



Cuts and semidefinite liftings for the complex cut polytope

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Abstract

We consider the complex cut polytope: the convex hull of Hermitian rank 1 matrices xx^H , where the elements of $x \in \mathbb{C}^n$ are m th unit roots. These polytopes have applications in MAX-3-CUT, digital communication technology, angular synchronization and more generally, complex quadratic programming. For $m = 2$, the complex cut polytope corresponds to the well-known cut polytope. We generalize valid cuts for this polytope to cuts for any complex cut polytope with finite $m > 2$ and provide a framework to compare them. Further, we consider a second semidefinite lifting of the complex cut polytope for $m = \infty$. This lifting is proven to be equivalent to other complex Lasserre-type liftings of the same order proposed in the literature, while being of smaller size. Our theoretical findings are supported by numerical experiments on various optimization problems.

Keywords Complex semidefinite programming · Complex cut polytope · Polyhedral combinatorics · MIMO · Angular synchronization

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1 Introduction

The maximum-cut problem (MAX-CUT) on a graph, is to find a partition of vertices in two disjoint subsets, that maximizes the number of edges that cross the partition. MAX-CUT finds applications in VLSI design and physics [3], data science [9], and is $\mathcal{NP}$ -hard. The convex hull of the rank 1 matrices representing all partitions is known as the cut polytope. This polytope admits an exponential number (in n) of extreme

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points, and it cannot be efficiently described, in contrast to its positive semidefinite (PSD) approximation, the elliptope [27].

We consider here complex generalizations of the cut polytope and elliptope, namely the complex cut polytope, denoted CUT_m^n , and the complex elliptope, denoted $\mathcal{E}_m^n$. For fixed integers m and n , CUT_m^n is defined as the convex hull of Hermitian rank 1 matrices xx^H , where the elements of the vectors $x \in \mathbb{C}^n$ are m th unit roots. For $m = 2$, CUT_m^n corresponds to the cut polytope. The set CUT_m^n finds applications in the multiple-input multiple-output detection problem (MIMO) [22, 34, 38, 57], angular synchronization [2], phase retrieval [48], radar signal processing [35, 45], and for $m = 3$, it can be used to model MAX-3-CUT [18]. For finite $m \geq 3$, algorithms for optimization over CUT_m^n are proposed in [33, 35], and approximation ratios are studied in [44, 56].

In this work, we derive novel cuts in the complex plane that separate $\mathcal{E}_m^n$ from CUT_m^n . In particular, we derive all facets of CUT_3^3 to obtain an exact description. We define a function str , that provides the approximation ratio of maximization over $\mathcal{E}_m^n$ and maximization over CUT_m^n , for given problem instances. This function is used for numerically evaluating the effect of adding valid cutting planes to $\mathcal{E}_m^n$. We prove that the cuts introduced here are invariant under rotations and taking the conjugate. We also investigate the effect of adding cuts to $\mathcal{E}_m^n$ for various optimization problems.

Optimization over $\mathcal{E}_m^n$ can be done in polynomial time (for fixed precision), by solving a complex semidefinite program (CSDP). CSDPs have recently received much attention in the literature [23, 36, 49–51, 58]. CSDPs with matrix variables of order n are solved by SDP solvers as real SDPs with matrix variables of order $2n$. In [10, Corollary 2.5.2] and [51], conditions are provided under which this doubling of the size can be avoided. In this work, we extend these conditions. Specifically, we show that CSDPs can be reformulated as real SDPs of same size, when the objective function contains only real coefficients, and the feasible set of the CSDP is closed under complex conjugation. In particular, we show that this is the case for CSDPs over $\mathcal{E}_m^n$, and that the derived complex facets can be equivalently reformulated to real facets.

The set CUT_∞^n is studied in [21]. The first semidefinite lifting of CUT_∞^n , denoted $\mathcal{E}_\infty^n$, is also known as the set of correlation matrices [20, 30]. Here, we extend the results of [21]. In particular, we consider second semidefinite Lasserre-type liftings of CUT_∞^n . Such liftings are defined in terms of moment matrices, and we study second liftings with smaller moment matrices than those proposed in the literature [21, 23]. Despite this decrease in size, we show that here considered liftings are equivalent to those proposed in the literature. Moreover, for $n = 4$ (the smallest n for which $\text{CUT}_\infty^n \subsetneq \mathcal{E}_\infty^n$), we prove that the second semidefinite lifting of CUT_∞^n excludes all rank 2 extreme points present in $\mathcal{E}_\infty^4$, and that matrices in this set satisfy a certain valid cut for CUT_∞^4 .

We also show, via a constructive proof, that $\mathcal{E}_m^n$ contains rank 2 extreme points for all integer $n, m \geq 3$. This shows the strict inclusion of CUT_m^n in $\mathcal{E}_m^n$ for these values of n and m . For $n = 3$, we provide necessary and sufficient conditions for matrices to be rank 2 extreme points of $\mathcal{E}_m^3$.

This paper is organized as follows. Notation is given in Sect. 1.1. We provide the definitions of CUT_m^n and $\mathcal{E}_m^n$ in Sect. 2. In Sect. 3, we introduce a framework for finding valid inequalities for CUT_m^n and provide some valid cuts. In Sect. 4, we provide an exact description of CUT_3^3 , and use the derived facets of CUT_3^3 to strengthen $\mathcal{E}_3^3$ for

general $n \geq 3$. In Sect. 5 we provide an efficient reformulation of CSDPs whose convex feasible sets are closed under complex conjugation. In Sect. 6 we investigate the sets CUT_∞^n and second semidefinite liftings of CUT_∞^n . In Sect. 7, we study rank 2 extreme points of $\mathcal{E}_m^n$ for integer $m > 2$. In Sect. 8, we numerically investigate the effect of adding cuts to $\mathcal{E}_m^n$ for various optimization problems from the literature. Lastly, in Sect. 9 we draw conclusions, and propose future research directions.

1.1 Notation

For $n \in \mathbb{N}$, $[n] := \{1, \dots, n\}$. The imaginary unit is denoted by $\mathbf{i} := \sqrt{-1}$. The complex conjugate of $z \in \mathbb{C}$ is denoted by $\bar{z}$, and its modulus by $|z| = \sqrt{z\bar{z}}$. The Hermitian transpose of a complex matrix A is denoted by A^H . For $z \in \mathbb{C}^n$, $\|z\| = \sqrt{z^H z}$. A matrix $A \in \mathbb{C}^{n \times n}$ is called Hermitian if $A = A^H$. A Hermitian matrix A is said to be Hermitian PSD, denoted by $A \succeq 0$, if $x^H A x \geq 0$ for all $x \in \mathbb{C}^n$. For any $z \in \mathbb{C}$, $\text{Re}(z) \in \mathbb{R}$ and $\text{Im}(z) \in \mathbb{R}$ denote the real and imaginary part of z , respectively. Additionally, by slight abuse of notation, for sets $U \subseteq \mathbb{C}^n$, we define $\text{Re}(U) := \{\text{Re}(u) \mid u \in U\} \subseteq \mathbb{R}^n$. The boundary of a set U is denoted ∂U .

We denote by $\mathcal{H}^n$ the set of Hermitian matrices of order n , and $\mathcal{H}_+^n$ for the set of positive semidefinite Hermitian matrices. Similarly, $\mathcal{S}^n$ and $\mathcal{S}_+^n$ denote, respectively, the sets of symmetric real matrices, and symmetric real positive semidefinite matrices, both of order n . If the context is clear, we omit the superscript n . The vector space $\mathcal{H}^n$ is equipped with the trace inner product, i.e., for $A, B \in \mathcal{H}^n$ we have $\langle A, B \rangle := \text{Tr}(AB)$. The rank of a matrix is denoted $\text{rk}(A)$.

For $n \in \mathbb{R}_+$, $\lfloor n \rfloor$ and $\lceil n \rceil$ denote the rounding down and rounding to nearest integer operators, respectively. The Hadamard product of two matrices $A = (a_{ij})$ and $B = (b_{ij})$ of the same size is denoted by $A \odot B$ and is defined as $(A \odot B)_{ij} := a_{ij}b_{ij}$.

Let J_n (resp. I_n) denote the all ones matrix (resp. identity matrix) of order n . The vector of all ones (resp. zeros) and length n is denoted by $\mathbf{1}_n$ (resp. $\mathbf{0}_n$). However, we omit n when the size of a matrix is clear from the context. Matrix E_{ij} denotes the matrix which is zero everywhere, except for entry (i, j) , which has value 1. For any matrix $X \in \mathcal{H}^n$, $\text{diag}(X) \in \mathbb{R}^n$ denotes the vector containing the diagonal entries of X . Similarly, for $x \in \mathbb{R}^n$, $\text{Diag}(x) \in \mathcal{S}^n$ denotes the diagonal matrix with x on the diagonal.

2 Preliminaries

We define, for fixed integer $m \geq 2$, the set

$$\mathcal{B}_m := \left\{ \exp(\theta \mathbf{i}) \mid \theta = \frac{2\pi k}{m}, k \in [m] \right\} \subseteq \mathbb{C}, \quad (1)$$

as the set of the complex m th roots of unity. We define $\mathcal{B}_m^n$ as the set containing m^n vectors of length n , in which each entry is restricted to be an element of $\mathcal{B}_m$.

In this paper, we consider a generalization of the well-known cut polytope [8], to which we refer as the *complex cut polytope*. For integers $n, m \geq 2$, the complex cut polytope is defined as

$$\text{CUT}_m^n := \text{Conv} \left\{ xx^H \mid x \in \mathcal{B}_m^n \right\}. \quad (2)$$

As $\mathcal{B}_2 = \{\pm 1\}$, the set CUT_2^n coincides with the well-known cut polytope, which is a feasible set for the maximum-cut problem [17, 27]. Optimization problems over CUT_m^n , $m \geq 2$, are $\mathcal{NP}$ -hard, as they include MAX-CUT.

Let us define the *complex elliptope* as follows:

$$\mathcal{E}_m^n := \left\{ X \in \mathcal{H}_+^n \mid \text{diag}(X) = \mathbf{1}, X_{ij} \in \text{Conv}(\mathcal{B}_m) \right\}. \quad (3)$$

Note that for $m = 2$, $X \in \mathcal{H}_+^n$ such that $\text{diag}(X) = \mathbf{1}$ implies $X_{ij} \in [-1, 1]$. Thus, the complex elliptope $\mathcal{E}_2^n$ corresponds to the elliptope that is defined by Laurent and Poljak [27]. For $m = 3$, the complex elliptope $\mathcal{E}_m^n$ corresponds to the feasible set of the complex SDP relaxation for MAX-3-CUT by Goemans and Williamson [18]. It is clear that $\text{CUT}_m^n \subseteq \mathcal{E}_m^n$.

Here, we derive strong approximations of CUT_m^n by using SDP. Besides considering second semidefinite liftings, we also derive cuts in the complex plane that separate $\mathcal{E}_m^n$ from CUT_m^n . Cuts in the complex plane have recently been studied by Jarre et al. [21], for the set CUT_∞^n , defined as

$$\text{CUT}_\infty^n := \text{Conv} \left\{ xx^H \mid x \in \mathbb{C}^n, |x_i| = 1 \ \forall i \in [n] \right\}. \quad (4)$$

We also define $\mathcal{B}_\infty := \{\exp(\theta i) \mid \theta \in \mathbb{R}\}$ as a natural extension of (1), and the complex elliptope

$$\mathcal{E}_\infty^n := \left\{ X \in \mathcal{H}_+^n \mid \text{diag}(X) = \mathbf{1}_n \right\}.$$

Note that for $X \in \mathcal{E}_\infty^n$, we have $X_{ij} \in \text{Conv}(\mathcal{B}_\infty) = \{x \in \mathbb{C} \mid |x| \leq 1\}$. The complex elliptope $\mathcal{E}_\infty^n$ can be considered as the first semidefinite lifting of CUT_∞^n . Additionally, one can define a second semidefinite lifting of CUT_∞^n , following [25], and also proposed by Jarre et al. [21] for $n = 4$.

2.1 Basic CSDP relaxations

In this section, we present the basic semidefinite program whose feasible set is the complex elliptope $\mathcal{E}_m^n$ for integer $m \geq 2$, see (3). The basic SDP relaxation for $m = 2$ was introduced by Goemans and Williamson [17], for $m = 3$ by Goemans and Williamson [18], and for general $m \geq 3$ by Lu et al. [33]. In the sections that follow, we will derive cuts that strengthen the basic SDP. Let $n, m \geq 2$ and $C \in \mathcal{H}^n$. From

the definitions of CUT_m^n and $\mathcal{E}_m^n$, we have

$$\max_{x \in \mathcal{B}_m^n} x^H C x = \max_{X \in \text{CUT}_m^n} \langle C, X \rangle \leq \max_{X \in \mathcal{E}_m^n} \langle C, X \rangle. \quad (\text{CSDP-P})$$

Note that the above upper bound (referred to as **CSDP-P**, with P for primal) is computable in polynomial time up to desired accuracy by the interior point method. The complex elliptope $\mathcal{E}_m^n$ contains positive definite matrices, e.g., the identity. For $X \in \mathcal{E}_m^n$, we require that $X_{ij} \in \text{Conv}(\mathcal{B}_m)$, see (1). One way to enforce this is to set

$$X_{ij} = \sum_{k=1}^m \lambda_k e^{\theta_k \mathbf{i}}, \text{ with } \sum_{k=1}^m \lambda_k = 1, \lambda \geq 0, \lambda \in \mathbb{R}^m$$

$$\text{and } \theta_k = \frac{2\pi k}{m} \text{ (i.e., } \exp(\theta_k \mathbf{i}) \in \mathcal{B}_m \text{)}.$$

Alternatively, X_{ij} can be restricted to lie in certain half-spaces. This perspective follows from the well-known fact that $\mathbb{C}$ is isomorphic to $\mathbb{R}^2$ via the bijective mapping

$$g: \mathbb{R}^2 \rightarrow \mathbb{C}, \quad g(a) = a_1 + a_2 \mathbf{i},$$

and that, for $a, b \in \mathbb{R}^2$, $a^\top b = \text{Re}(\overline{g(a)}g(b))$. Now, it is easy to see that the set $\text{Conv}(\mathcal{B}_m)$ is given by an m -sided regular convex polygon in $\mathbb{C}$. For the edge connecting $\exp(\theta_k \mathbf{i})$ and $\exp(\theta_{k-1} \mathbf{i})$, its normal vector (complex number) is given by $v_k := \exp[(\theta_k + \theta_{k-1})\mathbf{i}/2] = \exp[(2k-1)\pi \mathbf{i}/m]$ for $k \in [m]$. Thus,

$$X_{ij} \in \text{Conv}(\mathcal{B}_m) \iff \text{Re}(\bar{v}_k X_{ij}) \leq \cos\left(\frac{\pi}{m}\right) \quad \forall k \in [m], \quad (5)$$

see also [33].

Remark 1 The set $\text{Conv}(\mathcal{B}_m)$ is the regular m -sided polygon, and as (5) shows, this set can be described by its m facets. A more efficient encoding is derived by viewing $\text{Conv}(\mathcal{B}_m)$ as the projection of a higher dimensional polytope with possibly fewer facets. The earliest result in this direction is due to Ben-Tal and Nemirovski [4]. They showed that, for m a power of two, $\text{Conv}(\mathcal{B}_m)$ is equivalent to the projection of a polytope with $\mathcal{O}(\log m)$ number of facets. Later results extended this to general m [13, Theorem 2], and projections of higher dimensional spectrahedra [11, 12]. Since m is small in our numerical experiments, we do not use such liftings of the regular polygon in our CSDP relaxations.

To state (5) in terms of matrix inner products, we define, for $k \in [m]$, $i, j \in [n]$, $i < j$ the Hermitian matrices

$$W_{ij}^k := \frac{1}{2} (v_k E_{ij} + \bar{v}_k E_{ji})$$

so that $\text{Re}(\bar{v}_k X_{ij}) = \langle W_{ij}^k, X \rangle$. Now, from the SDP duality theory, it follows that the corresponding dual problem of **CSDP-P** is given by

$$\begin{aligned} \min \mathbf{1}^\top \mu + \cos\left(\frac{\pi}{m}\right) \sum_{ij \in [n]^2, i < j, k \in [m]} \omega_{ij}^k, \\ \text{s.t. } S = \text{Diag}(\mu) + \sum_{ij \in [n]^2, i < j, k \in [m]} \omega_{ij}^k W_{ij}^k - Q \succeq 0, \\ \mu \in \mathbb{R}^n, \omega_{ij} = (\omega_{ij}^1, \dots, \omega_{ij}^m)^\top \in \mathbb{R}_+^m, \quad \forall i, j \in [n], i < j. \end{aligned} \quad (\text{CSDP-D})$$

One can strengthen **CSDP-P** and **CSDP-D** (D for dual) via the moment and sum of squares hierarchies by Lasserre [25]. We consider this in more detail in Sects. 6 and 7, where we consider a second semidefinite lifting of CUT_∞^4 and CUT_m^3 for finite m , respectively. In Sect. 3 we strengthen **CSDP-P** by adding valid cuts to $\mathcal{E}_m^n$, which can be considered as the first semidefinite lifting of CUT_m^n .

3 Framework for finding valid inequalities for CUT_m^n

In this section we introduce a general framework to derive valid inequalities for CUT_m^n , see (2). These inequalities can be then used to strengthen the SDP relaxation **CSDP-P**. We show that these inequalities can be classified in equivalence classes, which we derive from the group structure of CUT_m^n .

Similar to the classical result by Rockafellar [42, Theorem 18.8], stating that any real closed convex set is the intersection of all its half-spaces containing it, the set CUT_m^n has an equivalent description as follows.

Proposition 1

$$\text{CUT}_m^n = \left\{ X \in \mathcal{H}^n \mid \langle Q, X \rangle \leq \max_{x \in \mathcal{B}_m^n} x^H Q x, \quad \forall Q \in \mathcal{H}^n \right\}. \quad (6)$$

The proof of Proposition 1 is similar to the proof of Rockafellar [42, Theorem 18.8] and therefore omitted. Observe that, by Hermiticity of Q , the values $\langle Q, X \rangle$ and $\max_{x \in \mathcal{B}_m^n} x^H Q x$ are real. Therefore, the inequalities in (6) are well defined.

Let us exploit the formulation of CUT_m^n given by (6) for deriving cuts that can be added to **CSDP-P** in order to improve that relaxation. We define the function $\text{str} : \mathcal{H}^n \setminus 0 \times \mathbb{N} \rightarrow [1, \infty)$ (str for strength), as follows:

$$\text{str}(Q, m) := \frac{\max_{X \in \mathcal{E}_m^n} \langle Q, X \rangle}{\max_{X \in \text{CUT}_m^n} \langle Q, X \rangle}. \quad (7)$$

We assume w.l.o.g. that both the numerator and denominator in fraction (7) are strictly positive. This is the case for all here considered matrices Q . Clearly, for a matrix Q for which $\max_{X \in \text{CUT}_m^n} \langle Q, X \rangle \leq 0$, one can appropriately adjust its diagonal.

Observe that str returns the approximation ratio of maximization over $\mathcal{E}_m^n$ and maximization over CUT_m^n , for a specific problem instance given by Q (see also [27, Section 4]). Since $\max_{X \in \mathcal{E}_m^n} \langle Q, X \rangle$ is an upper bound for $\max_{X \in \text{CUT}_m^n} \langle Q, X \rangle$ (both these values are assumed to be strictly positive), we have that $\text{str}(Q, m) \geq 1$. To improve the quality of this upper bound, one can find valid inequalities for CUT_m^n , that are violated by $\arg \max_{X \in \mathcal{E}_m^n} \langle Q, X \rangle$. Thus, if $\text{str}(Q, m) > 1$, then by adding the cut

$$\langle Q, X \rangle \leq \max_{X \in \text{CUT}_m^n} \langle Q, X \rangle, \quad (8)$$

to **CSDP-P** one may strengthen that relaxation. Note that it is, in general, $\mathcal{NP}$ -hard to compute $\text{str}(Q, m)$. However, for some Q we can find optimal solutions of both maximization problems in (7) analytically, and thus evaluate $\text{str}(Q, m)$, see Sect. 3.3.

Remark 2 For any $c \in \mathbb{R}_+^n$, $1 \leq \text{str}(Q + \text{Diag}(c), m) \leq \text{str}(Q, m)$. In order to fairly compare cuts, we consider matrices Q that satisfy $\langle Q, I \rangle = 0$.

3.1 Symmetries of CUT_m^n

In this section, we formally specify symmetries of the set CUT_m^n , for finite m , that follow from the underlying group structure of $\mathcal{B}_m$. These symmetries will be exploited later in Sects. 3.2 and 4.

As starting point, consider the set $\mathcal{B}_m$ defined in (1). With the usual multiplication of complex numbers, $\mathcal{B}_m$ forms a cyclic group of order m with identity element 1. Set $\mathcal{B}_m^n$ with the Hadamard product forms a finite abelian group, with identity element $\mathbf{1}_n$. Indeed, if $x \in \mathcal{B}_m^n$, its inverse element is given by $\bar{x}$, since $\bar{x} \odot x = \mathbf{1}_n$.

We define, for $\alpha \in \mathcal{B}_m^n$, the linear group action of $f_\alpha : \mathcal{H}^n \rightarrow \mathcal{H}^n$ as $f_\alpha(Z) = (\alpha\alpha^H) \odot Z = \text{Diag}(\alpha) Z \text{Diag}(\bar{\alpha})$. To see that f_α defines a group action, let $Z \in \mathcal{H}^n$ and note that $f_{\mathbf{1}_n}(Z) = Z$, and

$$f_\alpha(f_\beta(Z)) = (\alpha\alpha^H) \odot (\beta\beta^H) \odot Z = (\alpha \odot \beta)(\alpha \odot \beta)^H \odot Z = f_{\alpha \odot \beta}(Z). \quad (9)$$

Since f_α defines a group action, f_α is also invertible, with inverse $f_\alpha^{-1} = f_{\bar{\alpha}}$, which follows from (9) by taking $\beta = \bar{\alpha}$. That is, $f_\alpha(f_{\bar{\alpha}}(Z)) = f_{\alpha \odot \bar{\alpha}}(Z) = f_{\mathbf{1}_n}(Z) = Z$.

Note that for $Z, Z' \in \mathcal{H}^n$, we have

$$\langle f_\alpha(Z), f_\alpha(Z') \rangle = \langle Z, Z' \rangle. \quad (10)$$

Informally, function f_α can be considered as acting on $\mathcal{H}^n$ by applying some rotation to the elements of its input matrix. The number of such rotations is equal to the number of different functions f_α . This number is given by m^{n-1} , and not $|\mathcal{B}_m^n| = m^n$, because $f_\alpha = f_{x\alpha}$ for any $x \in \mathcal{B}_m$ and $\alpha \in \mathcal{B}_m^n$. Therefore, in the context of f_α , one element of α can be assumed fixed, say $\alpha_1 = 1$.

The sets CUT_m^n and $\mathcal{E}_m^n$ are closed under the group action f_α . To see this for CUT_m^n , note that $f_\alpha(x\alpha^H) \in \text{CUT}_m^n$ for $x \in \mathcal{B}_m^n$. Therefore, the action f_α on a convex

combination of rank one matrices in CUT_m^n returns a convex combination of (possibly different) rank one matrices in CUT_m^n . To see that $\mathcal{E}_m^n$ is also closed under f_α , note that the Hadamard product of positive semidefinite matrices is again positive semidefinite, due to the well-known Schur Product Theorem. Moreover, the elements of $f_\alpha(X)$, $X \in \mathcal{E}_m^n$, are contained in $\text{Conv}(\mathcal{B}_m)$, since $\text{Conv}(\mathcal{B}_m)$ itself is also closed under the Hadamard product. Specifically, $(f_\alpha(X))_{ij} = X_{ij}\alpha_i\bar{\alpha}_j \in \text{Conv}(\mathcal{B}_m)$.

Remark 3 We have not explicitly covered the symmetries of CUT_∞^n , see (4). However, the group structures of $\mathcal{B}_\infty$ and $\mathcal{B}_\infty^n$ are similar to those of $\mathcal{B}_m$ and $\mathcal{B}_m^n$ for m finite, and therefore do not warrant special consideration. In particular, $\mathcal{B}_\infty^n$ with the Hadamard product is abelian like $\mathcal{B}_m^n$, although its order is infinite, in contrast to $\mathcal{B}_m^n$. Also the group action f_α for $\alpha \in \mathcal{B}_\infty^n$ is defined similarly as f_α for $\alpha \in \mathcal{B}_m^n$, and there is an infinite number of such group actions.

3.2 Classes of valid inequalities

We show here that the strength of a valid inequality, generated by $Q \in \mathcal{H}_n$, is invariant under rotation of elements in Q , i.e., $f_\alpha(Q)$, and taking the conjugate of Q . Thus, each Q in (8) induces a class of valid inequalities.

Consider, for CUT_2^n , the triangle inequalities [26], given by

$$c_1X_{ij} + c_2X_{ik} + c_3X_{jk} \geq -1, \quad c \in \{\pm 1\}^3, \quad c_1c_2c_3 = 1. \quad (11)$$

There are four ways to choose the vector c , and we say that triangle inequalities induced by different c are equivalent under rotation of coefficients (*ROC equivalent*). We generalize the notion of ROC equivalence to CUT_m^n , $m \geq 2$, see also [21], by using the symmetries of CUT_m^n , as outlined in Sect. 3.1.

Lemma 1 *Let $m, n \geq 2$ be integer numbers, $Q \in \mathcal{H}_n$, and $\alpha \in \mathcal{B}_m^n$. Then*

$$\text{str}(Q, m) = \text{str}(Q \odot (\alpha\alpha^H), m),$$

see (7). We say that the cuts induced by Q and $Q \odot (\alpha\alpha^H)$ are ROC equivalent.

Proof It follows from (10) that

$$\max_{X \in \text{CUT}_m^n} \langle Q, X \rangle = \max_{X \in \text{CUT}_m^n} \langle f_\alpha(Q), f_\alpha(X) \rangle = \max_{X \in \text{CUT}_m^n} \langle f_\alpha(Q), X \rangle, \quad (12)$$

where the last inequality is due to the fact that CUT_m^n is closed under the action of f_α . Likewise, $\mathcal{E}_m^n$ is also closed under the action of f_α , as shown in Sect. 3.1. Therefore, (12) also holds when replacing CUT_m^n by $\mathcal{E}_m^n$. Thus, by definition of the function str , the lemma follows. $\square$

We provide an explicit example of such an ROC transformation. Let Q and X be Hermitian matrices of order n , with $\text{diag}(Q) = \mathbf{0}$. Then,

$$\langle Q, X \rangle = 2 \sum_{ij \in [n]^2, i < j} \text{Re}(\overline{Q_{ij}} X_{ij}). \quad (13)$$

Using $(Q \odot (\alpha\alpha^H))_{ij} = Q_{ij}\alpha_i\overline{\alpha_j}$ for $\alpha \in \mathcal{B}_m^n$, it is easy to see how the Hadamard product transforms (13). However, we simplify notation by considering $(\alpha_0, \alpha_1, \dots, \alpha_{n-1})^\top \in \mathcal{B}_m^n$ and $\beta = \alpha_0(1, \alpha_1, \dots, \alpha_{n-1})^\top \in \mathcal{B}_m^n$. Note that the first column of $\beta\beta^H$ is given by $[1 \ \alpha_1 \ \dots \ \alpha_{n-1}]^\top$, so that

$$\frac{1}{2} \langle Q \odot (\beta\beta^H), X \rangle = \text{Re} \left[\sum_{j=2}^n \overline{Q_{1j}} \alpha_{j-1} X_{1j} + \sum_{ij \in [n]^2, 1 < i < j} \overline{Q_{ij}} \alpha_{i-1} \alpha_{j-1} X_{ij} \right]. \quad (14)$$

We exploit the above equality to derive the ROC equivalent inequalities in the next section. The following lemma shows that one can also consider the conjugate of matrix Q without changing the strength of the corresponding valid inequality, resulting in *the conjugate equivalent inequality*.

Lemma 2 *Let $m, n \geq 2$ be integer numbers and $Q \in \mathcal{H}^n$. Then $\text{str}(Q, m) = \text{str}(\overline{Q}, m)$.*

Proof For $Z \in \mathcal{H}^n$, the complex conjugate function $Z \rightarrow \overline{Z}$ is conjugate-linear, invertible, and satisfies an equation similar to (10), i.e., $\langle \overline{Z}, \overline{Z'} \rangle = \langle Z, Z' \rangle$. Thus, (12) is also valid when f_α is replaced with the complex conjugate function. Hence, the same arguments that prove Lemma 1 also prove Lemma 2. $\square$

Example 1 (MAX-3-CUT) The maximum-three-cut problem (MAX-3-CUT) is to partition the vertex set of a graph into 3 subsets such that the total weight of edges joining different sets is maximized. MAX-3-CUT can be modeled using CUT_3^n as noted by Goemans and Williamson [18]. The same authors also derived a complex SDP relaxation for MAX-3-CUT whose feasible set is $\mathcal{E}_3^n$, see (3).

To model MAX-3-CUT on some graph $G = (V, E)$, $|V| = n$, we may associate to each vertex $i \in V$ a variable $x_i \in \mathcal{B}_3$, see (1). The value of any variable assignment (i.e., cut) equals the number of edges $\{i, j\} \in E$ for which $x_i \neq x_j$. Note that, if $x_i \neq x_j$, then $\overline{x_i}x_j \in \mathcal{B}_3 \setminus \{1\}$. Since $\{\text{Re}(z) \mid z \in \mathcal{B}_3 \setminus \{1\}\} = -1/2$, we have

$$\frac{2}{3} \text{Re}(1 - \overline{x_i}x_j) = \begin{cases} 1, & \text{if } x_i \neq x_j \\ 0, & \text{else.} \end{cases}$$

Thus, for a graph G , the value of the cut induced by $x \in \mathcal{B}_3^n$ is given as follows

$$v(G, x) = \frac{2}{3} \sum_{\{i, j\} \in E} \text{Re}(1 - \overline{x_i}x_j). \quad (15)$$

For the complete graph of order 4, denoted by K_4 , it is not difficult to verify that $v(K_4, x) \in \{0, 3, 4, 5\}$ for all $x \in \mathcal{B}_3^4$. That is, any 3-cut of K_4 cuts either 0, 3, 4 or 5 edges. By rewriting (15) for $G = K_4$, we find

$$\sum_{i < j} \operatorname{Re}(\overline{x_i} x_j) = 6 - \frac{3}{2} v(K_4, x) \in \left\{0, \pm \frac{3}{2}, 6\right\}.$$

Therefore, the inequality $\operatorname{Re}(X_{ij} + X_{ik} + X_{il} + X_{jk} + X_{jl} + X_{lk}) \geq -3/2$ is valid for CUT_3^n , along with its ROC equivalent inequalities. We show in the next section that this inequality is not implied by $\mathcal{E}_3^n$, by proving that the strength of the inequality is positive.

3.3 Generalized complex triangle and quadrangle inequalities

In this section, we first generalize the gap inequalities [28] from CUT_2^n to CUT_m^n , with $m > 2$ integer. Then, we derive some valid inequalities for CUT_m^n for different values of m by exploiting (8), and compute their strength. In particular, we show that the generalized complex triangle and complex quadrangle inequalities may strengthen CUT_m^n for finite $m \geq 2$.

To derive the gap inequalities from [28], we set

$$\gamma(b) := \min_{x \in \{\pm 1\}^n} |b^\top x| \quad \text{and} \quad \sigma(b) := \sum_{i \in [n]} b_i, \quad (16)$$

for any $b \in \mathbb{R}^n$, and $B = bb^\top - \text{Diag}(b_1^2, \dots, b_n^2)$. If the context is clear, we omit b in $\gamma(b)$ and $\sigma(b)$. The gap inequality is then defined as

$$\langle B, X \rangle \geq 2 \sum_{1 \leq i < j \leq n} b_i b_j + \gamma^2 - \sigma^2 \quad \forall X \in \text{CUT}_2^n. \quad (17)$$

Note that Laurent and Poljak [28] define the gap inequality in terms of $\{0, 1\}$ variables, rather than $\{\pm 1\}$, which explains the discrepancy between (17) and the gap inequality presented in [28]. We generalize the above inequality to $\mathbb{C}$ in the following lemma.

Lemma 3 *Let $b \in \mathbb{C}^n$, and set $B = bb^H - \text{Diag}(|b_1|^2, \dots, |b_n|^2)$. Then, for*

$$\gamma(b) := \min_{x \in \mathcal{B}_m^n} |b^H x|,$$

and $\sigma(b)$ as in (16), we have

$$\min_{X \in \text{CUT}_m^n} \langle B, X \rangle = 2 \operatorname{Re} \left(\sum_{1 \leq i < j \leq n} b_i \overline{b_j} \right) + \gamma^2 - \sigma \overline{\sigma}.$$

Proof The result follows from the fact that $\gamma^2 = \min_{X \in \text{CUT}_m^n} \langle bb^H, X \rangle = \min_{X \in \text{CUT}_m^n} \langle B, X \rangle + \|b\|^2$, and $\|b\|^2 = \sigma\bar{\sigma} - 2 \operatorname{Re} \left(\sum_{1 \leq i < j \leq n} b_i \bar{b}_j \right)$. $\square$

We use Lemma 3 also to prove the following result.

Proposition 2 Let $m \geq 2$, $n \in \{3, 4\}$, $Q_n = I_n - J_n$. Then

$$\begin{aligned} \max_{X \in \mathcal{E}_m^n} \langle Q_n, X \rangle &= n \text{ and} \\ \max_{X \in \text{CUT}_m^n} \langle Q_n, X \rangle &= \begin{cases} -4 \cos \left(\frac{2 \lfloor m/3 \rfloor \pi}{m} \right) - 2 \cos \left(\frac{4 \lfloor m/3 \rfloor \pi}{m} \right) & \text{if } n = 3 \text{ and } m \text{ not a multiple of } 3, \\ -2 - 8 \cos \left(\frac{2 \lfloor m/2 \rfloor \pi}{m} \right) - 2 \cos \left(\frac{4 \lfloor m/2 \rfloor \pi}{m} \right) & \text{if } n = 4 \text{ and } m \text{ odd,} \\ n & \text{else.} \end{cases} \end{aligned} \quad (18)$$

Proof For any $Y \in \mathcal{E}_m^n$, the value $\langle Q_n, Y \rangle$ provides a lower bound on $\max_{X \in \mathcal{E}_m^n} \langle Q_n, X \rangle$. Specifically for $Y = (nI_n - J_n)/(n-1)$, we have $\max_{X \in \mathcal{E}_m^n} \langle Q_n, X \rangle \geq \langle Q_n, Y \rangle = n$. Moreover, we have for all $X \in \mathcal{E}_m^n$, $\langle Q_n, X \rangle = n - \langle J_n, X \rangle \leq n$, since $J_n \succeq 0$. Thus $\max_{X \in \mathcal{E}_m^n} \langle Q_n, X \rangle = n$.

For optimization over CUT_m^n , note that $(-Q_n) = \mathbf{1}_n \mathbf{1}_n^H - \text{Diag}(\mathbf{1}_n)$, and we may apply Lemma 3, for $b = \mathbf{1}_n$. Consequently, $\sigma(\mathbf{1}_n) = n$, and

$$\max_{X \in \text{CUT}_m^n} \langle Q_n, X \rangle = - \min_{X \in \text{CUT}_m^n} \langle -Q_n, X \rangle = n^2 - 2 \binom{n}{2} - \gamma(\mathbf{1}_n)^2 = n - \min_{x \in \mathcal{B}_m^n} |\mathbf{1}^H x|^2. \quad (19)$$

It remains to determine $\gamma(\mathbf{1}_n) = \min_{x \in \mathcal{B}_m^n} |\mathbf{1}^H x|$. It is clear that when $n = 3$ and m a multiple of 3, or $n = 4$ and m even, $\gamma(\mathbf{1}) = 0$ (since then there exist n m th roots of unity that sum to 0).

For $n = 3$ and m not a multiple of 3, geometric arguments from [40] show that the optimal value is attained for $x^* = (1, z, \bar{z})^\top$, where $z = \exp \left(\frac{2 \lfloor m/3 \rfloor \pi}{m} \mathbf{i} \right)$. Then,

$$\begin{aligned} \gamma(\mathbf{1}_3)^2 &= |\mathbf{1}_3^H x^*|^2 = \left(1 + 2 \cos \left(\frac{2 \lfloor m/3 \rfloor \pi}{m} \right) \right)^2 \\ &= 3 + 4 \cos \left(\frac{2 \lfloor m/3 \rfloor \pi}{m} \right) + 2 \cos \left(\frac{4 \lfloor m/3 \rfloor \pi}{m} \right), \end{aligned}$$

and the result follows from substitution in (19).

For $n = 4$ and m odd, similar geometric arguments from [40] show that the minimizer of $\gamma(\mathbf{1}_4)$ is given by $x^* = (1, 1, z, \bar{z})^\top$, where $z = \exp \left(\frac{2 \lfloor m/2 \rfloor \pi}{m} \mathbf{i} \right)$. Using this to compute $\gamma(\mathbf{1}_4)^2$, and substituting the result in (19) yields the proof. $\square$

The coefficients of these valid inequalities can be multiplied by elements from $\mathcal{B}_m^n$ without altering their strength, see Lemma 1. Let us present these ROC equivalent inequalities explicitly below.

Corollary 1 *Let $m \geq 2$, $n \in \{3, 4\}$, $Q_n = I_n - J_n$. For $n = 3$, the ROC equivalent inequalities of the inequality induced by Proposition 2 read*

$$-2 \operatorname{Re}(\alpha_1 X_{12} + \alpha_2 X_{13} + \overline{\alpha_1} \alpha_2 X_{23}) \leq \max_{X \in \text{CUT}_m^3} \langle Q_3, X \rangle, \quad (20)$$

where $\alpha \in \mathcal{B}_m^2$. For $n = 4$, we have the following ROC equivalent inequalities

$$\begin{aligned} & -2 \operatorname{Re}(\alpha_1 X_{12} + \alpha_2 X_{13} + \alpha_3 X_{14} + \overline{\alpha_1} \alpha_2 X_{23} + \overline{\alpha_1} \alpha_3 X_{24} + \overline{\alpha_2} \alpha_3 X_{34}) \\ & \leq \max_{X \in \text{CUT}_m^4} \langle Q_4, X \rangle, \end{aligned} \quad (21)$$

where $\alpha \in \mathcal{B}_m^3$. Lastly, $\operatorname{str}(Q_n, m) > 1$, see (7), if and only if $\gcd(n, m) = 1$.

Proof The inequalities (20) and (21) are obtained from (8) and (14) where $Q := I_n - J_n$.

To show that str is positive whenever $\gcd(n, m) = 1$, we consider again separate cases. Let first $n = 3$ and $m \equiv 1 \pmod{3}$. Along with the earlier assumption that $m \geq 2$, this implies that $m \geq 4$. Then $\lfloor m/3 \rfloor = (m-1)/3$. Substituting this in (18) for $n = 3$, and using that $\cos(2z) = 2\cos^2(z) - 1$, we find

$$\begin{aligned} \max_{X \in \text{CUT}_m^3} \langle Q_3, X \rangle &= 2 - 4\cos(z_m) - 4\cos^2(z_m) := g(m), \\ \text{for } z_m &= \frac{2(m-1)\pi}{3m} \text{ and } m \equiv 1 \pmod{3}. \end{aligned}$$

Observe that $g(m)$ is a concave quadratic function in $\cos(z_m)$ that is maximized for $\cos(z_m) = -1/2 \Rightarrow z_m = 2\pi/3 + 2k\pi$, $k \in \mathbb{Z}$. The maximum equals 3, but

$$m \geq 4 \text{ and } m \equiv 1 \pmod{3} \Rightarrow \cos(z_m) \neq \cos\left(\frac{2\pi}{3}\right).$$

Hence, the maximum value of 3 is not attained for finite $m \geq 4$ in case $m \equiv 1 \pmod{3}$. Thus, for $m \equiv 1 \pmod{3}$, $\max_{X \in \text{CUT}_m^3} \langle Q_3, X \rangle < 3$, which proves that the strength of the corresponding inequality is strictly greater than 1. The proof for other values of n and m follows similarly. $\square$

Thus, the inequalities given by Corollary 1 separate $\mathcal{E}_m^n$ from CUT_m^n only when $\gcd(n, m) = 1$. The strength of these inequalities is greater for smaller values of m , as in the limit to infinity, the optimal value of the discrete programming problem in Proposition 2 equals n . For numerical evaluation of the strength of these inequalities, see Table 2 in Sect. 8.1. Note that the inequalities from Example 1 can be also derived from Proposition 2 for $n = 4$ and $m = 3$.

Let us highlight Proposition 2 for the real case, i.e., for $m = 2$. Considering $n = 3$, the expressions in Proposition 2 then provide

$$\max_{X \in \text{CUT}_2^3} \langle Q_3, X \rangle = 2,$$

and since $\mathcal{B}_2 = \{\pm 1\}$, the inequalities (20) then reduce to the well-known triangle inequalities (11) (after appropriate scaling). Hence, the inequalities (20) may be considered as *generalized complex triangle inequalities*.

Similarly, the inequalities (21) for $n = 4$ can be considered as *complex quadrangle inequalities*. For the real case, $m = 2$, we have that $\gcd(n, m) = \gcd(4, 2) = 2 > 1$. Thus, the quadrangle inequalities are implied by $\mathcal{E}_2^4$. This clarifies why in the real case, the triangle, pentagonal, heptagonal (etc.) inequalities are well-known, in contrast to real quadrangle inequalities. Note that real triangle, pentagonal, heptagonal, etc., inequalities belong to the family of hypermetric inequalities that are considered as a special case of the gap inequalities (17).

The inequalities derived in Corollary 1 are valid for $n \in \{3, 4\}$, and therefore can be applied to the principal submatrices of matrices in $\mathcal{E}_m^n$ for $\tilde{n} > 4$. Thus, the complex triangle and quadrangle inequalities apply to all n . We present this idea more formally in the next section, see (30), and exploit it in Sect. 8.

4 An exact description of CUT_3^3

We study CUT_3^3 by studying the set

$$\mathcal{V}(\text{CUT}_3^3) := \left\{ x \in \mathbb{C}^3 \mid \begin{bmatrix} 1 & x_1 & x_2 \\ \overline{x_1} & 1 & x_3 \\ \overline{x_2} & \overline{x_3} & 1 \end{bmatrix} \in \text{CUT}_3^3 \right\}. \quad (22)$$

We define the sets $\mathcal{V}(\text{CUT}_m^n)$, in the reminder of the paper, analogously. It is clear that there exists a bijection between the sets $\mathcal{V}(\text{CUT}_3^3)$ and CUT_3^3 . Since $\mathcal{V}(\text{CUT}_3^3)$ is small, we can tractably compute its facets.

We first require some intermediate lemmas.

Proposition 3 *The inequality*

$$\text{Re} \left(ix_1 + e^{\pi i/6} x_2 + ix_3 \right) \leq \frac{\sqrt{3}}{2}, \quad (23)$$

is facet defining for $\mathcal{V}(\text{CUT}_3^3)$. Additionally, the three linear inequalities that ensure $x_i \in \text{Conv}(\mathcal{B}_3)$ for $i \in [3]$, see (5), are also facet-defining.

The strength of inequality (23) equals $\frac{\sqrt{3} \cos(\frac{\pi}{18})}{\cos(\frac{\pi}{9})} \approx 1.81521$.

Proof We consider $\mathcal{V}(\text{CUT}_3^3)$ as a real space of dimension 6. Consider the six vectors $z_\theta := (e^{\theta_1 \mathbf{i}}, e^{\theta_2 \mathbf{i}}, e^{(\theta_2 - \theta_1) \mathbf{i}})^\top$, where $\theta = (\theta_1, \theta_2)$ and

$$\theta \in \left\{ (0, 0), \left(\frac{2\pi}{3}, 0 \right), \left(\frac{4\pi}{3}, 0 \right), \left(0, \frac{4\pi}{3} \right), \left(\frac{4\pi}{3}, \frac{2\pi}{3} \right), \left(\frac{4\pi}{3}, \frac{4\pi}{3} \right) \right\}.$$

These six vectors satisfy the following properties: each z_θ corresponds to the upper triangular entries of

$$Z_\theta := \begin{bmatrix} 1 \\ e^{-\theta_1 \mathbf{i}} \\ e^{-\theta_2 \mathbf{i}} \end{bmatrix} \begin{bmatrix} 1 \\ e^{-\theta_1 \mathbf{i}} \\ e^{-\theta_2 \mathbf{i}} \end{bmatrix}^H \in \text{CUT}_3^3,$$

as in (22), and therefore, $z_\theta \in \mathcal{V}(\text{CUT}_3^3)$. Moreover, since Z_θ is an extreme point of CUT_3^3 , z_θ is an extreme point of $\mathcal{V}(\text{CUT}_3^3)$. Additionally, all the six vectors z_θ satisfy (23) with equality.

Let us now consider the six real vectors $\tilde{z}_\theta := [\text{Re}(z_\theta)^\top \text{Im}(z_\theta)^\top]^\top \in \mathbb{R}^6$. It is not difficult to verify that the $\tilde{z}_\theta$ are affinely independent. This fact, together with the fact that all extreme points of $\mathcal{V}(\text{CUT}_3^3)$ satisfy the inequality (23), implies that (23) is facet-defining. The proof that $x_i \in \text{Conv}(\mathcal{B}_3)$ induces three facets follows similarly.

For computing the strength of the inequality, let Q be the unique Hermitian matrix corresponding to (23), given by

$$Q = \frac{1}{2} \begin{bmatrix} 0 & \mathbf{i} & e^{\pi \mathbf{i}/6} \\ -\mathbf{i} & 0 & \mathbf{i} \\ e^{-\pi \mathbf{i}/6} & -\mathbf{i} & 0 \end{bmatrix}. \quad (24)$$

We can show that $\max_{X \in \mathcal{E}_3^3} \langle Q, X \rangle = \frac{3 \cos(\frac{\pi}{18})}{2 \cos(\frac{\pi}{9})}$, see Lemma A1. By complete enumeration, we obtain $\max_{X \in \text{CUT}_3^3} \langle Q, X \rangle = \sqrt{3}/2$, which proves the result. $\square$

Remark 4 By similar arguments, one can also show that the cut from Proposition 2, for $n = 3$ and $m = 4$, is facet-defining for $\mathcal{V}(\text{CUT}_4^3)$.

Lemma 4 *The ROC equivalent inequalities (see Lemma 1) and the conjugate equivalent inequalities (see Lemma 2) of facet-defining inequalities of $\mathcal{V}(\text{CUT}_m^n)$, are again facet-defining.*

Proof Let $g(x) \leq c$, $c \in \mathbb{R}$, be a facet-defining inequality for $\mathcal{V}(\text{CUT}_m^n) \subseteq \mathbb{C}^{\binom{n}{2}}$. Then there exist vectors $y^j \in \mathcal{V}(\text{CUT}_m^n)$, $j \in [2n]$, that satisfy $g(y^j) = c$ and are affinely independent over the reals. That is,

$$\begin{bmatrix} 1 & 1 & \cdots & 1 \\ y^1 & y^2 & \cdots & y^{2n} \end{bmatrix} v = \mathbf{0}, \quad v \in \mathbb{R}^{2n} \iff v = \mathbf{0}. \quad (25)$$

Additionally, for each such y^j , there exists a $Y^j \in \text{CUT}_m^n$ such that the vector y^j corresponds to the upper triangular entries of Y^j . Let us slightly abuse the notation of

(22), and write this relation as $\mathcal{V}(Y^j) = y^j$, where the linear function $\mathcal{V} : \text{CUT}_m^n \rightarrow \mathbb{C}^{\binom{n}{2}}$ returns the upper triangular entries of its input matrix. We can write $g(x) \leq c$ in terms of matrices as $\langle G, X \rangle \leq c$ for some $G \in \mathcal{H}^n$, and $X \in \text{CUT}_m^n$. By construction,

$$\langle G, Y^j \rangle = c. \quad (26)$$

Recall now the symmetries of CUT_m^n (and therefore also $\mathcal{V}(\text{CUT}_m^n)$), as outlined in Sect. 3.1. In particular, recall the group action $f_\alpha(Z) = Z \odot (\alpha\alpha^H)$. Denote by $\tilde{g}(x) \leq c$ the inequality that is ROC equivalent with $g(x) \leq c$, following a rotation with some $\alpha \in \mathcal{B}_m^n$. This inequality may be written as $\langle f_\alpha(G), X \rangle \leq c$ for $X \in \text{CUT}_m^n$. From (10) and (26), we have $\langle f_\alpha(G), f_\alpha(Y^j) \rangle = c$.

Therefore, the vectors $\tilde{y}^j := \mathcal{V}(f_\alpha(Y^j)) \in \mathcal{V}(\text{CUT}_m^n)$ satisfy $\tilde{g}(\tilde{y}^j) = c$. Note that

$$\tilde{y}^j = \text{Diag}(\alpha_1\bar{\alpha}_2, \alpha_1\bar{\alpha}_3, \dots, \alpha_{n-1}\bar{\alpha}_n)y^j. \quad (27)$$

Using (25) and (27), it follows that the vectors $\tilde{y}^j$ are also affinely independent, since

$$\begin{bmatrix} 1 & \cdots & 1 \\ \tilde{y}^1 & \cdots & \tilde{y}^{2n} \end{bmatrix} v = \text{Diag}(1, \alpha_1\bar{\alpha}_2, \alpha_1\bar{\alpha}_3, \dots, \alpha_{n-1}\bar{\alpha}_n) \begin{bmatrix} 1 & \cdots & 1 \\ y^1 & \cdots & y^{2n} \end{bmatrix} v = \mathbf{0}, \\ v \in \mathbb{R}^{2n} \iff v = \mathbf{0}.$$

Hence, the result follows. The proof for conjugate equivalent inequalities is similar. $\square$

Let F denote the number of facets of $\mathcal{V}(\text{CUT}_3^3)$. Note that (23) has 9 ROC equivalent inequalities (counting itself), see (14), and its conjugate equivalent inequality also has 9 ROC equivalent inequalities (counting itself). Moreover, each of the three linear inequalities that ensure $x_i \in \text{Conv}(\mathcal{B}_3)$ for $i \in [3]$ has 3 ROC equivalent inequalities (counting itself). Thus,

$$F \geq 18 + 9 = 27. \quad (28)$$

We are now ready to show that these 27 inequalities fully describe the set $\mathcal{V}(\text{CUT}_3^3)$.

Theorem 1 *The set $\mathcal{V}(\text{CUT}_3^3)$ admits the following linear description:*

$$\mathcal{V}(\text{CUT}_3^3) = \left\{ x \in \mathbb{C}^3 \left| \begin{array}{l} x \in \text{Conv}(\mathcal{B}_3^3), \text{Re}(\eta x) \leq \frac{\sqrt{3}}{2}, \text{Re}(\bar{\eta}x) \leq \frac{\sqrt{3}}{2}, \\ \eta = (\alpha_1 e^{\pi i/2}, \alpha_2 e^{\pi i/6}, \bar{\alpha}_1 \alpha_2 e^{\pi i/2}), \alpha \in \mathcal{B}_3^2. \end{array} \right. \right\}. \quad (29)$$

Proof The Upper-bound theorem for convex polytopes [37] states the following: for any convex d -dimensional polytope P with v vertices, the number of j -dimensional faces (see Definition 3 in the appendix) is upper bounded by some explicit number $f_j(v, d)$. For our purposes, we consider $\mathcal{V}(\text{CUT}_3^3)$ as 6-dimensional real polytope. As its facets are 5-dimensional faces, the number of facets F is upper bounded by

$$F \leq f_5(9, 6) = 30,$$

see, e.g., [15, Section 1, Theorem 4]. Combined with (28), this implies $27 \leq F \leq 30$. We prove now, by contradiction, that $F = 27$. Thus, assume that $27 < F \leq 30$. If that is the case, then there must exist some facet-defining inequality $\text{Re}(\beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3) \leq c$, which is missing from the right hand side of (29). Note that the vector $\beta \in \mathbb{C}^3$ contains at least two nonzero entries: if β were to contain only a single nonzero entry, the inequality concerns only a single variable, say x_1 . But the restriction $x_1 \in \text{Conv}(\mathcal{B}_3)$ is already included in (29), and clearly cannot be made tighter.

Thus, β contains two or three nonzero entries. Now there must exist at least 8 other ROC equivalent inequalities, that are also facet-defining. This contradicts the result $F \leq 30$, which completes the proof. $\square$

In Appendix B, we verify Proposition 3 and Theorem 1 by listing all 27 facets found using SageMath [46].

We refer to the inequalities in (29), induced by η , as *the triangle facets (of CUT_3^3)*. One can strengthen the CSDP relaxation **CSDP-P** by adding the triangle facets to the complex ellipsope $\mathcal{E}_3^n$. Let us denote the resulting feasible set by:

$$\mathbf{T}(\mathcal{E}_3^n) = \left\{ X \in \mathcal{E}_3^n \mid X_J \in \text{CUT}_3^3, \forall J \subseteq [n], |J| = 3 \right\}. \quad (30)$$

Here, X_J denotes the $|J| \times |J|$ principal submatrix of X , with rows and columns indicated by J .

5 An efficient reformulation of a class of CSDPs

It is well known that MAX-3-CUT can be modeled using CUT_3^n , as demonstrated in Example 1, and first shown by Goemans and Williamson [18]. To approximate MAX-3-CUT, one can solve a CSDP over $\mathcal{E}_3^n$. On the other hand, Frieze and Jerrum [14] approximate MAX-3-CUT by a real SDP having matrix variables of order n , that is equivalent to the CSDP over $\mathcal{E}_3^n$. Here we specify a class of CSDPs that can be efficiently reformulated as real SDPs.

Modern SDP solvers solve CSDPs by representing $n \times n$ Hermitian matrices as $2n \times 2n$ symmetric matrices, via

$$X \in \mathcal{H}^n, X \succeq 0 \iff \tilde{X} = \begin{bmatrix} \text{Re}(X) & \text{Im}(X) \\ -\text{Im}(X) & \text{Re}(X) \end{bmatrix} \in \mathcal{S}^{2n}, \tilde{X} \succeq 0, \quad (31)$$

see also [16]. Consequently, CSDPs with matrix order n , require doubling the order to $2n$, and are therefore computationally more challenging than real SDPs with matrix order n . Wang and Magron [51] introduce a real moment-Hermitian-sum-of-squares hierarchy for complex polynomial optimization problems with real coefficients, without doubling the order. Moreover, Wang and Magron show that their real hierarchy is equivalent to the complex hierarchy from the literature. Here, we provide another class of problems for which a CSDP can be equivalently formulated as a real SDP of the same size.

Proposition 4 Let $U \subseteq \mathcal{H}_+^n$ be a closed convex set that is closed under complex conjugation, and $W \in \mathcal{S}^n$. Then

$$\max_{X \in U} \langle W, X \rangle = \max_{X \in \text{Re}(U)} \langle W, X \rangle.$$

Proof As U is closed under complex conjugation, $X \in U \iff \bar{X} \in U$. Additionally, by convexity of U , $\text{Re}(X) = (X + \bar{X})/2 \in U$. Since W is a real matrix, $\langle W, X \rangle = \langle W, \text{Re}(X) \rangle$. This implies $\max_{X \in U} \langle W, X \rangle = \max_{X \in U} \langle W, \text{Re}(X) \rangle = \max_{X \in \text{Re}(U)} \langle W, X \rangle$. $\square$

5.1 MAX-3-CUT

We investigate the implications of Proposition 4, for the case that the underlying (C)SDP corresponds to a relaxation of MAX-3-CUT, see Example 1.

Let us first formulate MAX-3-CUT as a real program. Without loss of generality, we assume that the graph underlying MAX-3-CUT is the complete graph on n vertices, with edge weights $w_{ij} \in \mathbb{R}$, $i, j \in [n]$, $i < j$. Following [14], let $\mathbf{a}^1, \mathbf{a}^2$ and $\mathbf{a}^3$ be a set of unit vectors in $\mathbb{R}^3$ satisfying

$$(\mathbf{a}^i)^\top \mathbf{a}^j = \begin{cases} 1, & \text{if } i = j, \\ -\frac{1}{2}, & \text{else.} \end{cases} \quad (32)$$

Frieze and Jerrum [14] model MAX-3-CUT as

$$\begin{aligned} \max_y \quad & \frac{2}{3} \sum_{i < j} w_{ij} (1 - y_i^\top y_j) \\ \text{s.t.} \quad & y_i \in \{\mathbf{a}^1, \mathbf{a}^2, \mathbf{a}^3\} \quad \forall i \in [n]. \end{aligned}$$

We investigate the feasible set of this program in terms of matrices, denoted $\text{Re}(\text{CUT}_3^n)$. This set is given by

$$\begin{aligned} \text{Re}(\text{CUT}_3^n) &= \{\text{Re}(Y) \mid Y \in \text{CUT}_3^n\} \\ &= \text{Conv} \left\{ Y \in \mathcal{S}_+^n \mid \exists y_1, \dots, y_n \in \{\mathbf{a}^1, \mathbf{a}^2, \mathbf{a}^3\} \text{ s.t. } Y_{ij} = y_i^\top y_j \quad \forall i, j \in [n] \right\}. \end{aligned}$$

To understand the second equality above, note that the objective in the Frieze and Jerrum model and (15) are similar. That is, $\text{Re}(\bar{x}_i x_j)$ is equal to the right-hand side of (32), for $x_i, x_j \in \mathcal{B}_3$.

As CUT_3^n satisfies the conditions for U in Proposition 4, we have, for $W \in \mathcal{S}^n$,

$$\max_{X \in \text{CUT}_3^n} \langle W, X \rangle = \max_{Y \in \text{Re}(\text{CUT}_3^n)} \langle W, Y \rangle.$$

Thus, $\text{Re}(\text{CUT}_3^n)$ is strictly smaller than CUT_3^n , but attains the same maxima of real linear forms, as it is the case for MAX-3-CUT. The same principle holds for the sets

$$\text{Re}(\mathcal{E}_3^n) := \{\text{Re}(X) \mid X \in \mathcal{E}_3^n\} = \left\{ X \in \mathcal{S}_+^n \mid \text{diag}(X) = \mathbf{1}_n, X_{ij} \geq -\frac{1}{2}, \forall i, j \in [n] \right\},$$

and $\mathcal{E}_3^n$, as it was already observed by Goemans and Williamson [18]. Note that $\text{Re}(\mathcal{E}_3^n)$ corresponds to the feasible set of the SDP relaxation for MAX-3-CUT by Frieze and Jerrum [14]. However, if the objective matrix W satisfies $\text{Im}(W) \neq \mathbf{0}$, then the complex SDP cannot be reformulated to a real SDP with same size.

Let us now study a relation between $\mathbf{T}(\mathcal{E}_3^n)$, see (30), and

$$\text{Re}(\mathbf{T}(\mathcal{E}_3^n)) := \{\text{Re}(X) \mid X \in \mathbf{T}(\mathcal{E}_3^n)\}.$$

To do so, we determine the facets of $\text{Re}(\mathcal{V}(\text{CUT}_3^3))$ in the following lemma.

Lemma 5 *The set $\text{Re}(\mathcal{V}(\text{CUT}_3^3)) := \{\text{Re}(x) \mid x \in \mathcal{V}(\text{CUT}_3^3)\}$, see (29), is given by*

$$\text{Re}(\mathcal{V}(\text{CUT}_3^3)) = \left\{ x \in \mathbb{R}^3 \mid \begin{array}{l} x_i \geq -\frac{1}{2} \quad \forall i \in [3], \quad x_1 + x_2 - x_3 \leq 1, \\ x_1 - x_2 + x_3 \leq 1, \quad -x_1 + x_2 + x_3 \leq 1 \end{array} \right\}. \quad (33)$$

Proof Starting from (29), we consider the following three vectors: $\eta = (e^{\pi i/2}, e^{\pi i/6}, e^{\pi i/2})$,

$$\begin{aligned} \eta_1 &= (e^{4\pi i/3} e^{\pi i/2}, e^{\pi i/6}, e^{-4\pi i/3} e^{\pi i/2}) \text{ and} \\ \eta_2 &= (e^{2\pi i/3} e^{-\pi i/2}, e^{-\pi i/6}, e^{-2\pi i/3} e^{-\pi i/2}). \end{aligned}$$

Note that η_1 can be obtained from η by performing a rotation of coefficients with $(\alpha_1, \alpha_2) = (\exp(4\pi i/3), 1)$. Similarly, η_2 can be obtained by taking $\bar{\eta}$, and then performing the rotation of coefficients with $(\alpha_1, \alpha_2) = (\exp(2\pi i/3), 1)$.

Thus $\text{Re}(\eta_1 x) \leq \sqrt{3}/2$, and $\text{Re}(\eta_2 x) \leq \sqrt{3}/2$ are both valid inequalities for $\mathcal{V}(\text{CUT}_3^3)$, see Sect. 3.2. Consequently, also the sum of these inequalities is valid for $\mathcal{V}(\text{CUT}_3^3)$. That is,

$$\text{Re}((\eta_1 + \eta_2)x) = \text{Re}(\sqrt{3}x_1 + \sqrt{3}x_2 - \sqrt{3}x_3) \leq \sqrt{3} \Rightarrow \text{Re}(x_1 + x_2 - x_3) \leq 1, \quad (34)$$

which corresponds to one of the inequalities given in (33). The above inequality describes a facet of $\text{Re}(\mathcal{V}(\text{CUT}_3^3))$, since the vectors $(1, 1, 1)^\top$, $(1, -\frac{1}{2}, -\frac{1}{2})^\top$, $(-\frac{1}{2}, 1, -\frac{1}{2})^\top$ are affinely independent, contained in $\text{Re}(\mathcal{V}(\text{CUT}_3^3))$, and satisfy (34) with equality. The other facets in (33) can be found in a similar manner.

Lastly, it can be shown that (33) contains all facets via a similar argument as the one used in the proof of Theorem 1. $\square$

Table 1 Comparison of solving times of optimization over $\text{Re}(\mathbf{T}(\mathcal{E}_3^n))$ and $\mathbf{T}(\mathcal{E}_3^n)$

Matrix size n		20	30	40	50	60	70	80	90	100
Solving time (s)	$\text{Re}(\mathbf{T}(\mathcal{E}_3^n))$	0.03	0.10	0.33	0.84	1.83	3.67	6.73	12.73	22.74
	$\mathbf{T}(\mathcal{E}_3^n)$	0.22	0.80	3.02	6.98	15.22	33.17	59.34	114.07	199.72

The facets provided in Lemma 5 are also given in [5, Equation 1.3] (they are stated in terms of $\{0, 1\}$ variables rather than $\{-\frac{1}{2}, 1\}$ as in (32)). However, our derivation from complex space is new. Using facets from (33), one can optimize over $\text{Re}(\mathbf{T}(\mathcal{E}_3^n))$. Note also that $\mathbf{T}(\mathcal{E}_3^n)$ satisfies the conditions for U in Proposition 4. Hence, it is beneficial to optimize over $\text{Re}(\mathbf{T}(\mathcal{E}_3^n))$ instead of $\mathbf{T}(\mathcal{E}_3^n)$ if the matrix W is real.

Table 1 investigates the difference in solving times for optimization over $\text{Re}(\mathbf{T}(\mathcal{E}_3^n))$ and $\mathbf{T}(\mathcal{E}_3^n)$. For various values of n , we generate uniformly at random a real matrix $C \in \{-5, -4, \dots, 4, 5\}^{n \times n}$, and solve the problem of maximizing $\langle C, X \rangle$ over $X \in \text{Re}(\mathbf{T}(\mathcal{E}_3^n))$, and over $X \in \mathbf{T}(\mathcal{E}_3^n)$. This maximization is repeated 5 times per value of n , and the average running time of those 5 runs is reported in Table 1. As solver, we used MOSEK [39]. Note that optimization over $\text{Re}(\mathbf{T}(\mathcal{E}_3^n))$ and $\mathbf{T}(\mathcal{E}_3^n)$ returns the same objective value since C is real, see Proposition 4. Table 1 clearly demonstrates that optimization over $\text{Re}(\mathbf{T}(\mathcal{E}_3^n))$ is more efficient compared to optimization over $\mathbf{T}(\mathcal{E}_3^n)$. The first reason for this is that solving real SDPs is computationally cheaper than solving complex SDPs, see (31). The other reason is that $\text{Re}(\mathbf{T}(\mathcal{E}_3^n))$ contains less inequalities than $\mathbf{T}(\mathcal{E}_3^n)$; compare (29) with (33).

The CSDP reformulation approach by Wang and Magron [51] mentioned in Sect. 5.1 does not apply to CSDPs over $\mathbf{T}(\mathcal{E}_3^n)$, as the facets provided in (29) have non-real coefficients. Our generalization, Proposition 4, shows that a real reformulation of same size is possible when only the objective is real, and the feasible set is closed under complex conjugation (as is the case for $\mathbf{T}(\mathcal{E}_3^n)$).

6 Second semidefinite lifting of CUT_∞^n

In this section we study approximations of CUT_∞^n , see (4). The approximation of CUT_∞^4 obtained from the second semidefinite lifting as proposed by Jarre et al. [21] is denoted here by $\mathbf{L}(\mathcal{B}_2)$. The matrices in set $\mathbf{L}(\mathcal{B}_2)$ are obtained as projections of certain Hermitian PSD matrices of order seven. We propose an approximation of CUT_∞^4 denoted by $\mathbf{L}(\mathcal{B}_1)$, whose elements are the projections of certain Hermitian PSD matrices of order six. Despite this difference in size of the lifted space, we show that $\mathbf{L}(\mathcal{B}_1) = \mathbf{L}(\mathcal{B}_2)$ (Lemma 7). Additionally, we show that $\mathbf{L}(\mathcal{B}_1)$ is also equivalent to the second semidefinite lifting of the complex Lasserre hierarchy proposed in [23] (Theorem 2), whose elements are the projections of certain Hermitian PSD matrices of order ten.

The results from this section imply that one may appropriately decrease a size of matrices in an CSDP relaxation of CUT_∞^n , while keeping the strength of the relaxation unchanged, see Lemma 13. We also show that $\mathbf{L}(\mathcal{B}_1)$ excludes all the rank 2 extreme

points of $\mathcal{E}_\infty^4$ (Theorem 3). Lastly, we show that all elements of $\mathbf{L}(\mathcal{B}_1)$ satisfy a valid inequality for CUT_∞^4 , derived in [21] (Lemma 12).

We begin our analysis with the following well-known result on a rank of extreme points of $\mathcal{E}_\infty^4$. The extreme points of $\mathcal{E}_\infty^n$ have been widely studied, see e.g., [6, 20, 30, 31].

Lemma 6 ([31]) *The extreme points of $\mathcal{E}_\infty^n$ have rank at most $\sqrt{n}$. Moreover, for every $k \leq \sqrt{n}$, the set $\mathcal{E}_\infty^n$ contains rank k extreme points.*

In case $n \leq 3$, the extreme points of $\mathcal{E}_\infty^n$ have rank 1, and thus $\mathcal{E}_\infty^n = \text{CUT}_\infty^n$ for $n \leq 3$. Therefore, in the sequel, we consider the smallest non-trivial case, that is $n = 4$. In this case, $\mathcal{E}_\infty^4$ contains rank 2 extreme points (see (49) below), unlike CUT_∞^4 , which shows that CUT_∞^4 is strictly contained in $\mathcal{E}_\infty^4$. This motivates the authors of [21] to investigate a second semidefinite lifting approximation to CUT_∞^4 . To present their lifting, we first require some notation and definitions.

For some $p \in \mathbb{N}$, let $\mathcal{B} \subseteq \mathbb{Z}^p$ be a finite basis satisfying $\mathbf{0}_p \in \mathcal{B}$. Consider a complex (truncated pseudo-moment) sequence

$(y_\alpha)_{\alpha \in \mathcal{B} - \mathcal{B}}$, satisfying $y_0 = 1$ and $y_\alpha = \bar{y}_{-\alpha}$, where $\mathcal{B} - \mathcal{B} := \{\alpha - \beta \mid \alpha, \beta \in \mathcal{B}\}$.

We define the *complex moment matrix* $M_{\mathcal{B}}(y)$, indexed by the elements of $\mathcal{B}$, satisfying

$$(M_{\mathcal{B}}(y))_{\alpha, \beta} = y_{\alpha - \beta}.$$

By the properties of y , $M_{\mathcal{B}}(y) \in \mathcal{H}^{|\mathcal{B}|}$ and $\text{diag}(M_{\mathcal{B}}(y)) = \mathbf{1}_{|\mathcal{B}|}$. Let $\tilde{\mathbb{C}}[x]$ be the space of polynomials defined by

$$\begin{aligned} \tilde{\mathbb{C}}[x] := & \left\{ \sum_{\alpha \in \mathbb{Z}^p} f_\alpha x^\alpha \mid f_\alpha \in \mathbb{C} \ \forall \alpha \in \mathbb{Z}^p \right\}, \text{ for } x^\alpha := \prod x_i^{\alpha_i}, \\ \text{where } x_i^{\alpha_i} = & \begin{cases} x_i^{\alpha_i} & \text{if } \alpha_i \geq 0, \\ (\bar{x}_i)^{-\alpha_i} & \text{if } \alpha_i < 0. \end{cases} \end{aligned} \quad (35)$$

Note that $\text{Re}(x) = (x + \bar{x})/2 \in \tilde{\mathbb{C}}[x]$. We set

$$\mathcal{F}(\mathcal{B}) := \{M_{\mathcal{B}}(y) \mid y_0 = 1 \text{ and } y_\alpha = \bar{y}_{-\alpha}\} \cap \mathcal{H}_+^{|\mathcal{B}|}. \quad (36)$$

In this section, we study the sets

$$\mathbf{L}(\mathcal{B}_i) := \left\{ X \in \mathcal{E}_\infty^4 \mid \exists Z \in \mathcal{F}(\mathcal{B}_i) \text{ satisfying } Z_{1:4, 1:4} = X \right\} \text{ for } i \in [6], \quad (37)$$

which are defined in terms of the (ordered) bases

$$\mathcal{B}_1 = \left\{ \mathbf{0}_3, \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix} \right\}, \quad \mathcal{B}_2 = \mathcal{B}_1 \cup \left\{ \begin{bmatrix} 0 \\ -1 \\ 1 \end{bmatrix} \right\}, \quad (38)$$

and $\mathcal{B}_3$ up to $\mathcal{B}_6$, which will be given later.

Observe that $\mathcal{B}_1$ and $\mathcal{B}_2$ do not contain monomial squares, i.e., $\alpha \in \mathcal{B}_k \Rightarrow |\alpha_i| < 2$ for all $i \in [3]$, $k \in \{1, 2\}$. Theorem 2 shows that by adding monomial squares to $\mathcal{B}_1$ does not lead to a tighter approximation of CUT_∞^4 . A similar result follows for $\mathcal{B}_2$, see Corollary 2. An example that will be used throughout is the following:

$$(M_{\mathcal{B}_2}(\mathbf{y}))_{\alpha, \beta} = L_{\mathbf{y}}(X_{\alpha, \beta}), \text{ for } X = \begin{bmatrix} 1 & \bar{x}_1 & \bar{x}_2 & \bar{x}_3 & x_1\bar{x}_2 & x_1\bar{x}_3 & x_2\bar{x}_3 \\ x_1 & 1 & x_1\bar{x}_2 & x_1\bar{x}_3 & x_1^2\bar{x}_2 & x_1^2\bar{x}_3 & x_1x_2\bar{x}_3 \\ x_2 & \bar{x}_1x_2 & 1 & x_2\bar{x}_3 & x_1 & x_1x_2\bar{x}_3 & x_2^2\bar{x}_3 \\ x_3 & \bar{x}_1x_3 & \bar{x}_2x_3 & 1 & x_1\bar{x}_2x_3 & x_1 & x_2 \\ \bar{x}_1x_2 & \bar{x}_1^2x_2 & \bar{x}_1 & \bar{x}_1x_2\bar{x}_3 & 1 & x_2\bar{x}_3 & \bar{x}_1x_2^2\bar{x}_3 \\ \bar{x}_1x_3 & \bar{x}_1^2x_3 & \bar{x}_1\bar{x}_2x_3 & \bar{x}_1 & \bar{x}_2x_3 & 1 & \bar{x}_1x_2 \\ \bar{x}_2x_3 & \bar{x}_1\bar{x}_2x_3 & \bar{x}_2^2x_3 & \bar{x}_2 & x_1\bar{x}_2^2x_3 & x_1\bar{x}_2 & 1 \end{bmatrix}, \quad (39)$$

where $L_{\mathbf{y}} : \tilde{\mathbb{C}}[x] \rightarrow \mathbb{C}$ is the linear *Riesz functional*, defined by

$$L_{\mathbf{y}}(f) = \sum_{\alpha \in \mathbb{Z}^p} f_{\alpha} y_{\alpha}, \quad (40)$$

see (35). Observe also that $M_{\mathcal{B}_1}(\mathbf{y})$ is the upper left 6×6 block of $M_{\mathcal{B}_2}(\mathbf{y})$.

We refer to the sets $\mathbf{L}(\mathcal{B}_i)$ as semidefinite liftings of CUT_∞^4 , since

$$\text{CUT}_\infty^4 \subseteq \mathbf{L}(\mathcal{B}_2) \subseteq \mathbf{L}(\mathcal{B}_1) \subseteq \mathcal{E}_\infty^4.$$

Jarre et al. [21] propose $\mathbf{L}(\mathcal{B}_2)$ as a tighter approximation of CUT_∞^4 than $\mathcal{E}_\infty^4$.

Remark 5 Jarre et al. originally present their relaxation as $\mathbf{L}(\mathcal{B}_3)$, see (37), for

$$\mathcal{B}_3 = \left\{ \mathbf{0}_4, \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ 0 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ 0 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ -1 \end{bmatrix} \right\}.$$

The linear function

$$g(x) = \begin{bmatrix} 1 & 1 & 1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} x$$

maps the elements of $\mathcal{B}_2$ to $\mathcal{B}_3$, while preserving equalities in $M_{\mathcal{B}}(y)$, i.e.,

$$(M_{\mathcal{B}_2}(y))_{\alpha_1, \alpha_2} = (M_{\mathcal{B}_2}(y))_{\alpha_3, \alpha_4} \Rightarrow (M_{\mathcal{B}_3}(y))_{g(\alpha_1), g(\alpha_2)} = (M_{\mathcal{B}_3}(y))_{g(\alpha_3), g(\alpha_4)}.$$

Hence, $\mathbf{L}(\mathcal{B}_3) = \mathbf{L}(\mathcal{B}_2)$. In the sequel, we will use $\mathbf{L}(\mathcal{B}_2)$ in favour of $\mathbf{L}(\mathcal{B}_3)$, due to its more compact representation.

We show now that, despite the smaller size of $\mathcal{F}(\mathcal{B}_1)$ compared to $\mathcal{F}(\mathcal{B}_2)$, see (36), their induced approximations of CUT_{∞}^4 are equally strong. To do so, we define the following partial order.

Definition 1 Let $\mathcal{B} \subseteq \mathbb{Z}^p$, and let $\tilde{\mathcal{B}}$ be any subset of $\mathcal{B}$, with $k := |\tilde{\mathcal{B}}|$. We say that $\mathcal{B}$ completes $\tilde{\mathcal{B}}$, denoted $\tilde{\mathcal{B}} \models \mathcal{B}$, if and only if, for each $\tilde{X} \in \mathcal{F}(\tilde{\mathcal{B}})$, there exists an $X \in \mathcal{F}(\mathcal{B})$ satisfying $X_{1:k, 1:k} = \tilde{X}$. Here, it is implicitly assumed that bases $\tilde{\mathcal{B}}$ and $\mathcal{B}$ are ordered, and that the first k elements of $\mathcal{B}$ are the elements of $\tilde{\mathcal{B}}$, in the same order.

It is not difficult to show the following implication

$$\mathcal{B}_1 \models \mathcal{B}_2 \Rightarrow \mathbf{L}(\mathcal{B}_1) = \mathbf{L}(\mathcal{B}_2), \quad (41)$$

see (37). The condition in Definition 1 may be stated alternatively as: any $\tilde{X} \in \mathcal{F}(\tilde{\mathcal{B}})$ is *completable* to an $X \in \mathcal{F}(\mathcal{B})$. We provide more details on this in the proof of the following result.

Lemma 7 $\mathbf{L}(\mathcal{B}_1) = \mathbf{L}(\mathcal{B}_2)$

Proof By (41), it suffices to show that $\mathcal{B}_1 \models \mathcal{B}_2$. Thus, we need to verify that all $X \in \mathcal{F}(\mathcal{B}_1)$ can be completed to a matrix in $Z \in \mathcal{F}(\mathcal{B}_2)$, see (39). That is, for given any $X \in \mathcal{F}(\mathcal{B}_1)$, and the corresponding partially specified matrix

$$Z = \begin{bmatrix} & & & X_{3,4} \\ & & & X_{3,6} \\ & & X & ? \\ & & & X_{3,1} \\ & & & ? \\ & & & X_{3,2} \\ X_{4,3} & X_{6,3} & ? & X_{1,3} & ? & X_{2,3} & 1 \end{bmatrix}, \quad (42)$$

can we find (possibly distinct) values for $?$ such that $Z \in \mathcal{F}(\mathcal{B}_2)$? Note that the only unspecified entries of Z are at position (3, 7) and (5, 7) (ignoring the lower triangular

part of Z). We associate to this pattern of unspecified entries a graph $\mathcal{G}$ of order 7, defined as

$$\begin{aligned} \mathcal{G} &= (V, E), \quad V = [7] \text{ and} \\ E &= \{\{i, j\} \mid i, j \in V, Z_{ij} \neq ?\} = \{\{i, j\} \mid 1 \leq i < j \leq 7\} \setminus (\{3, 7\} \cup \{5, 7\}) \end{aligned} \quad (43)$$

Observe that $\mathcal{G}$ is chordal. Then, by [19, Theorem 7], Z can be completed if and only if, every fully specified submatrix (i.e., not containing any ? values) of Z is positive semidefinite. To investigate this condition, we write Z_J , $J \subseteq [7]$, for the submatrix of Z , indexed by rows and columns in J . Before we consider all such fully specified submatrices Z_J , we consider first $Z_{\mathcal{J}}$, for $\mathcal{J} := \{1, 2, 4, 6, 7\}$. Note that $Z_{\mathcal{J}}$ is fully specified, and given by

$$(Z_{\mathcal{J}})_{ij} = L_Y(X_{ij}), \text{ for } X = \begin{bmatrix} 1 & \bar{x}_1 & \bar{x}_3 & x_1 \bar{x}_3 & x_2 \bar{x}_3 \\ x_1 & 1 & x_1 \bar{x}_3 & x_1^2 \bar{x}_3 & x_1 x_2 \bar{x}_3 \\ x_3 & \bar{x}_1 x_3 & 1 & x_1 & x_2 \\ \bar{x}_1 x_3 & \bar{x}_1^2 x_3 & \bar{x}_1 & 1 & \bar{x}_1 x_2 \\ \bar{x}_2 x_3 & \bar{x}_1 \bar{x}_2 x_3 & \bar{x}_2 & x_1 \bar{x}_2 & 1 \end{bmatrix},$$

and L_Y as in (40). Note that $P^\top Z_{\mathcal{J}} P = \bar{Z}_{J'}$ for $P = E_{14} + E_{25} + E_{31} + E_{42} + E_{53}$ and $J' = \{1, 2, 3, 4, 6\}$. Thus, matrix $Z_{\mathcal{J}}$ is similar to $\bar{Z}_{J'}$. It follows that

$$Z_{J'} \text{ is a (fully specified) submatrix of } X \Rightarrow Z_{J'} \succeq 0 \iff \bar{Z}_{J'} \succeq 0 \iff Z_{\mathcal{J}} \succeq 0.$$

Let us now show that for any $J \subseteq [7]$ such that Z_J is fully specified, $Z_J \succeq 0$. We distinguish two cases:

1. $J \subseteq \mathcal{J}$. Then Z_J is a submatrix of $Z_{\mathcal{J}}$, and therefore $Z_J \succeq 0$.
2. $J \not\subseteq \mathcal{J}$. Since $J \not\subseteq \mathcal{J}$, $3 \in J$ or $5 \in J$. As both $Z_{3,7}$ and $Z_{5,7}$ are unspecified, and Z_J is fully specified, it follows that $7 \notin J$. Thus $J \subseteq [6]$. Consequently, Z_J is a submatrix of X , and $X \in \mathcal{F}(\mathcal{B}_1)$ implies $X \succeq 0$, which shows $Z_J \succeq 0$.

To conclude, every fully specified submatrix of Z is positive semidefinite, and the associated graph $\mathcal{G}$ is chordal. By [19, Theorem 7], $X \in \mathcal{F}(\mathcal{B}_1)$ can always be completed to a matrix in $Z \in \mathcal{F}(\mathcal{B}_2)$, which implies that $\mathcal{B}_1 \models \mathcal{B}_2$. By (41), this completes the proof. $\square$

We now relate $\mathbf{L}(\mathcal{B}_1)$, see (37), to the second semidefinite lifting proposed in [23]. This second lifting is given by $\mathbf{L}(\mathcal{B}_4)$, where $\mathcal{B}_4 = \{\mathbf{0}_3\} \cup \{\alpha \in \mathbb{N}^3 \mid \sum_{i=1}^3 \alpha_i \leq 2\}$. Note that $|\mathcal{B}_4| = 10 > |\mathcal{B}_1| = 6$. Despite this difference, the induced relaxations of CUT_{∞}^4 are equivalent, as shown in the following result.

Theorem 2 For $\mathcal{B}_4 = \{\mathbf{0}_3\} \cup \{\alpha \in \mathbb{N}^3 \mid \sum_{i=1}^3 \alpha_i \leq 2\}$, we have $\mathbf{L}(\mathcal{B}_4) = \mathbf{L}(\mathcal{B}_1)$, see (37).

Proof We start by considering the proof of Lemma 7 more abstractly. Let $\tilde{\mathcal{B}} \subseteq \mathcal{B} \subseteq \mathbb{Z}^p$, where $|\tilde{\mathcal{B}}| = k = |\mathcal{B}| - 1$ (Note that this is the case for $\mathcal{B}_1$ and $\mathcal{B}_2$, see Lemma 7). Consider the problem of completing some $X \in \mathcal{F}(\tilde{\mathcal{B}})$ to some $Z \in \mathcal{F}(\mathcal{B})$. This Z should be thought of as in (42), possibly containing ? values. Let

$$\mathcal{J} := \{i \in \mathbb{N} \mid Z_{i,k+1} \neq ?\}, \quad (44)$$

so that matrix $Z_{\mathcal{J}}$, the submatrix of Z , is fully specified by X . Note that the associated graph $\mathcal{G}$, see e.g., (43), is chordal and we may apply again [19, Theorem 7]. By similar reasoning as in Lemma 7, the condition that $Z_{\mathcal{J}}$ is similar to a submatrix of X , is sufficient (although not necessary) for $\tilde{\mathcal{B}} \models \mathcal{B}$ to hold.

Following the above steps for specific sets $\tilde{\mathcal{B}}$ and $\mathcal{B}$, we are able to prove the following relations. Starting from

$$\mathcal{B}_5 = \left\{ \mathbf{0}_3, \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix} \right\},$$

we have (details omitted)

$$\begin{aligned} \mathcal{B}_5 \models \mathcal{B}_5 \cup \left\{ \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} \right\} &\models \mathcal{B}_5 \cup \left\{ \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 0 \end{bmatrix} \right\} \models \mathcal{B}_5 \cup \left\{ \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 2 \\ 0 \end{bmatrix} \right\} \\ &\models \mathcal{B}_5 \cup \left\{ \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 2 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 2 \end{bmatrix} \right\} = \mathcal{B}_4, \end{aligned} \quad (45)$$

$$\mathcal{B}_5 \models \mathcal{B}_5 \cup \left\{ \begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix} \right\} \models \mathcal{B}_5 \cup \left\{ \begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix} \right\} := \mathcal{B}_6, \quad (46)$$

and starting from $\mathcal{B}_1$ as in (38), we have

$$\mathcal{B}_1 \models \mathcal{B}_1 \cup \left\{ \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} \right\} \models \mathcal{B}_1 \cup \left\{ \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix} \right\} = \mathcal{B}_6. \quad (47)$$

Combining the implication (41) (which holds more generally for $\mathcal{B}_i$ and $\mathcal{B}_j$), with equations (46) and (47) yields $\mathbf{L}(\mathcal{B}_1) = \mathbf{L}(\mathcal{B}_5)$. Since $\mathbf{L}(\mathcal{B}_5) = \mathbf{L}(\mathcal{B}_4)$ by (45), the result follows. $\square$

By combining results of Lemma 7 and Theorem 2, we obtain the following corollary.

Corollary 2 For all $i, j \in [6]$, $\mathbf{L}(\mathcal{B}_i) = \mathbf{L}(\mathcal{B}_j)$.

In the sequel, we will only refer to $\mathbf{L}(\mathcal{B}_1)$ for compactness. Next, we show that $\mathbf{L}(\mathcal{B}_1)$ does not contain any of the rank 2 extreme points of $\mathcal{E}_\infty^4$. Let us first characterize the set of rank 2 extreme points of $\mathcal{E}_\infty^4$. For this, we require the following definition, see matrix F from [30, Section 2.2].

Definition 2 We say that

$$G = \begin{bmatrix} x_1 & u_1 & w_1 & v_1 \\ x_2 & u_2 & w_2 & v_2 \end{bmatrix} \in \mathbb{C}^{2 \times 4}$$

is an Extremal Gram Factor (EGF) if and only if its columns x, u, w, v have norm 1, and the matrix

$$F := \begin{bmatrix} |x_1|^2 & x_1 \bar{x}_2 & \bar{x}_1 x_2 & |x_2|^2 \\ |u_1|^2 & u_1 \bar{u}_2 & \bar{u}_1 u_2 & |u_2|^2 \\ |w_1|^2 & w_1 \bar{w}_2 & \bar{w}_1 w_2 & |w_2|^2 \\ |v_1|^2 & v_1 \bar{v}_2 & \bar{v}_1 v_2 & |v_2|^2 \end{bmatrix} \quad (48)$$

is non-singular.

Now P , the set of rank 2 extreme points of $\mathcal{E}_\infty^4$, is given by the product of EGFs, i.e.,

$$P = \left\{ G^H G \mid G \text{ is an EGF, see Definition 2} \right\}, \quad (49)$$

as proven in [30] (note that EGFs are defined for general matrix sizes in [30]). Thus, if A is a rank 2 extreme point of $\mathcal{E}_\infty^4$, it must be of the form $A = G^H G$, where G is an EGF. Given such A , the corresponding matrix G is unique up to unitary transformation of its columns. We will use MATLAB like notation for indexing submatrices of G , i.e., for some $J \subseteq [4]$, $G_{:,J} \in \mathbb{C}^{2 \times |J|}$ denotes the submatrix obtained by taking all rows of G , and columns of G indexed by J .

Let us prove several results related to EFGs.

Lemma 8 Let $G \in \mathbb{C}^{2 \times 4}$ be an EGF. Then for any $J \subseteq [4]$, $|J| = 2$ the matrix $G_{:,J}$ is invertible.

Proof Proof by contradiction: assume that G is an EGF, and that for some $J \subseteq [n]$, $|J| = 2$, matrix $G_{:,J} \in \mathbb{C}^{2 \times 2}$ is singular. A 2×2 matrix can only be singular if its second column equals its first column multiplied by some $r \in \mathbb{C}$. Since the columns of G have norm 1, we find that $|r| = 1$. But this implies that F , see (48), has two identical rows, and is thus singular. This contradicts the assumption that G is an EGF. $\square$

Lemma 9 Let $A \in P$, see (49), i.e., A is an extreme point of $\mathcal{E}_\infty^4$ with $\text{rk}(A) = 2$. Then, there exists an EGF $G \in \mathbb{C}^{2 \times 4}$, satisfying

$$G = \begin{bmatrix} 1 & u_1 & w_1 & v_1 \\ 0 & u_2 & w_2 & v_2 \end{bmatrix} = [\mathbf{e} \ u \ w \ v], \quad (50)$$

where u_2, w_2 , and v_2 are nonzero and $\mathbf{e} = [1, 0]^\top$.

Proof Since $A \in P$, there exists an EGF $\tilde{G}$ such that $A = \tilde{G}^H \tilde{G}$. Let $z := \tilde{G}_{:,1} \in \mathbb{C}^2$, and consider the matrix $Q := \begin{bmatrix} \bar{z}_1 & \bar{z}_2 \\ -z_2 & z_1 \end{bmatrix}$. It is easy to see that Q is unitary, and $Qz = [1, 0]^T$. Then $G := Q\tilde{G}$ is an EGF satisfying the properties of the lemma. Note that the entries u_2 , w_2 and v_2 are nonzero, because each 2 by 2 submatrix of G must be invertible (Lemma 8). $\square$

In the sequel, we will thus only consider EGFs of the form (50). Note that this simplifies matrix F from (48). We are now ready to prove the following.

Theorem 3 For P as in (49), we have $\mathbf{L}(\mathcal{B}_1) \cap P = \emptyset$.

Proof Let $A \in P$. Then, without loss of generality, $A = G^H G$, where G is an EGF of the form (50). Proof by contradiction: suppose $A \in \mathbf{L}(\mathcal{B}_1)$. Then $\exists Z \in \mathcal{F}(\mathcal{B}_1)$, see (36), satisfying $Z_{1:4,1:4} = A$. Let $\ell \in \{5, 6\}$ and denote by Z_ℓ the 5×5 principal submatrix of Z , with rows and columns indexed by $[4] \cup \ell$. Since $Z_\ell \succeq 0$, there exists a matrix G_ℓ such that $Z_\ell = G_\ell^H G_\ell$. We may assume that G_ℓ is of the form

$$G_\ell = \begin{bmatrix} G & z_\ell \\ \mathbf{0}_4^T & \alpha_\ell \end{bmatrix}, \text{ with } z_\ell \in \mathbb{C}^2, \alpha_\ell \in \mathbb{C} \text{ and } z_\ell^H z_\ell + |\alpha_\ell|^2 = 1. \quad (51)$$

Note that the last column of Z_ℓ is then given by $[z_\ell^H G \ 1]^H$. Moreover, for each $\ell \in \{5, 6\}$, precisely two of the entries in $G^H z_\ell$ are determined by A . For example, if $\ell = 5$, then we have

$$G_{:, \{1,3\}}^H z_5 = \begin{bmatrix} u^H w \\ u^H \mathbf{e} \end{bmatrix}, \text{ with } G_{:, \{1,3\}}^H = [\mathbf{e} \ w]^H = \begin{bmatrix} 1 & 0 \\ \bar{w}_1 & \bar{w}_2 \end{bmatrix}. \quad (52)$$

The above equations follow from the pattern of equalities in (39). In particular, $(G^H z_5)_1 = L_y(x_1 \bar{x}_2) = A_{2,3} = (G^H G)_{2,3} = u^H w$.

By Lemma 8, $G_{:, \{1,3\}}^H$ is invertible, hence z_5 is uniquely determined by this equation, and thus

$$z_5 = \begin{bmatrix} u^H w \\ (\bar{u}_1 - \bar{w}_1 u^H w) / \bar{w}_2 \end{bmatrix}$$

We now claim that $\|z_5\| = 1$, in which case $\alpha_5 = 0$, by (51). To verify this claim, we compute first

$$\operatorname{Re}(u_1 \bar{w}_1 u^H w) = |u_1|^2 |w_1|^2 + \operatorname{Re}(u_1 \bar{w}_1 \bar{u}_2 w_2), \quad (53)$$

which is a term appearing in the computation of $\|z_5\|^2 = z_5^H z_5$. Thus, using (53), we find

$$\begin{aligned} z_5^H z_5 &= |u^H w|^2 + \frac{|w_{2,1}|^2 + |w_1|^2 |u^H w|^2 - 2 \operatorname{Re}(u_1 \bar{w}_1 u^H w)}{|w_2|^2} \\ &= \frac{|u_1|^2 + |u^H w|^2 - 2 \operatorname{Re}(u_1 \bar{w}_1 u^H w)}{|w_2|^2} \\ &= \frac{|u_1|^2 + |u_1|^2 |w_1|^2 + |u_2|^2 |w_2|^2 + 2 \operatorname{Re}(\bar{u}_1 w_1 u_2 \bar{w}_2) - 2 \operatorname{Re}(u_1 \bar{w}_1 u^H w)}{|w_2|^2} \\ &= \frac{|u_1|^2 - |u_1|^2 |w_1|^2 + (1 - |u_1|^2)(1 - |w_1|^2)}{|w_2|^2} = 1. \end{aligned}$$

Vector z_6 satisfies the system

$$G_{:, \{1,4\} z_6}^H = \begin{bmatrix} u^H v \\ u^H \mathbf{e} \end{bmatrix},$$

which is similar to (52). It is therefore also straightforward to show that $\|z_6\| = 1$. This implies that Z is of the form

$$Z = V^H V, \text{ for } V = [\mathbf{e} \ u \ w \ v \ z_5 \ z_6]. \quad (54)$$

Now $Z \in \mathcal{F}(\mathcal{B}_1) \Rightarrow Z_{5,6} = Z_{3,4} = w^H v$, see (39), while (54) implies that $Z_{5,6} = z_5^H z_6$. Thus, it must hold that $z_5^H z_6$ equals $w^H v$. However, we have $z_5^H z_6 = w^H v + \det(F)/w_2 \bar{v}_2$. Since G is an EGF, $\det(F) \neq 0$ (Definition 2) which provides the desired contradiction. $\square$

We now provide a result on CUT_∞^4 , showing that it contains all rank 2 points of $\mathcal{E}_\infty^4$, if these are not extreme. For this result, we require the notion of a *perturbation*, see [30]. We say that a nonzero Hermitian matrix B is a perturbation of some $A \in \mathcal{E}_\infty^n$, if there exists some $t > 0$ such that $A \pm tB \in \mathcal{E}_\infty^n$. Thus, if A admits some perturbation B , it is not an extreme point of $\mathcal{E}_\infty^n$. Additionally, if $A = G^H G$, then the perturbation is of the form $B = G^H R G$ [30, Theorem 1(a)], with $\operatorname{diag}(B) = \mathbf{0}$ and R Hermitian.

The following result is also given in [30], in the proof of the sufficiency part of Corollary 4.

Lemma 10 *Let $A \in \mathcal{E}_\infty^4$, $\operatorname{rk}(A) = 2$. If A is not an extreme point of $\mathcal{E}_\infty^4$ (i.e., $A \notin P$), then $A \in \text{CUT}_\infty^4$.*

Proof We write $A = G^H G$, where $G \in \mathbb{C}^{2 \times 4}$. Since A is not extreme, it admits a nonzero perturbation $B = G^H R G$, for some $R \in \mathcal{H}^2$. Note that R must be indefinite. Then, there exist strictly positive numbers $t_1, t_2 \in \mathbb{R}$ such that both $I + t_1 R$ and $I - t_2 R$ are rank 1. It follows that the matrix $A + t_1 B = G^H (I + t_1 R) G$, is also rank 1, and

thus contained in CUT_{∞}^4 . Similarly, also $A - t_2 B \in \text{CUT}_{\infty}^4$. Then

$$A = \frac{t_2}{t_1 + t_2} \underbrace{(A + t_1 B)}_{\in \text{CUT}_{\infty}^4} + \frac{t_1}{t_1 + t_2} \underbrace{(A - t_2 B)}_{\in \text{CUT}_{\infty}^4} \in \text{CUT}_{\infty}^4. \quad (55)$$

□

Equation (55) also shows that A can be written as the convex combination of two extreme points of CUT_{∞}^4 . More generally, it is known that any $A \in \text{CUT}_{\infty}^n$, can be written as a convex combination of at most $n^2 - n + 1$ extreme points of CUT_{∞}^n [21, Lemma 3], which follows from Carathéodory's theorem. It is stated in [21] that 'a smaller bound would help in reducing the size of the problem for finding a nearest matrix in CUT_{∞}^n '. We provide such a smaller (optimal) bound in the following result, for general n .

Theorem 4 *For any $A \in \text{CUT}_{\infty}^n$, there exist $r := \text{rk}(A)$ rank one matrices $A_1, \dots, A_r \in \text{CUT}_{\infty}^n$, such that $A \in \text{Conv}\{A_1, \dots, A_r\}$.*

Proof We fix some $n \in \mathbb{N}$, and prove the result by induction. The base case $r = 1$ clearly holds. We assume the induction hypothesis and consider the case $\text{rk}(A) = r + 1$. Let A_1 be any extreme point of CUT_{∞}^n such that

$$\lambda^* := \max \{ \lambda \mid (1 - \lambda)A_1 + \lambda A \in \text{CUT}_{\infty}^n \} > 1,$$

and define $C := (1 - \lambda^*)A_1 + \lambda^*A$. Such a matrix A_1 exists, since A is not an extreme point of CUT_{∞}^n (due to its rank being strictly greater than 1). The matrices A_1 and C are the endpoints of a line segment in CUT_{∞}^n , through A . By construction, $C \in \text{CUT}_{\infty}^n$ and $\lambda^* > 1$. Hence,

$$A = \frac{\lambda^* - 1}{\lambda^*} A_1 + \frac{1}{\lambda^*} C \Rightarrow A \in \text{Conv}\{A_1, C\}. \quad (56)$$

Since $\text{rk}(A) = r + 1$ and $\text{rk}(A_1) = 1$, the rank of C is either r or $r + 1$. If $\text{rk}(C) = r$, the result follows trivially from (56) and the induction hypothesis. In the case that $\text{rk}(C) = r + 1$, we have

$$\text{rk} \left(\frac{\lambda^* - 1}{\lambda^*} A_1 + \frac{1}{\lambda^*} C \right) = \text{rk}(C) \Rightarrow C \in \text{Conv}\{A_1, \tilde{C}\},$$

for some $\tilde{C} \in \text{CUT}_{\infty}^n$ with $\text{rk}(\tilde{C}) = r$. Applying the induction hypothesis on $\tilde{C}$ proves the result.

Let us now return to the case $n = 4$, specifically the relation between CUT_{∞}^4 and $\mathbf{L}(\mathcal{B}_1)$. We have the following result.

Lemma 11 *The set CUT_{∞}^4 is strictly contained in $\mathbf{L}(\mathcal{B}_1)$ if and only if there exists a matrix Y satisfying the following: $\text{rk}(Y) = 3$, $Y \in \mathbf{L}(\mathcal{B}_1) \setminus \text{CUT}_{\infty}^4$, $Y \in \partial \mathcal{E}_{\infty}^4$, and $Y = \lambda J_4 + (1 - \lambda)A$, for some $\lambda \in (0, 1)$ and $A \in P$, see (49).*

Proof See Appendix A.1. $\square$

Unfortunately, we are not able to prove or disprove the existence of such rank 3 points. Numerical tests, see also [21], lead us to the following conjecture:

Conjecture 1 *The second semidefinite lifting is exact for CUT_{∞}^4 , i.e., $\mathbf{L}(\mathcal{B}_1) = \text{CUT}_{\infty}^4$.*

Remark 6 Conjecture 1 can be connected to the notion of a flat extension from the literature, see e.g., [7]. The term extension is related to the definition of completion as given in Definition 1. In that definition, the larger matrix X is considered an extension of the smaller matrix $\tilde{X}$. Matrix X is considered a flat extension of $\tilde{X}$ if, along with the properties outlined in Definition 1, we also have $\text{rk}(X) = \text{rk}(\tilde{X})$. In [23], there are several results related to such flat extensions, specifically for the bases $\mathbb{N}_r^p := \{\alpha \in \mathbb{N}^p \mid \sum_{i=1}^p \alpha_i \leq r\}$. Now [23, Theorem 5.2] leads to an equivalent reformulation of Conjecture 1. Namely, Conjecture 1 is true if and only if all $\tilde{X} \in \mathbf{L}(\mathcal{B}_1) \subseteq \mathcal{E}_{\infty}^m$ admit a flat extension $X \in \mathcal{F}(\mathbb{N}_3^3)$, for $\mathcal{F}(\cdot)$ as in (36).

We show now that all $X \in \mathbf{L}(\mathcal{B}_1)$ satisfy a valid inequality for CUT_{∞}^4 , found by the authors of [21]. This inequality is given as follows:

$$\langle H, X \rangle \leq 6 \quad \forall X \in \text{CUT}_{\infty}^4, \text{ where } H = \begin{bmatrix} 0 & -\mathbf{i} & \mathbf{i} & 1 \\ \mathbf{i} & 0 & -\mathbf{i} & 1 \\ -\mathbf{i} & \mathbf{i} & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix}. \quad (57)$$

The validity of this cut is proven in [21], and we provide an alternative proof in Lemma A2.

It is shown in [21] that the inequality $\langle H, X \rangle \leq 6$ is not satisfied for all $X \in \mathcal{E}_{\infty}^4$. We show here that matrices in $\mathbf{L}(\mathcal{B}_1)$ do satisfy this inequality.

Lemma 12 *Let $X \in \mathbf{L}(\mathcal{B}_1)$. Then $\langle H, X \rangle \leq 6$ for H as in (57). Additionally, for all integers $m \geq 3$ or $m = \infty$,*

$$\text{str}(H, m) = \frac{2}{\sqrt{3}} \approx 1.15470.$$

Proof Let $X \in \mathbf{L}(\mathcal{B}_1)$, and $Z \in \mathcal{F}(\mathcal{B}_1)$ be the matrix satisfying $Z_{1:4,1:4} = X$, see (37). We have

$$\langle H, X \rangle = 6 - \langle Q, Z \rangle, \text{ where } Q = \frac{1}{2} \begin{bmatrix} 4 & 0 & -2\mathbf{i} & -2 & 2\mathbf{i} & -2 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 2\mathbf{i} & 0 & 2 & -1 - \mathbf{i} & -1 - \mathbf{i} & 0 \\ -2 & 0 & -1 + \mathbf{i} & 2 & 0 & 1 - \mathbf{i} \\ -2\mathbf{i} & 0 & -1 + \mathbf{i} & 0 & 2 & -1 + \mathbf{i} \\ -2 & 0 & 0 & 1 + \mathbf{i} & -1 - \mathbf{i} & 2 \end{bmatrix}.$$

We claim that $Q \geq 0$. Then, since also $Z \geq 0$, we have $6 - \langle Q, Z \rangle \leq 6$, which proves the lemma. To show that $Q \geq 0$, we compute the Schur complement of Q with respect to $Q_{11} = 2$. The resulting matrix is given by

$$\frac{1}{2} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & -\mathbf{i} & \mathbf{i} \\ 0 & -1 & 1 & \mathbf{i} & -\mathbf{i} \\ 0 & \mathbf{i} & -\mathbf{i} & 1 & -1 \\ 0 & -\mathbf{i} & \mathbf{i} & -1 & 1 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 \\ \mathbf{i} \\ -\mathbf{i} \\ -1 \\ 1 \end{bmatrix} \begin{bmatrix} 0 \\ \mathbf{i} \\ -\mathbf{i} \\ -1 \\ 1 \end{bmatrix}^H \geq 0.$$

Computing the strength of the inequality $\langle H, X \rangle \leq 6$ is left to the appendix, Lemma A2. $\square$

Additionally, elements of $\mathbf{L}(\mathcal{B}_1)$ also satisfy all the infinite ROC equivalent cuts induced by H , see Lemma 1.

To conclude this section, we provide a generalization of Theorem 2 for any $n \geq 4$. We define, for $p \geq 3$, bases

$$\tilde{\mathcal{A}}^p := \left\{ \alpha \in \{0, 1\}^p \mid \sum_{i=1}^p \alpha_i \leq 2 \right\} \subsetneq \mathcal{A}^p := \left\{ \alpha \in \{0, 1, 2\}^p \mid \sum_{i=1}^p \alpha_i \leq 2 \right\},$$

where the first $p+1$ elements are $\{\mathbf{0}_p\}$ and the p unit vectors. Sets $\mathcal{F}(\tilde{\mathcal{A}}^p)$ and $\mathcal{F}(\mathcal{A}^p)$ are defined analogously to (36). Note that $\mathcal{A}^3 = \mathcal{B}_4$, for $\mathcal{B}_4$ as in Theorem 2. The above bases can be used to approximate CUT_{∞}^n . If we define sets, for $n \geq 4$,

$$\mathbf{L}^n(\tilde{\mathcal{A}}) = \left\{ X \in \mathcal{E}_{\infty}^n \mid \exists Z \in \mathcal{F}(\tilde{\mathcal{A}}^{n-1}) \text{ satisfying } Z_{1:n, 1:n} = X \right\}, \quad (58)$$

and similarly $\mathbf{L}^n(\mathcal{A})$, then $\text{CUT}_{\infty}^n \subseteq \mathbf{L}^n(\mathcal{A}) \subseteq \mathbf{L}^n(\tilde{\mathcal{A}}) \subseteq \mathcal{E}_{\infty}^n$. We are now ready to present the following result.

Lemma 13 $\mathbf{L}^n(\tilde{\mathcal{A}}) = \mathbf{L}^n(\mathcal{A})$

Proof See Appendix A.1. $\square$

Remark 7 Lemma 13 allows us to choose a smaller monomial basis, namely a basis without squared variables, without weakening the corresponding CSDP relaxation. There are several results in the literature on choosing a (smaller) monomial basis, though they are limited to real variables. For unconstrained polynomial optimization, the Newton polytope (see e.g., [32, Section III.A]) offers a monomial basis which is guaranteed to find sum of squares decompositions of sum of squares polynomials. Another, more broadly applicable, method is proposed in [52, Algorithm 4.1]. In contrast to our work, it is not proven in [52] that the basis returned by that algorithm preserves the relaxation strength, in comparison with the standard monomials basis.

7 Extreme points of $\mathcal{E}_m^3$

In this section we derive necessary and sufficient conditions for a matrix to be an extreme rank 2 point of $\mathcal{E}_m^3$, $m > 2$ finite. For any such m , we provide an explicit rank 2 extreme point of $\mathcal{E}_m^3$ (Lemma 16). Further, we extend this result for any finite n and m , which proves the strict inclusion of CUT_m^n in $\mathcal{E}_m^n$ (Corollary 3).

For $m > 2$, we consider a general rank 2 matrix, parameterized as

$$N = \begin{bmatrix} 1 & N_{12} & N_{13} \\ \bar{N}_{12} & 1 & N_{23} \\ \bar{N}_{13} & \bar{N}_{23} & 1 \end{bmatrix} = G^H G \in \mathcal{E}_m^3, \text{ for } G = [\mathbf{e} \ u \ v] = \begin{bmatrix} 1 & u_1 & v_1 \\ 0 & u_2 & v_2 \end{bmatrix},$$

where $\|u\| = \|v\| = 1$. We assume that at least one of u_2 and v_2 is nonzero (to ensure $\text{rk}(N) = 2$). Note that the above parametrization always exists, see e.g., Lemma 9 and [30]. We investigate under what conditions N is an extreme point.

A perturbation of $N \in \mathcal{E}_m^3$ (with respect to $\mathcal{E}_m^3$) is a nonzero Hermitian matrix $B = G^H R G$, satisfying $\text{diag}(B) = \mathbf{0}_3$, $R \in \mathcal{H}^2$, and for which there exists a $t > 0$ such that $N \pm tB \in \mathcal{E}_m^3$, see [30] and also Sect. 6. The constraint $\text{diag}(B) = \mathbf{0}_3$ implies $\mathbf{e}^H R \mathbf{e} = R_{11} = 0$, and $u^H R u = v^H R v = 0$. The latter system may be written in the following form:

$$R = \begin{bmatrix} 0 & \bar{\alpha} \\ \alpha & c \end{bmatrix}, \quad \begin{bmatrix} u_1 \bar{u}_2 & \bar{u}_1 u_2 & |u_2|^2 \\ v_1 \bar{v}_2 & \bar{v}_1 v_2 & |v_2|^2 \end{bmatrix} \begin{bmatrix} \alpha \\ \bar{\alpha} \\ c \end{bmatrix} = 0 \text{ for } c \in \mathbb{R}. \quad (59)$$

Note the similarity with (48). Any possible perturbation B of N is of the following form

$$B = \begin{bmatrix} 0 & b_{12} & b_{13} \\ \bar{b}_{12} & 0 & b_{23} \\ \bar{b}_{13} & \bar{b}_{23} & 0 \end{bmatrix} = G^H R G = G^H \begin{bmatrix} 0 & \bar{\alpha} \\ \alpha & c \end{bmatrix} G. \quad (60)$$

Recall that N is not an extreme point of $\mathcal{E}_m^3$ if and only if it admits a perturbation. There exist however simple sufficient conditions that show that a matrix N is not an extreme point, which we provide below.

Lemma 14 *Let $m > 2$, and $N \in \mathcal{E}_m^3$ such that $\text{rk}(N) = 2$. If all the off-diagonal elements of N are interior points of $\text{Conv}(\mathcal{B}_m)$, or any off-diagonal element of N is contained in $\mathcal{B}_m$, then N is not an extreme point of $\mathcal{E}_m^3$.*

Proof By Lemma 6, N is not an extreme point of $\mathcal{E}_\infty^3$. Thus, N admits some perturbation matrix B with respect to $\mathcal{E}_\infty^n$, i.e., there exists some $t^* > 0$ such that $N \pm tB \in \mathcal{E}_\infty^3$ for all $t \in [0, t^*]$. Assuming all off-diagonal elements of N are interior points of $\text{Conv}(\mathcal{B}_m)$, there exists some $t \in [0, t^*]$ small enough such that $N \pm tB \in \mathcal{E}_m^3$, and the result follows.

Let us now assume that N has exactly one upper-triangular off-diagonal element contained in $\mathcal{B}_m$. Then, without loss of generality, we have

$$N = G^H G, \text{ for } G = \begin{bmatrix} 1 & \kappa & u_1 \\ 0 & 0 & u_2 \end{bmatrix},$$

where κ is one of the m roots of unity, and $u_2 \neq 0$. The off-diagonal elements of N are given by κ , u_1 , and $\bar{\kappa}u_1$ and their complex conjugates. Therefore, N cannot have more than one upper-triangular off-diagonal element in $\mathcal{B}_m$. We distinguish two cases:

1. The complex number u_1 is an interior point of $\text{Conv}(\mathcal{B}_m)$. Again, there exists a perturbation matrix B and $t^* > 0$ such that $N \pm tB \in \mathcal{E}_\infty^3$ for all $t \in [0, t^*]$. Note that, since $N_{12} = \kappa \in \mathcal{B}_\infty$, $B_{12} = 0$. Note that the other off-diagonal elements of N are all interior points of $\text{Conv}(\mathcal{B}_m)$. Thus, there exists some small enough $t \in [0, t^*]$ such that $N \pm tB \in \mathcal{E}_3^3$, and hence, N is not an extreme point of $\mathcal{E}_m^3$.
2. The complex number $u_1 \in \partial\text{Conv}(\mathcal{B}_m) \setminus \mathcal{B}_m$. Then u_1 can be written as $u_1 = \lambda\delta + (1 - \lambda)\eta$, where $\lambda \in (0, 1)$ and δ, η are distinct m -roots of unity.

$$\begin{aligned} N &= \begin{bmatrix} 1 & \kappa & \lambda\delta + (1 - \lambda)\eta \\ \bar{\kappa} & 1 & \lambda\bar{\kappa}\delta + (1 - \lambda)\bar{\kappa}\eta \\ \lambda\bar{\delta} + (1 - \lambda)\bar{\eta} & \lambda\kappa\bar{\delta} + (1 - \lambda)\kappa\bar{\eta} & 1 \end{bmatrix} \\ &= \lambda \begin{bmatrix} 1 \\ \bar{\kappa} \\ \bar{\delta} \end{bmatrix} \begin{bmatrix} 1 \\ \bar{\kappa} \\ \bar{\delta} \end{bmatrix}^H + (1 - \lambda) \begin{bmatrix} 1 \\ \bar{\kappa} \\ \bar{\eta} \end{bmatrix} \begin{bmatrix} 1 \\ \bar{\kappa} \\ \bar{\eta} \end{bmatrix}^H, \end{aligned}$$

so that clearly, N is not an extreme point of $\mathcal{E}_m^3$.

□

Let us denote the boundary of $\text{Conv}(\mathcal{B}_m)$ by $\partial\text{Conv}(\mathcal{B}_m)$. Then, the set that contains the elements from $\partial\text{Conv}(\mathcal{B}_m)$ without the elements in $\mathcal{B}_m$ is denoted by

$$\partial\text{Conv}(\mathcal{B}_m) \setminus \mathcal{B}_m. \quad (61)$$

It follows from Lemma 14 that any rank 2 extreme point of $\mathcal{E}_m^3$ must have at least one element which is contained in the set (61), and its off-diagonal elements cannot be contained in $\mathcal{B}_m$. This allows us to characterize rank 2 extreme points of $\mathcal{E}_m^3$. We first require the following preparatory lemma.

Lemma 15 *Let $m > 2$ and $N \in \mathcal{E}_m^3$ be a rank 2 matrix. Let $K := \{\{i, j\} \in [3] \times [3] \mid N_{ij} \in \partial\text{Conv}(\mathcal{B}_m) \setminus \mathcal{B}_m\}$ and $f : K \rightarrow [m]$ be the function that satisfies $\text{Re}(\bar{v}_{f(ij)} N_{ij}) = \cos(\pi/m)$, for v as in (5). If $K \neq \emptyset$, then any possible perturbation B of N must satisfy $\text{Re}(\bar{v}_{f(ij)} b_{ij}) = 0$ for all $\{i, j\} \in K$.*

Proof Suppose B is a perturbation of N (with respect to $\mathcal{E}_m^3$) and $\{i, j\} \in K$. Then by definition of a perturbation, we must have $N \pm tB \in \mathcal{E}_m^3$ for some $t > 0$. In particular,

$(N \pm tB)_{ij} \in \text{Conv}(\mathcal{B}_m)$. Considering (5), this implies that

$$\begin{aligned} \text{Re}(\bar{v}_{f(ij)}(N \pm tB)_{ij}) &\leq \cos\left(\frac{\pi}{m}\right) \Rightarrow \cos\left(\frac{\pi}{m}\right) \pm t \text{Re}(\bar{v}_{f(ij)}b_{ij}) \\ &\leq \cos\left(\frac{\pi}{m}\right) \Rightarrow \text{Re}(\bar{w}_{f(ij)}b_{ij}) = 0. \end{aligned}$$

□

We now present the characterization of rank 2 extreme points of $\mathcal{E}_m^3$.

Proposition 5 *Let $m > 2$, and $N \in \mathcal{E}_m^3$ be a rank 2 matrix. Further, let $K := \{\{i, j\} \in [3] \times [3] \mid N_{ij} \in \partial \text{Conv}(\mathcal{B}_m) \setminus \mathcal{B}_m\}$ and $f : K \rightarrow [m]$ be the function that satisfies $\text{Re}(\bar{v}_{f(ij)}N_{ij}) = \cos(\pi/m)$, for v as in (5). Matrix N is an extreme point of $\mathcal{E}_m^3$, if and only if the following hold:*

1. $K \neq \emptyset$;
2. *There does not exist a perturbation B of N satisfying $\text{Re}(\bar{v}_{f(ij)}b_{ij}) = 0$ for all $\{i, j\} \in K$.*

Proof ($\Rightarrow$) Let N be a rank 2 extreme point of $\mathcal{E}_m^3$. By Lemma 14, not all off-diagonal elements of N can be in the interior of $\text{Conv}(\mathcal{B}_m)$, and none of the off-diagonal elements can be contained in $\mathcal{B}_m$. Thus $K \neq \emptyset$, satisfying Item 1. Since N is an extreme point, it does not admit a perturbation. In particular, it does not admit a perturbation that satisfies $\text{Re}(\bar{v}_{f(ij)}b_{ij}) = 0 \forall \{i, j\} \in K$, so Item 2 is satisfied.

($\Leftarrow$) Let $N \in \mathcal{E}_m^3$ be a rank 2 matrix and $K \neq \emptyset$. Lemma 15 states that any possible perturbation of a rank 2 matrix must satisfy $\text{Re}(\bar{v}_{f(ij)}b_{ij}) = 0 \forall \{i, j\} \in K$ when $K \neq \emptyset$. Because N satisfies Item 2, such a perturbation cannot exist. Thus, N admits no perturbation, and hence, is an extreme point. □

Using Proposition 5, we determine a rank 2 extreme point of $\mathcal{E}_m^3$, for any $m > 2$.

Lemma 16 *Fix some integer $m > 2$, and set*

$$G = \begin{bmatrix} 1 & \frac{1}{2} + \frac{1}{2} \exp(2\pi \mathbf{i}/m) & \sin(\pi/m) \\ 0 & \sin(\pi/m) & \frac{1}{2} + \frac{1}{2} \exp(2\pi \mathbf{i}/m) \end{bmatrix}.$$

Then $N = G^H G$ is a rank 2 extreme point of $\mathcal{E}_m^3$.

Proof See Appendix A.1. □

Now we can directly show the following.

Corollary 3 *For finite m and n , $m \geq 2$ and $n \geq 3$, we have $\text{CUT}_m^n \subsetneq \mathcal{E}_m^n$.*

Proof For the case $m = 2$ and $n = 3$, we take $N = \frac{3}{2}I_3 - \frac{1}{2}J_3 \geq 0 \Rightarrow N \in \mathcal{E}_2^3$. Since this N does not satisfy the triangle inequality $N_{12} + N_{13} + N_{23} \geq -1$, see (11), $N \notin \text{CUT}_2^3$.

Table 2 Numerical values of the strength of various cuts

Cut as in:	m								
	2	3	4	5	6	7	8	9	∞
Proposition 2, $n = 3$	1.500	1	1.500	1.146	1	1.114	1.061	1	1
Proposition 2, $n = 4$	1	1.333	1	1.038	1	1.010	1	1.004	1
Proposition 3, $n = 3$	1	1.815	1.169	1.077	1.075	1.011	1	1	1
Lemma 12, $n = 4$	1	1.155	1.155	1.155	1.155	1.155	1.155	1.155	1.155

Lemma 16 proves that $\text{CUT}_m^n \subsetneq \mathcal{E}_m^n$ for all finite $m > 2$ and $n = 3$. The case $m > 2$ and $n > 3$ follows by considering

$$\tilde{N} = \begin{bmatrix} N & \mathbf{0}_{3 \times (n-3)} \\ \mathbf{0}_{(n-3) \times 3} & I_{n-3} \end{bmatrix} \in \mathcal{E}_m^n, \text{ but not in } \text{CUT}_m^n, \quad (62)$$

for N as in Lemma 16. The same extension as (62) for $N = \frac{3}{2}I_3 - \frac{1}{2}J_3$ shows that $\text{CUT}_2^n \subsetneq \mathcal{E}_2^n$ for $n > 3$. $\square$

8 Numerical results

In this section, we provide some computational results related to the previous sections. All CSDPs are first reformulated to equivalent real SDPs and then solved using MOSEK [39] with default settings on a server with Intel Xeon Gold 6126 CPU, running at 2.60GHz, with 512 GB RAM and using 8 cores.

8.1 Strength of cuts

We provide the numerical values of str for the valid inequalities stated in Propositions 2 and 3, and Lemma 12. To provide a fair comparison, we have ensured that each matrix Q satisfies $\langle I, Q \rangle = 0$, see also Remark 2.

Results are provided in Table 2. Strength values that have not been analytically computed in the previous sections, have now been computed using MOSEK [39]. The strength of the cuts in Proposition 2 tend to 1 as $m \rightarrow \infty$. For $m = 3$, the strongest cut is given by the facet-defining inequalities from Proposition 3.

8.2 Random objective functions

We consider the following optimization problem

$$\max_{X \in K_m} \langle Q, X \rangle, \quad (63)$$

Table 3 Bounds, computation times and number of (in)equalities for (63) where $K_m = \mathcal{E}_m^n$ or $K_m = \mathbf{T}(\mathcal{E}_m^n)$, and $m \in \{3, 4\}$. Results are averaged over 250 runs

		$\mathcal{E}_m^{100}$	$\mathbf{T}(\mathcal{E}_m^{100})$	LB	Avg. time (s)		# (in)equality cons.	
					$\mathcal{E}_m^{100}$	$\mathbf{T}(\mathcal{E}_m^{100})$	$\mathcal{E}_m^{100}$	$\mathbf{T}(\mathcal{E}_m^{100})$
m	3	14337.7	13290.2	9939.7	35.4	173.0	14950	2925550
	4	14849.3	14018.0	11509.3	40.5	169.4	19900	2607100

for $K_m = \mathcal{E}_m^n$ or $K_m = \mathbf{T}(\mathcal{E}_m^n)$, and $m \in \{3, 4\}$. Here $Q \in \mathcal{H}^n$, $\text{Diag}(Q) = \mathbf{0}$, and $\text{Im}(Q) \neq \mathbf{0}$. The complex elliptope $\mathcal{E}_m^n$ is defined in (3), and $\mathbf{T}(\mathcal{E}_3^n)$ in (30). The set $\mathbf{T}(\mathcal{E}_4^n)$ is defined as the set of matrices in $\mathcal{E}_4^n$ for which each 3×3 submatrix satisfies (20), the 16 (ROC equivalent) facet defining inequalities from Proposition 2, see Remark 4.

We set $n = 100$, and generate 250 matrices Q per value of m in the following way. Upper triangular entries of a matrix Q are of the form $a + bi$, where a and b are independent random integer variables, drawn uniformly from the set $\{-10, -9, \dots, 9, 10\}$. For each such Q , we solve (63) for $K_m = \mathcal{E}_m^{100}$ and $K_m = \mathbf{T}(\mathcal{E}_m^{100})$. We perform a simple rounding procedure (see e.g., [56]) on the optimal value of the corresponding optimization problem to obtain a lower bound on (63), denoted LB. The resulting upper and lower bounds for fixed m are averaged over the 250 runs and presented in Table 3. The columns ‘Avg. time (s)’ report the average computation time per relaxation in seconds. We observe that optimization over $\mathbf{T}(\mathcal{E}_m^{100})$ provides significantly stronger bounds than optimization over $\mathcal{E}_m^{100}$, for both values of m . Thus, $\mathbf{T}(\mathcal{E}_m^n)$ approximates CUT_m^n better than the complex elliptope $\mathcal{E}_m^n$. To compute bounds over $\mathbf{T}(\mathcal{E}_m^{100})$, $m \in \{3, 4\}$ we add all triangle facets to $\mathcal{E}_m^{100}$ at once.

Table 3 also reports the total number of (in)equality constraints in the corresponding CSDP in the columns ‘# (in)equality cons.’. These numbers can be computed as follows. For $\mathcal{E}_m^n$, we have n equality constraints for the unit diagonal, and m inequalities for each of the $n(n-1)/2$ upper triangular entries, to ensure $X_{ij} \in \text{Conv}(\mathcal{B}_m)$. For $\mathbf{T}(\mathcal{E}_m^n)$ we have again n unit diagonal constraints, and m constraints for each of the $n(n-1)/2$ upper triangular entries. Moreover, for each of the $\binom{n}{3}$ principal 3×3 submatrices, we require an additional number of facets. In case $m = 3$, we need 18 additional facets that define CUT_3^3 , according to Theorem 1 (note that the other 9 facets are already included to ensure $X_{ij} \in \text{Conv}(\mathcal{B}_3)$). In case $m = 4$, we add the 16 ROC equivalent inequalities given by Proposition 2, see Remark 4, for each of the $\binom{n}{3}$ principal 3×3 submatrices.

8.3 MIMO

The multiple-input multiple-output detection problem is a fundamental problem in digital communications. The multiple-input multiple-output channel can be modelled as follows: given a complex channel matrix $D \in \mathbb{C}^{k \times n}$, we observe the vector of received signals

$$r := Dc + \sigma v,$$

where $\sigma > 0$, $c \in \mathcal{B}_m^n$ is the unobserved sent signal and v is an unobserved vector of noise. The parameter σ governs the so-called signal to noise ratio, see [22]. Observing only D and r , MIMO is to retrieve the original signal c . We refer to e.g., [22, 34, 55] for more details on MIMO. The maximum likelihood estimator (MLE) of c is

$$\arg \min_{x \in \mathcal{B}_m^n} \|Dx - r\|^2. \quad (64)$$

The above can be approximated by solving instead

$$\min_{X \in K_m} \left\langle \begin{bmatrix} r^H r & -r^H D \\ -D^H r & D^H D \end{bmatrix}, X \right\rangle, \quad (65)$$

for $K_m = \mathcal{E}_m^{n+1}$ or $K_m = \mathbf{T}(\mathcal{E}_m^{n+1})$. The complex ellipsope $\mathcal{E}_m^{n+1}$ is defined in (3), $\mathbf{T}(\mathcal{E}_3^{n+1})$ in (30), and $\mathbf{T}(\mathcal{E}_4^{n+1})$ in Sect. 8.2.

We investigate tightness of our new relaxations numerically. We consider $m \in \{3, 4\}$ and solve (65) for different choices of K_m . Specifically, we set $n = 99$, and let $\sigma \in \{1, 2, 3\}$. For each combination of m and σ , we generate 600 matrices $D \in \mathbb{C}^{109 \times n}$ and vectors $v \in \mathbb{C}^{109}$; these are generated by drawing independent standard complex Gaussians¹. For each such instance, we solve (65) for the different choices of K_m , and track the rate at which these CSDP relaxations return a (numerical) rank 1 solution. A returned solution matrix is deemed numerically rank 1 if its second largest eigenvalue is strictly smaller than 10^{-6} . If a CSDP relaxation returns a rank 1 solution, the CSDP is said to be tight, since the optimal rank 1 solution can be used to obtain a provably optimal solution to (64). Recall that Table 3 contains the number of (in)equality constraints for each K_m .

The results are presented in Table 4 for $m = 3$, and Table 5 for $m = 4$. Both tables report the average computation time in seconds, for each relaxation and each σ . We see that adding the facet-defining inequalities of CUT_3^3 , see (29), for $m = 3$ ensures that the CSDP relaxation is tight at a reasonable rate. A similar observation can be made for $m = 4$, see Table 5. As expected, for increasing values of σ , the CSDP with facet inequalities is tight less often. However, without the facet inequalities, the CSDP is observed to be tight only once out of the 1200 trials. The computation times for $\mathbf{T}(\mathcal{E}_m^{100})$ are significantly longer than for $\mathcal{E}_m^{100}$. Additionally, we observe that the computation times depend on the rank 1 rates. Indeed, for $\mathcal{E}_m^{100}$, $m \in \{3, 4\}$, both the rank 1 rates and the computation times are approximately constant for varying σ . In contrast, for $\mathbf{T}(\mathcal{E}_m^{100})$, $m \in \{3, 4\}$, the computation times differ for varying σ . In particular, $\mathbf{T}(\mathcal{E}_4^{100})$, $\sigma = 3$, attains the lowest rank 1 rate, and highest average computation time.

¹ The number $a + bi$ is said to be a standard complex Gaussian if a and b are independent, normally distributed random variables with mean 0 and variance $1/2$ [24, Definition 24.2.1].

Table 4 Average rate and computation time (over 600 runs) at which (65), the CSDP relaxation of MIMO for $m = 3$ returns a rank 1 solution

K_m	σ			Avg. time (s) per σ		
	1	2	3	1	2	3
$\mathcal{E}_3^{100}$	0.2%	0.0%	0.0%	56.8	52.7	51.0
$\mathbf{T}(\mathcal{E}_3^{100})$	50.8%	54.5%	51.3%	331.7	320.1	310.5

Table 5 Average rate and computation time (over 600 runs) at which (65), the CSDP relaxation of MIMO for $m = 4$ returns a rank 1 solution

K_m	σ			Avg. time (s) per σ		
	1	2	3	1	2	3
$\mathcal{E}_4^{100}$	0.0%	0.0%	0.0%	65.0	60.0	59.3
$\mathbf{T}(\mathcal{E}_4^{100})$	49.7%	38.7%	2.5%	271.6	290.5	342.4

8.4 Angular synchronization

In the angular synchronization problem [2], one is given a matrix $C := cc^H + \sigma W \in \mathbb{C}^{n \times n}$, where $c \in \mathcal{B}_\infty^n$ is an unobserved signal, $\sigma > 0$, and $W \in \mathcal{H}^n$ models noise in receiving the signal c , which one attempts to retrieve. The maximum likelihood estimator of c is given by $\arg \max_{x \in \mathcal{B}_\infty^n} x^H C x$, which may be approximated by

$$\arg \max_{X \in K} \langle cc^H + \sigma W, X \rangle, \quad (66)$$

for $K = \mathcal{E}_\infty^n$, or some second lifting of CUT_∞^n such as (58).

We investigate, for various σ , the rate at which the above CSDP returns a rank 1 solution for different choices of K . Specifically, we investigate the strength of a parametrized relaxation of CUT_∞^n , induced by basis $\mathcal{C}_p$, for $p \in [0, 1]$. This basis contains all n vectors $\alpha_i \in \{0, 1\}^{n-1}$ satisfying $\sum_{i=1}^{n-1} \alpha_i \leq 1$, plus the fraction p of vectors $\alpha \in \{0, 1\}^n$ satisfying $\sum_{i=1}^{n-1} \alpha_i = 2$, chosen uniformly at random (and rounded to nearest integer). The number of elements in this basis can therefore be computed as

$$|\mathcal{C}_p| = n + \left\lfloor p \binom{n-1}{2} \right\rfloor.$$

The induced relaxation of CUT_∞^n is denoted $\mathbf{L}^n(\mathcal{C}_p)$, defined analogously to (58). This relaxation is closely related to the relaxations considered in Sect. 7; note that

$$\text{CUT}_\infty^n \subseteq \mathbf{L}^n(\mathcal{C}_1) = \mathbf{L}^n(\tilde{\mathcal{A}}) \subseteq \mathbf{L}^n(\mathcal{C}_p) \subseteq \mathbf{L}^n(\mathcal{C}_0) = \mathcal{E}_\infty^n \quad \forall p \in [0, 1].$$

We fix $n = 25$, $c = \mathbf{1}_n$, and vary the level of noise $\sigma \in \{(2/3)\sqrt{n}, \sqrt{n}, (4/3)\sqrt{n}\}$. The chosen levels of σ are in line with [2, Figure 2], where it is empirically shown that for $\sigma = (1/3)\sqrt{n}$ and $K = \mathcal{E}_\infty^n$, (66) very often admits an optimal rank 1 solution. Since we test stronger relaxations than $\mathcal{E}_\infty^n$, we have therefore chosen larger

Table 6 Average rate (over 100 runs) at which the CSDP relaxation of the angular synchronization problem (66), over feasible sets $\mathbf{L}^n(\mathcal{C}_p)$ returns a rank 1 solution

p	$ \mathcal{C}_p $	Avg. time (s)	#cons.	$\sigma/\sqrt{n}$		
				2/3	1	4/3
0	25	0.16	25	18%	4%	1%
0.25	94	29	612	61%	34%	27%
0.5	163	316	1947	96%	88%	80%
0.75	232	1975	4063	99%	98%	99%
1	301	7946	6925	100%	100%	100%

values of σ . We generate 100 instances of Hermitian matrices W , for which the upper triangular entries are independent standard complex Gaussians, and track the rate at which the different relaxations, and varying levels of σ , return rank 1 solutions (with the same zero precision of 10^{-6} as in Sect. 8.3). Results are presented in Table 6. There, ‘#cons.’ denotes the number of (complex) equality constraints appearing in the CSDP, and ‘Avg. T. (s)’ stands for the average computation time per relaxation in seconds. Note also that $|\mathcal{C}_p|$ denotes the size of the corresponding CSDP, which is equivalent to a real SDP of size $2|\mathcal{C}_p|$.

At the tested levels of σ it can be observed that increasing the relaxation size (i.e., $p \rightarrow 1$) provides significantly more accurate solutions. For $p = 1$, the CSDP is always observed to return a rank 1 solution, and already $p = 0.75$ offers near-perfect rank 1 rates. The drawback is that the running times also greatly increase. However, in practice, if one is interested in computing the MLE of the unobserved signal c , one should not start by solving the $\mathbf{L}^n(\mathcal{C}_1)$ or $\mathbf{L}^n(\mathcal{C}_{0.75})$ relaxation; it is more efficient to solve a smaller relaxation first, say $\mathbf{L}^n(\mathcal{C}_{0.25})$, and inspect the optimal solution. If the optimal solution is rank 1, it provides the MLE of c . If it is not rank 1, one can increase the value of p and try again, continuing so until an optimal rank 1 matrix is observed.

9 Conclusions and future work

In this paper we study the complex cut polytope CUT_m^n , and its approximations by semidefinite liftings. The considered approximations of CUT_m^n are in general not exact, but we investigate under what conditions they are, see Theorem 1.

Our first approximation of CUT_m^n is the complex ellipsope $\mathcal{E}_m^n$. To strengthen it, we add valid inequalities. In Sect. 3 we introduce a framework for numerically comparing valid inequalities, and derive a number of cuts. In Sect. 4 we determine some facet defining inequalities of CUT_3^3 , and prove that these facets lead to an exact description of CUT_3^3 (Theorem 1). In Sect. 5 we show that a CSDP whose feasible set is closed under complex conjugation and objective function contains only real coefficients, can be equivalently reformulated as a real SDP of the same size (Proposition 4).

In Sect. 6, we consider the complex cut polytope CUT_∞^n . We derive several new results for $n = 4$, the smallest value for which $\mathcal{E}_\infty^n$ is not exact (Theorems 2 and 3). For general n we provide a method for reducing the size of a second semidefinite lifting without weakening the approximation of CUT_∞^n (Lemma 13). In Sect. 7 we

investigate the extreme points of $\mathcal{E}_m^n$ (finite m). We find an infinite family of rank 2 extreme points, which proves that the first semidefinite lifting of CUT_m^n is never exact (Corollary 3).

In Sect. 8 we investigate numerically the value of adding the valid inequalities introduced in Sect. 3 to $\mathcal{E}_m^n$, $m = 3, 4$ for CSDPs with randomly generated objectives and the MIMO detection problem. The numerical results show that adding our cuts significantly improves the bounds as well as greatly increases the rate at which the CSDPs return rank 1 solutions. We also test second semidefinite liftings for the angular synchronization problem, and observe that those induce much tighter CSDP relaxations as the size of a basis increases, at the cost of greater computational effort.

For future work, it would be interesting to have Conjecture 1 resolved. We are also interested in finding faster methods for solving large CSDPs arising from $\mathbf{L}^n(\mathcal{C}_p)$. Table 6 shows clearly that larger values of p greatly improve the strength of relaxations, although the required computational effort (both time and memory) to solve them with off-the-shelf interior point method solvers quickly becomes prohibitive. A tailored solver might be able to handle much larger values of n than 25. Many approaches for improving the scalability of real SDP have been proposed in the literature, most of them via exploiting some form of sparsity in the objective function and/or constraints, see e.g., [47, 52–54] (note that our numerical experiments involved only dense matrices). The authors of [51] remark that some of those approaches can be also applied to CSDPs with only real coefficients. Future research is to investigate how these methods translate for the case of CSDPs over relaxations of CUT_m^n .

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Declarations

Conflict of interest The authors have no conflicts of interest to declare.

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A Proofs and auxiliary lemmas

A.1 Proofs

For the proof of Lemma 11, on page 19, we require the following definitions from convex geometry.

Definition 3 For a convex set C , and a subset $F \subseteq C$, we say that F is a face of C if it satisfies the following: if $x, y \in C$ and $t \in (0, 1)$ are such that $tx + (1 - t)y \in F$, then $x, y \in F$.

Definition 4 A face F of C is said to be exposed, if F is equal to the intersection of some hyperplane with C , or if $F = C$.

We now present the proof.

Lemma 11 The set CUT_∞^4 is strictly contained in $\mathbf{L}(\mathcal{B}_1)$ if and only if there exists a matrix Y satisfying the following: $\text{rk}(Y) = 3$, $Y \in \mathbf{L}(\mathcal{B}_1) \setminus \text{CUT}_\infty^4$, $Y \in \partial \mathcal{E}_\infty^4$, and $Y = \lambda J_4 + (1 - \lambda)A$, for some $\lambda \in (0, 1)$ and $A \in P$, see (49).

Proof The direction $\Leftarrow$ is trivial. For the reverse direction, assume that CUT_∞^4 is strictly contained in $\mathbf{L}(\mathcal{B}_1)$. Then $\mathbf{L}(\mathcal{B}_1)$ contains an extreme point, say $Y \in \partial \mathbf{L}(\mathcal{B}_1)$, which is not in CUT_∞^4 . Since matrices of rank one are elements of CUT_∞^4 , it follows that $\text{rk}(Y) \geq 2$. Since $Y \in \mathbf{L}(\mathcal{B}_1)$, $Y \notin P$ (Theorem 3). Then, by Lemma 10, $\text{rk}(Y) \geq 3$.

We now show that $\text{rk}(Y) \leq 3$, using Definitions 3 and 4. Define

$$\mathcal{F}^{-1}(Y) := \{Z \in \mathcal{F}(\mathcal{B}_1) \mid Z_{1:4,1:4} = Y\}$$

as the set of matrices in $\mathcal{F}(\mathcal{B}_1)$ with Y as upper left submatrix. We show that $\mathcal{F}^{-1}(Y)$ is a face of $\mathcal{F}(\mathcal{B}_1)$. Let $U_1, U_2 \in \mathcal{F}(\mathcal{B}_1)$ and $t \in (0, 1)$ such that $tU_1 + (1 - t)U_2 \in \mathcal{F}^{-1}(Y)$. Denote by Y_i the upper left 4×4 submatrix of U_i , $i \in [2]$. Since $U_i \in \mathcal{F}(\mathcal{B}_1)$, their submatrices $Y_i \in \mathbf{L}(\mathcal{B}_1)$. Now

$$\begin{aligned} tU_1 + (1 - t)U_2 \in \mathcal{F}^{-1}(Y) &\Rightarrow Y = tY_1 + (1 - t)Y_2 \Rightarrow Y = Y_1 = Y_2 \\ &\Rightarrow U_1, U_2 \in \mathcal{F}^{-1}(Y), \end{aligned}$$

where the second implication follows from the fact that Y is an extreme point of $\mathbf{L}(\mathcal{B}_1)$. Thus $\mathcal{F}^{-1}(Y)$ is a face of $\mathcal{F}(\mathcal{B}_1)$ and the extreme points of $\mathcal{F}^{-1}(Y)$ form a subset of the extreme points of $\mathcal{F}(\mathcal{B}_1)$, see e.g., [43, Proposition 8.6].

Let us consider the extreme points of $\mathcal{F}(\mathcal{B}_1)$ in more detail. The set $\mathcal{F}(\mathcal{B}_1)$ is a (complex) spectrahedron. By [41, Corollary 1], every face of a spectrahedron is exposed². In particular, the extreme points of $\mathcal{F}(\mathcal{B}_1)$ are faces of $\mathcal{F}(\mathcal{B}_1)$, and are thus exposed. Therefore, if V denotes such an extreme point, there exists a $Q \in \mathcal{H}^6$ such that

$$V = \arg \max_{X \in \mathcal{F}(\mathcal{B}_1)} \langle Q, X \rangle,$$

i.e., V can be written as the unique optimum of some CSDP over $\mathcal{F}(\mathcal{B}_1)$. Such optima have rank at most $\lfloor \sqrt{k} \rfloor$, for k the number of affine constraints of the corresponding CSDP, see e.g. [29, Theorem 5.1]. As $\mathcal{F}(\mathcal{B}_1)$ has 11 affine constraints, it follows that

² Although the work [41] studies real spectrahedra, Section 1.4, Item 5 of the same work states that real and complex spectrahedra can be considered equivalent in the sense of their geometry.

$\text{rk}(V) \leq \lfloor \sqrt{11} \rfloor = 3$. Since V was arbitrarily chosen, any extreme point of $\mathcal{F}(\mathcal{B}_1)$ has rank at most three.

We now return to Y . Since Y is a submatrix of matrices in $\mathcal{F}^{-1}(Y)$, it follows that

$$\text{rk}(Y) \leq \min_{Z \in \mathcal{F}^{-1}(Y)} \text{rk}(Z).$$

We have shown that $\mathcal{F}^{-1}(Y)$ contains extreme points of $\mathcal{F}(\mathcal{B}_1)$, and that such extreme points have rank at most three. Therefore, $\min_{Z \in \mathcal{F}^{-1}(Y)} \text{rk}(Z) \leq 3$. Because we have previously deduced that $\text{rk}(Y) \geq 3$, it follows that $\text{rk}(Y) = 3$. Since the interior of $\mathcal{E}_\infty^4$ contains only rank 4 points, it follows that $Y \in \partial \mathcal{E}_\infty^4$.

We now prove the last claim on Y , stating that $Y = \lambda J_4 + (1 - \lambda)A$, for some $\lambda \in (0, 1)$ and $A \in P$. Let us write Y as

$$Y = B^H B, \text{ for } B = \begin{bmatrix} x & u & w & v \end{bmatrix}, \quad x, u, w, v \in \mathbb{C}^3 \text{ and } \|x\| = \|u\| = \|w\| = \|v\| = 1. \quad (67)$$

Note that, given Y , B is unique up to unitary multiplication, i.e., $B \rightarrow QB$, for Q a unitary matrix in $\mathbb{C}^{3 \times 3}$. Moreover,

$$\lambda J_4 + (1 - \lambda)A = C^H C, \text{ for } C = \begin{bmatrix} \sqrt{\lambda} \mathbf{1}_4^T \\ \sqrt{1 - \lambda} G \end{bmatrix}, \quad (68)$$

for G an EGF, see Definition 2. Thus, to prove the last claim on Y , we look for a unitary matrix Q such that QB is of the form presented in (68). Let $z \in \mathbb{C}^3$ be such that z^H is the first row of Q . This vector z must satisfy

$$\|z\| = 1 \text{ and } |z^H x| = |z^H u| = |z^H w| = |z^H v| (= \sqrt{\lambda}), \quad (69)$$

and we continue by proving its existence. Let us formulate a CSDP, with zz^H as a feasible solution (if it exists):

$$\begin{aligned} & \text{find } Z \in \mathcal{H}_+^3 \\ & \text{s.t. } \langle Z, xx^H - uu^H \rangle = 0, \\ & \quad \langle Z, xx^H - ww^H \rangle = 0, \\ & \quad \langle Z, xx^H - vv^H \rangle = 0. \end{aligned}$$

By (69), zz^H (if it exists) is feasible to the above CSDP. Note also that I is feasible to the above CSDP, by (67). Invoking [1, Theorem 2.2], we find that the above CSDP admits a rank one solution, say yy^H . Letting $z = y/\|y\|$ shows that a suitable vector z exists. Let Q now be any unitary matrix with such a suitable z^H as its first row. By construction, the entries in the first row of QB all have equal magnitude, but they are not necessarily purely real, as is required in (68).

Let $r \in \mathbb{R}^4$ be the vector containing the arguments of the entries in the first row of QB , and set $\alpha = \exp(r\mathbf{i}) \in \mathcal{B}_\infty^4$, where $\exp(\cdot)$ is evaluated element wise. Recall

the group action f_α from Sect. 3.1. By the fact that CUT_∞^n is closed under the group action f_α , we have

$$Y \notin \text{CUT}_\infty^4 \iff f_\alpha(Y) = (\alpha\alpha^H) \odot Y = \text{Diag}(\alpha)Y \text{Diag}(\bar{\alpha}) \notin \text{CUT}_\infty^4.$$

It follows that $f_\alpha(Y) = \tilde{B}^H \tilde{B}$, for $\tilde{B} = Q B \text{Diag}(\bar{\alpha})$, and matrix $\tilde{B}$ is of the desired form (68). Note also that $f_\alpha(Y)$ and Y are both extreme points of $\mathbf{L}(\mathcal{B}_1)$. $\square$

Below we prove Lemma 13, on page 13.

Lemma 13 $\mathbf{L}^n(\tilde{\mathcal{A}}) = \mathbf{L}^n(\mathcal{A})$

Proof It suffices to show that $\tilde{\mathcal{A}}^p \models \mathcal{A}^p$ for all $p \geq 3$. We fix some $p \geq 3$. For notational convenience, we omit the superscript p in sets $\tilde{\mathcal{A}}^p$ and $\mathcal{A}^p$.

The proof follows again from PSD matrix completion theory [19]. Let us first consider extending $\tilde{\mathcal{A}}$ by a single vector $2\mathbf{e}_1 := 2 \cdot (1, 0, \dots, 0)^\top \in \mathcal{A}$ (the unit vectors $\mathbf{e}_i$, $i \in [p]$ are defined similarly). We denote this new set $\mathcal{D} := \mathcal{A} \cup \{2\mathbf{e}_1\}$, and consider the problem of completing matrix $X \in \mathcal{F}(\tilde{\mathcal{A}})$ to matrix in $Z \in \mathcal{F}(\mathcal{D})$, for which $Z_{1:k, 1:k} = X$, with $k = |\tilde{\mathcal{A}}|$.

As in the proof of Theorem 2, the associated graph $\mathcal{G}$, see (43), is again chordal. Thus it remains to verify that matrix $Z_{\mathcal{J}}$, for $\mathcal{J}$ as in (44), is similar to a submatrix of X . Note that

$$\mathcal{J} = \{\alpha \in \mathcal{D} \mid Z_{\alpha, 2\mathbf{e}_1} \neq ?\} = \{(\alpha_1, \dots, \alpha_p)^\top \in \mathcal{D} \mid \alpha_1 \in \{1, 2\}\},$$

where the rows of Z are indexed by elements of $\mathcal{D}$. When entry $Z_{\alpha, 2\mathbf{e}_1} \neq ?$, its value, in terms of the sequence $\mathbf{y}$, is contained in the following set

$$V := \{(M_{\mathcal{D}}(\mathbf{y}))_{\alpha, 2\mathbf{e}_1} \mid Z_{\alpha, 2\mathbf{e}_1} \neq ?\} = \{\mathbf{y}_\beta \mid \beta = -\mathbf{e}_1 + \mathbf{e}_i, i \in [n]\} \cup \{\mathbf{y}_{-\mathbf{e}_1}\}.$$

Observe that all possible values in V also appear in a single column of $X \in \mathcal{F}(\tilde{\mathcal{A}})$. Specifically,

$$V \subseteq \{(M_{\tilde{\mathcal{A}}}(\mathbf{y}))_{\alpha, \mathbf{e}_1} \mid \alpha \in \tilde{\mathcal{A}}\},$$

i.e., all values in V also appear in the column of X that is indicated by $\mathbf{e}_1 \in \tilde{\mathcal{A}}$. Note that this implies that $Z_{\mathcal{J}}$ is similar to a submatrix of X , and thus PSD. Therefore, $\tilde{\mathcal{A}} \models \tilde{\mathcal{A}} \cup \{2\mathbf{e}_1\}$. In a similar manner, it can be shown that

$$\tilde{\mathcal{A}} \models \tilde{\mathcal{A}} \cup \{2\mathbf{e}_1\} \models \tilde{\mathcal{A}} \cup \{2\mathbf{e}_1, 2\mathbf{e}_2\} \models \dots \models \tilde{\mathcal{A}} \cup \{2\mathbf{e}_1, 2\mathbf{e}_2, \dots, 2\mathbf{e}_p\} = \mathcal{A},$$

which proves the result. $\square$

Below we prove Lemma 16, on page 16.

Lemma 16 Fix some integer $m > 2$, and set

$$G = \begin{bmatrix} 1 & \frac{1}{2} + \frac{1}{2} \exp(2\pi \mathbf{i}/m) & \sin(\pi/m) \\ 0 & \sin(\pi/m) & \frac{1}{2} + \frac{1}{2} \exp(2\pi \mathbf{i}/m) \end{bmatrix}.$$

Then $N = G^H G$ is a rank 2 extreme point of $\mathcal{E}_m^3$.

Proof We show that N satisfies Items 1 and 2 of Proposition 5. Denote by $\mathbf{e}, u, v \in \mathbb{C}^2$ the first three columns of G (in that order). Observe that u_1 is a convex combination of 1 and $\exp(2\pi \mathbf{i}/m)$, both m -roots of unity, and therefore

$$N_{12} = \mathbf{e}^H u = u_1 = \cos(\pi/m) e^{\pi \mathbf{i}/m} \in \partial \text{Conv}(\mathcal{B}_m) \setminus \mathcal{B}_m.$$

Hence, N satisfies Item 1 of Proposition 5. Let us now verify Item 2 by computing a possible perturbation. We have

$$u_1 \bar{u}_2 = \frac{\sin(2\pi/m)}{2} e^{\pi \mathbf{i}/m}.$$

To determine α up to real scaling, see (59), we assume without loss of generality that $c = 1$. Then

$$\frac{\sin(2\pi/m)}{2} \begin{bmatrix} e^{\pi \mathbf{i}/m} & e^{-\pi \mathbf{i}/m} \\ e^{-\pi \mathbf{i}/m} & e^{\pi \mathbf{i}/m} \end{bmatrix} \begin{bmatrix} \alpha \\ \bar{\alpha} \end{bmatrix} = \begin{bmatrix} -\sin^2(\pi/m) \\ -\cos^2(\pi/m) \end{bmatrix} = \begin{bmatrix} \frac{\cos(2\pi/m)-1}{2} \\ -\frac{\cos(2\pi/m)-1}{2} \end{bmatrix},$$

and is thus given by

$$\begin{aligned} \begin{bmatrix} \alpha \\ \bar{\alpha} \end{bmatrix} &= \frac{1}{\sin(2\pi/m)} \begin{bmatrix} e^{\pi \mathbf{i}/m} & e^{-\pi \mathbf{i}/m} \\ e^{-\pi \mathbf{i}/m} & e^{\pi \mathbf{i}/m} \end{bmatrix}^{-1} \begin{bmatrix} \cos(2\pi/m) - 1 \\ -\cos(2\pi/m) - 1 \end{bmatrix} \\ &= \frac{1}{2 \sin^2(2\pi/m) \mathbf{i}} \begin{bmatrix} e^{\pi \mathbf{i}/m} & -e^{-\pi \mathbf{i}/m} \\ -e^{-\pi \mathbf{i}/m} & e^{\pi \mathbf{i}/m} \end{bmatrix} \begin{bmatrix} \cos(2\pi/m) - 1 \\ -\cos(2\pi/m) - 1 \end{bmatrix}. \end{aligned}$$

This yields

$$\begin{aligned} \alpha &= \frac{-\mathbf{i}}{2 \sin^2(\frac{2\pi}{m})} \left(\cos\left(\frac{2\pi}{m}\right) \left[e^{-\frac{\pi \mathbf{i}}{m}} + e^{\frac{\pi \mathbf{i}}{m}} \right] + \left[e^{-\frac{\pi \mathbf{i}}{m}} - e^{\frac{\pi \mathbf{i}}{m}} \right] \right) \\ &= \frac{-1}{\sin^2(\frac{2\pi}{m})} \left(\sin\left(\frac{\pi}{m}\right) + \cos\left(\frac{\pi}{m}\right) \cos\left(\frac{2\pi}{m}\right) \mathbf{i} \right). \end{aligned}$$

Accordingly, b_{12} , see (60), is computed as follows (using $c = 1$):

$$b_{12} = \mathbf{e}^H \begin{bmatrix} 0 & \bar{\alpha} \\ \alpha & 1 \end{bmatrix} u = u_2 \bar{\alpha}.$$

It remains to show that $\operatorname{Re}(\bar{v}b_{12}) \neq 0$, for $v = \exp(\pi i/m)$. To do so, note that $u_2 = \sin(\pi/m) \in \mathbb{R}$, and thus,

$$\begin{aligned}\operatorname{Re}(\bar{v}b_{12}) &= \frac{-u_2}{\sin^2\left(\frac{2\pi}{m}\right)} \operatorname{Re}\left(e^{-\pi i/m} \left[\sin\left(\frac{\pi}{m}\right) - i \cos\left(\frac{\pi}{m}\right) \cos\left(\frac{2\pi}{m}\right) \right]\right) \\ &= \frac{-u_2}{\sin^2\left(\frac{2\pi}{m}\right)} \cos\left(\frac{\pi}{m}\right) \sin\left(\frac{\pi}{m}\right) \left[1 - \cos\left(\frac{2\pi}{m}\right) \right] \neq 0, \text{ since } m > 2.\end{aligned}$$

Since b_{12} is uniquely determined (up to real scaling), it follows that there does not exist a perturbation satisfying $\operatorname{Re}(\bar{v}b_{12}) = 0$. Hence, N satisfies Item 2 of Proposition 5. Thus N is a rank 2 extreme point of $\mathcal{E}_m^3$. $\square$

A.2 Auxiliary lemmas

The following result is used in the proof of Proposition 3, page 3.

Lemma A1 For Q as in (24),

$$\max_{X \in \mathcal{E}_3^3} \langle Q, X \rangle = \frac{3 \cos\left(\frac{\pi}{18}\right)}{2 \cos\left(\frac{\pi}{9}\right)}.$$

Proof For any $Y \in \mathcal{E}_3^3$, the value $\langle Q, Y \rangle$ provides a lower bound on $\max_{X \in \mathcal{E}_3^3} \langle Q, X \rangle$. Thus,

$$\max_{X \in \mathcal{E}_3^3} \langle Q, X \rangle \geq \left\langle Q, r \begin{bmatrix} r^{-1} & e^{4\pi i/9} & e^{2\pi i/9} \\ e^{-4\pi i/9} & r^{-1} & e^{4\pi i/9} \\ e^{-2\pi i/9} & e^{-4\pi i/9} & r^{-1} \end{bmatrix} \right\rangle = \frac{3 \cos\left(\frac{\pi}{18}\right)}{2 \cos\left(\frac{\pi}{9}\right)}, \text{ for } r = \frac{1}{2 \cos\left(\frac{\pi}{9}\right)}.$$

For the matching upper bound, we have that for any $X \in \mathcal{E}_3^3$, the inner product $\langle Q, X \rangle$ can be rewritten as follows:

$$\begin{aligned}\langle Q, X \rangle &= \frac{3 \cos\left(\frac{\pi}{18}\right)}{2 \cos\left(\frac{\pi}{9}\right)} - q \left\langle \begin{bmatrix} 1 & e^{-4\pi i/9} & e^{-8\pi i/9} \\ e^{4\pi i/9} & 1 & e^{-4\pi i/9} \\ e^{8\pi i/9} & e^{4\pi i/9} & 1 \end{bmatrix}, X \right\rangle \\ &\quad - \left(\sqrt{3} - \frac{2q}{r} \right) \sum_{1 \leq i < j \leq 3} \operatorname{Re} \left(\frac{1}{2} - X_{ij} \right) \\ &\leq \frac{3 \cos\left(\frac{\pi}{18}\right)}{2 \cos\left(\frac{\pi}{9}\right)} \quad \forall X \in \mathcal{E}_3^3,\end{aligned}$$

where $q = (4 \sin(2\pi/9))^{-1}$. The above upper bound follows from the fact that $\operatorname{Re}(\frac{1}{2} - X_{ij}) \geq 0$ for all i and j , $\sqrt{3} - \frac{2q}{r} \geq 0$, and the matrix in the inner product

being positive semidefinite (one can verify that this matrix is rank 1). This proves the result. $\square$

The following result is used in the proof of Lemma 12, page 12.

Lemma A2 *For any integer $m \geq 3$ or $m = \infty$, and for H as in (57), we have $\text{str}(H, m) = \frac{2}{\sqrt{3}}$.*

Proof Let $m \geq 3$ be an integer or $m = \infty$. For any $Y \in \mathcal{E}_m^4$, the value $\langle H, Y \rangle$ provides a lower bound on $\max_{X \in \mathcal{E}_m^4} \langle H, X \rangle$. Therefore,

$$\max_{X \in \mathcal{E}_m^4} \langle H, X \rangle \geq \left\langle H, r \begin{bmatrix} r^{-1} & e^{-\pi i/2} & e^{\pi i/2} & 1 \\ e^{\pi i/2} & r^{-1} & e^{-\pi i/2} & 1 \\ e^{-\pi i/2} & e^{\pi i/2} & r^{-1} & 1 \\ 1 & 1 & 1 & r^{-1} \end{bmatrix} \right\rangle = 4\sqrt{3}, \text{ for } r = \frac{1}{\sqrt{3}}.$$

We verify that this $Y \in \mathcal{E}_m^4$. To show that $Y \succeq 0$, we compute the Schur complement of Y with respect to the upper left entry. This gives

$$\frac{2}{3} \begin{bmatrix} 1 & e^{-2\pi i/3} & \mathbf{0}_2 \\ e^{2\pi i/3} & 1 & \mathbf{0}_2 \\ \mathbf{0}_2^\top & \mathbf{0}_2 & 0 \end{bmatrix} \succeq 0.$$

To verify that all elements of Y are contained in $\text{Conv}(\mathcal{B}_m)$, note that $1 \in \text{Conv}(\mathcal{B}_m)$. For $m = 3$, $re^{\pi i/2}$ is a convex combination of 1 and $e^{2\pi i/3} \in \mathcal{B}_3$. For $m = 4$, note that the polytope $\text{Conv}(\mathcal{B}_4)$ contains an inscribed circle of radius

$$\min_{x \in \partial \text{Conv}(\mathcal{B}_4)} \|x\| = \left\| \frac{1 + \mathbf{i}}{2} \right\| = \frac{1}{\sqrt{2}}. \quad (70)$$

Since

$$\|re^{\pi i/2}\| = \frac{1}{\sqrt{3}} < \frac{1}{\sqrt{2}}, \quad (71)$$

it follows that $re^{\pi i/2} \in \text{Conv}(\mathcal{B}_4)$. Now for the case $m > 4$: let R_m denote the radius of the inscribed circle of $\text{Conv}(\mathcal{B}_m)$ (by (70), $R_4 = 1/\sqrt{2}$). Note that R_m is increasing in m . Therefore, following (71), we have

$$\|re^{\pi i/2}\| \leq R_4 \leq R_m \Rightarrow re^{\pi i/2} \in \text{Conv}(\mathcal{B}_m) \quad \forall m \geq 4.$$

Clearly, also $re^{-\pi i/2} \in \text{Conv}(\mathcal{B}_m)$, since $\text{Conv}(\mathcal{B}_m)$ is closed under complex conjugation. Thus, we have shown that all elements of Y are contained in $\text{Conv}(\mathcal{B}_m)$ for all valid m . Therefore, $Y \in \mathcal{E}_m^4$.

Moreover, for any $X \in \mathcal{E}_m^4$, we have

$$\langle H, X \rangle = 4\sqrt{3} - \langle \sqrt{3}I_4 - H, X \rangle \leq 4\sqrt{3},$$

since matrix $\sqrt{3}I_4 - H \succeq 0$. This proves $\max_{X \in \mathcal{E}_m^4} \langle H, X \rangle = 4\sqrt{3}$, for all integers $m \geq 3$. To show that $\max_{X \in \text{CUT}_m^4} \langle H, X \rangle = 6$, we take $J_4 \in \text{CUT}_m^4$, for which it follows

$$\max_{X \in \text{CUT}_m^4} \langle H, X \rangle \geq \langle H, J_4 \rangle = 6.$$

For the matching upper bound, we have

$$\max_{X \in \text{CUT}_m^4} \langle H, X \rangle \leq \max_{X \in \text{CUT}_\infty^4} \langle H, X \rangle \leq \max_{X \in \mathcal{L}(\mathcal{B}_1)} \langle H, X \rangle = 6,$$

which follows from Lemma 12. Lastly, to compute the strength, see (7), we have $4\sqrt{3}/6 = 2/\sqrt{3}$. $\square$

B Facet enumeration of $\mathcal{V}(\text{CUT}_3^3)$

Table 7 provides a complete enumeration of the facets of $\mathcal{V}(\text{CUT}_3^3)$, see (22). These facets are given implicitly in Table 1, and one facet is given explicitly in Proposition 3.

The facets in Table 7 were verified using the SageMath software [46]. The precise code is provided in Listing 1.

```
# Create the field extension to symbolically evaluate sqrt(3)
x = polygen(ZZ, 'x')
K.<sqrt3> = NumberField(x^2 - 3, embedding=AA(3)**(1/2))

# Create the polyhedron with points of the cut polytope.
# Points are given as (Re(x), Im(x)).
P = Polyhedron([(1,1,1,0,0,0), (1,-0.5,-0.5,0,
-sqrt3/2,-sqrt3/2),
(1,-0.5,-0.5,0,sqrt3/2,sqrt3/2), (-0.5,1,-0.5,
-sqrt3/2,0,sqrt3/2),
(-0.5,-0.5,1,-sqrt3/2,0), (-0.5,-0.5,-0.5,-sqrt3/2,
sqrt3/2,-sqrt3/2),
(-0.5,1,-0.5,sqrt3/2,0,-sqrt3/2), (-0.5,-0.5,-0.5,sqrt3/2,
-sqrt3/2,sqrt3/2),
(-0.5,-0.5,1,sqrt3/2,sqrt3/2,0)])

# compute the facets (i.e., half-space representation)
of the cut polytope
P.Hrepresentation()
```

Listing 1 SageMath code for computing the facets of $\mathcal{V}(\text{CUT}_3^3)$.

Table 7 Coefficients of the facets $\text{Re}\left(\sum_{i=1}^3 \eta_i x_i\right) \leq \sqrt{3}/2$ for $\mathcal{V}(\text{CUT}_3^3)$

	η_1	η_2	η_3
1.	$\mathbf{i}$	$e^{\pi\mathbf{i}/6}$	$\mathbf{i}$
2.	$e^{5\pi\mathbf{i}/6}$	$e^{-\pi\mathbf{i}/6}$	$e^{\pi\mathbf{i}/6}$
4.	$e^{\pi\mathbf{i}/6}$	$e^{-\pi\mathbf{i}/6}$	$e^{5\pi\mathbf{i}/6}$
5.	$\mathbf{i}$	$-\mathbf{i}$	$e^{-\pi\mathbf{i}/6}$
5.	$e^{\pi\mathbf{i}/6}$	$e^{-5\pi\mathbf{i}/6}$	$e^{\pi\mathbf{i}/6}$
6.	$e^{-\pi\mathbf{i}/6}$	$-\mathbf{i}$	$\mathbf{i}$
7.	$e^{-5\pi\mathbf{i}/6}$	$e^{\pi\mathbf{i}/6}$	$e^{-\pi\mathbf{i}/6}$
8.	$-\mathbf{i}$	$\mathbf{i}$	$e^{\pi\mathbf{i}/6}$
9.	$e^{\pi\mathbf{i}/6}$	$\mathbf{i}$	$-\mathbf{i}$
10.	$e^{-\pi\mathbf{i}/6}$	$e^{\pi\mathbf{i}/6}$	$e^{-5\pi\mathbf{i}/6}$
11.	$e^{-\pi\mathbf{i}/6}$	$e^{5\pi\mathbf{i}/6}$	$e^{-\pi\mathbf{i}/6}$
12.	$-\mathbf{i}$	$e^{-\pi\mathbf{i}/6}$	$-\mathbf{i}$
13.	$e^{5\pi\mathbf{i}/6}$	$\mathbf{i}$	$e^{5\pi\mathbf{i}/6}$
14.	$e^{-5\pi\mathbf{i}/6}$	$e^{5\pi\mathbf{i}/6}$	$\mathbf{i}$
15.	$\mathbf{i}$	$e^{5\pi\mathbf{i}/6}$	$e^{-5\pi\mathbf{i}/6}$
16.	$e^{5\pi\mathbf{i}/6}$	$e^{-5\pi\mathbf{i}/6}$	$-\mathbf{i}$
17.	$e^{-5\pi\mathbf{i}/6}$	$-\mathbf{i}$	$e^{-5\pi\mathbf{i}/6}$
18.	$-\mathbf{i}$	$e^{-5\pi\mathbf{i}/6}$	$e^{5\pi\mathbf{i}/6}$
19.	$\sqrt{3}e^{\pi\mathbf{i}/3}$	0	0
20.	$\sqrt{3}e^{-\pi\mathbf{i}/3}$	0	0
21.	$-\sqrt{3}$	0	0
22.	0	$\sqrt{3}e^{-\pi\mathbf{i}/3}$	0
23.	0	$\sqrt{3}e^{\pi\mathbf{i}/3}$	0
24.	0	$-\sqrt{3}$	0
25.	0	0	$\sqrt{3}e^{\pi\mathbf{i}/3}$
26.	0	0	$\sqrt{3}e^{-\pi\mathbf{i}/3}$
27.	0	0	$-\sqrt{3}$

In Table 7, facets 1 up to and including 18 are the triangle facets, using the terminology of Sect. 4. Facets 19 up to and including 27 are the facets that ensure $x_i \in \text{Conv}(\mathcal{B}_3)$ for all $i \in [3]$, see (5).

References

1. Ai, W., Huang, Y., Zhang, S.: New results on Hermitian matrix rank-one decomposition. *Math. Program.* **128**(1–2), 253–283 (2011)
2. Bandeira, A.S., Boumal, N., Singer, A.: Tightness of the maximum likelihood semidefinite relaxation for angular synchronization. *Math. Program.* **163**, 145–167 (2017)
3. Barahona, F., Grötschel, M., Jünger, M., Reinelt, G.: An application of combinatorial optimization to statistical physics and circuit layout design. *Oper. Res.* **36**(3), 493–513 (1988)
4. Ben-Tal, A., Nemirovski, A.: On polyhedral approximations of the second-order cone. *Math. Oper. Res.* **26**(2), 193–205 (2001)
5. Chopra, S., Rao, M.R.: Facets of the k -partition polytope. *Discret. Appl. Math.* **61**(1), 27–48 (1995)
6. Christensen, J.P.R., Vesterstrøm, J.: A note on extreme positive definite matrices. *Math. Ann.* **244**, 65–68 (1979)
7. Curto, R.E., Fialkow, L.A.: *Flat Extensions of Positive Moment Matrices: Recursively Generated Relations*, volume 136 of *Memoirs of the American Mathematical Society*. American Mathematical Soc (1998)
8. Deza, M.M., Laurent, M.: *Geometry of Cuts and Metrics*. Springer, Berlin (1997)
9. Ding, C.H., He, X., Zha, H., Gu, M., Simon, H.D.: A min-max cut algorithm for graph partitioning and data clustering. In: *Proceedings 2001 IEEE International Conference on Data Mining*, pp. 107–114. IEEE (2001)
10. Dobre, C.: *Semidefinite programming approaches for structured combinatorial optimization problems*. PhD thesis, Tilburg University (2011)
11. Fawzi, H., Saunderson, J., Parrilo, P.A.: Sparse sums of squares on finite abelian groups and improved semidefinite lifts. *Math. Program.* **160**, 149–191 (2016)
12. Fawzi, H., Saunderson, J., Parrilo, P.A.: Equivariant semidefinite lifts of regular polygons. *Math. Oper. Res.* **42**(2), 472–494 (2017)
13. Fiorini, S., Rothvoß, T., Tiwary, H.R.: Extended formulations for polygons. *Discrete Comput. Geom.* **48**(3), 658–668 (2012)
14. Frieze, A., Jerrum, M.: Improved approximation algorithms for MAX k -CUT and MAX BISECTION. *Algorithmica* **18**(1), 67–81 (1997)
15. Gale, D.: Neighborly and cyclic polytopes. In: *Proceedings of Symposia in Pure Mathematics* **7**, 225–232 (1963)
16. Gilbert, J.C., Josz, C.: *Plea for a semidefinite optimization solver in complex numbers*. Technical report, LAAS-Laboratoire d'analyse et d'architecture des systèmes (Toulouse, France) (2017)
17. Goemans, M.X., Williamson, D.P.: Improved approximation algorithms for maximum cut and satisfiability problems using semidefinite programming. *J. ACM* **42**(6), 1115–1145 (1995)
18. Goemans, M.X., Williamson, D.P.: Approximation algorithms for MAX-3-CUT and other problems via complex semidefinite programming. *J. Comput. Syst. Sci.* **68**(2), 442–470 (2004)
19. Grone, R., Johnson, C.R., Sá, E.M., Wolkowicz, H.: Positive definite completions of partial Hermitian matrices. *Linear Algebra Appl.* **58**, 109–124 (1984)
20. Grone, R., Pierce, S., Watkins, W.: Extremal correlation matrices. *Linear Algebra Appl.* **134**, 63–70 (1990)
21. Jarre, F., Lieder, F., Liu, Y.-F., Lu, C.: Set-completely-positive representations and cuts for the max-cut polytope and the unit modulus lifting. *J. Glob. Optim.* **76**(4), 913–932 (2020)
22. Jiang, R., Liu, Y.-F., Bao, C., Jiang, B.: Tightness and equivalence of semidefinite relaxations for MIMO detection. *arXiv preprint [arXiv:2102.04586](https://arxiv.org/abs/2102.04586)*, (2021)
23. Josz, C., Molzahn, D.K.: Lasserre hierarchy for large scale polynomial optimization in real and complex variables. *SIAM J. Optim.* **28**(2), 1017–1048 (2018)
24. Lapidoth, A.: *A Foundation in Digital Communication*, 2nd edn. Cambridge University Press, Cambridge (2017)
25. Lasserre, J.-B.: Global optimization with polynomials and the problem of moments. *SIAM J. Optim.* **11**(3), 796–817 (2001)
26. Laurent, M.: Graphic vertices of the metric polytope. *Discret. Math.* **151**(1–3), 131–153 (1996)
27. Laurent, M., Poljak, S.: On a positive semidefinite relaxation of the cut polytope. *Linear Algebra Appl.* **223–224**, 439–461 (1995)
28. Laurent, M., Poljak, S.: Gap inequalities for the cut polytope. *Eur. J. Comb.* **17**(2), 233–254 (1996)

29. Lemon, A., So, A.M.-C., Ye, Y.: Low-rank semidefinite programming: theory and applications. *Found. Trends® Optim.* **2**(1–2), 1–156 (2016)
30. Li, C.-K., Tam, B.-S.: A note on extreme correlation matrices. *SIAM J. Matrix Anal. Appl.* **15**(3), 903–908 (1994)
31. Loewy, R.: Extreme points of a convex subset of the cone of positive semidefinite matrices. *Math. Ann.* **253**, 227–232 (1980)
32. Löfberg, J.: Pre-and post-processing sum-of-squares programs in practice. *IEEE Trans. Autom. Control* **54**(5), 1007–1011 (2009)
33. Lu, C., Deng, Z., Zhang, W.-Q., Fang, S.-C.: Argument division based branch-and-bound algorithm for unit-modulus constrained complex quadratic programming. *J. Glob. Optim.* **70**, 171–187 (2018)
34. Lu, C., Liu, Y.-F., Zhang, W.-Q., Zhang, S.: Tightness of a new and enhanced semidefinite relaxation for MIMO detection. *SIAM J. Optim.* **29**(1), 719–742 (2019)
35. Lu, C., Liu, Y.-F., Zhou, J.: An enhanced SDR based global algorithm for nonconvex complex quadratic programs with signal processing applications. *IEEE Open J. Signal Process.* **1**, 120–134 (2020)
36. Magron, V., Safey El Din, M., Schweighofer, M., Vu, T.H.: Exact SOHS decompositions of trigonometric univariate polynomials with Gaussian coefficients. In: *Proceedings of the 2022 International Symposium on Symbolic and Algebraic Computation*, pp. 325–332 (2022)
37. McMullen, P.: The maximum numbers of faces of a convex polytope. *Mathematika* **17**(2), 179–184 (1970)
38. Mobasher, A., Taherzadeh, M., Sotirov, R., Khandani, A.K.: A near-maximum-likelihood decoding algorithm for MIMO systems based on semi-definite programming. *IEEE Trans. Inf. Theory* **53**(11), 3869–3886 (2007)
39. MOSEK ApS. The MOSEK optimization toolbox for MATLAB manual. Version 10.1.21, 2023. URL <https://docs.mosek.com/10.1/toolbox/index.html>
40. Myerson, G.: How small can a sum of roots of unity be? *Am. Math. Mon.* **93**(6), 457–459 (1986)
41. Ramana, M., Goldman, A.J.: Some geometric results in semidefinite programming. *J. Glob. Optim.* **7**(1), 33–50 (1995)
42. Rockafellar, R.T.: *Convex Analysis*, vol. 11. Princeton University Press, Princeton (1997)
43. Simon, B.: *Convexity: An Analytic Viewpoint*, volume 187 of Cambridge Tracts in Mathematics. Cambridge University Press (2011)
44. So, A.M.-C., Zhang, J., Ye, Y.: On approximating complex quadratic optimization problems via semidefinite programming relaxations. *Math. Program.* **110**(1), 93–110 (2007)
45. Soltanalian, M., Stoica, P.: Designing unimodular codes via quadratic optimization. *IEEE Trans. Signal Process.* **62**, 1221–1234 (2013)
46. The Sage Developers. *SageMath, the Sage Mathematics Software System (Version 10.3)*, 2024. <https://www.sagemath.org>
47. Waki, H., Kim, S., Kojima, M., Muramatsu, M.: Sums of squares and semidefinite program relaxations for polynomial optimization problems with structured sparsity. *SIAM J. Optim.* **17**(1), 218–242 (2006)
48. Waldspurger, I., d’Aspremont, A., Mallat, S.: Phase recovery, MaxCut and complex semidefinite programming. *Math. Program.* **149**(1–2), 47–81 (2015)
49. Wang, J.: A more efficient reformulation of complex SDP as real SDP. arXiv preprint [arXiv:2307.11599](https://arxiv.org/abs/2307.11599) (2023)
50. Wang, J., Magron, V.: Exploiting sparsity in complex polynomial optimization. *J. Optim. Theory Appl.* (2022). <https://doi.org/10.1007/s10957-021-01975-z>
51. Wang, J., Magron, V.: A real moment-HSOS hierarchy for complex polynomial optimization with real coefficients. (2023) [arXiv:2308.14631](https://arxiv.org/abs/2308.14631)
52. Wang, J., Magron, V., Lasserre, J.-B.: Chordal-TSSOS: a moment-SOS hierarchy that exploits term sparsity with chordal extension. *SIAM J. Optim.* **31**(1), 114 (2021)
53. Wang, J., Magron, V., Lasserre, J.-B.: TSSOS: a moment-SOS hierarchy that exploits term sparsity. *SIAM J. Optim.* **31**(1), 30–58 (2021)
54. Wang, J., Magron, V., Mai, N.H.A.: CS-TSSOS: correlative and term sparsity for large-scale polynomial optimization. *ACM Trans. Math. Softw.* **48**(4), 1–26 (2022)
55. Yang, S., Hanzo, L.: Fifty years of MIMO detection: the road to large-scale MIMOs. *IEEE Commun. Surv. Tutor.* **17**, 1941–1988 (2015)
56. Zhang, S., Huang, Y.: Complex quadratic optimization and semidefinite programming. *SIAM J. Optim.* **16**(3), 871–890 (2006)

57. Zhang, Y.J.A., So, A.M.-C.: Optimal spectrum sharing in MIMO cognitive radio networks via semidefinite programming. *IEEE J. Sel. Areas Commun.* **29**(2), 362–373 (2011)
58. Zhong, Y., Boumal, N.: Near-optimal bounds for phase synchronization. *SIAM J. Optim.* **28**(2), 989–1016 (2018)

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