On the Relationships between Zero Forcing Numbers and Certain Graph Coverings

Abstract: The zero forcing number and the positive zero forcing number of a graph are two graph parameters that arise from two types of graph colourings. The zero forcing number is an upper bound on the minimum number of induced paths in the graph that cover all the vertices of the graph, while the positive zero forcing number is an upper bound on the minimum number of induced trees in the graph needed to cover all the vertices in the graph. We show that for a block-cycle graph the zero forcing number equals the path cover number. We also give a purely graph theoretical proof that the positive zero forcing number of any outerplanar graphs equals the tree cover number of the graph. These ideas are then extended to the setting of $k$-trees, where the relationship between the positive zero forcing number and the tree cover number becomes more complex.

Keywords: Zero forcing number, positive zero forcing number, path cover number, tree cover number

1 Introduction

The zero forcing number of a graph was introduced in [17] and the related terminology was extended in [4]. Since then this parameter has been considered by a wealth of researchers, see, for example, [3, 5, 12, 16, 19] for additional sources on this topic. Independently, physicists have studied this parameter, referring to it as the graph infection number, in conjunction with control of quantum systems [8–10, 21]. It also arises in computer science in the context of fast-mixed searching [22].

In general, when determining the zero forcing number of a graph we start with a set of initial vertices of the graph (which we say are coloured black, while all other vertices are white). Then, using a particular colour change rule applied to these vertices, we change the colour of white vertices in the graph to black. The repeated application of this colour change rule partitions the graph into disjoint induced paths and each of the initial vertices is an end point of one of these paths. The challenge is to determine the smallest set of initial vertices so that by repeatedly applying the colour change rule will change the colour of every white vertex of the graph to black. Recently a refinement of the colour change rule was introduced (called the positive zero forcing colour change rule) using this rule, the positive semi-definite zero forcing number was defined (see, for example, [4, 13, 14]). When the positive zero forcing colour change rule is applied to a set of initial vertices of a graph, the vertices are partitioned into disjoint induced trees, rather than paths. These parameters are both remarkable since they are graph parameters that provide an upper bound on the algebraic parameters of

Fatemeh Alinaghipour Taklimi: Department of Mathematics and Statistics, University of Regina, 3737 Wascana Parkway, S4S 0A4 Regina SK, Canada, E-mail: alinaghf@uregina.ca
*Corresponding Author: Shaun Fallat: Department of Mathematics and Statistics, University of Regina, 3737 Wascana Parkway, S4S 0A4 Regina SK, Canada, E-mail: shaun.fallat@uregina.ca, Research supported by an NSERC Discovery Research Grant.
Karen Meagher: Department of Mathematics and Statistics, University of Regina, 3737 Wascana Parkway, S4S 0A4 Regina SK, Canada, E-mail: karen.meagher@uregina.ca, Research supported by an NSERC Discovery Research Grant.

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maximum nullity of both symmetric and positive semi-definite matrices associated with a graph (see [4, 5]). That is, for a given graph $G = (V, E)$, we define

$$S(G) = \{ A = [a_{ij}] : A = A^T, \text{ for } i \neq j, a_{ij} \neq 0 \Leftrightarrow \{i, j\} \in E \},$$

and let $S_+(G)$ denote the subset of positive semi-definite matrices in $S(G)$. The maximum nullity of $G$ is $M(G) = \max \{ \text{null}(B) : B \in S(G) \}$ and define $M_+(G) = \max \{ \text{null}(B) : B \in S_+(G) \}$, is called the maximum positive semi-definite nullity of $G$. (Here null$(B)$ denotes the nullity of the matrix $B$.)

In the next section, we define the first colour change rule, along with stating the definition of a zero forcing set and the zero forcing number of a graph. The relationship between these sets and induced paths in the graph will become clear with these definitions. In Sections 3 and 4 we prove the equality between the zero forcing number and the path cover number for the following three families of graphs: block-cycle graphs, double paths, and graphs that we call series of double paths. In Section 5 we define the positive semi-definite colour change rule along with the positive semi-definite forcing number and forcing trees. The positive semi-definite forcing number for graphs that are formed by the graph operation called the vertex sum are considered in Section 6. In Sections 7 and 8 we establish results similar to those in Sections 3 and 4 for the positive semi-definite forcing number. Specifically, we show that the parameters tree cover number and positive zero forcing number agree on double trees and outerplanar graphs. Finally, in Section 9 we give some families of $k$-trees in which we can track both the tree cover number and the positive zero forcing number.

## 2 Zero forcing sets

Let $G$ be a graph in which every vertex is initially coloured either black or white. If $u$ is a black vertex of $G$ and $u$ has exactly one white neighbour, say $v$, then we change the colour of $v$ to black; this rule is called the colour change rule. In this case we say “$u$ forces $v$” which is denoted by $u \rightarrow v$. The procedure of colouring a graph using the colour rule is called a zero forcing process or simply a forcing process. Given an initial colouring of $G$, in which a set of the vertices is black and all other vertices are white, the derived set is the set of all black vertices resulting from repeatedly applying the colour-change rule until no more changes are possible. If the derived set for a given initial subset of black vertices is the entire vertex set of the graph, then the set of initial black vertices is called a zero forcing set. The zero forcing number of a graph $G$ is the size of the smallest zero forcing set of $G$; it is denoted by $Z(G)$. A zero forcing process is called minimal if the initial set of black vertices is a zero forcing set of the smallest possible size.

For any non-empty graph $G$

$$1 \leq Z(G) \leq |V(G)| - 1.$$\)

The lower bound holds with equality if and only if $G$ is a path and the upper bound holds with equality if and only if $G$ is a complete graph. In fact, the parameter $Z(G)$ is also interesting since $M(G) \leq Z(G)$ [4].

If $Z$ is a zero forcing set of a graph $G$, then it is possible to produce a list of the forces in the order in which they are performed in the zero forcing process. This list is called the chronological list of forces. A forcing chain is a sequence of vertices $(v_1, v_2, \ldots, v_k)$ such that $v_i \rightarrow v_{i+1}$, for $i = 1, \ldots, k - 1$ in the forcing process. The forcing chains are not unique for a zero forcing set, as different zero forcing processes can produce distinct sets of forcing chains.

In every step of a forcing process, each vertex can force at most one other vertex; conversely every vertex not in the zero forcing set is forced by exactly one vertex. Thus the maximal forcing chains partition the vertices of a graph into disjoint induced paths. The number of these paths is equal to the size of the zero forcing set and the elements of the zero forcing set are the initial vertices of the forcing chains and hence end-points of these paths (see [4, Proposition 2.10] for more details).

A path covering of a graph is a family of induced disjoint paths in the graph that cover (or include) all vertices of the graph. The minimum number of such paths that cover the vertices of a graph $G$ is the path cover number of $G$ and is denoted by $P(G)$. Since the forcing chains form a set of covering paths we have the following basic result.
Proposition 1. Let \( G \) be a graph, then \( P(G) \leq Z(G) \).

This inequality can be strict, in fact, complete graphs are examples for which the difference between these two parameters can be arbitrarily large, since if \( n > 3 \) we have
\[
P(K_n) = \left\lfloor \frac{n}{2} \right\rfloor < n - 1 = Z(K_n).
\]

Conversely, there are many examples where this inequality holds with equality, for example a path on \( n \) vertices. In the next section we consider families of graphs for which the zero forcing number equals the path cover number.

3 Block-cycle graphs

The most famous family of graphs for which the path cover number agrees with the zero forcing number is trees (see [17, Proposition 4.2]). In this section, we establish this equality for the block-cycle graphs. This result was shown to hold by Row [20]. The proof we give is quite different from Row’s and we also show a relationship between the forcing chains and the covering paths of the graph. We refer readers to [6] where some initial work comparing the maximum nullity and the path cover number for block-cycle graphs appeared.

A graph is called non-separable if it is connected and has no cut-vertices. A block of a graph is a maximal non-separable induced subgraph. A block-cycle graph (also known as cacti) is a graph in which every block is either an edge or a cycle. A block-cycle graph with only one cycle is a unicyclic graph. A cut vertex is a vertex whose removal disconnects the graph; thus any block-cycle graph with no cut vertex is either a cycle or an edge.

It is not hard to see that in a block-cycle graph each pair of cycles can intersect in at most one vertex, since otherwise there will be a block in the graph which is neither a cycle nor an edge. Thus two blocks are said to be adjacent if they have exactly one vertex in common. A pendant vertex in a graph is a vertex that is adjacent to only one other vertex in the graph. A block in a block-cycle graph is a pendant block if it shares only one of its vertices with other blocks of the graph. The next result demonstrates that just as a tree must have at least two pendant vertices, a block-cycle graph must have at least two pendant blocks.

A graph \( H \) is a graph minor of a graph \( G \) if \( H \) can be obtained for \( G \) by removing edges, removing vertices or contracting edges. The proof of the next result involves constructing a graph minor.

Lemma 2. Any block-cycle graph has at least two pendant blocks.

Proof. Let \( G \) be a block-cycle graph with exactly \( n \) blocks. To prove this theorem, we will construct a graph with \( n \) vertices that is a minor of \( G \). We will show that the end-points of the longest induced path in \( G \) are associated to pendant blocks in the original graph.

Let \( B_1, \ldots, B_n \) be the blocks in \( G \). Note that \( B_i \) is either an edge or a cycle, for any \( 1 \leq i \leq N \).

The vertices of \( G \) are \( \{v_1, v_2, \ldots, v_n\} \) and the vertex \( v_i \) is associated to the block \( B_i \). Vertices \( v_i \) and \( v_j \) are adjacent in \( G \) if and only if the blocks \( B_i \) and \( B_j \) share a vertex.

Let \( P = \{u_1, u_2, \ldots, u_k\} \) be the longest induced path in \( G \) and assume that each \( u_i \) corresponds to the block \( B_i \). We will show that both \( B_1 \) and \( B_2 \) are pendant blocks.

If \( B_1 \) is not a pendant block, then there is another block, \( B \), that shares a vertex with \( B_1 \) different from the vertex that \( B_1 \) shares with \( B_2 \). Since \( P \) is a longest induced path, the block \( B \) must also share a vertex with some \( B_i \) with \( i = 2, \ldots, k \). However, in this case the blocks \( B, B_1, B_2, \ldots, B_i \) form a non-separable subgraph that is neither a cycle nor an edge.

The following lemma is straightforward to prove.

Lemma 3. If \( B \) is a pendant block in a block-cycle graph, then
\[
P(G \setminus B) \leq P(G).
\]
**Theorem 4.** Let $G$ be a block-cycle graph. Then

$$Z(G) = P(G).$$

Furthermore, the paths in any minimal path covering of $G$ are precisely the forcing chains in a minimal zero forcing process initiated by an appropriate selection of the end-points of the paths in this collection.

**Proof.** We prove this theorem by induction on the number of blocks in $G$ along with Lemma 2. The only block-cycle graphs with one block are either an edge or a cycle; the theorem is clearly true for these two graphs. Assume that the theorem is true for all block-cycle graphs $G'$ with fewer than $t$ blocks.

Let $G$ be a block-cycle graph, then according to Lemma 2, there is a pendant block, $B$, in $G$ which is connected to the other blocks in $G$ only through the vertex $u$. Let $G'$ be the graph formed by removing all the vertices of the block $B$, except $u$, from $G$.

The graph $G'$ has $t - 1$ blocks, so by the induction hypothesis $Z(G') = P(G')$ and appropriately chosen end-points of the paths in a minimal path covering of $G'$ forms a zero forcing set. By Lemma 3, we have $P(G') \leq P(G)$ and there are two possible cases to consider.

**Case 1:** There is a minimal path-cover $\mathcal{P}$ for the graph $G'$ in which $u$ is the end-point of a path $P$.

First assume that $B$ is the edge $uv$. Then $G'$ is the graph formed by removing the pendant vertex $v$ from $G$. Since $u$ is an end-point of $P$ and $v$ is only connected to $u$, returning $B$ to $G'$ does not change the path cover number of the graph. By the induction hypothesis, the paths in the path-cover $\mathcal{P}$ are the forcing chains of the forcing process initiated by the end-points of the paths in $\mathcal{P}$. Also since $u$ is an end-point of $P$, we can assume that it does not perform any forces. Therefore, the zero forcing process will be continued by using $u$ to force $v$. Thus,

$$P(G') = P(G) \leq Z(G) \leq Z(G') = P(G'),$$

which implies $Z(G) = P(G)$.

Next assume that $B$ is a pendant cycle. Then

$$P(G') + 1 \leq P(G),$$

since at least two paths are needed to cover the vertices of a cycle. Let $v$ and $w$ be the two neighbours of $u$ in $B$. Then, since $u$ is an end-point of $P$, the induced path $P' = P \cup (V(B) \setminus \{v\})$ covers all vertices in the cycle $B$ except $v$. Thus $(\mathcal{P} \setminus \{P\}) \cup \{P', \{v\}\}$ is a path cover for $G$ and $P(G) = P(G') + 1$.

We also need that these paths are forcing chains. By assigning colour black to the vertex $v$, all vertices in $B$ will be coloured by continuing the forcing process in $P$ through $u$. Thus,

$$P(G') + 1 = P(G) \leq Z(G) \leq Z(G') + 1 = P(G') + 1,$$

which implies $Z(G) = P(G)$.

**Case 2:** In every minimal path covering $\mathcal{P}$ of $G'$, the vertex $u$ is an inner vertex of a path $P$ in $\mathcal{P}$.

Again, we first assume that $B$ is an edge $uv$. Since $\mathcal{P} \cup \{v\}$ covers all the vertices of $G$, we have that $P(G) \leq P(G') + 1$. But if $P(G) = P(G')$, then $v$ is covered in the same path as $u$ in a path covering of $G'$; this contradicts the fact that $u$ is not an end-point of any path in any path covering of $G$. Thus $P(G) = P(G') + 1$.

If the vertex $v$ is assigned the colour black, then we are able to colour the graph $G$ following the same forcing process which we followed to colour the graph $G'$. Thus,

$$P(G') + 1 = P(G) \leq Z(G) \leq Z(G') + 1 = P(G') + 1,$$

which implies $Z(G) = P(G)$.

If $B$ is a cycle, then $P(G) = P(G') + 1$, since $\mathcal{P}$ along with a path covering the vertices of $B \setminus \{u\}$, covers all vertices of $G$.

Let $w$ be a vertex in $B$ that is a neighbour of $u$. The set of initial set of black vertices in the zero forcing set of $G$ along with $w$ forms a zero forcing set for $G$. Thus,

$$P(G') + 1 = P(G) \leq Z(G) \leq Z(G') + 1 = P(G') + 1,$$
which implies $Z(G) = P(G)$. □

The following corollary is obtained from the fact that any unicyclic graph is a block-cycle graph. This result was also recently shown to be true in [19].

**Corollary 5.** If $G$ is a unicyclic graph, then $Z(G) = P(G)$. □

It seems that for general graphs it is rare to have the equality $Z(G) = P(G)$. To show this, along with the fact that the discrepancy between $Z(G)$ and $P(G)$ can be arbitrarily large, we focus on the family of graphs with $P(G) = 2$.

**Proposition 6.** Let $G$ be a graph with $P(G) = 2$ and two covering paths $P_1$ and $P_2$ with $|P_1| = m$ and $|P_2| = n$. Then

$$2 \leq Z(G) \leq \min\{n, m\} + 1.$$  

Moreover, for any number $k$ in this interval, there is a graph $G$ satisfying $P(G) = 2$ with $Z(G) = k$.

**Proof.** Assume that $m \leq n$ and note that the claim that $Z(G) \geq 2$ is trivial.

Let $B$ be the set consisting of $V(P_1)$ and an end-point of $P_2$. Obviously $B$ is a zero forcing set for $G$. Thus $Z(G) \leq |B| = m + 1 \leq \min\{n, m\} + 1$.

Let $k$ be any number in the interval $\{1, \ldots, \min\{m, n\}\}$ and $P_1$ and $P_2$ be two paths with $|P_1| = m$ and $|P_2| = n$. Starting with an end-point of $P_1$ make each of the first $k$ consecutive vertices of $P_1$ adjacent to all of the vertices of $P_2$. Then, it is easy to observe that forcing number of this graph is $k + 1$ (the forcing set consists on the consecutive $k$ vertices of $P_1$ along with an end-point of $P_2$). □

In the next section we discuss a family of graphs for which $P(G) = Z(G) = 2$.

## 4 Double paths

A graph is outerplanar if there exists a planar embedding of the graph in which all the vertices are contained in a single face. If an outerplanar graph, that is not a path, has the property that its vertices can be covered with two induced paths, then the graph is called a double path or a parallel path. Such graphs were also called a graph of two parallel paths in [18]. We refer to these two induced paths, naturally, as the covering paths. Clearly if $G$ is a double path, then $P(G) = 2$. We will show that $Z(G)$ is also 2, so double paths are another family of graphs for which the path cover number equals the zero forcing number.

**Theorem 7.** If $G$ is a double path, then $Z(G) = 2$.

**Proof.** Assume that $P_1$ and $P_2$ are the two covering paths of $G$ in a given embedding of $G$. Thus the paths are fixed and we can talk about the left end points of the paths (or, equivalently, the right end points). Let $u$ be the left end point of $P_1$ and $v$ the left end point of $P_2$. It is not difficult to deduce that since no edges are cross in this graph, the set $\{u, v\}$ forms a minimal zero forcing set for $G$. □

Note, if we choose the left endpoints $\{u, v\}$ of a double path, then it follows that $P_1$ and $P_2$ (as in the proof above) will also form the corresponding zero forcing chains for a double path.

Row [19] proves that both Theorem 7 and its converse hold. The proof of the converse follows since if $Z(G) = 2$ for some graph $G$, then $M(G) \leq 2$ and the graphs with $M(G) = 2$ have been characterized [18].

The concept of a double path can be generalized. If the vertices of a graph $G$ can be partitioned into paths $P_1, P_2, \ldots, P_k$ so that:

1. the only vertices not in the path $P_i$ that are adjacent to a vertex in $P_i$ are in either $P_{i-1}$ or $P_{i+1}$ (assume $P_0$ and $P_{k+1}$ are the empty set), and
2. the graph induced by $P_i$ and $P_{i+1}$ is a double path for $i = 1, \ldots, k - 1$,
then $G$ is called a *series of parallel paths*.

**Theorem 8.** If $G$ is a series of parallel paths, then $Z(G) = P(G)$. Moreover, the left (or right) endpoints of the covering paths form a zero forcing set.

**Proof.** We use induction on the number of paths. If there are two paths, then the result follows from Theorem 7 and assume the result holds for any series of parallel paths with $k$ paths.

Let $G$ be a graph that is the series of $k + 1$ parallel paths and assume that $P_{k+1}$ is the final path. Set $G' = G\backslash(P_{k+1})$. The set of left end points of the path covering of $G'$ forms a zero forcing set of $G'$. Then these end points, together with the left end point of $P_{k+1}$ forms a zero forcing set for $G$ and the forcing chains are the paths, $P_1, P_2, \ldots, P_{k+1}$. \qed

We note here that Theorem 8 may be used to yield the zero forcing number of the grid, namely the Cartesian product of two paths (see also [1]). That is, the zero forcing number of the $m$-by-$n$ grid is given by $\min\{m, n\}$. Theorem 7 can also be obtained from [18, Theorem 5.1], although zero forcing is not considered in [18]. In fact, they show that among all the graphs with $P(G) = 2$, only those that are also outerplanar satisfy $M(G) = 2$.

There are outerplanar graphs for which the path cover number and the zero forcing number are arbitrarily far apart (see, for example, [4, Ex. 2.11]). Motivated by this, in the next section we consider positive zero forcing sets, and the positive zero forcing number.

## 5 Positive zero forcing sets

In 2010, a variant of the zero forcing number, called positive semi-definite zero forcing or the positive zero forcing number, was introduced in [4], and a collection of its properties were discussed in [13] and [14]. The positive zero forcing number is also based on a colour change rule that is very similar to the zero forcing colour change rule. Let $G$ be a graph and $B$ a set of vertices; we will initially colour the vertices of $B$ black and all other vertices white. Let $W_1, \ldots, W_k$ be the set of vertices of the connected components of $G \backslash B$. If $u$ is a vertex in $B$ and $w$ is the only white neighbour of $u$ in the graph induced by $V(W_i \cup B)$, then $u$ can force the colour of $w$ to black. This is the *positive colour change rule*. The definitions and terminology for the positive zero forcing process, such as, colouring, derived set, positive zero forcing number etc., are identical to those for the zero forcing number, except we use the positive semi-definite colour change rule.

The size of the smallest positive zero forcing set of a graph $G$ is denoted by $Z_+(G)$. Note that for any non-empty graph

$$1 \leq Z_+(G) \leq |V(G)| - 1;$$

the lower bound holds with equality if and only if $G$ is a tree and the upper bound only for complete graphs. Also for all graphs $G$, since a zero forcing set is also a positive zero forcing set we have that $Z_+(G) \leq Z(G)$. Moreover, in [4] it was observed that $M_+(G) \leq Z_+(G)$, for any graph $G$.

We have seen that applying the zero forcing colour change rule to the vertices of a graph produces a path covering for the graph. Analogously, applying the positive colour change rule produces a set of induced trees in the graph, and we refer to these trees as *forcing trees*. To define these trees, let $G$ be a graph and $Z_p$ be a positive zero forcing set of $G$. Construct the derived set, recording the forces in the order in which they are performed; this is the chronological list of forces. Note that in applying the colour change rule once, two or more vertices can perform forces at the same time and a vertex can force multiple vertices from different components at the same time. For any chronological list of forces, a forcing tree is an induced rooted tree, $T_r$, formed by a sequence of sets of vertices $(r, X_1, \ldots, X_k)$, where $r \in Z_p$ is the root and the vertices in $X_i$ are at distance $i$ from $r$ in the tree. The vertices of $X_i$ for $i = 1, \ldots, k$, are forced by applying the positive semi-definite colour change rule with the vertices in $X_{i-1}$; so for any $v \in X_i$ there is a $u \in X_{i-1}$, such that $u$ forces $v$ if and only if $v$ is a neighbour of $u$. 

In a forcing tree, the vertices in $X_i$ are said to be the vertices of the $i$-th level in the tree. Note that the vertices in a specific level may have been forced in different steps of the positive semi-definite colour change procedure and they may also perform forces in different steps.

**Example 9.** The positive zero forcing number of the graph $G$ in Figure 1 is three and $\{1, 3, 10\}$ is a positive zero forcing set for the graph. The forcing trees in this colouring procedure (as depicted in Figure 1) are as follows:

- $T_1 = \{1, X_1, X_2, X_3\}$, where $X_1 = \{2, 6\}$, $X_2 = \{5, 7\}$, $X_3 = \{4, 8\}$,
- $T_3 = \{3\}$, $T_{10} = \{10, X_1\}$, where $X_1 = \{9\}$.

Our next concept is analogous to the path cover number of a graph. A tree covering of a graph is a family of induced vertex disjoint trees in the graph that cover all vertices of the graph. The minimum number of such trees that cover the vertices of a graph $G$ is the tree cover number of $G$ and is denoted by $T(G)$. Any set of forcing trees corresponding to a minimal positive zero forcing set is of size $Z_+(G)$ and covers all vertices of the graph. This implies the following.

**Proposition 10.** For any graph $G$, we have $T(G) \leq Z_+(G)$.

This bound is clearly tight for trees and cycles. But there are graphs, such as complete bipartite graphs, for which the discrepancy between these parameters can be arbitrarily large. It is, hence, an interesting question to ask for which families of graphs does equality hold between these two parameters. One way to approach this problem is to find a graph operation which preserves the equality in graphs for which these parameters agree. Using this approach, in the next section we will prove that equality between these two parameters holds for block-cyclic graphs. In Section 7 we will define a family of graphs called double trees, these are analogous to the double paths of Section 4 and we will show that the positive zero forcing number and the tree cover number of these graphs coincide. We will also show these parameters are equal for a much larger family of graphs in Section 8.

## 6 Vertex-sum of graphs

Let $G$ and $H$ be two graphs and assume that $v$ is a vertex of both $G$ and $H$, then the vertex sum of $G$ and $H$ over $v$ is the graph formed by identifying $v$ in the two graphs. The vertex-sum is denoted by $G \uplus_H v$.

A block-cycle graph can be recursively defined as the vertex sum of a block-cycle graph with a cycle or a path. The next result shows how to calculate the tree cover number of the vertex sum of two graphs.

**Lemma 11.** For any graphs $G$ and $H$, both with an identified vertex $v$, we have

$$T(G \uplus_H v) = T(G) + T(H) - 1.$$
Proof. Let \( \mathcal{T}_G \) and \( \mathcal{T}_H \) be minimal tree coverings of \( G \) and \( H \), respectively, and suppose \( T_1 \in \mathcal{T}_G \) and \( T_2 \in \mathcal{T}_H \) are the trees covering \( v \). Let \( T_v = T_1 + T_2 \). Observe that \( T_v \) is an induced tree in \( G + H \) that also covers \( v \). Therefore,

\[
((\mathcal{T}_G \cup \mathcal{T}_H) \setminus \{T_1, T_2\}) \cup T_v
\]

is a tree covering of \( G + H \).

Next we show, in fact, the vertices of \( G + H \) can not be covered with fewer trees. Suppose that the vertices of \( G + H \) can be covered with \( T(G) + T(H) - 2 \) induced disjoint trees. Let \( T \) be the tree that covers \( v \) in such a tree covering of \( G + H \). At least \( T(G) - 1 \) trees are needed to cover the vertices of \( G \setminus T \). Since the number of trees in the covering of \( G + H \) is \( T(G) + T(H) - 2 \), the vertices of \( H \setminus T \) are covered by at most \( (T(H) - 2) \) trees, but this contradicts the fact that \( T(H) \) is the least number of trees that cover the vertices of \( H \). \( \square \)

Lemma 12. For any graphs \( G \) and \( H \), both with an identified vertex \( v \), we have

\[
Z_\nu(G + H) = Z_\nu(G) + Z_\nu(H) - 1.
\]

Proof. To prove this equality, let \( \mathcal{T}_G \) and \( \mathcal{T}_H \) be the sets of forcing trees for a minimal positive zero forcing set in \( G \) and \( H \) respectively. Let \( T_1 \in \mathcal{T}_G \) and \( T_2 \in \mathcal{T}_H \) be the trees that contain \( v \). Then \( T_1 + T_2 \) is a forcing tree in \( G + H \) covering \( v \). Then similar reasoning as in the previous lemma applies. \( \square \)

Corollary 13. If \( G \) and \( H \) are two graphs that satisfy \( Z_\nu(G) = T(G) \) and \( Z_\nu(H) = T(H) \), then

\[
Z_\nu(G + H) = T(G + H),
\]

where \( v \) is an identified vertex in both \( G \) and \( H \). \( \square \)

Since a block-cycle graph is the vertex sum of a block-cycle graph and either a cycle or a path we have the following result.

Corollary 14. If \( G \) is a block-cycle graph, then \( Z_\nu(G) = T(G) \). \( \square \)

7 Double trees

In the next section, we will show that \( Z_\nu(G) = T(G) \) for every outerplanar graph. The first step towards verifying this claim is to show that it holds for a subset of these graphs called double trees. Recall that in Section 4 we defined a double path, whereas a double tree can be viewed as an extension of the concept of a double path. If the vertices of a connected outerplanar graph, which is not a tree, can be covered with two induced trees, then the graph is called a double tree.

Our first step will be to show that if \( G \) is a double path, then \( Z_\nu(G) = T(G) = 2 \). Then any double tree can be constructed by applying an appropriate series of vertex sums of trees with an appropriate double path. Thus, from Corollary 13, we will be able to conclude that \( Z_\nu(G) = T(G) = 2 \) holds for any double tree.

In the following three lemmas we find different positive zero forcing sets for double paths. In all of these lemmas we will assume that \( G \) is a double path with a specific planar embedding of \( G \) with covering paths \( P_1 \) and \( P_2 \). Since this planar embedding of \( G \) is fixed, we can refer to the end points of a covering path as the right end point and the left end point.

Lemma 15. If \( u \) and \( v \) are both right (or both left) end points of \( P_1 \) and \( P_2 \), respectively, then \( \{u, v\} \) is a positive zero forcing set of \( G \). Moreover, if \( \{u, v\} \) is initially coloured black, then there is a positive zero forcing process in which the forcing trees are \( P_1 \) and \( P_2 \).

Proof. We prove this lemma by induction on the number of vertices. The result is true for \( C_3 \), which is a connected double path on the fewest number of vertices. Assume that it is true for all graphs \( H \) with \( |V(H)| < n \).
Let $G$ be a graph on $n$ vertices. Assume that $u$ and $v$ are left end points of $P_1$ and $P_2$, respectively. By assigning the colour black to each of these vertices we claim that $\{u, v\}$ is a positive zero forcing set of $G$.

If $u$ is a pendant vertex, then it forces its only neighbour, say $w$ (which must be in $P_1$), which is a left end point of a covering path in $G \setminus u$. Thus by the induction hypothesis $\{w, v\}$ is a positive zero forcing set of $G$ and there is a positive zero forcing process in which the forcing trees are $P_1$ and $P_2$. Similarly if $v$ is a pendant vertex, using a similar reasoning, the lemma follows.

If neither $u$ nor $v$ are pendant, then $u$ and $v$ are adjacent and since both are left end points, at least one of them, say $u$, is of degree two. Let $w$ be the only neighbour of $u$ in $P_1$. Thus $u$ can force $w$ (its only white neighbour) and again by the induction hypothesis $\{w, v\}$ is a positive zero forcing set of $G$ and there is a positive zero forcing process in which the forcing trees are $P_1$ and $P_2$. The same reasoning applies when $u$ and $v$ are the right end points of $P_1$ and $P_2$, respectively.

**Lemma 16.** If $u$ and $v$ are two vertices of $P_1$ and $P_2$, respectively, which form a cut set for $G$, then $\{u, v\}$ is a positive zero forcing set for $G$. Moreover, there is a positive zero forcing forcing process in which $P_1$ and $P_2$ are the forcing trees (with $u$ and $v$ the roots of the trees).

**Proof.** Let $W_1 \subseteq V(G)$ and $W_2 \subseteq V(G)$ be the vertices of the left hand side and the right hand side components of $G \setminus \{u, v\}$, respectively, and let $G_1$ and $G_2$ be the subgraphs induced by $\{u, v\} \cup W_1$ and $\{u, v\} \cup W_2$, respectively. Then according to Lemma 15, $\{u, v\}$ is a positive zero forcing set for both $G_1$ and $G_2$ and thus a positive zero forcing set for $G$ and there is a positive zero forcing process in which $P_1$ and $P_2$ are the forcing trees.

**Lemma 17.** If $u$ is a vertex in $P_1$ which is not an end point, then there is always a vertex $v$ in $P_2$ such that $\{u, v\}$ is a cut set of $G$.

**Proof.** If $P_2$ contains at most two vertices this result is clear since $u$ is not an end point. Suppose there is a vertex $u$ in $P_1$ for which there is no vertex $v$ in $P_2$ such that $\{u, v\}$ is a cut set for $G$. This implies that $|P_2| \geq 3$ since if $P_2 = \{v_1, v_2\}$, then at least one of $\{u, v_1\}$ or $\{u, v_2\}$ is a cut set.

Let $v$ be any non-pendant vertex of $P_2$. Obviously $u$ is a cut vertex of $P_1$ and $v$ is a cut vertex of $P_2$. Since $\{u, v\}$ is not a cut set of $G$, there is a vertex on the left hand side (or right hand side) of $u$ that is adjacent to a vertex in the right hand side (or left hand side) of $v$. Assume that $w$ is the farthest vertex from $v$ in $P_2$ having this property. Since $w$ is the farthest vertex from $v$ with the described property and $G$ is an outerplanar graph, $\{u, w\}$ is a cut set of $G$ which contradicts with the fact that, there is no vertex in $P_2$ that forms a cut set along with $u$ for $G$.

Combining Lemmas 15, 16 and 17 along with the fact that in the proof of all three lemmas forces are performed along the covering paths, we have the following.

**Corollary 18.** Let $G$ be a double path with covering paths $P_1$ and $P_2$. Then for any vertex $v$ in $P_1$, there is always another vertex $u$ in $P_2$ such that $\{u, v\}$ is a positive zero forcing set for $G$. Moreover there is a positive zero forcing process in which the two paths $P_1$ and $P_2$ are a minimal set of forcing trees in $G$.

The following result is a consequence of Corollary 18.

**Corollary 19.** Let $G$ be a double tree with covering trees $T_1$ and $T_2$. Then for any vertex $v$ in $T_1$, there is always another vertex $u$ in $T_2$ such that $\{u, v\}$ is a positive zero forcing set for $G$. Moreover $\{T_1, T_2\}$ coincides with a minimal collection of forcing trees in $G$. 


8 Outerplanar graphs

In [7] it is shown that the maximum positive semi-definite nullity is equal to the tree cover number for any outerplanar graph. Since the positive zero forcing number is an upper bound on the maximum positive semi-definite nullity, we have that \( Z_+(G) \geq T(G) \); however, \( Z_+(G) = T(G) \) holds for any outerplanar graph. This equality was shown to be true in [7] and [14] (where the proof is generalized to 2-trees), in this section we give a different proof of this fact that does not rely on Schur-complements or orthogonal removal. Moreover, we show that any minimum tree covering of an outerplanar graph coincides with a minimum collection of zero forcing trees.

In a fixed tree covering of a graph, two trees, \( T_1 \) and \( T_2 \), are said to be adjacent if there is at least one edge \( uv \in E(G) \) such that \( v \in V(T_1) \) and \( u \in V(T_2) \). A tree is called pendant if it is adjacent to only one other tree from this given tree covering.

Throughout this section, \( G \) will be an outerplanar graph with a planar embedding in which all the vertices are on the same face. An edge of \( G \) is called outer if it lies on the face containing all of the vertices; if an edge is not outer, then it is called inner. Further, let \( \mathcal{T}(G) \) be a minimal tree covering for \( G \). Define \( H_T \) to be the graph whose vertices correspond to the trees in \( \mathcal{T}(G) \) and two vertices in \( H_T \) are adjacent if there is an outer edge between the corresponding trees in the graph \( G \). Two trees of \( \mathcal{T}(G) \) are called consecutive, if their corresponding vertices in \( H_T \) are adjacent vertices each of degree two.

**Theorem 20.** Let \( G \) be an outerplanar graph and \( \mathcal{T}(G) \) a minimum tree covering for \( G \). If there is no pendant tree in \( \mathcal{T}(G) \), then there is at least one pair of consecutive trees in \( \mathcal{T}(G) \).

**Proof.** Assume that \( \mathcal{T}(G) \) is a minimum tree covering for \( G \) in which there is no pendant tree. Then, two cases are possible:

**Case 1.** There is no tree in \( \mathcal{T}(G) \) with at least one of the inner edges of \( G \) in its edge set (see Figure 2 for an example of such a graph). Therefore \( H_T \) is a cycle. Accordingly, any adjacent pair of trees in \( \mathcal{T}(G) \) are consecutive.

![Fig. 2. Forcing trees with no inner edge in their edge set](image)

**Case 2.** There is at least one tree in \( \mathcal{T}(G) \) that has an inner edge of \( G \) in its edge set (Figure 3 gives an example of such a graph).

The idea in this case is that we will select a “left-most” such inner edge of \( G \). Then the subgraph induced by this edge, and all the vertices to the left of the edge, form an outerplanar graph in which no tree includes an inner edge of \( G \). In case 1, we showed that such a subgraph will have a consecutive pair of trees, and thus so will \( G \).

First, let \( W \) be the set of all vertices which are the end-points of an inner edge of \( G \) that are also included in the edge set of a tree in \( \mathcal{T}(G) \). Second, note that any inner edge \( e = \{u, v\} \) of \( G \) partitions the plane into two parts and, consequently, partitions the set of vertices of \( G \setminus \{u, v\} \) into two subsets \( V_e \) and \( V_e^c \). Since \( G \) is
outerplanar and finite, there exists an inner edge, $e$ in $W$ such that at least one of $V_e$ or $V_e^c$ does not contain any of the vertices in $W$. We will assume that $V_e$ is the vertex set that is disjoint from $W$.

The subgraph of $G$ induced by the vertices $V_e \cup \{u, v\}$ is an outerplanar graph; call this $H$. The trees in $\mathcal{T}(G)$ that intersect with $H$ form a minimal tree covering of $H$, which we will call $\mathcal{T}(H)$. None of the trees in $\mathcal{T}(H)$ can include an inner edge of $H$ (this follows as there are no vertices that are both in $H$ and in $W$). By Case 1, there is a pair of adjacent trees in $\mathcal{T}(H)$ and therefore there is at least one pair of consecutive trees in $\mathcal{T}(G)$.

The following theorem shows that for any outerplanar graph, it is possible to find a minimal tree covering that has a pendant tree; this plays a key role in the proof of the fact that outerplanar graphs satisfy $Z_r(G) = T(G)$.

**Theorem 21.** Let $G$ be an outerplanar graph. Then there is a minimum tree covering for $G$ in which there is a pendant tree.

**Proof.** Assume that $\mathcal{T}(G)$ is a minimum tree covering for $G$ in which there is no pendant tree. We use Theorem 20 to construct a new tree covering $\mathcal{T}'(G)$ of $G$ with $|\mathcal{T}'(G)| = |\mathcal{T}(G)|$ in which there is a pendant tree.

By Theorem 20 there are two trees $T_1$ and $T_2$ in $\mathcal{T}(G)$, which are consecutive. Let $H$ be the outerplanar graph induced by $V(T_1) \cup V(T_2)$. There are two outer edges in $H$ that have an end-point from each of trees $T_1$ and $T_2$ (otherwise $T_1 \cup T_2$ would be a tree and $\mathcal{T}(G)$ would not be a minimum tree covering). One of these outer edges of $H$, call it $e = \{u, v\}$, is an inner edge in $G$; we will assume that $u \in T_1$ and $v \in T_2$.

Similarly, if $u$ has any neighbour, other than $v$, in $T_2$, then $v$ has no other neighbours in $T_1$. Thus we will assume that $v$ is the only neighbour of $u$ in $T_2$.

In fact, the subgraph $T_1 \setminus \{u\}$ is a forest and exactly one of the trees in the forest has vertices which are adjacent to a vertex in $T_2$. Call this tree $S_1$. Define a second new tree by

$$S_2 = \left( T_2 + \{u, v\} \right) +_u (T_1 \setminus S_1).$$

By replacing $T_1$ and $T_2$ in $\mathcal{T}(G)$ with $S_1$ and $S_2$ we can construct a new minimum tree covering for $G$ in which $S_1$ is a pendant tree.
A similar argument applies when \( u \) has another neighbour in \( T_2 \). If neither \( u \) nor \( v \) has any other neighbour in \( T_2 \) and \( T_1 \), respectively, then either case mentioned above is applicable.

We now have all the necessary tools to prove the main result of this section.

**Theorem 22.** Let \( G \) be an outerplanar graph. Then

\[
Z_*(G) = T(G).
\]

Moreover, any minimal tree covering of the graph \( \mathcal{T}(G) \) coincides with a collection of forcing trees with \( |\mathcal{T}(G)| = Z_*(G) \).

**Proof.** We prove the claim by induction on the tree cover number and using Theorem 21. It is obviously true for \( T(G) = 1 \). Assume that it is true for any outerplanar graph \( G' \) with \( T(G') < k \). Now let \( G \) be an outerplanar graph with \( T(G) = k \). By Proposition 10, we have \( Z_*(G) \leq T(G) \).

Let \( \mathcal{T}(G) = \{T_1, T_2, \ldots, T_k\} \) be a minimum tree covering of \( G \). We first consider the case when \( \mathcal{T}(G) \) contains a pendant tree.

**Case 1.** Assume that \( T_1 \) is a pendant tree and that \( T_2 \) is the only tree adjacent to \( T_1 \). Let \( G' \) be the graph induced by the vertex set \( V(G) \setminus V(T_1) \), then the induction hypothesis holds, so \( T(G') = Z_*(G') = k - 1 \). Further, \( T_2, T_3, \ldots, T_k \) are forcing trees in a positive zero forcing process whose initial set of black vertices, \( Z_p \), has a vertex from each tree in \( \mathcal{T}(G) \setminus T_1 \).

A positive zero forcing process in \( G \) starting with the black vertices in \( Z_p \) can proceed as it does in \( G' \) until the first vertex of \( T_2 \), say \( x \), that is adjacent to some vertex in \( T_1 \) gets forced. Since the graph induced by \( V(T_1) \cup V(T_2) \) is a double tree, according to Corollary 19, the vertex \( x \) determines a vertex \( y \) in \( T_1 \) such that \( \{x, y\} \) is a positive zero forcing set for the subgraph induced by \( V(T_1) \cup V(T_2) \). Since the induction hypothesis holds for this subgraph, the tree \( T_2 \) is a forcing tree in this subgraph as well. Thus the vertices of \( T_2 \) get forced in the same order as they were forced in \( G' \).

Therefore we can complete the colouring of \( G \) by adding the vertex \( y \) to the initial set of black vertices. Thus, \( Z_p = Z_p \cup \{y\} \) is a positive zero forcing set of \( G \) with \( T_1, T_2, \ldots, T_k \) as the forcing trees in this positive zero forcing process. Thus, \( Z_*(G) = T(G) \).

**Case 2.** If \( \mathcal{T}(G) \) does not contain a pendant tree, then by Theorem 21, it is possible to build a new tree covering that does have a pendant tree. By Case 1, this new tree covering has exactly \( Z_*(G) \) trees and the trees of this new tree covering are forcing trees. Now we need to show that the original minimal tree covering of the graph \( G \) also coincides with a collection of forcing trees associated with a positive zero forcing set of \( G \).

We will assume that \( T_1 \) and \( T_2 \) are a pair of consecutive trees in \( \mathcal{T}(G) \) (from Theorem 20 we know that such a pair exists). Using the same notation as in Theorem 21 we assume that \( v \in T_2 \) has a neighbour, other than \( u \), in \( T_1 \) (the other cases are similar). In the procedure of constructing a pendant tree in the minimal tree covering of \( G \), the pair of consecutive trees \( T_1 \) and \( T_2 \) were modified to obtain two new trees called \( S_1 \) and \( S_2 \). The tree \( S_1 \) is pendant and only adjacent to the tree \( S_2 \) in the new minimal tree covering. Let

\[
\mathcal{T}(G)' = \left( \mathcal{T}(G) \setminus \{T_1, T_2\} \right) \cup \{S_1, S_2\},
\]

and define

\[
T_1' = T_1 \setminus S_1, \quad T_1' = S_1.
\]

We will use a similar decomposition of \( T_2 \). Let \( T_2' \) be the set of all the trees in the forest \( T_2 \setminus \{v\} \) that have a vertex which is adjacent to some vertex in \( T_1' \). Define \( T_2'' = T_2 \setminus T_2' \).

Let \( Z_p \) be a positive zero forcing set for \( G \) for which \( \mathcal{T}(G)' \) is a set of zero forcing trees. Assume that \( x \in V(S_2) \) and \( y \in V(S_1) \) are the two vertices in \( Z_p \) from the trees \( S_1 \) and \( S_2 \) (from Case 1 such the zero forcing set must have two such vertices). We will consider two cases, the first is when \( x \) is a vertex in \( T_2 \) and second is when \( x \in T_1 \).

In the first case \( x \in T_2 \) and \( y \in T_1 \). We claim that \( Z_p \) is a positive zero forcing set and there is positive zero forcing process in which the trees of \( \mathcal{T}(G) \) are the zero forcing trees. To see this we will describe the positive zero forcing process.
The positive zero forcing process proceeds along the forcing trees $S_1$ and $S_2$ until the vertex $v$ is forced. Note that in the original process, $v$ must force $u$. If the vertices $v$ and $y$ are removed then one of the connected components will include all of $T_2'$ and some of the vertices from $T_1'$. Starting with $v$ and $y$ it is possible to force all the vertices in this component following the trees $T_2'$ and the portion of $T_1'$ in the component. Once all the vertices of $T_2'$ are black, $y$ can force the remaining vertices along the tree $T_1'$. Then the vertex in $T_1'$ that is adjacent to $u$ will force $u$. Then $u$ can force the remaining vertices of $T_1'$.

In the second case both $x$ and $y$ are vertices in $T_1$. We claim that $(Z_2 \setminus \{x\}) \cup \{v\}$ is a positive zero forcing set and there is a positive zero forcing process in which the trees of $T(G)$ are the zero forcing trees. Just as in the previous case, using $v$ and $y$ all the vertices of $T_2'$ will be forced. Then, starting with $y$, all the vertices for $T_1'$ will be forced with $T_1'$ the forcing tree. Then the unique vertex in $T_1'$ adjacent to $u$ will force $u$ and the positive zero forcing process will continue along $T_1'$. Finally, starting with $v$, the vertices along $T_2'$ will be forced.

9 $k$-Trees

A $k$-tree is constructed inductively by starting with a complete graph $K_{k+1}$ and at each step a new vertex is added and this vertex is adjacent to exactly $k$ vertices in an existing $K_k$. A partial $k$-tree is any graph that is the subgraph of a $k$-tree. In particular, a graph is a partial 2-tree if and only if it does not have a $K_4$ minor (see [11, p. 327]). Since outerplanar graphs are exactly the graphs with no $K_4$ and $K_{2,3}$ minors (see [11, p. 107], it is easy to see that every outerplanar graph is a partial 2-tree. In [14] it is shown that the proof that the maximum positive semi-definite nullity for outerplanar graphs is equal to the tree cover number from [7], can be extended to include any partial 2-tree. From this it follows that if $G$ is a partial 2-tree, then $Z_2(G) = T(G)$.

In this section, we will give a purely graph theoretical version of this result for a subset of 2-trees. We also try to track the variations between the positive zero forcing number and the tree cover number in this subset of $k$-trees with $k > 2$. This demonstrates that 2-trees are rather special when it comes to comparing $Z_2(G)$ and $T(G)$.

We will define a type of $k$-tree that we call a $k$-cluster. These $k$-trees are constructed recursively starting with a $H = K_{k+1}$. At each step a new vertex is added to the graph and this new vertex is adjacent to exactly $k$ of the vertices in $H$. A $k$-clique is a set of $k$ vertices in which any two are adjacent; at each step the new vertex is adjacent to all the vertices in a $k$-clique in $H$. In a general $k$-tree the new vertices are adjacent to any $k$-clique in the graph, but in a $k$-cluster the new vertices must be adjacent to a $k$-clique in $H$. Observe that for each vertex $v$ not in $H$, there is exactly one vertex in $H$ that is not adjacent to it.

If $G$ is a $k$-cluster, then define $S(G)$ to be the set of all distinct $k$-cliques $H' \subset H$ with the property that $H' \cup \{v\}$ forms a clique of size $k + 1$ in $G$, for some $v \in V(G) \setminus V(H)$. The size of $S(G)$ can be no more than $k + 1$.

**Theorem 23.** Suppose $G$ is a $k$-cluster and let $S(G)$ be as defined above.

1. If $|S(G)| \geq 3$, then $Z_2(G) = k + 1$.
2. If $|S(G)| < 3$, then $Z_2(G) = k$.
3. If $|S(G)| = k + 1$ and $k$ is even, then $T(G) = \left\lceil \frac{k+1}{2} \right\rceil + 1$.
4. If $|S(G)| < k + 1$ and $k$ is even, then $T(G) = \left\lceil \frac{k+1}{2} \right\rceil$.

**Proof.** Since the minimum degree of $G$ is $k$, it is clear that $Z_2(G) \geq k$. Suppose $H$ is the initial $K_{k+1}$ in the $k$-cluster. Obviously, the set $V(H)$ is a positive zero forcing set for $G$ and $Z_2(G) \leq k + 1$.

To prove the first statement suppose $B$ is a positive zero forcing set of $G$ with $|B| = k$. Since $|S(G)| \geq 3$, there are three vertices $u, v, w \in V(G) \setminus V(H)$ that are adjacent to distinct $k$-sets in $H$. Thus any vertex $x \in V(H)$ is adjacent to at least two of these vertices. So no positive zero forcing set can be contained in $V(H)$. Thus there must be a vertex $z \in B$ such that $z \not\in H$. If $z$ has only one white neighbour, then all the $k - 1$ other vertices in $B$ must all be in $H$ and the one white neighbour of $z$ neighbour must be in $H$. So $z$ can force its only white neighbour. But then no black vertex in $H$ can force a vertex, since every such vertex will be adjacent to at least
one white vertex in $H$ and at least one white vertex in $V(G) \setminus V(H)$. If $z$ has two or more white neighbours, then no vertex of $B$ can perform a force and again we reach a contradiction.

To verify the second statement observe that if $|S(G)| < 3$, then there is at least one vertex $v \in V(H)$, that has at most one neighbour $u \in V(G) \setminus V(H)$. The set $V(H) \setminus \{v\}$ forms a positive zero forcing set. To see this, first note that after removing this set, all the vertices in $V(G) \setminus (V(H) \cup \{u\})$ are disjoint. Finally, there is one vertex in $V(H)$ that is not adjacent to $u$, this vertex can force $v$.

For the third statement assume $k$ is even and $|S(G)| = k + 1$. Since $K_{k+1}$ is a subgraph of $G$, the tree cover number of $G$ is no less than $\lceil \frac{k+1}{2} \rceil$. Suppose that $T$ is a minimal tree covering for $G$ with $|T| = \lceil \frac{k+1}{2} \rceil$. Since no tree in $T$ can contain more than two vertices of $H$ and $T(G) = \lceil \frac{k+1}{2} \rceil$, each tree in $T$, except one, contains exactly two vertices of $H$. Assume that $T_1$ is the tree that contains only a single vertex of $H$.

The size of $S(G)$ is $k + 1$, so for any vertex, $w \in V(H)$, there is a corresponding vertex in $V(G) \setminus V(H)$ which is adjacent to all of the vertices of $H$ except $w$. In particular, if $w$ is the single vertex of $H$ in the tree $T_1$, then there is a vertex $u$ which is adjacent to all vertices in $H$ except $w$. Since $N_0(u) = V(H) \setminus \{w\}$, the vertex $u$ can not be covered by extending any of the trees of $T$ (as $u$ is adjacent to both vertices in any tree from $T$). This contradicts $T$ being a tree covering for $G$. Thus

$$T(G) = \left\lceil \frac{k+1}{2} \right\rceil + 1.$$

Finally we will show that we can construct a tree covering of this size. Let $T'$ be a minimal tree covering for $H$. Thus $|T'| = \lceil \frac{k+1}{2} \rceil$ and exactly one tree in $T'$ contains only one vertex (all other trees contain exactly two vertices). Call this tree $T = \{u\}$. Extend $T$ to include every vertex in $V(G) \setminus V(H)$ that is adjacent to $u$. Now the only vertices in $G$ that are not covered by a tree in $T'$ are the vertices in $V(G) \setminus V(H)$ that are adjacent to every vertex in $H$, except $u$, call these vertices $v_1, v_2, \ldots, v_\ell$. Take any tree in $T'$, except $T = \{u\}$. Then this tree will have two vertices, say $\{x, y\}$. Remove this tree from $T'$ and replace it with the two trees, $\{x\}$ and $\{\{y, v_1\}, \{y, v_2\}, \ldots, \{y, v_\ell\}\}$. This gives a tree covering of size $\left\lceil \frac{k+1}{2} \right\rceil + 1$.

For the fourth statement, assume $|S(G)| < k + 1$ and $k$ is even. Thus there is a vertex, $v \in V(H)$ that is adjacent to all of the vertices in the graph $G$. Let $T'$ be a tree covering of $H$ with $\lceil \frac{k+1}{2} \rceil$ trees in which $T = \{v\}$ is a covering tree. Then $T$ can be extended to cover all the vertices of $V(G) \setminus V(H)$. Thus $T(G) = |T'| = \lceil \frac{k+1}{2} \rceil$. \hfill \Box

Note that if in Theorem 23 we have $k = 2$, then the positive zero forcing number and the tree cover number coincide (this result is also proved in [14]).

**Theorem 24.** Let $G$ be a $k$-tree with $k$ odd, then $T(G) = \frac{k+1}{2}$.  

**Proof.** We prove this by induction on the number of vertices added to the initial $k+1$ clique; so the induction will be on $|G| - (k + 1)$.

If $k$ is odd, then the result is clearly true for $K_{k+1}$ (a perfect matching is a minimal tree covering). So the result is true when $|G| - (k + 1) = 0$.

Assume that the statement is true for all $k$-trees $G'$ with $|G| - (k + 1) < n$. Assume that $G$ is a $k$-tree with $|G| - (k + 1) = n$.

Let $v \in V(G)$ be a vertex of degree $k$ (such a vertex always exists). By the induction hypothesis there exists a tree covering $T$ of $G \setminus v$ with exactly $\frac{k+1}{2}$ trees. Since neighbours of $v$ form a $k$-clique, any tree in $T$ covers at most two of the neighbours of $v$. Moreover, $v$ has an odd number of neighbours, thus there is exactly one tree $T$ in $T$ that covers only one of the neighbours of $v$. Therefore we can extend $T$ to cover $v$, and conclude $T(G) = \frac{k+1}{2}$. \hfill \Box

Recall that a graph is called chordal if it contains no induced cycles on four or more vertices. For instance, all $k$-trees are examples of chordal graphs. In general it is known for any chordal graph $G$, that $M_+(G) = |G| - cc(G)$, where $cc(G)$ denotes the fewest number of cliques needed to cover (or to include) all the edges in $G$ (see [15]). This number, $cc(G)$, is often called the clique cover number of the graph $G$. Further inspection of the work in [15] actually reveals that, in fact, for any chordal graph, $cc(G)$ is equal to the ordered set number $(OS(G))$ of $G$. In [4], it was proved that for any graph $G$, the ordered set number of $G$ and the positive zero forcing number of
$G$ are related and satisfy, $Z_+(G) + OS(G) = |G|$. As a consequence, we have that $M_+(G) = Z_+(G)$ for any chordal graph $G$, and, in particular, $Z_+(G) = |G| - cc(G)$. So studies of the positive zero forcing number of chordal graphs, including $k$-trees, boils down to determining the clique cover number and vice-versa.

10 Further work

In Section 3 we introduced families of graphs for which the zero forcing number and the path cover number coincide. In fact, we showed that for the family of block-cycle graphs this is true. However, there are additional families for which equality holds between these two parameters. For example, the graph $G = K_3 - e$, where $e$ is an edge of $K_3$, has $Z(G) = P(G)$. It is, therefore, natural to propose characterizing all the graphs $G$ for which $Z(G) = P(G)$.

In [2] it is conjectured that the result analogous to Corollary 13 holds for zero forcing sets; if this conjecture is confirmed, then there would be a much larger family of graphs for which the path cover number and zero forcing number coincide. To this end, we state the following problem as a beginning to this study.

**Conjecture 25.** Let $G$ and $H$ be two graphs, both with an identified vertex $v$, and both satisfy $Z(G) = P(G)$ and $Z(H) = P(H)$. Then $Z(G \upharpoonright H) = P(G \upharpoonright H)$.

It is not difficult to verify that for any tree, any minimal path cover coincides with a collection of forcing chains. We conjecture that this is also the case for the block-cycle graphs (and refer the reader to [2, Section 5.2] for more details). In general, it is an interesting question if for a graph $G$ with $Z(G) = P(G)$, is it true that any minimal path cover of $G$ coincides with a collection of forcing chains of $G$?

In Section 5, we proved the equality $Z_+(G) = T(G)$ where $G$ is an outerplanar graph. The structure of a planar embedding of outerplanar graphs was the key point to establishing the equality. There are many non-outerplanar graphs with a similar structure; generalizing this structure will lead to discovering more graphs that satisfy $Z_+(G) = T(G)$. In general, we are interested in characterizing all the graphs $G$ for which $Z_+(G) = T(G)$.

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**References**


