 0 \pmod n$ and hence all 2^{l-1} first kind Frobenius circulant graphs of order n and valency four.

3. Optimal routing and gossiping

Let $n \geq 5$ be an integer with each prime factor congruent to 1 modulo 4, and let h be a solution to $x^2 + 1 \equiv 0 \pmod n$. Then $h \neq n/2$. Let $\Gamma = DL_n(1, h)$, $H = \langle [h] \rangle = \{[1], -[1], [h], -[h]\}$, and let d be the diameter and $(n_1, n_2, \dots, n_d)$ the type of Γ . Let $\Gamma_i[u] = \{[v] \in \mathbb{Z}_n \mid d([u], [v]) = i\}$ for $[u] \in \mathbb{Z}_n$ and $1 \leq i \leq d$, where $d([u], [v])$ is the distance in Γ between $[u]$ and $[v]$. Then $\Gamma_i[0]$ is a union of n_i H -orbits; in particular, $\Gamma_1[0] = H$ (as a set) and $n_1 = 1$. Since $H \leq \mathbb{Z}_n^*$ is semi-regular on $\mathbb{Z}_n \setminus \{[0]\}$ by Theorem 2, all H -orbits on $\mathbb{Z}_n \setminus \{[0]\}$ contain four vertices of Γ .

Geometrically, we may represent Γ by a plane tessellation of squares [11, 21, 22] or an integer lattice [24]. See Figure 1 for an illustration. Let $\mathbb{Z}^2$ be the two-dimensional integer lattice. Then each $(x, y) \in \mathbb{Z}^2$ represents a vertex $[x + yh]$ of Γ , and this defines a mapping from $\mathbb{Z}^2$ to $\mathbb{Z}_n$. By the definition of Γ , for $0 \leq v \leq n - 1$,

$$d([0], [v]) = \min\{|x| + |y| : (x, y) \in \mathbb{Z}^2, v \equiv x + yh \pmod n\} \leq v.$$

Let r be the largest v such that $d([0], [v]) = v$. Since $d([0], [1]) = 1$, r is well defined. Since the H -orbit containing $[v]$ is $[v]H = \{[v], [vh], -[v], -[vh]\}$, r is also the largest v such that $d([0], [vh]) = v$ ($d([0], -[v]) = v$, $d([0], -[vh]) = v$, respectively). Hence $1 \leq r \leq (n - 1)/4$. Moreover, for $0 \leq k \leq r$,

$$d([0], [k]) = d([0], [kh]) = d([0], -[k]) = d([0], -[kh]) = k. \quad (3)$$

In fact, since $H \leq \text{Aut}(\Gamma)$ fixes $[0]$, the four distances above must be equal. If $d([0], [k]) \leq k - 1$, then there exist $(x, y) \in \mathbb{Z}^2$ such that $k \equiv x + yh \pmod n$ and $d([0], [k]) = |x| + |y| \leq k - 1$. Thus $r = k + (r - k) \equiv x + yh + (r - k) \pmod n$ and so $r = d([0], [r]) \leq |x| + |y| + (r - k) \leq r - 1$. This contradiction proves (3).

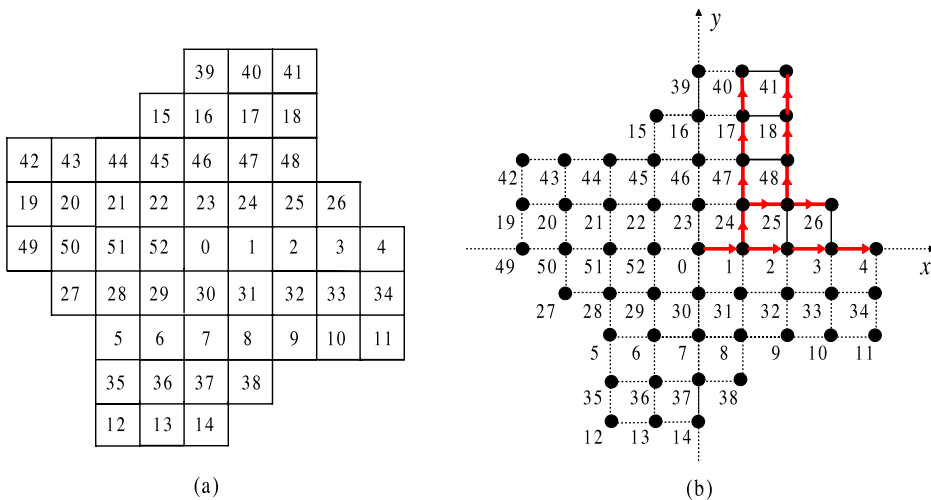


FIGURE 1. Geometric representations of $DL_{53}(1, 23)$ by (a) a plane tessellation and (b) an integer lattice. For this graph, $r = x_0 = 4$, $x_1 = 3$, $x_2 = x_3 = x_4 = 2$, X consists of those vertices connected by solid lines, and lines with arrows form the part T_0^1 of a shortest path spanning tree T_0 in the first quadrant.

In general, for $0 \leq k \leq r$ let $x_k \geq 0$ be the largest integer such that $d([0], [x_k + kh]) = x_k + k$. Note that x_k is well defined because of (3). Let

$$X = \{[j + kh] \mid 1 \leq j \leq x_k, 0 \leq k \leq r\}.$$

Since the H -orbit containing $[j + kh] \in X$ is $[j + kh]H = \{[j + kh], [-k + jh], [-j - kh], [k - jh]\}$, the image of X under the action of H (namely $\bigcup_{[j+kh] \in X} [j + kh]H$) is given by

$$XH = \{[j + kh], [-k + jh], [-j - kh], [k - jh] \mid 1 \leq j \leq x_k, 0 \leq k \leq r\}.$$

The following results can be verified easily and hence we omit their proofs.

LEMMA 7. *With the notation above, the following hold:*

- (a) for $[j + kh] \in X$, $d([0], [j + kh]) = d([0], [-k + jh]) = d([0], [-j - kh]) = d([0], [k - jh]) = j + k$;
- (b) $(n - 1)/4 \geq r = x_0 \geq x_1 \geq \dots \geq x_r$;
- (c) $XH = \mathbb{Z}_n \setminus \{[0]\}$ and each element of $\mathbb{Z}_n \setminus \{[0]\}$ appears in XH exactly once;
- (d) $d = \max\{x_k + k \mid 0 \leq k \leq r\}$, $XH \subseteq \{[x + yh] : (x, y) \in \mathbb{Z}^2, |x| + |y| \leq d\}$, and if $d = x_{k^*} + k^*$ then $x_k \leq x_{k^*} - (k - k^*)$ for $0 \leq k \leq r$;
- (e) for $1 \leq i \leq d$,

$$n_i = |\{[j + kh] \in X : j + k = i\}| \quad \text{and} \quad \Gamma_i[0] = \bigcup_{[j+kh] \in X, j+k=i} [j + kh]H.$$

- REMARK 8.** (a) XH is an algebraic expression of the minimum distance diagram [11, 22, 21] of Γ . In the current situation this diagram is symmetric and the group H permutes the four parts of XH cyclically: the part in the first quadrant is X , and the parts in the other three quadrants are $X[h]$, $-X$, $-X[h]$ successively. The lattice $\mathbb{Z}^2$ is covered by copies of XH periodically, and $XH \cup \{[0]\}$ is a subgraph of Γ in which each ‘interior vertex’ is fully connected to four vertices of Γ .
- (b) In general, it is hard to give a formula for x_k in terms of n and h , $0 \leq k \leq r$, because otherwise we could get a formula for the diameter of Γ . The latter task is very difficult, as shown in the literature [11, 24]. The minimum distance diagram XH can be constructed [21] by labelling the vertices $(x, y) \in \mathbb{Z}^2$ by $|x| + |y|$ in increasing order of $|x| + |y|$, discarding repeated labels, until all integers $0, 1, \dots, n-1$ are present. We obtain all x_k easily once we find the minimum distance diagram.
- (c) In [24] an $O(\log n)$ algorithm for computing the diameter of any circulant graph of valency four was given. This can be used to compute the diameter d of Γ .

Now we construct a spanning tree T_0 of Γ rooted at $[0]$ by using XH . The branch T_0^1 of T_0 in the first quadrant can be chosen as any subtree of Γ with vertex set $X \cup \{[0]\}$ and containing the edge between $[0]$ and $[1]$ such that, for $1 \leq i < d$, each vertex in $\Gamma_{i+1}[0] \cap X$ is adjacent to exactly one vertex in $\Gamma_i[0] \cap X$. To obtain the branches of T_0 in the other three quadrants we rotate T_0^1 by 90° , 180° , and 270° , respectively. In other words, these branches have vertex sets $X[h] \cup \{[0]\}$, $-X \cup \{[0]\}$, $-X[h] \cup \{[0]\}$ and edges $\{[uh], [vh]\}$, $\{-[u], -[v]\}$, $\{-[uh], -[vh]\}$, respectively, with $\{[u], [v]\}$ running over all edges of T_0^1 . It is clear that T_0 is a *shortest path spanning tree* of Γ with root $[0]$, that is, the unique path in T_0 between $[0]$ and any vertex is a shortest path in Γ . Consequently, for $0 \leq i \leq d$, the set $T_0(i)$ of vertices distant i from $[0]$ in T_0 is identical to $\Gamma_i[0]$. Let $A_{1,1}$ be the set of four arcs from $[0]$ to $\Gamma_1[0]$, namely $A_{1,1} = \{([0], [1]), ([0], [h]), ([0], -[1]), ([0], -[h])\}$. For $0 \leq i < d$, since $|\Gamma_{i+1}[0] \cap X| = n_{i+1}$, we may denote the vertices in $\Gamma_{i+1}[0] \cap X$ by $[v_{i+1,j}]$, $1 \leq j \leq n_{i+1}$; then for each $1 \leq j \leq n_{i+1}$ let $A_{i+1,j}$ be the image of the unique arc of T_0 from a vertex of $\Gamma_i[0] \cap X$ to $[v_{i+1,j}]$ under the action of H . Thus the set of arcs of T_0 from $T_0(i)$ to $T_0(i+1)$ is $\bigcup_{1 \leq j \leq n_{i+1}} A_{i+1,j}$. Since H is semi-regular on $\mathbb{Z}_n \setminus \{[0]\}$, for $1 \leq i < d$ and $1 \leq j \leq n_{i+1}$, $A_{i+1,j}$ is a matching of four arcs.

Given $[u] \in \mathbb{Z}_n$, $W \subseteq \mathbb{Z}_n$ and $A \subseteq \mathbb{Z}_n \times \mathbb{Z}_n$, denote $W + [u] = \{[w + u] \mid [w] \in W\}$ and $A + [u] = \{([x + u], [y + u]) \mid ([x], [y]) \in A\}$. Define T_u to be the tree with vertex set $\mathbb{Z}_n$ and arc set $\text{Arc}(T_0) + [u]$, that is, T_u is obtained from T_0 by translation by $[u]$. Since $\mathbb{Z}_n$ acts on itself (by translation) as a group of automorphisms of Γ , T_u is a shortest path spanning tree of Γ with root $[u]$. Let

$$\mathcal{P} = \{P_{uv} \mid [u], [v] \in \mathbb{Z}_n, [u] \neq [v]\} \quad (4)$$

where P_{uv} is the unique path in T_u from $[u]$ to $[v]$. The following algorithm gives the promised optimal gossiping scheme as we will see soon.

ALGORITHM 9. Let M_u denote the message originating at $[u] \in \mathbb{Z}_n$.

Phase 1. Initially, M_u is transmitted from $[u]$ to $T_0(1) + [u] (= H + [u])$ along the four arcs of $A_{1,1} + [u]$, and this is carried out for all $[u] \in \mathbb{Z}_n$ simultaneously.

Phase $i + 1$. Do the following for $i = 1, 2, \dots, d - 1$ successively: for $j = 1, 2, \dots, n_{i+1}$, in the j th step of the $(i + 1)$ th phase, for all $[u] \in \mathbb{Z}_n$ transmit M_u from $T_0(i) + [u]$ to $T_0(i + 1) + [u]$ along the four arcs of $A_{i+1,j} + [u]$ at the same time step.

PROOF OF THEOREM 3. Since each T_u is a shortest path spanning tree, $\mathcal{P}$ as defined in (4) is a shortest path routing of Γ . Since T_0 is invariant under H , $\mathbb{Z}_n \rtimes H$ leaves $\{T_u \mid [u] \in \mathbb{Z}_n\}$, and hence $\mathcal{P}$, invariant. Since Γ is $\mathbb{Z}_n \rtimes H$ -arc transitive (Theorem 2(d)), $\mathcal{P}$ is a $\mathbb{Z}_n \rtimes H$ -arc transitive routing. Thus, $\mathcal{P}$ is arc- and hence edge-uniform. Consequently, $\pi(\Gamma) = 2\vec{\pi}(\Gamma) = 2\vec{\pi}_m(\Gamma) = \pi_m(\Gamma)$ and $\mathcal{P}$ is optimal for the four indices simultaneously. Moreover, by Lemma 7,

$$\pi(\Gamma) = \sum_{[u],[v] \in \mathbb{Z}_n} d([u], [v]) / |E(\Gamma)| = 4n \sum_{k=0}^r \sum_{j=1}^{x_k} (j + k) / 2n = \sum_{k=0}^r x_k(x_k + 2k + 1).$$

Clearly, $\{A_{1,1} + [u] \mid [u] \in \mathbb{Z}_n\}$ is a partition of $\text{Arc}(\Gamma)$. For $1 \leq i < d$, $1 \leq j \leq n_{i+1}$, since Γ is $\mathbb{Z}_n \rtimes H$ -arc transitive and $A_{i+1,j}$ is invariant under H , each arc of $\text{Arc}(\Gamma)$ is contained in at least one $A_{i+1,j} + [u]$, $[u] \in \mathbb{Z}_n$. Since $\sum_{[u] \in \mathbb{Z}_n} |A_{i+1,j} + [u]| = 4n = |\text{Arc}(\Gamma)|$, it follows that $\{A_{i+1,j} + [u] \mid [u] \in \mathbb{Z}_n\}$ is a partition of $\text{Arc}(\Gamma)$. Hence Algorithm 9 is a gossiping scheme such that at any time each arc is used exactly once. Clearly, it requires $|X| = (n - 1)/4$ time steps. However, $t(\Gamma) \geq (n - 1)/4$, because $n - 1$ messages are to be sent to $[0]$, and at any time $[0]$ can process at most four messages. Therefore, $t(\Gamma) = (n - 1)/4$ and Algorithm 9 gives an optimal gossiping scheme. Obviously, it has the features described in (a)–(c) of Theorem 3. $\square$

4. Concluding remarks

It is known [22] that the maximum order of a connected 4-valent circulant graph with a given diameter $d \geq 2$ is $n_d = 2d^2 + 2d + 1$. Moreover, up to isomorphism there is a unique connected 4-valent circulant graph [22] with diameter d and order n_d , namely $DL_{n_d}(1, 2d + 1)$. (In fact, for any such graph $DL_{n_d}(a, b)$, we have $a(d + 1) - bd \equiv 0$, $ad + b(d + 1) \equiv 0 \pmod{n_d}$ by [22, Equation (3)] and so $a \equiv b(2d + 1) \pmod{n_d}$. Thus, since $DL_{n_d}(a, b)$ is connected, we have $\gcd(b, n_d) = \gcd(a, b, n_d) = 1$. Hence $[b] \in \mathbb{Z}_{n_d}^*$ and $DL_{n_d}(a, b) \cong DL_{n_d}(b(2d + 1), b) \cong DL_{n_d}(1, 2d + 1)$.) From the discussion in [22], $DL_{n_d}(1, 2d + 1)$ has type $(1, 2, \dots, d)$, and hence $r = d$ and $x_k = d - k$ for $0 \leq k \leq d$. Since $2d + 1$ is a solution to $x^2 + 1 \equiv 0 \pmod{n_d}$, we obtain the following corollary of Theorems 2 and 3.

COROLLARY 10. Let $d \geq 2$ be an integer, and let $\Gamma = DL_{n_d}(1, 2d + 1)$ be the unique connected 4-valent circulant graph of diameter d and maximum order

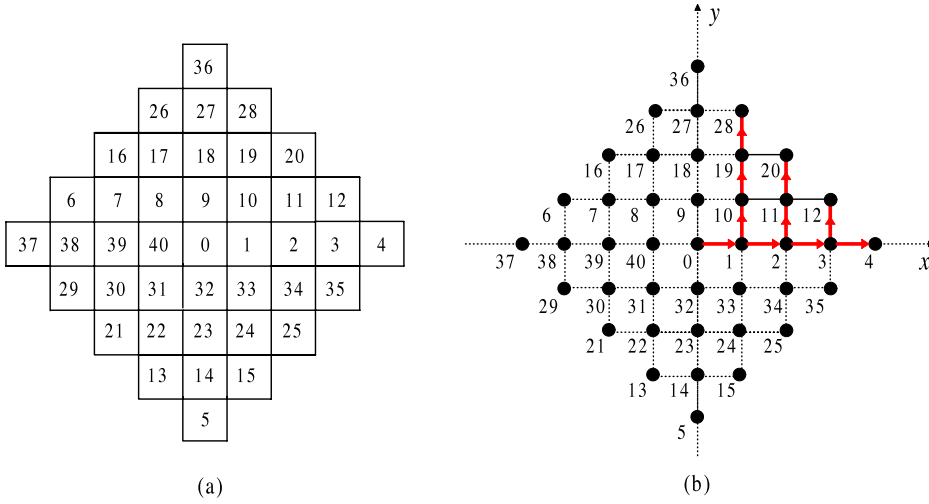


FIGURE 2. Part of a shortest path spanning tree of $DL_{41}(1, 9)$ in the first quadrant.

$n_d = 2d^2 + 2d + 1$. Then Γ is a $\mathbb{Z}_{n_d} \rtimes H(d)$ -arc transitive $\mathbb{Z}_{n_d} \rtimes H(d)$ -Frobenius graph, where $H(d) = \{[1], [2d + 1], -[1], -[2d + 1]\}$, and

$$\pi(\Gamma) = 2\tilde{\pi}(\Gamma) = 2\tilde{\pi}_m(\Gamma) = \pi_m(\Gamma) = \frac{d(d+1)(2d+1)}{3}$$

$$t(\Gamma) = \frac{d(d+1)}{2}.$$

Moreover, we can give explicitly optimal routing and gossiping schemes (not unique) for Γ with the properties described in Theorem 3.

That $\tilde{\pi}(DL_{n_d}(1, 2d + 1)) = d(d + 1)(2d + 1)/6$ was obtained in [15] by pure combinatorial arguments. Here we recovered this formula as a special case of a general result. Moreover, instead of giving only one specific optimal routing [15], by choosing different shortest path spanning trees T_0 and using the algorithms in the previous section we can give a number of optimal routing and gossiping schemes for $DL_{n_d}(1, 2d + 1)$. (An example of T_0 is given in Figure 2.) Furthermore, each T_0 gives rise to a near optimal broadcasting scheme: at time $t = 1, 2, 3, 4$ send the message at $[0]$ to $[1]$, $[h]$, $-[1]$, $-[h]$ via the arcs of $A_{1,1}$ successively; inductively, since $n_i = n_{i-1} + 1$, assume without loss of generality that $A_{i,1}$, $A_{i,2}$ are joined to the same $H(d)$ -orbit in $T_0(i - 1)$ ($1 < i \leq d$); after all vertices in $T_0(i)$ have received the message, for $i = 2, \dots, d$ at time $i + 3$ transmit the message along the arcs of $A_{i,1}$, $A_{i-1,2}, \dots, A_{i-1,i-1}$ simultaneously, and at time $d + 4$ send the message along the arcs of $A_{d,2}, \dots, A_{d,d}$ simultaneously. This is a broadcasting scheme which requires $d + 4$ time steps. It is near optimal since by [23] the minimum broadcasting time is $d + 2$.

Besides the ‘optimal’ double-loop networks $DL_{nd}(1, 2d + 1)$ above, there are other first kind Frobenius circulant graphs of valency four for which we can describe optimal routing and gossiping schemes explicitly. Consider $\Gamma_m = DL_n(1, 2m)$ for example, where $m \geq 1$ and $n = 4m^2 + 1$. Since $2m$ is a solution to $x^2 + 1 \equiv 0 \pmod n$, by Theorem 2, Γ_m is a $\mathbb{Z}_n \rtimes H$ -arc transitive $\mathbb{Z}_n \rtimes H$ -Frobenius graph, where $H = \{[1], [2m], -[1], -[2m]\}$. For this graph we can easily find that

$$r = m, x_0 = x_1 = \cdots = x_{r-1} = m \quad \text{and} \quad x_r = 0$$

and hence give explicitly optimal routing and gossiping schemes by invoking the algorithms in the previous section.

The following problems arise naturally from our study in this paper. Note that problem (a) is different from the one of determining the minimum diameter among all 4-valent circulant graphs of order n , the latter being solved in [5].

PROBLEM 11. Given an integer $n \geq 5$ with each of its prime factors congruent to 1 modulo 4, determine (a) the minimum diameter of $DL_n(1, h)$, and (b) the minimum edge-forwarding index of $DL_n(1, h)$, for h running over all solutions to $x^2 + 1 \equiv 0 \pmod n$.

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