Orienting Cayley graphs generated by transposition trees

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Received 31 May 2007; received in revised form 7 September 2007; accepted 10 October 2007

Abstract


Keywords: Interconnection networks; Unidirectional graphs; Cayley graphs; Connectivity

1. Introduction

Directed interconnection networks have gained much attention in the area of interconnection networks. Some recent research in this area includes [1,3–11]. In particular, [5] gave an application and an architectural model for the studies of unidirectional graph topologies as well as a comparison of the diameters among many known unidirectional interconnection networks. In addition, [6] proposed unidirectional hypercubes as the basis for high speed networking.

One of the most popular interconnection network is the star graph proposed by [12]. It has many advantages over the hypercube such as lower degree and a smaller diameter. Day and Tripathi [1] first proposed an orientation of the star graph so that the resulting graph is almost regular. One of the main criteria of a good unidirectional graph topology is that it has good connectivity properties. Indeed, [8] showed this for the unidirectional hypercube proposed in [6] and [2,3] showed this for the unidirectional star graph proposed in [1].

In this paper, we orient the edges of Cayley graphs generated by transposition trees and show that the resulting unidirectional graphs have good connectivity properties. This class of graphs is a common generalization of the star graphs and the bubble sort graphs [13] studied in [14]. Interests in them have recently been rejuvenated by [15].

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doi:10.1016j.camwa.2007.10.016
2. Preliminaries

Basic terminology in graph theory can be found in [16]. Let \( H \) be a graph and \( X \) be a proper nonempty subset of the vertex set. Define \( d_H(X) \) to be the number of edges with exactly one end in \( X \). Let \( G \) be a directed graph and \( X \) be a proper nonempty subset of the vertex set. Define \( \delta_G(X) \) (respectively, \( \rho_G(X) \)) to be the number of arcs leaving (respectively, entering) \( X \), that is, the number of arcs with their head (respectively, tail) in \( \overline{X} \). Observe that \( \delta_G(X) = \rho_G(\overline{X}) \). A graph \( H \) is \( k \)-edge-connected if the deletion of any \( k - 1 \) edges will not disconnect the graph. This is equivalent to \( d_H(X) \geq k \) for every \( \emptyset \neq X \subseteq V \). A directed graph \( G \) is \( k \)-arc-connected if the deletion of any \( k - 1 \) arcs will not disconnect the graph, that is, the resulting graph is strongly connected. This is equivalent to \( \delta_G(X) \geq k \) for every \( \emptyset \neq X \subseteq V \). The edge-connectivity (respectively, arc-connectivity) of a graph (respectively, directed graph) is \( r \) if it is \( r \)-edge-connected (respectively, \( r \)-arc-connected) but not \( (r + 1) \)-edge-connected (respectively, \( (r + 1) \)-arc-connected). A graph (respectively, directed graph) \( G = (V, E) \) is \( k \)-connected with \( k \leq |V| - 1 \) if it remains connected (respectively, strongly connected) after deleting at most \( k - 1 \) vertices. The vertex-connectivity or simply connectivity of a graph (or directed graph) \( G \) is \( r \) if it is \( r \)-connected but not \( (r + 1) \)-connected. A graph (respectively, directed graph) \( G = (V, E) \) is maximally connected if it is \( r \)-connected where \( r = \min\{d(v) : v \in V\} \) (respectively, \( r = \min\{\rho(v), \delta(v) : v \in V\} \)). Similarly, we can define the terms maximally edge-connected and maximally arc-connected. Given a digraph \( G \), a strong component of \( G \) is a maximal strongly connected subgraph of \( G \). Since vertex-connectivity is stronger than edge-connectivity and arc-connectivity, we will deal with vertex-connectivity in this paper. In fact, we study properties that are stronger than vertex-connectivity.

Let \( \Gamma \) be a finite group and let \( S \) be a set of elements of \( \Gamma \) such that the identity of the group does not belong to \( S \). The Cayley graph for \((\Gamma, S)\) is the directed graph with vertex set being the set of elements of \( \Gamma \) in which there is an arc from \( u \) to \( v \) if there is an \( s \in S \) such that \( u = vs \). The Cayley graph for \((\Gamma, S)\) is connected if and only if \( S \) is a generating set for \( \Gamma \). A Cayley graph is always vertex-transitive,\(^1\) so it is maximally arc-connected if it is connected; however, its vertex-connectivity may be low. (Note that not all vertex-transitive graphs are Cayley graphs; for example, the Petersen graph.)

Throughout the paper, a permutation is shown in the form \([a_1, a_2, \ldots, a_n]\) as an arrangement. However, for simplicity, it is expressed as \(a_1 a_2 \ldots a_n\) in figures. In addition, when we refer to a transposition (that is, a permutation where the symbols in every position is fixed, except positions \( i \) and \( j \) where the symbols are interchanged), we will use the cycle notation; in other words, we use the notation \((i j)\) for this transposition. In this paper, we choose the finite group to be \(\mathbb{Z}_n\), the symmetric group on \([1, 2, \ldots, n]\), and the generating set \(S\) to be a set of transpositions. The vertices of the corresponding Cayley graph are permutations, and since \(S\) only has transpositions, there is an arc from vertex \( u \) to vertex \( v \) if and only if there is an arc from \( v \) to \( u \). Hence we can regard these Cayley graphs as undirected graphs by replacing each pair of arcs in opposite directions by an edge. With transpositions as the generating set, a simple way to depict \(S\) is via a graph with vertex set \([1, 2, \ldots, n]\) where there is an edge between \(i\) and \(j\) if and only if the transposition \((i j)\) belongs to \(S\). This graph is called the transposition generating graph of \((\mathbb{Z}_n, S)\) or simply (transposition) generating graph if it is clear from the context. In fact, the star graphs were introduced via the generating graph \(K_{1, n-1}\), where the centre is 1 and the leaves are 2, 3, \ldots, \(n\). Hence they are called star graphs, though perhaps the more descriptive term should be “star-generated graphs”. In this paper, we consider connectivity properties of a class of good orientation of these graphs. We note that the Cayley graph generated by the transpositions in \(S\) is connected if and only if the generating graph corresponding to \(S\) is connected. Since an interconnection network needs to be connected, we require the transposition generating graph to be connected.

Some important properties of interconnection networks are low degree and high connectivity. The Cayley graph that we consider has \(n!\) vertices. In this paper, we restrict ourselves to graphs obtained from transposition generating graphs that are trees. The Cayley graphs obtained by these generating trees are \((n - 1)\)-regular and bipartite. For convenience, we refer to a transposition generating graph that is a tree as a (transposition) generating tree. In this paper, we give an orientation of these graphs and we prove that they have good connectivity properties. This includes the star graph whose generating tree is \(K_{1, n-1}\) and the bubble-sort graph whose generating tree is a path of length \(n\) usually labelled with the symbols 1, 2, \ldots, \(n\) in this order. Fig. 1 gives the star graph and Fig. 2 gives the bubble-sort graph.

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\(^1\) Two vertices \(u\) and \(v\) are equivalent if there is an automorphism \(\phi\) such that \(\phi(u) = v\). A graph is vertex-transitive if every pair of vertices are equivalent.
graph when \( n = 4 \). Throughout this paper, we use \( G_n \) to denote a graph generated by some transposition generating tree on \( n \) vertices. To avoid trivial cases, we assume that a generating tree has at least three vertices.

3. Orienting \( G_n \)

Let \( G_n \) be the Cayley graph generated by a transposition generating tree \( T_n \). So \( T_n \) has \( n - 1 \) edges. In the definition of a transposition generating tree, the vertices are labelled from 1 to \( n \). Clearly, permuting these vertex labellings will not effect the Cayley graph generated by it via isomorphism. So we will label them in a convenient way. In fact, to describe the orientation of the edges, we will also label the edges using the symbols in the set \( \{2, \ldots, n\} \). We now describe this labelling: Pick a leaf and its corresponding leaf-edge, label this leaf with \( n \), label this leaf-edge with \( n \) and delete this leaf; pick a leaf and its corresponding leaf-edge in the resulting graph, label the leaf with \( n - 1 \), label this leaf-edge \( n - 1 \) and delete this leaf; repeat until all edges are labelled, and label this last vertex with 1. We will call an edge in \( G_n \) an \( i \)-edge if it is generated by the edge with label \( i \) in the transposition generating tree. Note that the vertex with label \( n \) is a leaf. We can now describe the orientation. Let \( \pi_0 \) and \( \pi_1 \) be adjacent corresponding to an \( i \)-edge. We may assume \( \pi_0 \) is even and \( \pi_1 \) is odd. Then the edge is oriented from \( \pi_0 \) to \( \pi_1 \) if \( i \) is even and the edge is oriented from \( \pi_1 \) to \( \pi_0 \) if \( i \) is odd. We note that for star graphs, we have only two ways to label \( K_{1,n-1} \). Figs. 3 and 4 give the two possible labellings of \( K_{1,5} \). Note that we did not label the edges. It is clear from the labelling rule that the label on an edge is the larger of the two labels of its end vertices. It is clear that the two graphs that they generate are isomorphic as undirected graphs. The next proposition addresses the orientation of these graphs:

**Proposition 3.1.** Let \( T_n \) be the generating tree for the Cayley graph \( G_n \) where \( n \geq 3 \). Suppose \( L^1_n \) and \( L^2_n \) are two labellings of \( T_n \) such that they are identical except the vertices labelled 1 and 2 (that is, the end vertices of the edge labelled 2) are exchanged. Let \( \overrightarrow{G}_n^1 \) and \( \overrightarrow{G}_n^2 \) be the resulting orientation of \( G_n \) according to \( L^1_n \) and \( L^2_n \), respectively. Then \( \overrightarrow{G}_n^1 \) is isomorphic to the graph obtained from \( \overrightarrow{G}_n^2 \) by reversing the direction of every edge.
Proof. Clearly $G_1^n$ and $G_2^n$ are isomorphic via the bijection $\psi : V(G_1^n) \rightarrow V(G_2^n)$ that maps $[a_1, a_2, a_3, \ldots, a_n]$ to $[a_2, a_1, a_3, \ldots, a_n]$. Let $\overrightarrow{G}_n^2$ be the graph obtained from $\overrightarrow{G}_n^2$ by reversing the direction of every edge. Then the same function will work, that is, the bijection $\phi : V(\overrightarrow{G}_1^n) \rightarrow V(\overrightarrow{G}_2^n)$ that maps $[a_1, a_2, a_3, \ldots, a_n]$ to $[a_1, a_2, a_3, \ldots, a_n]$ is the desired isomorphism. There are three cases to check. Consider an edge $e$ in $L_1^n$ and $L_2^n$. Note that the edge labellings of the two trees are identical.

1. Suppose that both end vertices of $e$ have labels at least 3. Then since $[a_1, a_2, a_3, \ldots, a_n]$ and $[a_2, a_1, a_3, \ldots, a_n]$ have opposite parity and the label of $e$ is the same in both $L_1^n$ and $L_2^n$, the result follows.

2. Suppose that exactly one of the end vertices of $e$ has label at least 3. Then we may assume the end vertices of $e$ in $L_1^n$ are labelled 1 and $i$, and respectively labelled 2 and $i$ in $L_2^n$ where $i \geq 3$. For notational convenience, assume $i = 3$. Now consider an edge in $G_n$ generated by $e$; its two end vertices are $[a_1, a_2, a_3, \ldots, a_n]$ and $[a_3, a_2, a_1, a_4, \ldots, a_n]$. Now, under $\phi$, this edge maps to one that with end vertices $[a_2, a_1, a_3, \ldots, a_n]$ and $[a_2, a_3, a_1, a_4, \ldots, a_n]$. Again, it is clear from our orientation rule that these two edges are oriented in the opposite direction.

3. Suppose the end vertices of $e$ are labelled 1 and 2. This is similar to the above cases. □

By Proposition 3.1, one can conclude that, by using this rule, there is essentially one way to orient the Cayley graph generated by $K_{1,n-1}$. Fig. 5 gives the orientation for the graph generated by $K_{1,3}$, that is, a star graph. This labelling generates an orientation that coincides with the orientation given in [1]. We observe that our orientation rule is determined by a local orientation rule, that is, the orientation of an edge is given by the labels of its two ends. We
will denote the resulting directed graph by $\overrightarrow{G}_n$. We will show that $\overrightarrow{G}_n$ is maximally connected. In fact, we will show that $\overrightarrow{G}_n$ is “more than” maximally connected. The following result follows directly from the orientation rule.

**Proposition 3.2.** Let $\overrightarrow{G}_n$ be an unidirectional Cayley graph generated by a transposition generating tree on $n$ vertices. If $\pi$ is an even permutation, then the outdegree and indegree of $\pi$ are $\lceil \frac{n-1}{2} \rceil$ and $\lfloor \frac{n-1}{2} \rfloor$, respectively. If $\pi$ is an odd permutation, then the indegree and outdegree of $\pi$ are $\lceil \frac{n-1}{2} \rceil$ and $\lfloor \frac{n-1}{2} \rfloor$, respectively.

A quick way to remember Proposition 3.2 is that the orientation is an *odd-more-in* orientation, that is, the indegree is greater than or equal to the outdegree for an odd vertex. Moreover, $\overrightarrow{G}_n$ is regular if $n$ is odd.

As we noted earlier, there is essentially only one way to label $K_{1,n-1}$ for “distinct” orientation of the resulting Cayley graph. One may wonder whether this is true in general. We note that for $n = 4$, a generating tree is either $K_{1,3}$ or $P_4$, a path of length three. We claim that there are two ways to label $P_4$ so that the resulting orientations are “different.” It is clear that any such labelling can be reduced to either the one in Fig. 7 or the one in Fig. 8. Of course, Figs. 7 and 8 generate isomorphic undirected graphs. In fact, Fig. 7 generates Fig. 6 and Fig. 8 generates Fig. 2. However, they generate nonisomorphic digraphs. To see this, observe that Fig. 9 is the orientation of Fig. 2 using Fig. 7, and Fig. 10 is the orientation of Fig. 6 using Fig. 8. Now, these two digraphs are fundamentally different as the
Theorem 3.4. Let $n \geq 3$ and $G_n$ be the Cayley graph generated by a transposition tree on $n$ vertices where a leaf has label $n$. Then the following holds:

(1) $G_n$ is an $(n - 1)$-regular bipartite graph on $n!$ vertices.
(2) $G_n$ is vertex-transitive.

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2 The girth of a graph is the length of a shortest cycle in the graph.
(3) \( G_n \) is maximally connected and maximally edge-connected.
(4) Let \( H_i \) be the subgraph of \( G_n \) \((n \geq 4)\) induced by the vertices with \( i \) in the last position for \( 1 \leq i \leq n \). Then \( H_i \) is isomorphic to some Cayley graph \( G_{n-1} \). Moreover, there are \((n - 2)!\) independent\(^3\) edges between \( V(H_i) \) and \( V(H_j) \) for \( 1 \leq i < j \leq n \). In addition, every vertex in \( H_i \) has exactly one neighbour not in \( H_i \) via the n-edge for \( 1 \leq i \leq n \).

The first statement of Theorem 3.4 is obvious. We note that \( G_n \) is not edge-transitive\(^4\) in general. It is not difficult to see that \( G_n \) is indeed vertex-transitive. The edge-connectivity portion of Theorem 3.4 can be found in [17]: If \( G = (V, E) \) is a connected vertex-transitive r-regular graph, then \( G \) has edge-connectivity \( r \). The connectivity portion follows from a general result given in [18]: A minimal Cayley graph\(^5\) is maximally connected. It is also proved directly in [19]. For additional structural properties for this class of Cayley graph, we refer the reader to [19–22]. The fourth statement of the theorem is easy to check.

Another proposition that will be helpful in our discussion will be the following result:

**Proposition 3.5.** Let \( H_i \) be the (directed) subgraph of \( \overrightarrow{G}_n \) \((n \geq 4)\) induced by vertices with \( i \) in the last position for \( 1 \leq i \leq n \). Then there exists a Cayley graph \( G_{n-1} \) such that \( H_i \) has the same connectivity as \( \overrightarrow{G}_{n-1} \). Moreover, for \( 1 \leq i < j \leq n \), among the \((n - 2)!\) independent edges between \( V(H_i) \) and \( V(H_j) \) in \( G_n \), exactly half of them are directed from \( V(H_i) \) to \( V(H_j) \) in \( \overrightarrow{G}_n \).

**Proof.** Let \( T_n \) be the generating tree for \( G_n \). Consider a vertex \( \pi = [a_1, a_2, \ldots, a_{n-1}, i] \) in \( H_i \). Then \( \pi \) is even if and only if the number of transpositions required to take \( \pi \) to \([1, 2, \ldots, n]\) is even. Clearly \( H_i \) is isomorphic to some \( G_{n-1} \) as an undirected graph via the natural mapping \( [a_1, a_2, \ldots, a_{n-1}, i] \mapsto [a_1, a_2, \ldots, a_{n-1}] \) and the mapping of the symbols \( a_1, a_2, \ldots, a_{n-1} \) to \( 1, 2, \ldots, n - 1 \) in the usual way. To be precise, \( G_{n-1} \) is the graph generated by the graph obtained by deleting the leaf labelled \( n \) in \( T_n \). Hence an i-edge in \( G_{n-1} \) is an i-edge in \( G_n \) where \( 1 \leq i \leq n - 1 \) and vice versa. Now, \([a_1, a_2, \ldots, a_{n-1}]\) is even if and only if the number of transpositions required to take it to \([1, 2, \ldots, i - 1, i + 1, \ldots, n]\) is even. But one can first go from \([a_1, a_2, \ldots, a_{n-1}, i]\) to \([1, 2, \ldots, n]\) and then to \([1, 2, \ldots, i - 1, i + 1, \ldots, n, i]\). Since the second sequence depends only on \( i \), \([a_1, a_2, \ldots, a_{n-1}, i]\) and \([a_1, a_2, \ldots, a_{n-1}, i]\) will either have the same parity for every pair or opposite parity for every pair. Hence the natural mapping will either show \( H_i \) is isomorphic to such a \( \overrightarrow{G}_{n-1} \) or isomorphic to the graph obtained by reversing the direction of every arc in such a \( \overrightarrow{G}_{n-1} \). In either case, the first statement is proved.

To prove the second part, we first note that the edges whose end vertices are in different \( H_i \)'s are precisely the edges generated by the leaf-edge of \( T_n \) with its leaf labelled \( n \). Suppose this vertex’s unique neighbour is labelled \( \alpha \). Since \( n \geq 4 \), there are two more symbols \( \beta \) and \( \gamma \) that are neither \( n \) nor \( \alpha \). For notational convenience, assume \( \alpha = n - 1, \beta = 1 \) and \( \gamma = 2 \). Then an edge between \( H_i \) and \( H_j \) must have end vertices of the form \([a_1, a_2, \ldots, a_{n-2}, j, i]\) and \([a_1, a_2, \ldots, a_{n-2}, i, j]\). Hence, there are \((n - 2)!\) of them. Now since \( n \geq 4 \), we can consider the two edges where the first arc is between the vertices \([a_1, a_2, a_3, \ldots, a_{n-2}, j, i]\) and \([a_1, a_2, a_3, \ldots, a_{n-2}, i, j]\), and the second arc is between the vertices \([a_2, a_3, \ldots, a_{n-2}, j, i]\) and \([a_2, a_3, \ldots, a_{n-2}, i, j]\). Clearly, the two arcs will be oriented in an opposite way. This construction pairs up all the arcs between \( H_i \) and \( H_j \), and hence we are done. \( \square \)

We will now digress and prove the next result that we stated earlier.

**Proposition 3.6.** Let \( \overrightarrow{G}_n \) be the unidirectional Cayley graph generated by a labelling of a transposition generating tree \( T_n \) on \( n \) vertices. Then every arc in \( \overrightarrow{G}_n \) is either on a directed 4-cycle or on a directed 6-cycle.

**Proof.** Consider an edge \( e \) in \( G_n \) that is generated by the edge corresponding to the edge/transposition \((ab)\) in \( T_n \). As seen in the proof of Lemma 3.3, we can pick another edge \((cd)\) in \( T_n \), such that \( a, b, c, d \) are distinct and that the edge \( e \) is in a 4-cycle. Now it is clear from our orientation rule that this 4-cycle is a directed 4-cycle if and only if the edges \((ab)\) and \((cd)\) in \( T_n \) have labels of different parity. Without loss of generality, assume the edge \((ab)\) in \( T_n \) has an even label. If there is an edge \((cd)\) in \( T_n \) with an odd label where \( a, b, c, d \) are distinct, then we are done. So all the edges

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\(^3\)A set of edges are independent if no two of them are incident to the same vertex.

\(^4\)Two edges \((u, v)\) and \((x, y)\) are equivalent if there is an automorphism \( \phi \) such that \( \phi(u) = x \) and \( \phi(v) = y \), or \( \phi(u) = y \) and \( \phi(v) = x \). A graph is edge-transitive if every pair of edges are equivalent.

\(^5\)A Cayley graph is minimal if the set \( S \) generates \( \Gamma \), but no strict subset of it does.
of \( T_n \) with an odd label must be incident to either \( a \) or \( b \). Without loss of generality, assume an edge with an odd label is \((ac)\). So using \((ab)\) and \((ac)\) gives us a 6-cycle. Again, it is clear from our orientation rule that this 6-cycle is a directed 6-cycle since the edges \((ab)\) and \((ac)\) have labels of opposite parity. □

We note that the proof of Proposition 3.6 gives a necessary and sufficient condition of whether an arc is on a directed 4-cycle. Consider Fig. 12 as a labelled generating tree. (Again, the label on an edge is the maximum of the labels of its end vertices.) Then an arc generated by edge 2 is not on a 4-cycle as there is no odd labelled edge in Fig. 12 that is independent with edge 2. Fig. 13 provides another example.

4. Connectivity properties

**Theorem 4.1.** Let \( \overrightarrow{G}_n \) be the unidirectional Cayley graph generated by a labelling of a transposition generating tree \( T_n \) on \( n \) vertices where \( n \geq 3 \). Then \( \overrightarrow{G}_n \) is maximally connected, that is, it has connectivity \( \left\lceil \frac{n-1}{2} \right\rceil \).

**Proof.** We apply induction on \( n \). Since \( \overrightarrow{G}_3 \) is a directed 6-cycle, the result is true for \( n = 3 \). For \( n = 4 \), one can check that the result is true for the graphs in Figs. 5, 9 and 10. We assume that the result is true for every \( \overrightarrow{G}_{n-1} \) where \( n \geq 5 \) is fixed. We now consider a particular \( \overrightarrow{G}_n \). Let \( H_i \) be the subgraph of \( \overrightarrow{G}_n \) with \( i \) in the last position for \( 1 \leq i \leq n \). Then \( H_i \) and \( \overrightarrow{G}_{n-1} \) have the same connectivity. Recall that every vertex in \( H_i \) has exactly one neighbour not in \( H_i \). Let \( T \) be a set of vertices in \( \overrightarrow{G}_n \) such that \( |T| \leq \left\lceil \frac{n-1}{2} \right\rceil - 1 \). Let \( T_i = V(H_i) \cap T \) and \( t_i = |T_i| \) for \( 1 \leq i \leq n \). We want to show that \( \overrightarrow{G}_n \setminus T \) is strongly connected. Suppose \( n \) is even. Then \( \left\lfloor \frac{n-1}{2} \right\rfloor - 1 = \left\lfloor \frac{n-2}{2} \right\rfloor = 1 = \frac{n-2}{2} - 1 \). Since \( H_i \) is \( \left\lfloor \frac{n-2}{2} \right\rfloor \)-connected, \( H_i \setminus T_i \) is strongly connected for \( 1 \leq i \leq n \). Let \( 1 \leq i, j \leq n \) be arbitrary. Since \( (n-2)!/2 - (\left\lfloor \frac{n-1}{2} \right\rfloor - 1) \geq 1 \), there is at least one arc remaining from \( V(H_i) \) to \( V(H_j) \) and at least one arc remaining from \( V(H_j) \) to \( V(H_i) \). Hence \( \overrightarrow{G}_n \setminus T \) is strongly connected.

Suppose \( n \) is odd with \( n = 2k + 1 \). Since \( n \geq 5 \), \( k \geq 2 \). Moreover, \( \left\lceil \frac{n-1}{2} \right\rceil = k \) and \( \left\lfloor \frac{n-2}{2} \right\rfloor = k - 1 \). We consider two cases. The first case is \( t_i \leq k - 2 \) for all \( 1 \leq i \leq n \). In this case, \( H_i \setminus T_i \) is strongly connected for \( 1 \leq i \leq n \). Let \( 1 \leq i, j \leq n \) be arbitrary. Since \( (n-2)!/2 - (\left\lfloor \frac{n-1}{2} \right\rfloor - 1) = (2k-1)!/2 - (k-1) \geq 1 \), there is at least one arc remaining from \( V(H_i) \) to \( V(H_j) \) and at least one arc remaining from \( V(H_j) \) to \( V(H_i) \). Hence \( \overrightarrow{G}_n \setminus T \) is strongly connected.

In the second case, without loss of generality, we may assume \( t_1 = k - 1 \) and \( t_2 = 0 \) for \( 2 \leq j \leq n \). It is clear that \( W = \overrightarrow{G}_n \setminus V(H_1) \) is strongly connected. Let \( Y \) be the strong component of \( \overrightarrow{G}_n \setminus T \) containing \( W \). Let \( C \) be a strong component in \( H_1 \setminus T_1 \). We want to show that \( C \) is part of \( Y \). It is enough to show that there is a directed path from a vertex in \( V(C) \) to a vertex in \( V(W) \) and a directed path from a vertex in \( V(W) \) to a vertex in \( V(C) \). Suppose \( C \) has at least two vertices. Pick an arc \( \pi_1 \rightarrow \pi_2 \). Let \( \pi_3 \) and \( \pi_4 \) be the unique neighbours of \( \pi_1 \) and \( \pi_2 \), respectively, that are in \( W \). Note that \( \pi_3 \) and \( \pi_4 \) are distinct. Since \( t_j = 0 \) for \( 2 \leq j \leq n \), \( \pi_3, \pi_4 \notin T \). If \( \pi_1 \) is even, then \( \pi_2 \) is odd, \( \pi_3 \) is odd and \( \pi_4 \) is even. Since \( (\pi_1, \pi_3) \) and \( (\pi_2, \pi_4) \) are \( n \)-edges in \( G_n \) and \( n \) is odd, we have \( \pi_3 \rightarrow \pi_1 \) and \( \pi_2 \rightarrow \pi_4 \). Hence \( C \) is part of \( Y \). The case \( \pi_1 \) being odd is similar. Suppose \( C \) has only one vertex \( \pi_1 \). We further assume that \( \pi_1 \) is even. Let \( \pi_2 \) be the unique neighbour of \( \pi_1 \) in \( W \). Note that \( \pi_2 \notin T \) and it is odd. Moreover, we have the arc \( \pi_2 \rightarrow \pi_1 \) since \( n \) is odd. There are \( k \) distinct odd vertices \( y_1, y_2, \ldots, y_k \in H_1 \) such that \( \pi_1 \rightarrow y_i \) is an arc for \( 1 \leq i \leq k \). Since \( T_1 = k - 1 \), we may assume that \( y_1 \notin T \). Let \( z \) be the unique neighbour of \( y_1 \) in \( W \). Since \( n \) is odd, we have the arc \( y_1 \rightarrow z \). Hence we have the directed path \( \pi_1 \rightarrow y_1 \rightarrow z \) in \( \overrightarrow{G}_n \setminus T \). Therefore \( C \) is part of \( Y \). The case \( \pi_1 \) being odd is similar. □

Fig. 12.

Fig. 13.
We have shown that \( \overline{G}_n \) is maximally connected. At first glance, it seems that it is the best possible result. However, it is important to study the resulting disconnected directed graph when a sufficient number of vertices have been deleted. A graph (respectively, directed graph) with connectivity \( r \) is loosely super connected if for any \( r \) vertices deleted, the resulting graph (respectively, directed graph) is either still connected (respectively, strongly connected) or has at most one component (respectively, strong component) of size greater than one. The notion of “superness” was first introduced in [23]. One can immediately see that this is an important concept in the study of interconnection networks as this provides an insight into the severity of a disconnection. “Superness” suggests that the “core” of the network remains intact if the network is minimally disconnected. It is shown in [19] that \( G_n \) has this property; we will show that \( \overline{G}_n \) also has this property.

**Lemma 4.2.** Suppose \( \overline{G}_n \) is the unidirectional Cayley graph generated by a labelling of a transposition generating tree \( T_n \) on \( n \) vertices where \( n \geq 3 \). Let \( T \) be a set of vertices in \( \overline{G}_n \). If \( C \) is a strong component of \( \overline{G}_n \setminus T \), then \( T \) is either a singleton or it is of size at least 4 and has a directed path of length 3.

**Proof.** Suppose \( C \) is not a singleton. Let \( \pi_1 \rightarrow \pi_2 \) be an arc in \( C \). Since \( C \) is strongly connected, there is a directed path from \( \pi_2 \) to \( \pi_1 \). The result now follows from the fact that \( G_n \) has girth at least four. \( \square \)

**Theorem 4.3.** Suppose \( \overline{G}_n \) is the unidirectional Cayley graph generated by a labelling of a transposition generating tree \( T_n \) on \( n \) vertices where \( n \geq 3 \). Then \( \overline{G}_n \) is loosely super connected.

**Proof.** Suppose we delete \( \lfloor \frac{n-1}{2} \rfloor \) vertices. Let this set of vertices be \( T \). We first consider the case that \( n \) is even. For \( n = 4 \), we can check that the statement is true for every possible \( \overline{G}_4 \), that is, the graphs in Figs. 5, 9 and 10. From now on, we assume \( n = 2k \) with \( k \geq 3 \). So \( |T| = k-1 \). Let \( H_i \) be the subgraph of \( \overline{G}_n \) with \( i \) in the last position for \( 1 \leq i \leq n \). Then \( H_i \) and \( \overline{G}_n-1 \) have the same connectivity (by Proposition 3.2). So the connectivity is \( \lfloor \frac{2k-2}{2} \rfloor = k-1 \). As before, let \( T_i = V(H_i) \cap T \) and \( t_i = |T_i| \) for \( 1 \leq i \leq n \).

Suppose \( t_i \leq k-2 \) for all \( 1 \leq i \leq n \). Then \( H_i \setminus T_i \) is strongly connected for \( 1 \leq i \leq n \). Let \( 1 \leq i, j \leq n \) be arbitrary. If we can show that there is at least one arc from \( V(H_i) \) to \( V(H_j) \) and at least one arc from \( V(H_i) \) to \( V(H_t) \), then we can conclude that \( \overline{G}_n \) is strongly connected. This can be accomplished by showing \( (2k-2)!/2 > t_i + t_j \). Since \( t_i + t_j \leq k-1 \) and \( k \geq 3 \), we are done as \( (2k-2)!/2 > k-1 \).

Suppose there is a \( t_i \geq k-1 \). Without loss of generality, let this be \( t_1 \). Then \( t_1 = k-1 \) and \( T = T_1 \). It is clear that \( W = \overline{G}_n \setminus V(H_1) \) is strongly connected. Let \( Y \) be the strong component in \( \overline{G}_n \setminus T \) containing \( W \). Let \( C \) be a strong component in \( H_1 \setminus T_1 \). We want to show that \( C \) is part of \( Y \) or \( C \) is a singleton. Suppose \( C \) is not a singleton. Then by Lemma 4.2, it has a directed path \( \pi_1 \rightarrow \pi_2 \rightarrow \pi_3 \rightarrow \pi_4 \) where \( \pi_1, \pi_2, \pi_3, \pi_4 \) are distinct vertices in \( C \). Let \( \pi_5, \pi_6, \pi_7, \pi_8 \) be the unique neighbours of \( \pi_1, \pi_2, \pi_3, \pi_4 \) in \( W \) through an \( n \)-edge in \( G_n \), respectively. Note that \( \pi_5, \pi_6, \pi_7, \pi_8 \) are distinct. Suppose \( \pi_1 \) is even. Then \( \pi_3, \pi_6, \pi_8 \) are even and \( \pi_2, \pi_4, \pi_5, \pi_7 \) are odd. Since \( n \) is even, we have the following arcs: \( \pi_1 \rightarrow \pi_3, \pi_6 \rightarrow \pi_2, \pi_3 \rightarrow \pi_7, \pi_8 \rightarrow \pi_4 \). The arcs \( \pi_1 \rightarrow \pi_5 \) and \( \pi_6 \rightarrow \pi_2 \) show that \( C \) is part of \( Y \). The case \( \pi_1 \) being odd is similar.

We now consider the case that \( n \) is odd. We can check that the statement is true for \( \overline{G}_3 \) (one possibility). From now on, we assume \( n = 2k + 1 \) with \( k \geq 2 \). So \( |T| = k \). Let \( H_i \) be the subgraph of \( \overline{G}_n \) with \( i \) in the last position for \( 1 \leq i \leq n \). Then \( H_i \) and \( \overline{G}_n-1 \) have the same connectivity, which is \( \lfloor \frac{2k-1}{2} \rfloor = k-1 \). Let \( T_i = V(H_i) \cap T \) and \( t_i = |T_i| \) for \( 1 \leq i \leq n \).

Suppose \( t_i \leq k-2 \) for all \( 1 \leq i \leq n \). Then \( H_i \setminus T_i \) is strongly connected for \( 1 \leq i \leq n \). Let \( 1 \leq i, j \leq n \) be arbitrary. Since \( k \geq 2 \), we have \( (2k-1)!/2 \geq k \). This together with \( t_i + t_j \leq k \) implies \( (2k-1)!/2 > t_i + t_j \).

Suppose there is a \( t_i \geq k-1 \). Without loss of generality, let this be \( t_1 \). Then \( t_1 = k-1 \) or \( k \). It is clear that \( W = \overline{G}_n \setminus V(H_1) \) is strongly connected. Let \( Y \) be the strong component in \( \overline{G}_n \setminus T \) containing \( W \). Let \( C \) be a strong component in \( H_1 \setminus T_1 \). We want to show that \( C \) is part of \( Y \) or \( C \) is a singleton. Suppose \( C \) is not a singleton. Then by Lemma 4.2, it has a directed path \( \pi_1 \rightarrow \pi_2 \rightarrow \pi_3 \rightarrow \pi_4 \) where \( \pi_1, \pi_2, \pi_3, \pi_4 \) are distinct vertices in \( C \). Let \( \pi_5, \pi_6, \pi_7, \pi_8 \) be the unique neighbours of \( \pi_1, \pi_2, \pi_3, \pi_4 \) in \( W \) through an \( n \)-edge in \( G_n \), respectively. Note that \( \pi_5, \pi_6, \pi_7, \pi_8 \) are distinct. Suppose \( \pi_1 \) is odd. Then \( \pi_3, \pi_6, \pi_8 \) are odd and \( \pi_2, \pi_4, \pi_5, \pi_7 \) are even. Since \( n \) is odd, we have the following arcs: \( \pi_1 \rightarrow \pi_5, \pi_6 \rightarrow \pi_2, \pi_3 \rightarrow \pi_7, \pi_8 \rightarrow \pi_4 \). Since at most one of \( \pi_5, \pi_6, \pi_7, \pi_8 \) is in \( T \), there are arcs from \( C \) to \( W \) and from \( W \) to \( C \), and we are done. The case \( \pi_1 \) being even is similar. \( \square \)

Consider deleting a vertex in \( \overline{G}_3 \). Then the resulting directed graph is a directed path of length five, and hence it has five singleton strong components. So we need to consider a property stronger than loosely super connectedness.
A graph (respectively, directed graph) with connectivity \( r \) is tightly super connected if, for any \( r \) vertices deleted, the resulting graph (respectively, directed graph) is either still connected (respectively, strongly connected) or has exactly two components (respectively, strong components), one of which is a singleton. In [19], it is shown that for \( n \geq 3 \), \( G_n \) is tightly super connected. The next result shows that \( \overline{G}_n \) has the same property.

**Theorem 4.4.** Let \( \overline{G}_n \) be the unidirectional Cayley graph generated by a labelling of a transposition generating tree \( T_n \) on \( n \) vertices where \( n \geq 8 \). Then \( \overline{G}_n \) is tightly super connected.

**Proof.** Suppose we delete \( \lceil \frac{n-1}{2} \rceil \) vertices. By Theorem 4.3, the resulting graph has at most one non-singleton strong component. We only have to show that there is at most one singleton strong component. We follow the notation we have defined in the proof of Theorem 4.3. We first consider the case when \( n = 2k \) with \( k \geq 4 \). Suppose there are two singleton strong components in \( \overline{G}_n \setminus T \), say one with vertex \( a \) and one with vertex \( b \). Then from the proof of Theorem 4.3, without loss of generality, we may assume \( t_1 = k - 1 \), and both \( a \) and \( b \) are singleton strong components in \( H_1 \setminus T_1 \). Let \( A \subseteq B \) be such a set. Similarly, \( T \) contains \( k - 1 \) neighbours of \( a \); let \( A \) be such a set. By Lemma 3.3, \( A \cap B \) has at most two vertices. This is impossible since \( k \geq 4 \).

We now consider the case when \( n = 2k + 1 \geq 9 \). Suppose there are two singleton strong components in \( \overline{G}_n \setminus T \), say one with vertex \( a \) and one with vertex \( b \). Then we may assume \( t_1 = k - 1 \) or \( k \), and both \( a \) and \( b \) are singleton strong components in \( H_1 \setminus T_1 \). We first consider the case when \( t_1 = k \), so \( T = T_1 \). Suppose \( a \) is odd. Then there is a vertex \( y \) in \( W \) such that \( a \rightarrow y \) is an arc. (This is a directed \( n \)-edge with \( n \) even.) Now \( a \) has \( k - 1 \) predecessors in \( H_1 \). If one of them, say \( \pi \), is not in \( T \), then \( \pi \) is odd and there is an even vertex \( z \) in \( W \) such that \( z \rightarrow \pi \) is an arc. Hence we have the directed path \( z \rightarrow \pi \rightarrow a \) and the arc \( a \rightarrow y \). Therefore \( a \) belongs to \( Y \). Suppose \( a \) is odd. Then there is a vertex \( y \) in \( W \) such that \( y \rightarrow a \) is an arc. Now \( a \) has \( k - 1 \) successors in \( H_1 \). If one of them, say \( \pi \), is not in \( T \), then \( \pi \) is even and there is an odd vertex \( z \) in \( W \) such that \( \pi \rightarrow z \rightarrow \pi \) is an arc. Hence we have the directed path \( a \rightarrow \pi \rightarrow z \) and the arc \( y \rightarrow a \). Therefore \( a \) belongs to \( Y \). Hence if \( a \) is a strong component in \( \overline{G}_n \setminus T \), \( T \) contains \( k - 1 \) neighbours of \( a \); let \( A \) be such a set. By Lemma 3.3, \( A \cap B \) has at most two vertices. This is impossible since \( k \geq 4 \).

We now consider the case when \( t_1 = k - 1 \). Let \( g \) be the unique vertex in \( T \setminus T_1 \). Suppose \( a \) is odd. Then there is a vertex \( y \) in \( W \) such that \( a \rightarrow y \) is an arc. We consider whether \( y = g \). If \( y \neq g \), then we have a directed path from \( a \) to a vertex in \( W \). Now \( a \) has \( k \) predecessors in \( H_1 \). Every one of them is even and hence has an odd predecessor in \( \overline{G}_n \setminus H_1 \) and these odd vertices are all distinct and one of them is \( g \in T \). This will give a directed path from a vertex in \( W \) to \( a \) (which implies \( a \) is part of \( Y \)) unless \( T \) contains a vertex from each of these directed paths. Hence \( k - 1 \) predecessors of \( a \) are in \( T \). Note that this implies \( a \) is of distance 2 from \( g \) via a vertex in \( H_1 \) and every other vertex in \( T_1 \) is a predecessor of \( a \). If \( y = g \), then \( a \) has \( k \) predecessors in \( H_1 \). Every one of them is even and hence has an odd predecessor in \( W \) and these odd vertices are all distinct. Moreover, these odd vertices are distinct from \( g \). This gives a directed path from a vertex in \( W \) to \( a \). Note that this implies \( a \) is of distance 2 from \( g \) via a vertex in \( H_1 \) and every other vertex in \( T_1 \) is a predecessor of \( a \). If \( y = g \), then \( a \) has \( k \) predecessors in \( H_1 \). At least one of them is not in \( T \) and it has a successor in \( W \) (distance 3 from \( a \)) which is not in \( T \), as \( y = g \). This gives a directed path from \( a \) to a vertex in \( W \) (and hence \( a \) is part of \( Y \)) unless the \( k - 1 \) successors of \( a \) belong to \( T \). Note that in this case, every vertex in \( T \) is a successor of \( a \). The case \( a \) being even is similar. To sum up, \( T_1 \) contains \( k - 1 \) neighbours of \( a \) and \( g \) is of at most distance 2 from \( a \) in \( G_n \). In a similar way, \( T_1 \) contains \( k - 1 \) neighbours of \( b \) and \( g \) is of at most distance 2 from \( b \) in \( G_n \).

Since \( |T_1| = k - 1 \), every vertex in \( T_1 \) is a neighbour of \( a \) and \( b \). Since \( k \geq 4 \), this is impossible by Lemma 3.3. \( \square \)

5. Conclusion

In this paper, we proved that \( \overline{G}_n \) is not only maximally connected but also tightly super connected. So even when the graph is disconnected when \( \lceil \frac{n-1}{2} \rceil \) vertices are deleted, it has two strong components, with one of them being a singleton. Hence the “core” of the graph is still intact. This means \( \overline{G}_n \) has good structural properties. Moreover,
this generalized the result for the Day–Tripathi unidirectional star graph given in [3]. We note that Theorem 4.1 is not surprising as it follows from Nash–Williams [24] that such an orientation exists to give maximal connectivity. However, the orientation that we gave here is a local orientation rule. Moreover, this orientation has stronger connectivity properties as given in Theorems 4.3 and 4.4. In addition, Proposition 3.6 implies that the diameter of $\overrightarrow{G}_n$ is at most 5 times the diameter of $G_n$. So our orientation rule produces maximum connectivity and low diameter in the resulting directed graph, which is a difficult task for general graphs.

One may wonder why we labelled the generating trees as stated. If $n$ is even, then $\overrightarrow{G}_n$ is almost regular. In our proof, we require each $H_j$ to have the same connectivity as $\overrightarrow{G}_{n-1}$ for some $\overrightarrow{G}_{n-1}$. In particular, $H_i$ needs to be regular. So the edges between the $H_j$’s should be $k$-edges where $k$ is even. A simple way to guarantee this is for the chosen leaf-edge to have label $n$.

Finally, one may wonder whether $n \geq 8$ is necessary in Theorem 4.4. We have already seen that the result is not true if $n = 3$. For example, the result is true for $n \geq 4$ for the Day–Tripathi unidirectional star graph as shown in [3]. One can indeed do a tighter analysis on the possible orientation of 4-cycles to present the cases for $n = 4, 5, 6, 7$. However, we feel that it is not worthwhile to lengthen the paper for several small cases.

Acknowledgements

We would like to thank the two anonymous referees for a number of helpful comments and suggestions.

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