Quantum State Transfer in Coronas

Ethan Ackelsberg  
Division of Science, Mathematics and Computing  
Bard College at Simon’s Rock  
Great Barrington, MA, U.S.A.  
eackelsberg@gmail.com

Zachary Brehm  
Department of Mathematics  
SUNY Potsdam  
Potsdam, NY, U.S.A.  
zachbrehm@gmail.com

Ada Chan  
Department of Mathematics and Statistics  
York University  
Toronto, ON, Canada  
ssachan@york.ca

Joshua Mundinger  
Department of Mathematics and Statistics  
Swarthmore College  
Swarthmore, PA, U.S.A.  
josh.mundinger@gmail.com

Christino Tamon  
Department of Computer Science  
Clarkson University  
Potsdam, New York, U.S.A.  
tino@clarkson.edu

Submitted: May 18, 2016; Accepted: May 2, 2017; Published: May 19, 2017  
Mathematics Subject Classifications: 05C50

Abstract

We study state transfer in quantum walks on graphs relative to the adjacency matrix. Our motivation is to understand how the addition of pendant subgraphs affect state transfer. For two graphs $G$ and $H$, the Frucht-Harary corona product $G \circ H$ is obtained by taking $|G|$ copies of the cone $K_1 + H$ and by identifying the conical vertices according to $G$. Our work explores conditions under which the corona $G \circ H$ exhibits state transfer. We also describe new families of graphs with state transfer based on the corona product. Some of these constructions provide a generalization of related known results.

Keywords: Quantum walk; state transfer; corona.

1 Introduction

Quantum walk is a natural generalization of classical random walk on graphs. It has received strong interest due to its important applications in quantum information and
computation. Farhi and Gutmann [15] introduced quantum walk algorithms for solving search problems on graphs. In their framework, given a graph $G$ with adjacency matrix $A$, the time-varying unitary matrix $U(t) := e^{-itA}$ defines a continuous-time quantum walk on $G$. Subsequently Childs et al. [8] showed that these algorithms may provide exponential speedup over classical probabilistic algorithms. The work by Farhi et al. [14] described an intriguing continuous-time quantum walk algorithm with nontrivial speedup for a concrete problem called Boolean formula evaluation.

In quantum information, Bose [5] studied the problem of information transmission in quantum spin chains. Christandl et al. [10, 9] showed that this problem may be reduced to the following phenomenon in quantum walk. Given two vertices $u$ and $v$ in $G$, we say perfect state transfer occurs between $u$ and $v$ in $G$ at time $\tau$ if the $(u,v)$-entry of $U(\tau)$ has unit magnitude. It was quickly apparent that perfect state transfer is an exotic phenomenon. Godsil [20] proved that for every positive integer $k$ there are only finitely many graphs of maximum degree $k$ which have perfect state transfer. Therefore, the following relaxation of this notion is often more useful to consider. The state transfer between $u$ and $v$ is called “pretty good” (see Godsil [19]) or “almost perfect” (see Vinet and Zhedanov [30]) if the $(u,v)$-entry of the unitary matrix $U(t)$ can be made arbitrarily close to one by varying $t$.

Two vertices in a graph are antipodal if their distance is the diameter of the graph. Christandl et al. [10, 9] observed that the path $P_n$ on $n$ vertices has antipodal perfect state transfer if and only if $n = 2, 3$. In a striking result, Godsil et al. [22] proved that $P_n$ has antipodal pretty good state transfer if and only if $n + 1$ is a prime, twice a prime, or a power of two. This provides the first family of graphs with pretty good state transfer which correspond to the quantum spin chains originally studied by Bose.

Shortly after, Fan and Godsil [13] studied a family of graphs obtained by taking two cones $K_1 + K_m$ and then connecting the two conical vertices. They showed that these graphs, which are called double stars, have no perfect state transfer, but have pretty good state transfer between the two conical vertices if and only if $4m + 1$ is a perfect square. These graphs provide the second family of graphs known to have pretty good state transfer.

In this work, we provide new families of graphs with pretty good state transfer. Our constructions are based on a natural generalization of Fan and Godsil’s double stars. The corona product of an $n$-vertex graph $G$ with another graph $H$, typically denoted $G \circ H$, is obtained by taking $n$ copies of the cone $K_1 + H$ and by identifying the conical vertices according to $G$. In a corona product $G \circ H$, we sometimes call $G$ the base graph and $H$ the pendant graph. This graph product was introduced by Frucht and Harary [16] in their study of automorphism groups of graphs which are obtained by wreath products.

We first observe that perfect state transfer on corona products is extremely rare. This is mainly due to the specific forms of the corona eigenvalues (which unsurprisingly resemble the eigenvalues of cones) coupled with the fact that periodicity is a necessary condition for perfect state transfer. Our negative results apply to corona families $G \circ H$ when $H$ is either the empty or the complete graph, under suitable conditions on $G$. In a companion work [1], we observed an optimal negative result which holds for all $H$ but in
a Laplacian setting.

Given that perfect state transfer is rare, our subsequent results mainly focus on pretty good state transfer. We prove that the family of graphs $K_2 \circ K_m$, which are called barbell graphs (see Ghosh et al. [17]), admit pretty good state transfer for all $m$. Here, state transfer occurs between the two vertices of $K_2$. This is in contrast to the double stars $K_2 \circ \overline{K}_m$ where pretty good state transfer requires number-theoretic conditions on $m$.

We observe something curious for corona products when the base graph is complete. It is known that the complete graphs $K_n$, $n \geq 3$, are periodic but have no perfect state transfer, and hence have no pretty good state transfer. We observe that although $K_n \circ \overline{K}_2$ has no pretty good state transfer, $(K_n + I) \circ \overline{K}_2$ has pretty good state transfer, where $K_n + I$ denotes the graph obtained by adding loops to each vertex of $K_n$. This provides another example where loops are useful for state transfer (see Casaccino et al. [7] and Kempton et al. [26]).

Our other results involve graphs of the form $G \circ K_1$ which are called thorny graphs (see Gutman [24]). We show that if $G$ is a graph with perfect state transfer at time $\pi/g$, for some positive integer $g$, then $G \circ K_1$ has pretty good state transfer, provided that the adjacency matrix of $G$ is nonsingular. On the other hand, if the adjacency matrix of $G$ is singular, we derive the same result if $G$ has perfect state transfer at time $\pi/2$. Taken together, this proves that the thorny cube $Q_d \circ K_1$ has pretty good state transfer for all $d$. This confirms some of the numerical observations of Makmal et al. [28] on embedded hypercubes albeit for the continuous-time setting (since their results were stated for discrete-time quantum walks).

It turns out that perfect state transfer is not necessary for a thorny graph to have state transfer. Coutinho et al. [12] proved that the cocktail party graph $\overline{nK}_2$ has perfect state transfer if and only if $n$ is even. We show that the thorny graph $\overline{nK}_2 \circ K_1$ has pretty good state transfer for all $n$. This observation holds in the Laplacian setting as well (see [1]).

Returning to the double stars, we also observe that $C_2 \circ \overline{K}_m$ has perfect state transfer whenever $m + 1$ is an even square. Here, $C_2$ is the digon (which is a multigraph on two vertices connected by two parallel edges). This shows that certain double stars are one additional edge away from having perfect state transfer. This is akin to using weighted edges on paths for perfect state transfer (see Christandl et al. [10]). Here, we merely use an integer weight in a non-unimodal weighting scheme on a path.

2 Preliminaries

Given an undirected graph $G = (V, E)$ on $n$ vertices, the adjacency matrix of $G$ is an $n \times n$ symmetric matrix $A(G)$ where, for all vertices $u$ and $v$, the $(u, v)$ entry of $A(G)$ is 1, if $(u, v) \in E$, and 0, otherwise. The spectrum of $G$, which we denote as $\text{Sp}(G)$, is the set of distinct eigenvalues of $A(G)$. We use $\rho(G)$ to denote the spectral radius of $G$. By the spectral theorem, we may write

$$A(G) = \sum_{\lambda \in \text{Sp}(G)} \lambda E_{\lambda}(G)$$

(1)
where $E_\lambda(G)$ is the eigenprojector (orthogonal projector onto an eigenspace) corresponding to eigenvalue $\lambda$.

The eigenvalue support of a vertex $u$ in $G$, denoted $\text{supp}_G(u)$, is the set of eigenvalues $\lambda$ of $G$ for which $E_\lambda(G)e_u \neq 0$, where $e_u$ is the characteristic vector corresponding to vertex $u$. Two vertices $u$ and $v$ of $G$ are called strongly cospectral if $E_\lambda(G)e_u = \pm E_\lambda(G)e_v$ for each eigenvalue $\lambda$ of $G$.

A continuous-time quantum walk on $G$ is defined by the time-varying unitary matrix $U(t) = e^{-itA(G)}$. We say such a quantum walk has perfect state transfer between vertices $u$ and $v$ at time $\tau$ if

$$e^T_v U(\tau)e_u = \gamma,$$

for some complex unimodular $\gamma$. We call $\gamma$ the phase of the perfect state transfer. Note that $U(t)$ is symmetric for all $t$. In the special case where perfect state transfer occurs with $u = v$, we say the quantum walk is periodic at vertex $u$. Moreover, if $U(\tau)$ is a scalar multiple of the identity matrix, then the quantum walk is periodic.

Given that perfect state transfer is rare, we consider the following relaxation of this phenomenon proposed by Godsil. The quantum walk on $G$ has pretty good state transfer between $u$ and $v$ if for all $\epsilon > 0$ there is a time $\tau$ so that

$$\|e^{-itA(G)}e_u - \gamma e_v\| < \epsilon,$$

for some complex unimodular $\gamma$.

In what follows, we state some useful facts about state transfer on graphs. The following formulation by Coutinho (which summarized the most relevant facts) will be useful for our purposes.

**Theorem 2.1** (Coutinho [11], Theorem 2.4.4). Let $G$ be a graph and let $u, v$ be two vertices of $G$. Then there is perfect state transfer between $u$ and $v$ at time $t$ with phase $\gamma$ if and only if all of the following conditions hold.

i) Vertices $u$ and $v$ are strongly cospectral.

ii) There are integers $a, \Delta$ where $\Delta$ is square-free so that for each eigenvalue $\lambda$ in $\text{supp}_G(u)$:

   a) $\lambda = \frac{1}{2}(a + b\sqrt{\Delta})$, for some integer $b$.

   b) $e^T_u E_\lambda(G)e_v$ is positive if and only if $(\rho(G) - \lambda)/g\sqrt{\Delta}$ is even, where

   $$g := \gcd\left(\left\{\frac{\rho(G) - \lambda}{\sqrt{\Delta}} : \lambda \in \text{supp}_G(u)\right\}\right).$$

Moreover, if the above conditions hold, then the following also hold.

i) There is a minimum time of perfect state transfer between $u$ and $v$ given by

$$t_0 := \frac{\pi}{g\sqrt{\Delta}}.$$
ii) The time of perfect state transfer $t$ is an odd multiple of $t_0$.

iii) The phase of perfect state transfer is given by $\gamma = e^{-\imath t \rho(G)}$.

We state some strong properties proved by Godsil which relate perfect state transfer with periodicity in a fundamental way.

**Lemma 2.2** (Godsil [18]). If $G$ has perfect state transfer between vertices $u$ and $v$ at time $t$, then $G$ is periodic at $u$ at time $2t$.

**Theorem 2.3** (Godsil [20]). A graph $G$ is periodic at vertex $u$ if and only if either:

i) all eigenvalues in $\text{supp}_G(u)$ are integers; or

ii) there is a square-free integer $\Delta$ and an integer $a$ so that each eigenvalue $\lambda$ in $\text{supp}_G(u)$ is of the form $\lambda = \frac{1}{2}(a + b\sqrt{\Delta})$, for some integer $b\lambda$.

We also state some necessary conditions for perfect state transfer and pretty good state transfer in terms of the automorphisms of $G$.

**Theorem 2.4** (Godsil [20, 21]). Let $G$ be a graph with state transfer (perfect or pretty good) between vertices $u$ and $v$. Then $u$ and $v$ are strongly cospectral, and each automorphism of $G$ fixing $u$ must fix $v$.

In our analysis, we will need some tools from number theory. For example, we will need the following form of Kronecker’s approximation theorem.

**Theorem 2.5.** (Kronecker’s Theorem: Hardy and Wright [25], Theorem 442) Let $1, \lambda_1, \ldots, \lambda_m$ be linearly independent over $\mathbb{Q}$. Let $\alpha_1, \ldots, \alpha_m$ be arbitrary real numbers, and let $N, \epsilon$ be positive real numbers. Then there are integers $\ell > N$ and $q_1, \ldots, q_m$ so that

$$|\ell \lambda_k - q_k - \alpha_k| < \epsilon,$$

for each $k = 1, \ldots, m$. (6)

For brevity, whenever we have an inequality of the form $|\alpha - \beta| < \epsilon$, for arbitrarily small $\epsilon$, we will write instead $\alpha \approx \beta$ and omit the explicit dependence on $\epsilon$. For example, (6) will be represented as $\ell \lambda_k - q_k \approx \alpha_k$.

In our applications of Kronecker’s Theorem, we will use the following lemma to identify sets of numbers which are linearly independent over the rationals.

**Lemma 2.6** (Newman and Flanders [29]). Let $a_1, \ldots, a_n$ be positive integers, coprime in pairs, no one of which is a perfect square. Then the $2^n$ algebraic integers

$$\sqrt{a_1^{e_1} \ldots a_n^{e_n}}, \quad e_j = 0, 1,$$

are linearly independent over the field $\mathbb{Q}$ of rationals.
Notation: We describe some notation used throughout the rest of the paper.

The all-one and all-zero vectors of dimension $n$ are denoted $\mathbf{1}_n$, $\mathbf{0}_n$, respectively. The $m \times n$ all-one matrix is denoted $J_{m,n}$ or simply $J_n$ if $m = n$. The identity matrix of size $n$ is denoted $I_n$.

For standard families of graphs, we use $K_n$ for the complete graph on $n$ vertices, $P_n$ for the path on $n$ vertices, and $Q_n$ for the $n$-dimensional cube. In what follows, let $G$ and $H$ be graphs. The complement of $G$ is denoted $\overline{G}$. The disjoint union of $G$ and $H$ is written as $G \cup H$, while the disjoint union of $n$ copies $G$ is denoted $nG$. The join $G + H$ of $G$ and $H$ is the graph $\overline{G \cup H}$. Further background on algebraic graph theory may be found in Godsil and Royle [23].

3 Corona of Graphs

We define the Frucht-Harary corona product of two graphs (see [16]). Let $G$ be a graph on the vertex set $\{v_1, \ldots, v_n\}$ and $H$ be a graph on the vertex set $\{1, \ldots, m\}$. The latter is chosen for notational convenience. The corona $G \circ H$ is formed by taking the disjoint union of $G$ and $n$ copies of $H$ and then adding an edge from each vertex of the $j$th copy of $H$ to the vertex $v_j$ in $G$. Formally, the corona $G \circ H$ has the vertex set

$$V(G \circ H) = V(G) \times (\{0\} \cup V(H)), \quad (8)$$

and the adjacency relation

$$((v, w), (v', w')) \in E(G \circ H) \iff \begin{cases} w = w' = 0 \text{ and } (v, v') \in E(G) \quad \text{or} \\ v = v' \text{ and } (w, w') \in E(H) \quad \text{or} \\ v = v' \text{ and exactly one of } w \text{ and } w' \text{ is } 0. \end{cases} \quad (9)$$

Figure 1: A corona $G \circ H$.

The adjacency matrix of $G \circ H$ where $H$ has $m$ vertices is given by

$$A(G \circ H) = A(G) \otimes \mathbf{e}_0\mathbf{e}_0^T + I_n \otimes \begin{bmatrix} 0 & \mathbf{j}_m^T \\ \mathbf{j}_m & A(H) \end{bmatrix}. \quad (10)$$

The spectrum of $G \circ H$ when $H$ is a $k$-regular graph is known and we state this in the following.
Theorem 3.1 (Barik et al. [4]). Suppose that \( G \) is a graph and \( H \) is a \( k \)-regular graph on \( m \) vertices. Suppose \( G \) has eigenvalues \( \lambda_0 > \ldots > \lambda_p \) with multiplicities \( r_0, \ldots, r_p \), and \( H \) has eigenvalues \( k = \mu_0 > \mu_1 > \ldots > \mu_q \) with multiplicities \( s_0, \ldots, s_q \). Then \( G \circ H \) has the following spectrum.

i) \( k \) is an eigenvalue with multiplicity \( n(s_0 - 1) \).

ii) \( \mu_j \) is an eigenvalue with multiplicity \( ns_j \) for \( j = 1, \ldots, q \).

iii) \( \frac{1}{2}(\lambda_j + k \pm \sqrt{(\lambda_j - k)^2 + 4m}) \) are eigenvalues each with multiplicity \( r_j \) for \( j = 0, \ldots, p \).

Theorem 3.1 gives the spectrum of \( G \circ H \) when \( H \) is \( k \)-regular. We now provide the corresponding eigenprojectors which will be crucial in our subsequent analyses.

Proposition 3.2. Let \( G \) be a graph on \( n \) vertices and let \( H \) be a \( k \)-regular graph on \( m \) vertices. Then the eigenprojectors of \( G \circ H \) are given by the following.

i) For each eigenvalue \( \mu \) of \( H \), let
\[
E_\mu := I_n \otimes \begin{bmatrix} 0 & 0^T_m \\ 0_m & E_\mu(H) - \delta_{\mu,k} J_m \end{bmatrix}.
\]

ii) For each eigenvalue \( \lambda \) of \( G \), define a pair of eigenvalues
\[
\lambda_{\pm} := \frac{\lambda + k \pm \sqrt{(\lambda - k)^2 + 4m}}{2},
\]
and let
\[
E_{\lambda_{\pm}} := E_\lambda(G) \otimes \frac{1}{(\lambda_{\pm} - k)^2 + m} \begin{bmatrix} (\lambda_{\pm} - k)^2 & (\lambda_{\pm} - k) J_m \\ (\lambda_{\pm} - k) J_m & J_m \end{bmatrix}.
\]

Then the spectral decomposition of the corona \( G \circ H \) is given by
\[
A(G \circ H) = \sum_{\lambda \in \text{Sp}(G)} \sum_{\pm} \lambda_{\pm} E_{\lambda_{\pm}} + \sum_{\mu \in \text{Sp}(H)} \mu E_\mu.
\]

Proof. Recall that the adjacency matrix of \( G \circ H \) is given in (10).

For an eigenvalue \( \mu \) of \( H \), let \( B_\mu \) be an orthonormal basis of the \( \mu \)-eigenspace that is orthogonal to \( j_m \). If \( H \) is a connected \( k \)-regular graph, then \( B_k \) is empty. Suppose \( \mu \) has an eigenvalue multiplicity of \( r \). Then the cardinality of \( B_\mu \) is \( r \) if \( \mu < k \), and is \( r - 1 \) if \( \mu = k \). Moreover, \( \mu \) is also an eigenvalue of \( G \circ H \) since for each \( x \in B_\mu \) and for every \( y \) in \( \mathbb{C}^n \), we have
\[
A(G \circ H)y \otimes \begin{bmatrix} 0 \\ x \end{bmatrix} = \mu y \otimes \begin{bmatrix} 0 \\ x \end{bmatrix}.
\]

An orthonormal basis for the \( \mu \)-eigenspace of \( G \circ H \) is given by
\[
\left\{ e_v \otimes \begin{bmatrix} 0 \\ x \end{bmatrix} : v \in V(G), x \in B_\mu \right\}.
\]
The cardinality of this set is \( nr \) if \( \mu < k \), and is \( n(r - 1) \) if \( \mu = k \). These match the multiplicities given in Theorem 3.1. Note that the eigenprojector of \( \mu \) in \( H \) is given by

\[
E_\mu(H) = \begin{cases} 
\sum_{x \in B_\mu} xx^\dagger & \text{if } \mu < k \\
\frac{1}{m} \mathbf{J}_m + \sum_{x \in B_\mu} xx^\dagger & \text{if } \mu = k
\end{cases}
\]

Therefore, the eigenprojector of \( \mu \) in \( G \circ H \) is given by

\[
E_\mu(G \circ H) = I_n \otimes \begin{bmatrix} \mathbf{0} & \mathbf{0}^T_m \\
\mathbf{0}_m & E_\mu(H) - \delta_{\mu,k} \frac{1}{m} \mathbf{J}_m \end{bmatrix}.
\]

Next, for each eigenvalue \( \lambda \) of \( G \) with a corresponding (normalized) eigenvector \( \mathbf{x} \), we have

\[
A(G \circ H) \left( \mathbf{x} \otimes \begin{bmatrix} \lambda_+ - k \\
\mathbf{J}_m \end{bmatrix} \right) = \lambda_\pm \mathbf{x} \otimes \begin{bmatrix} \lambda_\pm - k \\
\mathbf{J}_m \end{bmatrix}
\]

provided that

\[
\lambda_\pm := \frac{\lambda + k \pm \sqrt{(\lambda + k)^2 + 4m - 4\lambda k}}{2} = \frac{\lambda + k \pm \sqrt{(\lambda - k)^2 + 4m}}{2}.
\]

After normalizing the above eigenvectors, we see that the eigenprojectors of \( \lambda_\pm \) are given by

\[
E_{\lambda_\pm}(G \circ H) = E_\lambda(G) \otimes \frac{1}{(\lambda_\pm - k)^2 + m} \begin{bmatrix} (\lambda_\pm - k)^2 & (\lambda_\pm - k)\mathbf{J}_m^T \\
(\lambda_\pm - k)\mathbf{J}_m & \mathbf{J}_m \end{bmatrix}
\]

These provide the remaining \( 2n \) eigenvectors of \( G \circ H \).

For state transfer in \( G \circ H \), we need to analyze the elements of the transition matrix \( e^{-itA(G \circ H)} \). We use Proposition 3.2 to derive a convenient form for our analysis.

**Proposition 3.3.** Let \( G \) be a graph and let \( H \) be a \( k \)-regular graph on \( m \) vertices. For vertices \( v \) and \( v' \) of \( G \), we have

\[
e^T_{(v,0)} e^{-itA(G \circ H)} e^T_{(v',0)} = \sum_{\lambda \in \text{Sp}(G)} e^{-it(\lambda + k) \Lambda_\lambda} e^T_v E_\lambda(G) e_{v'} \left( \cos \left( t\Lambda_\lambda/2 \right) - \frac{(\lambda - k)}{\Lambda_\lambda} \right) \sin \left( t\Lambda_\lambda/2 \right)
\]

where \( \Lambda_\lambda = \sqrt{(\lambda - k)^2 + 4m} \).

**Proof.** Let \( \lambda_\pm = \frac{1}{2}(\lambda + k \pm \Lambda_\lambda) \). From Proposition 3.2, we get that

\[
e^T_{(v,v')} e^{-itA(G \circ H)} e^T_{(v',v')} = \sum_{\lambda \in \text{Sp}(G)} e^{-it(\lambda + k) \Lambda_\lambda} e^T_v E_\lambda(G) e_{v'} \left( \sum_{\mu} e^{\pm it\Lambda_\mu/2} e^T_w M_{\lambda \mu} e_w \right)
\]

\[+ \delta_{v,v'}(1 - \delta_{w,0})(1 - \delta_{w',0}) \sum_{\mu \in \text{Sp}(H)} e^{-it\mu} \left( e^T_w E_\mu(H) e_{w'} - \frac{1}{m} \delta_{\mu,k} \right) \]

\[
e^T_{(v,v')} e^{-itA(G \circ H)} e^T_{(v',v')} = \sum_{\lambda \in \text{Sp}(G)} e^{-it(\lambda + k) \Lambda_\lambda} e^T_v E_\lambda(G) e_{v'} \left( \sum_{\mu} e^{\pm it\Lambda_\mu/2} e^T_w M_{\lambda \mu} e_w \right)
\]

\[+ \delta_{v,v'}(1 - \delta_{w,0})(1 - \delta_{w',0}) \sum_{\mu \in \text{Sp}(H)} e^{-it\mu} \left( e^T_w E_\mu(H) e_{w'} - \frac{1}{m} \delta_{\mu,k} \right),
\]
where
\[ M_{\lambda_\pm} = \frac{1}{(\lambda_\pm - k)^2 + m} \left[ (\lambda_\pm - k)^2 (\lambda_\pm - k) J_m \right]. \] (24)

Therefore,
\[ e^T (v,0) e^{-itA(G\circ H)} e(v',0) = \sum_{\lambda \in \text{Sp}(G)} e^{-it(\lambda+k)/2} e^T \mathcal{E}_\lambda(G) e(v') \sum_{\pm} e^{\pm it\lambda \lambda / 2} (\lambda_\pm - k)^2 / (\lambda_\pm - k)^2 + m. \] (25)

But, the inner summation in (25) simplifies to
\[ \sum_{\pm} e^{\pm it\lambda \lambda / 2} (\lambda_\pm - k)^2 / (\lambda_\pm - k)^2 + m = \cos(t\lambda \lambda / 2) - \frac{(\lambda - k)}{\lambda \lambda} i \sin(t\lambda \lambda / 2), \] (26)

since \( \prod_{\pm}((\lambda_\pm - k)^2 + m) = m\lambda^2 \) and \( \prod_{\pm}(\lambda_\pm - k) = -m \). This proves the claim. \( \square \)

4 Perfect State Transfer

Lemma 2.2 shows that periodicity is a necessary condition for perfect state transfer. We show that there is no perfect state transfer in most coronas since their vertices are not periodic.

4.1 Conditions on Periodicity

To investigate periodicity in a corona \( G \circ H \), the following lemma shows that it is sufficient to consider base vertices of the form \( (v,0) \), where \( v \) is a vertex in \( G \).

**Lemma 4.1.** Let \( G \) be a graph and let \( H \) be a regular graph. If \((v,w)\) is periodic in \( G \circ H \), then \((v,0)\) is periodic in \( G \circ H \).

**Proof.** The eigenvalue support of \((v,0)\) is contained within the eigenvalue support of \((v,w)\), which is evident from the eigenprojectors given in Proposition 3.2. \( \square \)

Theorem 2.3 provides necessary and sufficient conditions for periodicity. In the following, we show that periodicity in a corona places a strong condition on the eigenvalues of the base graph.

**Lemma 4.2.** Suppose that \( G \) is a connected graph on at least two vertices and \( H \) is a \( k \)-regular graph on \( m \) vertices. Then a vertex \((v,0)\) is periodic in \( G \circ H \) if and only if there exists a positive square-free integer \( \Delta \) such that for all eigenvalues \( \lambda \in \text{supp}_G(v) \), both \( \lambda - k \) and \( \sqrt{(\lambda - k)^2 + 4m} \) are integer multiples of \( \sqrt{\Delta} \). Moreover, if this holds, we have that \( \Delta \) divides \( 2m \).

**Proof.** For each eigenvalue \( \lambda \) of \( G \), let
\[ \lambda_\pm := \frac{1}{2} \left( \lambda + k \pm \sqrt{(\lambda - k)^2 + 4m} \right). \] (27)
By Proposition 3.2, the eigenvalue support of \((v, 0)\) in \(G \circ H\) is given by \(\{\lambda_{\pm} : \lambda \in \text{supp}_G(v)\}\). If there is a positive square-free integer \(\Delta\) so that for each eigenvalue \(\lambda\) in the support of \(v\) in \(G\), both \(\lambda - k\) and \(\sqrt{(\lambda - k)^2 + 4m}\) are integer multiples of \(\sqrt{\Delta}\), then \((v, 0)\) is periodic in \(G \circ H\), by Theorem 2.3. This shows sufficiency.

Now for necessity. Suppose that \((v, 0)\) is periodic in \(G \circ H\). By Theorem 2.3, either all eigenvalues in the support of \((v, 0)\) in \(G \circ H\) are integers or there is an integer \(a\) and a square-free integer \(\Delta\) so that all eigenvalues in the support of \((v, 0)\) in \(G \circ H\) are of the form \(\lambda = \frac{1}{2}(a + b_{\pm}\sqrt{\Delta})\), for some integers \(b_{\pm}\).

If the eigenvalue support of \((v, 0)\) is entirely integers, then for each eigenvalue \(\lambda\) in the support of \(v\), we conclude that \(\lambda + k = \lambda_{\pm} + \lambda\) and \(\sqrt{(\lambda - k)^2 + 4m} = \lambda_{\pm} - \lambda\) are integers.

Now suppose there is an integer \(a\) and a square-free integer \(\Delta > 1\) so that all eigenvalues \(\lambda_{\pm}\) in the support of \((v, 0)\) are of the form

\[
\lambda_{\pm} = \frac{1}{2}(a + b_{\pm}\sqrt{\Delta}),
\]

where \(b_{\pm}\) are integers (which depend on \(\lambda_{\pm}\)). Recall from the proof of Proposition 3.3 that \((\lambda_{\pm} - k)(\lambda - k) = -m\). Thus,

\[
-m = \frac{1}{4}((a - 2k)^2 + (b_{\pm}b_{\pm})\Delta) + \frac{1}{4}(a - 2k)(b_{\pm} + b_{\pm})\sqrt{\Delta}.
\]

Since \(\sqrt{\Delta}\) is not rational, either \(a - 2k\) or \(b_{\pm} + b_{\pm}\) is zero. If \(b_{\pm} = -b_{\pm}\) then we conclude that \(a = \lambda_{\pm} + \lambda = \lambda + k\). This implies that \(|\text{supp}_G(v)| = 1\) which contradicts that \(G\) is connected on at least two vertices. Otherwise, we have \(a = 2k\), from which we conclude that \(\lambda_{\pm} = k + \frac{1}{2}b_{\pm}\sqrt{\Delta}\). From the definition of \(\lambda_{\pm}\) in (27), we have

\[
(\lambda_{\pm} - k)(\lambda - k) = \lambda_{\pm} = \lambda - k,
\]

\[
(\lambda_{\pm} - k) - (\lambda_{\pm} - k) = \sqrt{(\lambda - k)^2 + 4m}.
\]

Given the alternate form in (28), this also implies that \(\lambda - k\) and \(\sqrt{(\lambda - k)^2 + 4m}\) are half-integer multiples of \(\sqrt{\Delta}\). Since their squares are rational algebraic integers, their squares must be integers. Thus, \(\lambda - k\) and \(\sqrt{(\lambda - k)^2 + 4m}\) are integer multiples of \(\sqrt{\Delta}\).

It remains to show that \(\Delta\) divides \(2m\). The condition that \(\sqrt{(\lambda - k)^2 + 4m}\) is an integer multiple of \(\sqrt{\Delta}\) implies that

\[
\sqrt{(\lambda - k)^2 + 4m}/\Delta
\]

is an integer. Furthermore, since \(\Delta\) divides \((\lambda - k)^2\), it must be that \(\Delta\) divides \(4m\). Since \(\Delta\) is square-free, \(\Delta\) divides \(2m\).

\(\square\)

**Remark 1.** The conditions for periodicity at \((v, w)\) in the corona \(G \circ H\) imply that \(\lambda \in k + \mathbb{Z}\sqrt{\Delta}\) for all \(\lambda\) in the eigenvalue support of \(v\) in \(G\). In particular, \(v\) must be periodic in \(G\).
Remark 2. The eigenvalues of $G$ need not be integers for $G \circ H$ to have a periodic vertex. Consider $P_3$ whose spectrum is $\{0, \pm \sqrt{2}\}$. The eigenvalue support of the middle vertex is $\{\pm \sqrt{2}\}$. Thus we may apply Lemma 4.2 to see that the middle vertex of $P_3$ is periodic in $P_3 \circ K_m$ if and only if $\sqrt{2 + 4m}$ is an integer multiple of $\sqrt{2}$, i.e. if and only if $\sqrt{1 + 2m}$ is an integer. Let us take the specific example of $m = 4$. If we let $v$ denote the center vertex of $P_3$, then the eigenvalue support of $(v, 0)$ in $P_3 \circ K_4$ is $\{\pm \sqrt{2}, \pm 2\sqrt{2}\}$, so $(v, 0)$ is periodic.

Figure 2: The white vertex in $P_3 \circ K_4$ is periodic.

The heart of our applications of Lemma 4.2 is the following. For the conditions of Lemma 4.2 to be satisfied, it must be that $4m/\Delta$ is a difference of squares. Since there are only finitely many pairs of squares whose difference is $4m/\Delta$, this allows us to restrict possible values of $\lambda - k$ in various ways. Our first application is to show that the eigenvalues in the support of a periodic vertex can not be too close together.

**Theorem 4.3.** Let $G$ be a graph and $H$ be a $k$-regular graph on $m \geq 1$ vertices. Suppose $v$ is a vertex of $G$ for which there are two distinct eigenvalues $\lambda, \mu \in \text{supp}_G(v)$ such that

$$|\lambda - k| - |\mu - k| \in \{\sqrt{\Delta}, 2\sqrt{\Delta}\}$$

for some square-free integer $\Delta$. Then $(v, w)$ is not periodic vertex in $G \circ H$, for all $w \in V(H) \cup \{0\}$.

**Proof.** By Lemma 4.1, it suffices to show $(v, 0)$ is not periodic. Suppose towards contradiction that $(v, 0)$ is periodic. By Lemma 4.2, there exists a square-free integer $\Delta$ such that for each eigenvalue $\lambda$ in the support of $v$, both $\lambda - k$ and $\sqrt{(\lambda - k)^2 + 4m}$ are integer multiples of $\sqrt{\Delta}$. We define

$$\sigma := \frac{1}{\sqrt{\Delta}} \min \left\{ |\lambda_1 - k| - |\lambda_2 - k| : \lambda_1, \lambda_2 \in \text{supp}_G(v) \right\}. \quad (33)$$

Let $\lambda$ and $\mu$ be the eigenvalues in the support of $v$ which achieve the above minimum. Now, define

$$n_\lambda := \frac{|\lambda - k|}{\sqrt{\Delta}}, \quad n_\mu := \frac{|\mu - k|}{\sqrt{\Delta}}, \quad (34)$$

and suppose that $\sigma := n_\lambda - n_\mu$.

By the assumption in (32), we have two cases to consider: $\sigma = 1$ and $\sigma = 2$.

By Lemma 4.2, both $n_\lambda^2 + 4m/\Delta$ and $n_\mu^2 + 4m/\Delta$ are squares. If we let

$$p := \sqrt{n_\lambda^2 + \frac{4m}{\Delta}} \quad \text{and} \quad q := \sqrt{n_\mu^2 + \frac{4m}{\Delta}}, \quad (35)$$

\text{THE ELECTRONIC JOURNAL OF COMBINATORICS} 24(2) (2017), #P2.24

11
then
\[ q + p > n_\lambda + n_\mu = 2n_\mu + \sigma \quad \text{and} \quad q^2 - p^2 = (2n_\mu + \sigma)\sigma. \] (36)

Hence \( q - p < \sigma \) which is impossible when \( \sigma = 1 \).

When \( \sigma = 2 \), \( p \) and \( q \) have the same parity which contradicts \( 0 < q - p < 2 \).

**Corollary 4.4.** Suppose \( G \) is a graph and \( H \) is a \( k \)-regular graph on \( m \geq 1 \) vertices. Let \( v \in V(G) \) and suppose there are eigenvalues \( \lambda, \mu \in \text{supp}_G(v) \) such that \( 0 < |\lambda - k| - |\mu - k| < 3 \). Then \((v, w)\) is not periodic in \( G \circ H \) for every \( w \in V(H) \cup \{0\} \).

**Proof.** Suppose towards contradiction that \((v, 0)\) is periodic. Then by Lemma 4.2, we have that \( \lambda - k \) and \( \mu - k \) are integer multiples of \( \sqrt{\Delta} \), for some square-free integer \( \Delta \). Since \( 0 < |\lambda - k| - |\mu - k| < 3 \), we have
\[ |\lambda - k| - |\mu - k| \in \{\sqrt{1}, \sqrt{2}, \sqrt{3}, 2\sqrt{1}, \sqrt{5}, \sqrt{6}, \sqrt{7}, 2\sqrt{2}\}. \] (37)

Note that Theorem 4.3 applies to all of these cases.

We apply our machinery above to show that the corona products of certain distance-regular graphs with an arbitrary regular graph have no perfect state transfer. In particular, we show this for some families of distance-regular graphs which have perfect state transfer (see Coutinho et al. [12]). These examples confirm that perfect state transfer is highly sensitive to perturbations.

**Corollary 4.5.** Let \( G \) be a graph from one of the following families:
- \( d \)-cubes \( Q_d \), for \( d \geq 2 \).
- Cocktail party graphs \( nK_2 \), for \( n \geq 2 \).
- Halved \( 2d \)-cubes \( \frac{1}{2}Q_{2d} \), for \( d \geq 1 \), where the vertices are elements of \( \mathbb{Z}_2^{2d} \) of even Hamming weight and two vertices are adjacent if their Hamming distance is exactly two.

Then the corona product \( G \circ H \), where \( H \) is a regular graph, has no perfect state transfer.

**Proof.** The spectra of these graphs are well known (see Brouwer et al. [6]) and are given by:
- \( \text{Spec}(Q_d) = \{d - 2\ell : 0 \leq \ell \leq d\} \).
- \( \text{Spec}(nK_2) = \{2n - 2, 0, -2\} \).
- \( \text{Spec}(\frac{1}{2}Q_{2d}) = \{(2d)\frac{1}{2} - 2\ell(2d - \ell) : 0 \leq \ell \leq d\} \).

Since these graphs are distance-regular, every eigenvalue is in the support of every vertex. Moreover, the eigenvalues satisfy the conditions of Corollary 4.4. In particular, \( 2 - d \) and \( -d \) are always eigenvalues of the \( d \)-cube and the halved \( 2d \)-cube. Therefore, the corona of these graphs with an arbitrary regular graph do not have periodic vertices. Hence, by Lemma 2.2, they do not have perfect state transfer.
4.2 Corona with the Complete Graph

The main result of this section is that there is no perfect state transfer on $G \circ K_m$ when $G$ is connected on at least two vertices. This is achieved by bounding the number of vertices in $H$ for the corona product $G \circ H$ to have a periodic vertex.

**Lemma 4.6.** Suppose that $G$ is a graph and $H$ is a $k$-regular graph on $m \geq 1$ vertices. If $(v,0)$ is periodic in $G \circ H$, then for all $\lambda \in \text{supp}_G(v)$ we have

$$m \geq |\lambda - k| + 1.$$  \hspace{1cm} (38)

**Proof.** Suppose that $(v,0)$ is periodic in $G \circ H$. By Lemma 4.2, there exists a positive square-free integer $\Delta$ such that for all $\lambda \in \text{supp}_G(v)$, both $(\lambda - k)^2/\Delta$ and $((\lambda - k)^2 + 4m)/\Delta$ are squares. Moreover, $\Delta$ divides $2m$, and therefore, these squares have the same parity. This yields the bound

$$\frac{4m}{\Delta} \geq \left(\frac{|\lambda - k|}{\sqrt{\Delta}} + 2\right)^2 - \left(\frac{|\lambda - k|}{\sqrt{\Delta}}\right)^2 = 4\left(\frac{|\lambda - k|}{\sqrt{\Delta}} + 1\right).$$  \hspace{1cm} (39)

After rearranging, we see that

$$m \geq |\lambda - k|\sqrt{\Delta} + \Delta \geq |\lambda - k| + 1,$$  \hspace{1cm} (40)

since $\Delta \geq 1$. \hfill \Box

**Theorem 4.7.** Let $G$ be a connected graph on at least 2 vertices. Then for all $m \geq 1$, the corona product $G \circ K_m$ has no periodic vertices, and, therefore, has no perfect state transfer.

**Proof.** Suppose towards contradiction that the vertex $(v,w)$ of $G \circ K_m$ is periodic. If the eigenvalue support of $v$ in $G$ contains a negative eigenvalue $\lambda$, then $\lambda - (m - 1) < 0$. Thus, Lemma 4.6 yields

$$m \geq |\lambda - (m - 1)| + 1 = -\lambda + (m - 1) + 1 > m.$$  \hspace{1cm} (41)

So, it suffices to show that the support of $v$ contains a negative eigenvalue.

Since $G$ has no loops, we have

$$e_v^T A e_v = \sum_{\lambda \in \text{Sp} G} \lambda e_v^T E_{\lambda} e_v = 0.$$  \hspace{1cm} (42)

If $v$ has no negative eigenvalue in its support, then $E_{\lambda} e_v = 0$ for all $\lambda \neq 0$. In this case, $A e_v$ is the zero vector and $G$ is not connected. \hfill \Box
4.3 Corona with the Empty Graph

In this section, we show that the corona of any graph with $\overline{K}_m$, where $m$ is one or a prime number, has no perfect state transfer. We will need the following spectral characterization of when a vertex is conical in a star graph.

**Lemma 4.8.** Let $v$ be a vertex in a connected graph $G$. If $\text{supp}_G(v) = \{\pm \lambda\}$, for some $\lambda > 0$, then $\lambda^2 \in \mathbb{Z}$ and $v$ is the conical vertex of the star graph $K_{1,\lambda^2}$.

**Proof.** Suppose that $\text{supp}_G(v) = \{\pm \lambda\}$. If $A = \sum_\theta \theta E_\theta$ is the spectral decomposition of the adjacency matrix of $G$, then $(E_\lambda + E_{-\lambda})e_v = e_v$. Moreover, $A^2e_v = \lambda^2e_v$. Since $A^2$ has integer entries, we observe that $\lambda^2 \in \mathbb{Z}$. This means that every walk of length $2$ starting from $v$ must return to $v$, i.e. that every neighbor of $v$ has degree $1$. The number of closed walks of length two from $v$ is then exactly the degree of $v$, and thus we see that $v$ is the center vertex of $K_{1,\lambda^2}$.

**Lemma 4.9.** $K_{1,n} \circ \overline{K}_m$ has no perfect state transfer, for every $n, m \geq 1$.

**Proof.** The case for $n = 1$ is a result of Fan and Godsil [13]. For $n = 2$, that is, $P_2 \circ \overline{K}_m$, we may apply Theorems 2.4 and 2.1 and Lemma 4.2 to rule out perfect state transfer. For $n > 2$ and $m \neq 2$, we may apply Theorems 2.4 and 2.1 to show no perfect state transfer exists.

So, we consider $K_{1,n} \circ \overline{K}_2$ where $n > 2$, and assume that it has perfect state transfer between vertices $(v, 1)$ and $(v, 2)$ where $v$ is a vertex of $K_{1,n}$. Note that perfect state transfer between other pairs of vertices are ruled out by Theorems 2.4 and 2.1. Thus, $(v, 0)$ is a periodic vertex. By Lemma 4.2, there is a square-free integer $\Delta$ so that for each eigenvalue $\lambda \in \text{supp}(v)$, both $\lambda$ and $\sqrt{\lambda^2 + 8}$ are integer multiples of $\sqrt{\Delta}$. Moreover, $\Delta$ divides $4$ and thus $\Delta \in \{1, 2\}$.

If $\Delta = 1$, both $\lambda$ and $\sqrt{\lambda^2 + 8}$ are integers for each eigenvalue $\lambda \in \text{supp}(v)$. Thus, $\text{supp}(v) = \{\pm 1\}$. By Lemma 4.8, $v$ is a conical vertex of $K_{1,1}$. But, $K_{1,1} \circ \overline{K}_2$ has no perfect state transfer (see [13]).

If $\Delta = 2$, both $\lambda$ and $\sqrt{\lambda^2 + 8}$ are integer multiples of $\sqrt{2}$ for each eigenvalue $\lambda \in \text{supp}(v)$. Suppose $\lambda = \ell \sqrt{2}$ for some integer $\ell$. Then, $\ell^2 + 4$ is a square which implies $\ell = 0$. Thus, $\text{supp}(v) = \{0\}$. But, this implies $v$ is an isolated vertex, which is a contradiction.

**Theorem 4.10.** If $G$ is a connected graph on at least two vertices and $m$ is either $1$ or a prime number, then $G \circ \overline{K}_m$ has no perfect state transfer.

**Proof.** By Lemma 4.9, we may assume $G$ is connected and is not a star. By Lemma 2.2, it suffices to show $G \circ \overline{K}_m$ has no perfect vertices for $m \geq 1$. Suppose for contradiction that vertex $(v, w)$ is periodic in $G \circ \overline{K}_m$. Then by Lemma 4.1, $(v, 0)$ is periodic. Since $G \neq K_{1,n}$ is connected, by Lemma 4.8, the eigenvalue support of $v$ in $G$ contains eigenvalues $\lambda$ and $\mu$ such that $|\lambda| \neq |\mu|$. Assume $|\mu| < |\lambda|$. By Lemma 4.2, there must exist a square-free integer $\Delta$ dividing $2m$ such that $\lambda$, $\mu$, $\sqrt{\lambda^2 + 4m}$, and $\sqrt{\mu^2 + 4m}$ are all integer multiples of $\sqrt{\Delta}$.
We define the integers
\[ n_\lambda := \left\lfloor \frac{|\lambda|}{\sqrt{\Delta}} \right\rfloor, \quad n_\mu := \left\lfloor \frac{|\mu|}{\sqrt{\Delta}} \right\rfloor, \quad \ell := \frac{2m}{\Delta}. \] (43)

Since \( \sqrt{\mu^2 + 4m} \) and \( \sqrt{\lambda^2 + 4m} \) are integer multiples of \( \sqrt{\Delta} \), both \( n_\mu^2 + 2\ell \) and \( n_\lambda^2 + 2\ell \) are perfect squares. So, let \( N_\mu^2 := n_\mu^2 + 2\ell \) and \( N_\lambda^2 := n_\lambda^2 + 2\ell \). Therefore, we have four perfect squares: \( n_\mu^2, N_\mu^2, n_\lambda^2 \), and \( N_\lambda^2 \). Since \( |\mu| < |\lambda| \), we know \( n_\mu < n_\lambda \).

If \( m = 1 \) or \( m = 2 \), then \( \ell \) equals one, two or four and \( 2\ell \) equals two, four or eight. First note that a difference of two squares is never two or four. For the last case, the only perfect squares:
\[ n \mid n^2 \pm 4. \]
Since \( \Delta \) are perfect squares. So, let \( N \). Now, consider when \( m = 2 \). By Proposition 4.11, the clique on two vertices whose edge has weight \( \alpha \). In what follows, we consider the weighted path \( K_2(\alpha) \circ K_1 \).

![Figure 3: The weighted path \( K_2(\alpha) \circ K_1 \).](image)

**Proposition 4.11.** In \( K_2(\alpha) \circ K_1 \), perfect state transfer occurs between the vertices of \( K_2 \) if and only if
\[ \alpha = \frac{2(2s + 1)}{\sqrt{(2\ell)^2 - (2s + 1)^2}} \quad \text{for some integers } \ell > s \geq 0. \] (44)

In this case, perfect state transfer occurs at time
\[ t = \frac{\pi}{2} \sqrt{(2\ell)^2 - (2s + 1)^2}. \]

**Proof.** Let \( u, v \) denote the vertices of \( K_2 \). The eigenvalues of \( K_2(\alpha) \) are \( \pm \alpha \) with corresponding eigenprojectors \( E_{\pm\alpha} \) which satisfy \( E_+^\alpha E_{\pm\alpha} e_e = \pm 1 \). By Proposition 3.3, the
transition element between \((u, 0)\) and \((v, 0)\) is given by

\[
e_{(u, 0)}^T e^{-i t A(K_2(\alpha) \circ K_1)} e_{(v, 0)} = -i \sin \left( \frac{t}{2} \alpha \right) \cos \left( \frac{t}{2} \Lambda_\alpha \right) - i \frac{\alpha}{\Lambda_\alpha} \cos \left( \frac{t}{2} \alpha \right) \sin \left( \frac{t}{2} \Lambda_\alpha \right),
\]

(45)

where \(\Lambda_\alpha := \sqrt{\alpha^2 + 4}\). Since \(|\alpha/\Lambda_\alpha| < 1\), there is perfect state transfer at time \(t\) if and only if

\[
\left| \sin \left( \frac{t}{2} \alpha \right) \cos \left( \frac{t}{2} \Lambda_\alpha \right) \right| = 1.
\]

(46)

Equivalently, this gives the conditions

\[
\frac{t}{2} \sqrt{\alpha^2 + 4} = \ell \pi, \quad \text{and} \quad \frac{t}{2} \alpha = \left( s + \frac{1}{2} \right) \pi,
\]

(47)

for some integers \(\ell > s \geq 0\). Hence perfect state transfer occurs at time \(t\) if and only if

\[
\alpha = 2(2s + 1)/\sqrt{(2\ell)^2 - (2s + 1)^2}.
\]

\(\square\)

Figure 4: For a positive integer \(r\), \(C_2 \circ K_{4, r^2 - 1}\) has perfect state transfer between \(u\) and \(v\), and \(C_4 \circ K_{4, r^2 - 1}\) has real perfect state transfer between \(\{u_1, u_2\}\) and \(\{v_1, v_2\}\).

In a graph \(G = (V, E)\), for a subset \(U \subseteq V\) of vertices, we denote the real uniform superposition of vertices in \(U\) as \(e_U = |U|^{-1/2} \sum_{v \in U} e_v\). We say \(G\) has real perfect state transfer between two subsets \(U_1, U_2 \subseteq V\) if \(|e_{U_1}^T e^{-i t A(G)} e_{U_2}| = 1\) (see [21]).

**Theorem 4.12.** For each positive integer \(r\), the following hold.

\(\text{i)}\ C_2 \circ K_{4, r^2 - 1}\) has perfect state transfer between the vertices of \(C_2\) at time \(\pi/2\).

\(\text{ii)}\ C_4 \circ K_{4, r^2 - 1}\) has real perfect state transfer between its two antipodal pairs of vertices at time \(\pi/2\).

**Proof.** We apply Proposition 4.11 with \(s = 0\) and \(\ell = r\) for a positive integer \(r\). This shows that \(P_4(r) := K_2(2/\sqrt{4r^2 - 1}) \circ K_1\) has perfect state transfer between the inner two vertices at time \(\tau = \frac{\pi}{2} \sqrt{4r^2 - 1}\). Hence there exists a unimodular complex number \(\gamma\) such that \(e^{-i \tau A(P_4(r))} e_{(u, 0)} = \gamma e_{(v, 0)}\). It follows from

\[
A(P_4(r)) \left( e^{-i \tau A(P_4(r))} e_{(u, 0)} \right) = e^{-i \tau A(P_4(r))} e_{(u, 0)} = \gamma A(P_4(r)) e_{(v, 0)}
\]

(48)
that perfect state transfer also occurs between the antipodal vertices.

By multiplying all weights of this graph by $\sqrt{4r^2-1}$, we obtain a weighted graph $\mathcal{G}_r$ whose adjacency matrix is $A(\mathcal{G}_r) = \sqrt{4r^2-1}A(P_4(r))$; see Figure 5. Note $\mathcal{G}_r$ has perfect state transfer at time $\pi/2$ between the two inner vertices.

Figure 5: A family of weighted paths $\mathcal{G}_r$, for positive integer $r$, with perfect state transfer (between $u$ and $v$, and between $a$ and $b$).

Moreover, $\mathcal{G}_r$ is the quotient of both $C_2 \circ \overline{K}_{4r^2-1}$ and $C_4 \circ \overline{K}_{4r^2-1}$ under natural equitable partitions. Since perfect state transfer is closed under taking quotient and lifting (see Bachman et al. [2], Theorem 1), this completes both claims.

Consider the family of weighted paths $\mathcal{G}_r$ given in Figure 5. The weighted path $\mathcal{G}_1$ corresponds to the distance quotient of the cube $Q_3$ (see also Figure 6). It is known that the distance quotients of the cube $Q_n$ provide a family of weighted paths with perfect state transfer. The weighting schemes of these weighted paths are unimodal (single peaked), where the edge weight between the $k$th and $(k+1)$th vertices is $\sqrt{(k+1)(n-k)}$ for $k = 0, \ldots, n-1$. In contrast, the weighted paths $\mathcal{G}_r$, for $r > 1$, exhibit weighting schemes that are not unimodal.

Figure 6: Example: a quotient and a lift of the hypercube $Q_3$.

5 Pretty Good State Transfer

We consider several families of corona graphs and explore their pretty good state transfer properties. In our analysis, we use the following characterization of pretty good state transfer observed by Banchi et al. [3]. We state a version that appeared in Kempton et al. [27].

Lemma 5.1. ([27], see Lemma 2.2)
Let $G$ be a graph with adjacency matrix $A$ and let $u, v$ be two vertices of $G$. Then, there is pretty good state transfer from $u$ to $v$ in $G$ if and only if the following conditions hold:

1. For each eigenvalue $\theta$ in the support of $u$ and $v$, we have $E_\theta e_u = \pm E_\theta e_v$. 

2. Let \( \{\lambda_i\} \) be the eigenvalues of \( A \) for which \( E_{\lambda_i} e_u = E_{\lambda_i} e_v \). Let \( \{\mu_j\} \) be the eigenvalues of \( A \) for which \( E_{\mu_j} e_u = -E_{\mu_j} e_v \). Then, for all integers \( \ell_i \) and \( m_j \), if
\[
\sum_i \ell_i \lambda_i + \sum_j m_j \mu_j = 0, \quad \sum_i \ell_i + \sum_j m_j = 0
\]
then
\[
\sum_j m_j \equiv 0 \pmod{2}.
\]

5.1 Barbell Graphs

We consider the family of barbell graphs (see Ghosh et al. [17]) and show that they exhibit pretty good state transfer.

![Figure 7: K_2 \circ K_7 has pretty good state transfer between vertices marked white.](image7)

**Lemma 5.2.** For real numbers \( a, b \), let \( G \) be a weighted path with adjacency matrix \( A \) where
\[
A = \begin{bmatrix}
  b & 1 & 0 & 0 \\
  1 & 0 & a & 0 \\
  0 & a & 0 & 1 \\
  0 & 0 & 1 & b \\
\end{bmatrix}.
\]
If \( \{a, \sqrt{(b \pm a)^2 + 4}\} \) is linearly independent over \( \mathbb{Q} \), then \( G \) has pretty good state transfer between the inner vertices.

![Figure 8: The quotient of K_2 \circ K_m where a = 1/\sqrt{m} and b = (m - 1)/\sqrt{m}.](image8)

**Proof.** The eigenvalues of \( A \) are given by
\[
\lambda_{\pm} = \frac{1}{2}(b + a \pm \sqrt{(b-a)^2 + 4}), \quad \mu_{\pm} = \frac{1}{2}(b - a \pm \sqrt{(b+a)^2 + 4}).
\]
It can be verified that \( E_{\lambda_{\pm}} e_u = E_{\lambda_{\pm}} e_v \) and \( E_{\mu_{\pm}} e_u = -E_{\mu_{\pm}} e_v \).
Suppose there are integers $\ell_\pm$ and $m_\pm$ so that $\sum_\pm \ell_\pm \lambda_\pm + \sum_\pm m_\pm \mu_\pm = 0$ and $\sum_\pm \ell_\pm + \sum_\pm m_\pm = 0$. So, we have
\[
-2a \sum_\pm m_\pm + (\ell_+ - \ell_-) \sqrt{(b-a)^2 + 4} + (m_+ - m_-) \sqrt{(b+a)^2 + 4} = 0. \tag{53}
\]

Since $\{a, \sqrt{(b \pm a)^2 + 4}\}$ is linearly independent over $\mathbb{Q}$, we have $\sum_\pm m_\pm = 0$. By Lemma 5.1, $G$ has pretty good state transfer between the inner vertices. \hfill \Box

**Theorem 5.3.** $K_2 \circ K_m$ has pretty good state transfer between the vertices of $K_2$ for all $m \geq 1$.

**Proof.** We take the quotient of $K_2 \circ K_m$ and apply Lemma 5.2. Here, we have $a = 1/\sqrt{m}$ and $b = (m - 1)/\sqrt{m}$. Thus, $\{a, \sqrt{(b \pm a)^2 + 4}\}$ is given by
\[
\left\{ \frac{1}{\sqrt{m}}, \frac{1}{\sqrt{m}} \sqrt{m^2 + 4}, \frac{1}{\sqrt{m}} \sqrt{m^2 + 4m} \right\},
\]
which is linearly independent over $\mathbb{Q}$ for $m \geq 1$. \hfill \Box

### 5.2 Hairy Cliques

By Theorem 4.10, we know that there is no perfect state transfer between $(v, 1)$ and $(v, 2)$ in $G \circ \overline{K}_2$ unless $v$ is isolated in $G$. We show a stronger result that there is no pretty good state transfer when $G$ is the complete graph.

Let $K_n + I$ denote the graph whose adjacency matrix is the all-one matrix $J_n$. That is, $K_n + I$ is obtained from the complete graph by adding loops to each vertex. Although the quantum walks on $K_n$ and on $K_n + I$ are equivalent up to phase factors, we show that in contrast to Theorem 4.10 with $K_n \circ \overline{K}_2$, the corona $(K_n + I) \circ \overline{K}_2$ has pretty good state transfer between the vertices of $\overline{K}_2$.

Figure 9: $K_8 \circ \overline{K}_2$ has no pretty good state transfer, while $(K_8 + I) \circ \overline{K}_2$ has pretty good state transfer between every two vertices of degree 1 at distance 2.

We will derive the above results from the following observation.
Fact 1. For an integer $n \geq 1$, let $G$ be a weighted graph with adjacency matrix

$$A = \begin{bmatrix}
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
1 & 1 & 0 & \sqrt{n} & 0 \\
0 & \sqrt{n} & k & \sqrt{2} & 0 \\
0 & 0 & 0 & \sqrt{2} & 0
\end{bmatrix}. \quad (54)$$

The eigenvalues of $A$ are given by $\mu_1 = 0$ and by

$$\lambda_{a,b} = \frac{1}{4} \left( k + (-1)^a \sqrt{k^2 + 4n} + (-1)^b \sqrt{2k^2 + 4n + 32 + (-1)^a 2\sqrt{k^2 + 4n}} \right), \quad (55)$$

for $a, b = 0, 1$. Moreover, $E_{\mu_1} e_u = -E_{\mu_1} e_v$ and that $E_{\lambda_{a,b}} e_u = E_{\lambda_{a,b}} e_v$, for all $a, b = 0, 1$.

Figure 10: The quotient of $K_n \circ \overline{K}_2$ where $k = n - 1$.

Theorem 5.4. For $n \geq 3$, there is no pretty good state transfer in $K_n \circ \overline{K}_2$.

Proof. By Theorem 2.4, we may rule out pretty good state transfer from $(v, 0)$ to $(v, a)$ for $a = 1, 2$, and from $(v, a)$ to $(w, b)$ for $a, b = 0, 1, 2$ and $v \neq w$.

Next, we rule out pretty good state transfer between $(v, 1)$ and $(v, 2)$ for each vertex $v$ of $K_n$. We take the quotient of $K_n \circ \overline{K}_2$ and apply Fact 1 with $k = n - 1$. The eigenvalues are $\mu_1 = 0$ and $\lambda_{0,b} = \frac{1}{2} (n + (-1)^b \sqrt{n^2 + 8})$, for $b = 0, 1$, and $\lambda_{1,0} = 1$, $\lambda_{1,1} = -2$. Take $m_1 = -3$, $\ell_{0,b} = 0$, for $b = 0, 1$, and $\ell_{1,0} = 2$, $\ell_{1,1} = 1$. Note that

$$\sum_{a,b=0,1} \ell_{a,b} \lambda_{a,b} + m_1 \mu_1 = 0, \quad \sum_{a,b=0,1} \ell_{a,b} + m_1 = 0 \quad (56)$$

but $m_1 = -3$ is odd. By Lemma 5.1, there is no pretty good state transfer.

Theorem 5.5. Let $K_n + I$ denote the graph obtained by adding loop to each vertex of the complete graph $K_n$, where $n \geq 1$. Then for $n \geq 2$, there is pretty good state transfer in $(K_n + I) \circ \overline{K}_2$ between vertices $(v, 1)$ and $(v, 2)$, for each vertex $v$ of $K_n$, where the vertices of $\overline{K}_2$ are denoted by 1 and 2.

Proof. Take the quotient of $(K_n + I) \circ \overline{K}_2$ and apply Fact 1 with $k = n$. The eigenvalues are $\mu_1 = 0$ and

$$\lambda_{a,b} = \frac{1}{4} \left( n + (-1)^a \sqrt{n^2 + 4n} + (-1)^b \sqrt{2n^2 + 4n + 32 + (-1)^a 2n \sqrt{n^2 + 4n}} \right), \quad (57)$$
for $a, b = 0, 1$. Suppose $m_1$ and $\ell_{a,b}$ are integers for which $\sum_{a,b=0,1} \ell_{a,b} \lambda_{a,b} = 0$ and

$$m_1 = - \sum_{a,b=0,1} \ell_{a,b}. \text{ Let } \alpha = \sqrt{n^2 + 4n} \text{ and } \beta = \sqrt{2n^2 + 4n + 32 + 2n\sqrt{n^2 + 4n}}. \text{ We restate the first condition as}$$

$$n \sum_{a,b} \ell_{a,b} + \alpha \sum_{a,b} (-1)^a \ell_{a,b} + \beta_+ (\ell_{0,0} - \ell_{0,1}) + \beta_- (\ell_{1,0} - \ell_{1,1}) = 0. \quad (58)$$

Since $\alpha$ and $\beta_\pm$ are irrational, we have $\sum_{a,b} \ell_{a,b} = -m_1 = 0$. By Lemma 5.1, there is pretty good state transfer between $u$ and $v$. \hfill \square

We observe that $(K_1 + I) \circ K_2$ is periodic but has no pretty good state transfer. The eigenvalues of the corona $(K_1 + I) \circ K_2$ are $\lambda_1 = 2$, $\lambda_2 = -1$, and $\mu = 0$, which shows periodicity. However, there is no pretty good state transfer, since we may apply Lemma 5.1. with $\ell_1 = 1$, $\ell_2 = 2$ and $m = -3$.

### 5.3 Thorny Graphs

The corona product of a graph with $K_1$ is called a **thorny graph** (see Gutman [24]).

**Theorem 5.6.** Let $G$ be a graph and let $u, v$ be two of its vertices. Suppose there is perfect state transfer between $u$ and $v$ at time $t = \pi/g$, for some positive integer $g$, and that $0$ is not in the eigenvalue support of $u$. Then there is pretty good state transfer between $(u, 0)$ and $(v, 0)$ in $G \circ K_1$.

**Proof.** Let $S$ be the eigenvalue support of $u$ in $G$. By Theorem 2.1, if $G$ has perfect state transfer at time $\pi/g$ between the vertices $u$ and $v$, for some integer $g$, all eigenvalues in $S$ must be integers. For each eigenvalue $\lambda$ in $S$, let $c_{\lambda}$ be the square-free part of $\lambda^2 + 4$, so that $\Lambda_{\lambda} = \sqrt{\lambda^2 + 4} = s_{\lambda} \sqrt{c_{\lambda}}$ for some integers $s_{\lambda}$. Since $0$ is not in the eigenvalue support of $u$, then $\Lambda_{\lambda}$ is irrational and $c_{\lambda} > 1$ for each $\lambda$ in $S$. By Lemma 2.6,

$$\{\sqrt{c_{\lambda}} : \lambda \in \supp_G(u) \} \cup \{1\} \quad (59)$$

is linearly independent over $\mathbb{Q}$. Kronecker’s Theorem implies that there exist integers $\ell, q_{\lambda}$ such that

$$\ell \sqrt{c_{\lambda}} + q_{\lambda} \approx -\frac{\sqrt{c_{\lambda}}}{2g}. \quad (60)$$

Multiplying by $4s_{\lambda}$ yields that

$$\left(4\ell + \frac{2}{g}\right) \Lambda_{\lambda} \approx 4q_{s_{\lambda}}s_{\lambda}. \quad (61)$$

Therefore, at $t = (4\ell + 2/g)\pi$, we have $\cos(\Lambda_{\lambda}t/2) \approx 1$ for each $\lambda$ in $S$. By Proposition 3.3,

$$e^T_{(u, 0)} e^{-iAt}(G \circ K_1)e_{(v, 0)} = \sum_{\lambda \in \supp(G)} e^{-i\lambda t/2} \left(\cos(\Lambda_{\lambda}t/2) - i \frac{\lambda}{\Lambda_{\lambda}} \sin(\Lambda_{\lambda}t/2)\right) e^T_{u} E_{\lambda}(G)e_{v}$$

$$\approx \sum_{\lambda \in \supp(G)} e^{-i(2\pi/\lambda)\lambda} e^{-i\frac{\pi}{g}} e^T_{u} E_{\lambda}(G)e_{v}$$

$$= e^T_{u} e^{-i(\pi/g)A(G)}e_{v}, \quad (62)$$

**THE ELECTRONIC JOURNAL OF COMBINATORICS 24(2) (2017), #P2.24**
because all the eigenvalues $\lambda$ in the support of $u$ are integers. Since $G$ has perfect state transfer between $u$ and $v$ at time $\pi/g$, this completes the proof. \hfill $\blacksquare$

When zero is in the eigenvalue support of $u$, we need a slightly stronger condition to get pretty good state transfer in $G \circ K_1$.

**Theorem 5.7.** Let $G$ be a graph having zero as an eigenvalue. Suppose that $G$ has perfect state transfer at time $\pi/2$ between vertices $u$ and $v$. Then there is pretty good state transfer between $(u, 0)$ and $(v, 0)$ in the corona $G \circ K_1$.

**Proof.** Similar to the proof of Theorem 5.6, for each $\lambda \in \text{supp}_G(u)$, we can write $\Lambda_\lambda = s_\lambda \sqrt{c_\lambda}$ where $c_\lambda$ is the square-free part of $\lambda^2 + 4$ and $s_\lambda$ is an integer. Note that $c_\lambda = 1$ if and only if $\lambda = 0$. The set

$$\{\sqrt{c_\lambda} : \lambda \in \text{supp}_G(u), \lambda \neq 0\} \cup \{1\}$$

is linearly independent over $\mathbb{Q}$.

For $\lambda \neq 0$, Kronecker’s Theorem implies that there exist integers $l$ and $q_\lambda$ such that

$$\ell \sqrt{c_\lambda} - q_\lambda \approx -\frac{\sqrt{c_\lambda}}{4} + \frac{1}{2s_\lambda}.$$

At time $t = (4\ell + 1)\pi$, we have $\cos(\Lambda_0 t/2) = -1$, and $\cos(\Lambda_\lambda t/2) \approx -1$ for $\lambda \neq 0$. By Proposition 3.3,

$$e^T_{(u, 0)} e^{-itA(G \circ K_1)} e_{(v, 0)} = \sum_{\lambda \in \text{Sp}(G)} e^{-i\lambda t/2} \left( \cos(\Lambda_\lambda t/2) - i \frac{\lambda}{\Lambda_\lambda} \sin(\Lambda_\lambda t/2) \right) e^T u E_\lambda(G) e_v$$

$$\approx -\sum_{\lambda \in \text{Sp}(G)} e^{-i(2\pi)\ell \lambda} e^{-i\frac{\pi}{2} \lambda} e^T u E_\lambda(G) e_v$$

$$= -e^T u e^{-i(\pi/2)A(G)} e_v.$$

Since $G$ has perfect state transfer between $u$ and $v$ at time $\pi/2$, this completes the proof. \hfill $\blacksquare$

In contrast to Corollary 4.5, the following shows that certain thorny distance-regular graphs have pretty good state transfer, but not perfect state transfer.

**Corollary 5.8.** Let $G$ be a graph from one of the following families:

- $d$-cubes $Q_d$, for $d \geq 2$.
- Cocktail party graphs $nK_2$ when $n$ is even.
- Halved $2d$-cubes $\frac{1}{2} Q_{2d}$, for $d \geq 1$.

Then $G \circ K_1$ has pretty good state transfer between antipodal vertices in $G$. 

---

THE ELECTRONIC JOURNAL OF COMBINATORICS 24(2) (2017), #P2.24
For a distance-regular graph $G$ with diameter $d$, let $G_\ell$ be a graph obtained from $G$ by connecting two vertices $u$ and $v$ if they are at distance $\ell$ from each other, where $\ell$ ranges from 0 to $d$. It is customary to denote $A_\ell(G)$ as the adjacency matrix of graph $G_\ell$. We say $G$ is antipodal if $G_d$ is a disjoint union of cliques of the same size; here, these cliques are called the antipodal classes or fibres of $G$.

**Lemma 5.9** (Coutinho et al. [12], Lemma 4.4). Let $G$ be a distance-regular graph of diameter $d$ with eigenvalues $\lambda_0 > \lambda_1 > \ldots > \lambda_d$. Let the spectral decomposition of the adjacency matrix of $G$ be given by $A(G) = \sum_{j=0}^d \lambda_j E_j(G)$. Suppose that $G$ is antipodal with classes of size two. Then

$$A_d(G)E_j(G) = (-1)^j E_j(G).$$

Figure 11: $Q_4 \circ K_1$ has PGST between the white vertices.

The following observation shows that it is not necessary for $G$ to have perfect state transfer in order for $G \circ H$ to have pretty good state transfer.

**Theorem 5.10.** Let $n \geq 3$ be an odd integer, and let $u$ and $v$ be antipodal vertices of the cocktail party graph $nK_2$. Then there is pretty good state transfer between $(u,0)$ and $(v,0)$ in $nK_2 \circ K_1$.

**Proof.** The eigenvalues of $nK_2$ are $\lambda_0 = 2n - 2$, $\lambda_1 = 0$, and $\lambda_2 = -2$. Since the cocktail-party graph is an antipodal distance-regular graph with fibers of size two, from Lemma 5.9, the eigenprojectors satisfy

$$e^T_u E_j(nK_2)e_v = (-1)^j e^T_u E_j(nK_2)e_u$$

for $j = 0, 1, 2$. From Proposition 3.3, letting $\Lambda_j = \sqrt{\lambda^2_j + 4}$, it suffices to approximate $e^{-it\Lambda_j/2} \approx 1$ and $\cos(\Lambda_j t/2) \approx (-1)^{j+1}$.

For all integers $\ell$, at time $t = 4\pi \ell$, we have $e^{-it\Lambda_0/2} = 1$ and $\cos(\Lambda_1 t/2) = 1$. We will apply Kronecker’s Theorem to $\Lambda_0$ and $\Lambda_2$. Note that $\Lambda_2 = 2\sqrt{2}$ while

$$\Lambda_0 = \sqrt{4 + 4(n - 1)^2} = 2\sqrt{1 + (n - 1)^2},$$

THE ELECTRONIC JOURNAL OF COMBINATORICS 24(2) (2017), #P2.24

23
and $1 + (n - 1)^2$ is always odd when $n$ is odd. Let $c_0$ denote the square-free part of $\Lambda_0^2$; then, $\Lambda_0 = 2s_0\sqrt{c_0}$ for some odd integer $s_0$. Choose integers $\ell$, $q_0$, and $q_2$ such that

$$\ell\sqrt{c_0} - q_0 \approx \frac{1}{4},$$

(70)

$$\ell\sqrt{2} - q_2 \approx \frac{1}{4}.$$  

(71)

At time $t = 4\pi\ell$, we note $t\Lambda_0/2 \approx 4\pi q_0 s_0 + \pi s_0$ and $t\Lambda_2/2 \approx 4\pi q_2 + \pi$, implying that (68) is satisfied. □

Acknowledgments

We thank Chris Godsil for helpful remarks on state transfer and Adi Makmal for discussions about embedded hypercubes. The research of E.A., Z.B., J.M., and C.T. was supported by NSF grant DMS-1262737 and NSA grant H98230-15-1-0044. C.T. would like to thank Institut Henri Poincaré (Centre Émile Borel) for hospitality and support during a visit where part of this work was done. We also thank the reviewer whose insightful comments improved our manuscript considerably and who had kindly pointed out [3, 26] to us.

References


