

Approximation Methods for Inhomogeneous Polynomial Optimization

Simai HE ^{*} Zhening LI [†] Shuzhong ZHANG [‡]

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Abstract

In this paper, we consider computational methods for optimizing a multivariate inhomogeneous polynomial function over a compact set. The focus is on the design and analysis of polynomial-time approximation algorithms. The references on approximation algorithms for inhomogeneous polynomial optimization problems are extremely scarce in the literature. To the best of our knowledge, the only result so far was due to Nemirovski, Roos and Terlaky [26], who obtained an $\Omega(1/\log m)$ -approximation ratio for maximizing an inhomogeneous *quadratic* polynomial over the intersection of m co-centered ellipsoids. In this paper we aim at developing computational methods to deal with optimization models with polynomial objective functions in *any fixed degrees*. In particular, we first study the problem of maximizing an inhomogeneous polynomial over the Euclidean ball. A polynomial-time approximation algorithm is proposed for this problem with an assured (relative) worst-case performance ratio, which is dependent only on the dimensions of the model. The method and approximation ratio are then generalized to optimize an inhomogeneous polynomial over the intersection of a finite number of co-centered ellipsoids. Finally, the constraint set is extended to a general compact set. Specifically, we propose a polynomial-time approximation algorithm with a (relative) worst-case performance ratio for polynomial optimization over some convex compact sets, e.g., a polytope.

Keywords: polynomial optimization; nonlinear programming; approximation algorithm; tensor optimization.

Mathematics Subject Classification: 90C26, 90C59, 65Y20, 68W25, 15A69.

^{*}Department of Management Sciences, City University of Hong Kong, Kowloon Tong, Hong Kong. Email: simai-he@cityu.edu.hk

[†]Department of Systems Engineering and Engineering Management, The Chinese University of Hong Kong, Shatin, Hong Kong. Email: zheningli@gmail.com

[‡]Industrial and Systems Engineering Program, University of Minnesota, Minneapolis, MN 55455. Email: zhangs@umn.edu (On leave from Department of Systems Engineering and Engineering Management, The Chinese University of Hong Kong, Shatin, Hong Kong)

1 Introduction

In this paper, we consider the general constrained polynomial optimization model

$$(G) \quad \begin{aligned} & \max \quad p(\mathbf{x}) \\ & \text{s.t.} \quad \mathbf{x} \in S, \end{aligned}$$

where $p(\mathbf{x})$ is a multivariate inhomogeneous polynomial function of $\mathbf{x} \in \mathbb{R}^n$, and $S \subseteq \mathbb{R}^n$ is a given compact set, typically defined by some polynomial equalities or inequalities. This general optimization problem is one of the fundamental model in the field of optimization. Such problems and formulations are encountered frequently in the literature, with an amazingly wide spectrum of applications: quantum mechanics [8, 5], biomedical engineering such as magnetic resonance imaging [6, 3], signal processing [23, 37], numerical linear algebra [35, 36, 29], investment science [2, 33, 12, 30, 24], among many others. For example, the least square formulation to the sensor network localization problem proposed in Luo and Zhang [22] takes the form of

$$(G_1) \quad \begin{aligned} & \min \quad \sum_{i,j \in \mathcal{S}} \left(\|\mathbf{x}^i - \mathbf{x}^j\|_2^2 - d_{ij}^2 \right)^2 + \sum_{i \in \mathcal{S}, j \in \mathcal{A}} \left(\|\mathbf{x}^i - \mathbf{a}^j\|_2^2 - d_{ij}^2 \right)^2 \\ & \text{s.t.} \quad \mathbf{x}^i \in G, i \in \mathcal{S}, \end{aligned}$$

where \mathcal{A} and \mathcal{S} denote the set of anchor nodes and sensor nodes respectively, d_{ij} 's are (possibly noisy) distance measurements, \mathbf{a}^j 's denote the known positions of anchor nodes, while \mathbf{x}^i 's represent the positions of sensor nodes in the compact region $G \subseteq \mathbb{R}^3$ to be estimated. Another example is the portfolio management problem involving more than the first two moments (e.g., the skewness and the kurtosis of the investment returns). That problem has been receiving much attention in the literature (cf. De Athayde and Flôre [2], Prakash, Chang and Pactwa [33], Jondeau and Rockinger [12], Kleniati, Parpas and Rusterm [16]). In particular, a very general model in [16] is

$$(G_2) \quad \begin{aligned} & \max \quad \alpha \sum_{i=1}^n \mu_i x_i - \beta \sum_{i,j=1}^n \sigma_{ij} x_i x_j + \gamma \sum_{i,j,k=1}^n \varsigma_{ijk} x_i x_j x_k - \delta \sum_{i,j,k,\ell=1}^n \kappa_{ijkl} x_i x_j x_k x_\ell \\ & \text{s.t.} \quad \mathbf{e}^T \mathbf{x} = 1, \mathbf{x} \geq \mathbf{0}, \mathbf{x} \in \mathbb{R}^n, \end{aligned}$$

where $(\mu_i), (\sigma_{ij}), (\varsigma_{ijk}), (\kappa_{ijkl})$ are the first four moments of the given n assets, and \mathbf{e} is the all-one vector. The non-negative parameters $\alpha, \beta, \gamma, \delta$ measure the investor's preference to the four moments, and they sum up to one, i.e., $\alpha + \beta + \gamma + \delta = 1$.

The polynomial optimization problems are typically non-convex, highly nonlinear, and NP-hard in general. The search for general and efficient algorithms for polynomial optimization has been a priority for many mathematical optimizers. Indeed, generic solution methods based on nonlinear programming and global optimization have been studied and tested; see e.g., Qi [34], and Qi et al. [38]. Recent years, an entirely different and systematic approach based on the *Sum of Squares* (SOS) was proposed by Lasserre [17, 18] and Parrilo [31, 32]. The SOS approach has a strong theoretical appeal, since it can in principle solve any general polynomial optimization model to any precision, by resorting to a (possibly large) Semidefinite Program (SDP). However, the SDP problems required to be solved by the SOS approach grow exponentially, making the SOS approach

only viable for low dimensional problems. Henrion et al. [11] developed a specialized tool known as GloptiPoly 3 for finding a global optimal solution for polynomial optimization based on the SOS approach. For an overview on the recent theoretical developments, we refer to the excellent survey by Laurent [19].

On the other side, the intractability of general polynomial optimizations therefore motivates the search for suboptimal, or more formally, approximate solutions. In the case that the objective polynomial is quadratic, a well known example is the SDP relaxation and randomization approach for the max-cut problem due to Goemans and Williamson [7], where essentially a 0.878-approximation ratio of the model $\max_{\mathbf{x} \in \{1, -1\}^n} \mathbf{x}^T \mathbf{F} \mathbf{x}$ is shown with \mathbf{F} being the Laplacian of a given graph. Note that the approach in [7] has been generalized subsequently by many authors, including Nesterov [27], Ye [42, 43], Nemirovski et al. [26], Zhang [45], Alon and Naor [1], Zhang and Huang [46], Luo et al. [21], and He et al. [10]. In particular, when the matrix \mathbf{F} is only known to be positive semidefinite, Nesterov [27] derived a 0.636-approximation bound for $\max_{\mathbf{x} \in \{1, -1\}^n} \mathbf{x}^T \mathbf{F} \mathbf{x}$. Nemirovski et al. [26] proposed an $\Omega(1/\log m)$ -approximation bound for maximizing a quadratic form over the intersection of m co-centered ellipsoids. Their models are further studied and generalized by Luo et al. [21] and He et al. [10].

Beyond quadratic objectives, the approximation methods for high degree polynomial optimizations have attracted much attention recently. Luo and Zhang [22] considered quartic optimization, and showed that optimizing a homogenous quartic form over the intersection of some co-centered ellipsoids is essentially equivalent to its (quadratic) SDP relaxation problem, which is itself also NP-hard. However, this gives a handle on the design of approximation algorithms with provable worst-case approximation ratios. Ling et al. [20] considered a special quartic optimization model. Basically, the problem is to minimize a biquadratic function over two spherical constraints. In [20], approximate solutions as well as exact solutions using the SOS method are considered. The approximation bounds in [20] are indeed comparable to the bound in [22]. A breakthrough in approximation methods for any degree polynomial objective was due to He, Li, and Zhang [9], where the authors proposed polynomial-time approximation algorithms for any fixed degree homogeneous polynomial with quadratic constraints, including the spherical constraints and the intersection of a finite number of co-centered ellipsoids, and the approximation ratios beats that in [22] and [20] specialized to degree 4. In the meantime, Zhang, Qi, and Ye [47] studied cubic form optimization with spherical constraints, and proposed polynomial-time approximation algorithms, and the ratio is comparable to that in [9], specialized to degree 3. Very recently, So [39] improved the approximation ratios for any fixed degree spherical constrained homogeneous polynomial optimization problems studied in [9].

All the above successful approximation methods only tackle optimization of *homogeneous* polynomials, while the study of approximation algorithms for *inhomogeneous* polynomial optimization is scarcely found in the literature, despite the fact that inhomogeneous polynomial optimization is commonplace as we discussed earlier. To our best knowledge, the only result so far was due

to Nemirovski et al. [26]; however, their technique only works for an inhomogeneous quadratic polynomial objective function. In fact, extending the solution methods and the corresponding analysis from *homogeneous* polynomial optimization to the general *inhomogeneous* polynomials is not straightforward. Technically, a homogenous polynomial function allows one to *scale* the overall function value along a given direction, which is an essential operation in proving the quality bound of the approximation algorithms. The current paper breaks its path from the preceding practices, by directly dealing with a *homogenizing* variable. Although homogenization is a natural way to deal with inhomogeneous polynomials, it is quite a different matter when it comes to the worst-case performance ratio analysis. In fact, the usual homogenization does not lead to any assured performance ratio. In this paper we shall point out a specific route to get around this difficulty, and we actually provide a general scheme to approximately solve such problems.

The paper is organized as follows. First in Section 2, we introduce the notations and the models. Then in Section 3, we analyze the model where the constraint set is the Euclidean ball and propose polynomial-time approximation algorithms with guaranteed performance ratios, which serves as a basis for the subsequent analysis. In Section 4, the discussion is extended to cover the problem where the constraint set is the intersection of a finite number of co-centered ellipsoids. In Section 5, the approximation bounds will be derived even under some very general compact sets, e.g., a polytope. It turns out that for such general problems, it is still possible to derive relative approximation ratios, which is still depended on the problem dimensions only.

2 Notations, Models, and the Organization

To make a clear visual distinction, in this paper we shall use the boldface letters to denote vectors, matrices, and tensors in general (e.g., the decision variable \mathbf{x} , the data matrix \mathbf{Q} , and the tensor form \mathbf{F}), while the usual lowercase letters are reserved for scalars (e.g., the homogenizing variable x_h to be introduced later). The Greek letters ξ , η and β are reserved to denote binary variables (e.g., $\boldsymbol{\xi} \in \mathbb{B}^d := \{1, -1\}^d$). The letter τ , however, is reserved to indicate the *approximation ratio*, which is a key ingredient throughout this paper.

Let us start by defining the following multilinear function

$$F(\mathbf{x}^1, \mathbf{x}^2, \dots, \mathbf{x}^d) = \sum_{1 \leq i_1 \leq n_1, 1 \leq i_2 \leq n_2, \dots, 1 \leq i_d \leq n_d} F_{i_1 i_2 \dots i_d} x_{i_1}^1 x_{i_2}^2 \dots x_{i_d}^d,$$

where $\mathbf{x}^k \in \mathfrak{R}^{n_k}$ for $k = 1, 2, \dots, d$, and $\mathbf{F} = (F_{i_1 i_2 \dots i_d}) \in \mathfrak{R}^{n_1 \times n_2 \times \dots \times n_d}$ is a d -th order tensor with F being its associated multilinear function.

Closely related to the tensor form \mathbf{F} is a general d -th degree homogeneous polynomial function $f(\mathbf{x})$ of $\mathbf{x} \in \mathfrak{R}^n$. We call the tensor form *super-symmetric* (see [14]) if $F_{i_1 i_2 \dots i_d}$ is invariant under all permutations of $\{i_1, i_2, \dots, i_d\}$. As any quadratic function uniquely determines a symmetric matrix, a given homogeneous polynomial function $f(\mathbf{x})$ also uniquely determines a super-symmetric tensor

form. For a given super-symmetric tensor form \mathbf{F} , we denote by F the multilinear function induced by it, and by f the homogeneous polynomial function, i.e., $f(\mathbf{x}) = F(\underbrace{\mathbf{x}, \mathbf{x}, \dots, \mathbf{x}}_d)$. The Frobenius norm of the tensor form \mathbf{F} is the usual Euclidean norm (or the 2-norm) defined as

$$\|\mathbf{F}\| := \sqrt{\sum_{1 \leq i_1 \leq n_1, 1 \leq i_2 \leq n_2, \dots, 1 \leq i_d \leq n_d} F_{i_1 i_2 \dots i_d}^2}.$$

In this paper we shall exclusively use only the 2-norm for the vectors, the matrices, and the tensors.

A generic d -th degree multivariate (inhomogeneous) polynomial function $p(\mathbf{x})$, can be explicitly written as a summation of homogenous polynomial functions in decreasing degrees, namely

$$p(\mathbf{x}) := \sum_{i=1}^d f_i(\mathbf{x}) + f_0 = \sum_{i=1}^d F_i(\underbrace{\mathbf{x}, \mathbf{x}, \dots, \mathbf{x}}_i) + f_0,$$

where $\mathbf{x} \in \mathfrak{R}^n$, $f_0 \in \mathfrak{R}$ and $f_i(\mathbf{x}) = F_i(\underbrace{\mathbf{x}, \mathbf{x}, \dots, \mathbf{x}}_i)$ is a homogenous polynomial function of degree i for $i = 1, 2, \dots, d$.

One natural way to deal with inhomogeneous polynomial function is through *homogenization*; that is, we introduce a new variable, to be denoted by x_h in this paper, which is actually set to be 1, to yield a homogeneous form

$$p(\mathbf{x}) = \sum_{i=1}^d f_i(\mathbf{x}) + f_0 = \sum_{i=1}^d f_i(\mathbf{x}) x_h^{d-i} + f_0 x_h^d = f(\bar{\mathbf{x}}), \quad (1)$$

where $f(\bar{\mathbf{x}})$ is an $(n+1)$ -dimensional homogeneous polynomial function of degree d , with variable $\bar{\mathbf{x}} \in \mathfrak{R}^{n+1}$. Throughout this paper, the ‘bar’ notation, e.g., $\bar{\mathbf{x}}$, is reserved for an $(n+1)$ -dimensional vector, with the underlying letter \mathbf{x} referring to the vector of its first n components, and the subscript ‘ h ’ (the subscript of x_h) referring to its last component. For instance, if $\bar{\mathbf{x}} = (x_1, x_2, \dots, x_n, x_{n+1})^T \in \mathfrak{R}^{n+1}$, then $\mathbf{x} = (x_1, x_2, \dots, x_n)^T \in \mathfrak{R}^n$ and $x_h = x_{n+1} \in \mathfrak{R}$.

In this paper we shall study optimization of a generic inhomogeneous polynomial $p(\mathbf{x})$, under three types of constraint sets: **(B)** The Euclidean ball: $\{\mathbf{x} \in \mathfrak{R}^n : \|\mathbf{x}\| \leq 1\}$; **(Q)** The intersection of co-centered ellipsoids: $\{\mathbf{x} \in \mathfrak{R}^n : \mathbf{x}^T \mathbf{Q}_i \mathbf{x} \leq 1, i = 1, 2, \dots, m\}$; **(G)** a general compact set $S \subseteq \mathfrak{R}^n$.

The models and results for type **(B)** are presented in Section 3; the models and results for type **(Q)** are presented in Section 4. Applying the above results, models and results for type **(G)** are presented in Section 5. Since all these models are NP-hard in general, we shall propose polynomial-time approximation algorithms and derive worst-case performance ratios.

Throughout this paper, for any maximization model (P) defined as $\max_{\mathbf{x} \in S} f(\mathbf{x})$, we use $v_{\max}(P)$ to denote its optimal value, and $v_{\min}(P)$ to denote the optimal value of its minimization counterpart, i.e., $v_{\max}(P) := \max_{\mathbf{x} \in S} f(\mathbf{x})$ and $v_{\min}(P) := \min_{\mathbf{x} \in S} f(\mathbf{x})$.

Definition 2.1 A maximization problem (P) admits a polynomial-time approximation algorithm with approximation ratio $\tau \in (0, 1]$, if $v_{\max}(P) \geq 0$ and a feasible solution $\mathbf{y} \in S$ can be found in polynomial-time such that $f(\mathbf{y}) \geq \tau v_{\max}(P)$.

Definition 2.2 A maximization problem (P) admits a polynomial-time approximation algorithm with relative approximation ratio $\tau \in (0, 1]$, if a feasible solution $\mathbf{y} \in S$ can be found in polynomial-time such that $f(\mathbf{y}) - v_{\min}(P) \geq \tau (v_{\max}(P) - v_{\min}(P))$.

Regarding the relative approximation ratio in Definition 2.2, in some cases it is convenient to use the equivalent form: $v_{\max}(P) - f(\mathbf{y}) \leq (1 - \tau) (v_{\max}(P) - v_{\min}(P))$. Since this paper is mostly concerned with the relative approximation ratios, we may without loss of generality assume that the inhomogeneous polynomial function $p(\mathbf{x})$ has no constant term, i.e., $f_0 = 0$ in (1). The degree of the objective polynomial function $p(\mathbf{x})$, d , is deemed a fixed parameter in our subsequent discussions.

3 Polynomial Optimization with the Euclidean Ball Constraint

Our first model under consideration is to maximize a generic multivariate polynomial function subject to the Euclidean ball constraint, i.e.

$$(B) \quad \begin{aligned} \max \quad & p(\mathbf{x}) \\ \text{s.t.} \quad & \|\mathbf{x}\| \leq 1, \mathbf{x} \in \mathfrak{R}^n. \end{aligned}$$

Since we assume $p(\mathbf{x})$ to have no constant term, the optimal value of this problem is obviously nonnegative, i.e. $v_{\max}(B) \geq 0$.

The complexity to solve Problem (B) can be summarized by the following proposition.

Proposition 3.1 *If $d \leq 2$, then Problem (B) can be solved in polynomial-time; if $d \geq 3$, then Problem (B) is NP-hard; if $d \geq 4$, then there is no polynomial-time approximation algorithm with a positive approximation ratio unless $P = NP$.*

Proof. For $d \leq 2$, Problem (B) is a standard trust region subproblem. As such it is well known to be solvable in polynomial-time (cf. [44, 41, 40] and the references therein). For $d = 3$, in a special case when $p(\mathbf{x})$ is a homogeneous polynomial function, it is easy to see that Problem (B) is equivalent to $\max_{\|\mathbf{x}\|=1} p(\mathbf{x})$, which is shown to be NP-hard by Nesterov [28].

Consider now $d \geq 4$. As a subclass of Problem (B), we may let $p(\mathbf{x})$ be a 4th order homogeneous polynomial function, i.e., $p(\mathbf{x}) = F(\mathbf{x}, \mathbf{x}, \mathbf{x}, \mathbf{x})$, where \mathbf{F} is a super-symmetric 4th order tensor. We call $F(\mathbf{x}, \mathbf{x}, \mathbf{x}, \mathbf{x})$ to be positive semidefinite if $F(\mathbf{x}, \mathbf{x}, \mathbf{x}, \mathbf{x}) \geq 0$ for all $\mathbf{x} \in \mathfrak{R}^n$. It is well known that checking the positive semidefiniteness of $F(\mathbf{x}, \mathbf{x}, \mathbf{x}, \mathbf{x})$ is co-NP-complete (cf. [22]). If we are able to find a polynomial-time approximation algorithm to get a positive approximation ratio τ

for $-F(\mathbf{x}, \mathbf{x}, \mathbf{x}, \mathbf{x})$, then this algorithm can be used to check the positive semidefiniteness of tensor \mathbf{F} . To see why, suppose this algorithm returns a feasible solution \mathbf{y} with $-F(\mathbf{y}, \mathbf{y}, \mathbf{y}, \mathbf{y}) > 0$, then $F(\mathbf{x}, \mathbf{x}, \mathbf{x}, \mathbf{x})$ is not positive semidefinite. Otherwise the algorithm must return a feasible solution \mathbf{y} with $0 \geq -F(\mathbf{y}, \mathbf{y}, \mathbf{y}, \mathbf{y}) \geq \tau v_{\max}(B)$, which implies $v_{\max}(B) = 0$; hence, $F(\mathbf{x}, \mathbf{x}, \mathbf{x}, \mathbf{x})$ is positive semidefinite in this case. Therefore, such algorithm cannot exist unless $P = NP$. \square

The negative result in Proposition 3.1 rules out any polynomial-time approximation algorithms with a positive approximation ratio for Problem (B). However a positive *relative* approximation ratio is still possible, which is the main target of this section. Below we shall first present a polynomial-time algorithm for approximately solving Problem (B), which admits a (relative) worst-case performance ratio. In fact, we shall present a general scheme aiming at solving the inhomogeneous polynomial optimization Problem (B). This scheme breaks down to the following four major steps:

- Step 1:* Introduce a proper (equivalent) model with a homogenous objective;
- Step 2:* Solve a relaxed model with the objective being a multilinear function;
- Step 3:* Adjust to get a solution based on the solution of the relaxed model;
- Step 4:* Assemble a solution for the original inhomogeneous model.

Some of these steps can be designed separately. The algorithm below can be considered as one realization of the general scheme for solving Problem (B), with each step being carried out by a specific procedure. We shall first present the specialized algorithm, and then in the remainder of the section, we shall elaborate on these four general steps, and prove that in combination they lead to a polynomial-time approximation algorithm with a quality-assured solution.

Algorithm 3.2

Input: an n -dimensional d -th degree polynomial function $p(\mathbf{x})$ with $p(\mathbf{0}) = 0$.

1. Rewrite $p(\mathbf{x}) = F(\underbrace{\bar{\mathbf{x}}, \bar{\mathbf{x}}, \dots, \bar{\mathbf{x}}}_d)$ when $x_h = 1$ as in (3), where \mathbf{F} is an $(n+1)$ -dimensional d -th order super-symmetric tensor.
2. Approximately solve the problem

$$\begin{aligned} \max \quad & F(\bar{\mathbf{x}}^1, \bar{\mathbf{x}}^2, \dots, \bar{\mathbf{x}}^d) \\ \text{s.t.} \quad & \|\bar{\mathbf{x}}^k\| = 1, k = 1, 2, \dots, d \end{aligned}$$

using Algorithm 1 of [9], and get an approximate solution $(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d)$.

3. Compute $(\bar{\mathbf{z}}^1, \bar{\mathbf{z}}^2, \dots, \bar{\mathbf{z}}^d) = \operatorname{argmax} \left\{ F \left((\beta_1 \mathbf{y}_1^{1/d}), (\beta_2 \mathbf{y}_1^{2/d}), \dots, (\beta_d \mathbf{y}_1^{d/d}) \right), \beta \in \mathbb{B}^d \right\}$.

4. Compute $\mathbf{z} = \operatorname{argmax} \left\{ p(\mathbf{0}); p \left(\frac{\mathbf{z}(\beta)}{z_h(\beta)} \right), \beta \in \mathbb{B}^d \text{ and } \beta_1 = \prod_{k=2}^n \beta_k = 1 \right\}$, where

$$\bar{\mathbf{z}}(\beta) = \beta_1(d+1)\bar{\mathbf{z}}^1 + \sum_{k=2}^d \beta_k \bar{\mathbf{z}}^k.$$

Output: a feasible solution \mathbf{z} .

In Step 2 of Algorithm 3.2, an algorithm in [9] is called to approximately solve spherically constrained multilinear function optimization, which is actually a deterministic polynomial-time algorithm. In our analysis, the degree of $p(\mathbf{x})$ is deemed a fixed parameter, and thus Algorithm 3.2 runs in polynomial-time, and is deterministic too. Our main result in this section is the following:

Theorem 3.3 *Problem (B) admits a polynomial-time approximation algorithm (Algorithm 3.2) with relative approximation ratio τ_B , i.e., a feasible solution \mathbf{z} can be found in polynomial-time, such that*

$$p(\mathbf{z}) - v_{\min}(B) \geq \tau_B (v_{\max}(B) - v_{\min}(B)),$$

where $\tau_B := 2^{-\frac{5d}{2}}(d+1)!d^{-2d}(n+1)^{-\frac{d-2}{2}} = \Omega\left(n^{-\frac{d-2}{2}}\right)$.

Although homogenization is a natural way to deal with inhomogeneous polynomial functions, the worst-case performance ratio does not follow straightforwardly. What is lacking is that an inhomogeneous polynomial function does not allow one to scale the overall function value along a given direction, which is however an essential operation to prove the quality bound of the approximation algorithms (cf. [26, 21, 10, 22, 9]). Below we shall study in detail how a particular implementation of these four steps of the scheme (which becomes Algorithm 3.2) leads to the promised worst-case relative performance ratio. As we shall see later, our solution scheme can be applied to solve a very general polynomial optimization model (Section 5).

3.1 Homogenization

The method of homogenization depends on the form of the polynomial $p(\mathbf{x})$. If $p(\mathbf{x})$ is given as a summation of homogeneous polynomial functions of different degrees, i.e., $f_i(\mathbf{x})$ ($1 \leq i \leq d$) is a homogeneous polynomial function of degree i , then we may first write

$$f_i(\mathbf{x}) = F_i(\underbrace{\mathbf{x}, \mathbf{x}, \dots, \mathbf{x}}_i) \quad (2)$$

with F_i being an i -th order super-symmetric tensor. Then by introducing a homogenizing variable x_h , which is always equal to 1, we may rewrite $p(\mathbf{x})$ as

$$p(\mathbf{x}) = \sum_{i=1}^d F_i(\underbrace{\mathbf{x}, \mathbf{x}, \dots, \mathbf{x}}_i) x_h^{d-i} = F\left(\underbrace{\begin{pmatrix} \mathbf{x} \\ x_h \end{pmatrix}, \begin{pmatrix} \mathbf{x} \\ x_h \end{pmatrix}, \dots, \begin{pmatrix} \mathbf{x} \\ x_h \end{pmatrix}}_d\right) = F(\underbrace{\bar{\mathbf{x}}, \bar{\mathbf{x}}, \dots, \bar{\mathbf{x}}}_d) = f(\bar{\mathbf{x}}), \quad (3)$$

where F is an $(n+1)$ -dimensional d -th order super-symmetric tensor, whose last component is 0 (since $p(\mathbf{x})$ has no constant term).

If the polynomial $p(\mathbf{x})$ is given in terms of summation of monomials, we should first group them according to their degrees, and then rewrite the summation of monomials in each group as homogeneous polynomial function. After that, we then proceed according to (2) and (3) to obtain the tensor form F , as required.

Finally in this step, we may equivalently reformulate Problem (B) as

$$\begin{aligned} (\bar{B}) \quad & \max \quad f(\bar{\mathbf{x}}) \\ & \text{s.t.} \quad \bar{\mathbf{x}} = \begin{pmatrix} \mathbf{x} \\ x_h \end{pmatrix}, \\ & \quad \|\mathbf{x}\| \leq 1, \mathbf{x} \in \mathfrak{R}^n, \\ & \quad x_h = 1. \end{aligned}$$

Obviously, we have $v_{\max}(B) = v_{\max}(\bar{B})$ and $v_{\min}(B) = v_{\min}(\bar{B})$.

3.2 Multilinear relaxation

Multilinear relaxation refers to the approach that one relaxes the homogeneous polynomial function to the (separate) multilinear form. This relaxation proves to be effective (see e.g. [13, 9]). Now we relax Problem (\bar{B}) to an inhomogeneous multilinear function optimization problem as:

$$\begin{aligned} (T_B) \quad & \max \quad F(\bar{\mathbf{x}}^1, \bar{\mathbf{x}}^2, \dots, \bar{\mathbf{x}}^d) \\ & \text{s.t.} \quad \bar{\mathbf{x}}^k = \begin{pmatrix} \mathbf{x}^k \\ x_h^k \end{pmatrix}, k = 1, 2, \dots, d, \\ & \quad \|\mathbf{x}^k\| \leq 1, \mathbf{x}^k \in \mathfrak{R}^n, k = 1, 2, \dots, d, \\ & \quad x_h^k = 1, k = 1, 2, \dots, d. \end{aligned}$$

Obviously, we have $v_{\max}(T_B) \geq v_{\max}(\bar{B}) = v_{\max}(B)$. Before proceeding, let us first settle the computational complexity issue for solving Problem (T_B) .

Proposition 3.4 *Problem (T_B) is NP-hard whenever $d \geq 3$.*

Proof. Notice that the following problem

$$\begin{aligned} \max \quad & F(\mathbf{x}, \mathbf{y}, \mathbf{z}) \\ \text{s.t.} \quad & \|\mathbf{x}\| = \|\mathbf{y}\| = \|\mathbf{z}\| = 1, \\ & \mathbf{x}, \mathbf{y}, \mathbf{z} \in \mathfrak{R}^n \end{aligned}$$

is proven to be NP-hard by He, Li, and Zhang [9], and Zhang, Qi, and Ye [47]. When $d = 3$ and a special case where $\mathbf{F} = (F_{i,j,k})$ has the form $F_{n+1,j,k} = F_{i,n+1,k} = F_{i,j,n+1} = 0$ for all $1 \leq i, j, k \leq n+1$, Problem (T_B) is equivalent to the above model, and thus is NP-hard. \square

Problem (T_B) is still difficult to solve, and moreover it remains inhomogeneous, since x_h^k is required to be 1. To our best knowledge, no polynomial-time approximation algorithm is available in the literature to solve this problem. Furthermore, we shall relax the constraint $x_h^k = 1$, and introduce the following parameterized and homogenized problem:

$$\begin{aligned} (T_B(t)) \quad \max \quad & F(\bar{\mathbf{x}}^1, \bar{\mathbf{x}}^2, \dots, \bar{\mathbf{x}}^d) \\ \text{s.t.} \quad & \|\bar{\mathbf{x}}^k\| \leq t, \bar{\mathbf{x}}^k \in \mathfrak{R}^{n+1}, k = 1, 2, \dots, d. \end{aligned}$$

Obviously, Problem (T_B) can be relaxed to Problem $(T_B(\sqrt{2}))$, since if $\bar{\mathbf{x}}$ is feasible for Problem (T_B) then $\|\bar{\mathbf{x}}\|^2 = \|\mathbf{x}\|^2 + x_h^2 \leq 1 + 1 = 2$. Consequently, $v_{\max}(T_B(\sqrt{2})) \geq v_{\max}(T_B)$.

Both the objective and the constraints are now homogeneous, and it is easy to see for all $t > 0$, Problem $(T_B(t))$ is equivalent to each other by a simple scaling method. Moreover, Problem $(T_B(1))$ is equivalent to

$$\begin{aligned} \max \quad & F(\bar{\mathbf{x}}^1, \bar{\mathbf{x}}^2, \dots, \bar{\mathbf{x}}^d) \\ \text{s.t.} \quad & \|\bar{\mathbf{x}}^k\| = 1, \bar{\mathbf{x}}^k \in \mathfrak{R}^{n+1}, k = 1, 2, \dots, d, \end{aligned}$$

which was studied in [9, 39], with available approximation algorithms to cope with. Here we quote one corresponding result as follows:

Theorem 3.5 (He, Li, and Zhang [9]) *Suppose F is a d -th order multilinear function. The problem*

$$\begin{aligned} \max \quad & F(\mathbf{x}^1, \mathbf{x}^2, \dots, \mathbf{x}^d) \\ \text{s.t.} \quad & \|\mathbf{x}^k\| = 1, \mathbf{x}^k \in \mathfrak{R}^{n_k}, k = 1, 2, \dots, d \end{aligned}$$

admits a polynomial-time approximation algorithm with approximation ratio $1/\sqrt{n_1 n_2 \cdots n_{d-2}}$.

The intrinsic algorithm of Theorem 3.5 is described in Algorithm 1 of [9]. By applying this result, Problem $(T_B(1))$ admits a polynomial-time approximation algorithm with approximation ratio

$(n+1)^{-\frac{d-2}{2}}$. Therefore, for all $t > 0$, Problem $(T_B(t))$ also admits a polynomial-time approximation algorithm with approximation ratio $(n+1)^{-\frac{d-2}{2}}$, and $v_{\max}(T_B(t)) = t^d v_{\max}(T_B(1))$. After this relaxation step (Step 2 in Algorithm 3.2), we are able to find a feasible solution $(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d)$ of Problem $(T_B(1))$ in polynomial-time, such that

$$\begin{aligned} F(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d) &\geq (n+1)^{-\frac{d-2}{2}} v_{\max}(T_B(1)) \\ &= 2^{-\frac{d}{2}} (n+1)^{-\frac{d-2}{2}} v_{\max}(T_B(\sqrt{2})) \\ &\geq 2^{-\frac{d}{2}} (n+1)^{-\frac{d-2}{2}} v_{\max}(T_B). \end{aligned} \quad (4)$$

Theorem 3.5 (or specifically Algorithm 1 of [9]) is the engine enabling *Step 2* of our scheme. Problem $(T_B(1))$ itself is an independent and very interesting topic; for details, one is referred to [9, 39]. In fact, any polynomial-time approximation algorithm of Problem $(T_B(1))$ can be used as an engine to yield a realization (algorithm) of our scheme. As will become evident later, any improvement of the approximation ratio of Problem $(T_B(1))$ leads to the improvement of relative approximation ratio in Theorem 3.3. For example, recently So [39] improved the approximation bound of Problem $(T_B(1))$ to $\Omega\left(\left(\frac{\log n}{n}\right)^{-\frac{d-2}{2}}\right)$ (though the algorithm is largely only of a theoretical interest). Consequently, the relative approximation ratio under our scheme is improved to $\Omega\left(\left(\frac{\log n}{n}\right)^{-\frac{d-2}{2}}\right)$ too. Of course, one may apply any other favorite algorithm to solve the relaxation Problem $(T_B(1))$. For instance, the *alternating least square* method (see [15]) can be another alternative for Step 2.

3.3 Adjustment of the homogenizing component

The approximate solution $(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d)$ of Problem $(T_B(1))$ satisfies $\|\bar{\mathbf{y}}^k\| \leq 1$ for all $1 \leq k \leq d$, which implies $\|\mathbf{y}^k\| \leq 1$, but in general we do not have any control on the size of y_h^k , and thus $(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d)$ may not be a feasible solution for Problem (T_B) . The following lemma plays the role of a bridge in our analysis, to ensure that the construction of a feasible solution to the inhomogeneous Problem (T_B) is possible.

Lemma 3.6 *Suppose $\bar{\mathbf{x}}^k \in \mathbb{R}^{n+1}$ with $|x_h^k| \leq 1$ for all $1 \leq k \leq d$. Let $\eta_1, \eta_2, \dots, \eta_d$ be independent random variables, each takes values 1 and -1 with $\mathbb{E}[\eta_k] = x_h^k$ for all $1 \leq k \leq d$, and let $\xi_1, \xi_2, \dots, \xi_d$ be the i.i.d. random variables, taking values 1 and -1 with equal probability (thus the mean is 0). If the last component of the tensor \mathbf{F} is 0, then we have*

$$\mathbb{E} \left[\prod_{k=1}^d \eta_k F \left(\begin{pmatrix} \eta_1 \mathbf{x}^1 \\ 1 \end{pmatrix}, \begin{pmatrix} \eta_2 \mathbf{x}^2 \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} \eta_d \mathbf{x}^d \\ 1 \end{pmatrix} \right) \right] = F(\bar{\mathbf{x}}^1, \bar{\mathbf{x}}^2, \dots, \bar{\mathbf{x}}^d), \quad (5)$$

and

$$\mathbb{E} \left[F \left(\begin{pmatrix} \xi_1 \mathbf{x}^1 \\ 1 \end{pmatrix}, \begin{pmatrix} \xi_2 \mathbf{x}^2 \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} \xi_d \mathbf{x}^d \\ 1 \end{pmatrix} \right) \right] = 0. \quad (6)$$

Proof. The claimed equations readily result from the following observations

$$\begin{aligned}
& \mathbb{E} \left[\prod_{k=1}^d \eta_k F \left(\begin{pmatrix} (\eta_1 \mathbf{x}^1) \\ 1 \end{pmatrix}, \begin{pmatrix} (\eta_2 \mathbf{x}^2) \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} (\eta_d \mathbf{x}^d) \\ 1 \end{pmatrix} \right) \right] \\
\stackrel{\text{(multilinearity of } F)}{=} & \mathbb{E} \left[F \left(\begin{pmatrix} ((\eta_1)^2 \mathbf{x}^1) \\ \eta_1 \end{pmatrix}, \begin{pmatrix} ((\eta_2)^2 \mathbf{x}^2) \\ \eta_2 \end{pmatrix}, \dots, \begin{pmatrix} ((\eta_d)^2 \mathbf{x}^d) \\ \eta_d \end{pmatrix} \right) \right] \\
\stackrel{\text{(independence of } \eta_k \text{'s)}}{=} & F \left(\mathbb{E} \left[\begin{pmatrix} \mathbf{x}^1 \\ \eta_1 \end{pmatrix} \right], \mathbb{E} \left[\begin{pmatrix} \mathbf{x}^2 \\ \eta_2 \end{pmatrix} \right], \dots, \mathbb{E} \left[\begin{pmatrix} \mathbf{x}^d \\ \eta_d \end{pmatrix} \right] \right) \\
= & F(\bar{\mathbf{x}}^1, \bar{\mathbf{x}}^2, \dots, \bar{\mathbf{x}}^d),
\end{aligned}$$

and

$$\begin{aligned}
& \mathbb{E} \left[F \left(\begin{pmatrix} (\xi_1 \mathbf{x}^1) \\ 1 \end{pmatrix}, \begin{pmatrix} (\xi_2 \mathbf{x}^2) \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} (\xi_d \mathbf{x}^d) \\ 1 \end{pmatrix} \right) \right] \\
\stackrel{\text{(independence of } \xi_k \text{'s)}}{=} & F \left(\mathbb{E} \left[\begin{pmatrix} \xi_1 \mathbf{x}^1 \\ 1 \end{pmatrix} \right], \mathbb{E} \left[\begin{pmatrix} \xi_2 \mathbf{x}^2 \\ 1 \end{pmatrix} \right], \dots, \mathbb{E} \left[\begin{pmatrix} \xi_d \mathbf{x}^d \\ 1 \end{pmatrix} \right] \right) \\
\stackrel{\text{(zero-mean of } \xi_k \text{'s)}}{=} & F \left(\begin{pmatrix} \mathbf{0} \\ 1 \end{pmatrix}, \begin{pmatrix} \mathbf{0} \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} \mathbf{0} \\ 1 \end{pmatrix} \right) \\
= & 0,
\end{aligned}$$

where the last equality is due to the fact that the last component of \mathbf{F} is 0. \square

Lemma 3.6 suggests that one may enumerate the 2^d possible combinations of $(\xi_1 \mathbf{y}^1), (\xi_2 \mathbf{y}^2), \dots, (\xi_d \mathbf{y}^d)$ and pick the one with the largest value of function F (or via a simple randomization procedure), to generate a feasible solution for the inhomogeneous multilinear function optimization Problem (T_B) from a feasible solution of the homogeneous multilinear function optimization Problem $(T_B(1))$, with a controlled quality deterioration. It plays a key role in proving the approximation ratio for Problem (T_B) , which is a by-product in this section.

Theorem 3.7 *Problem (T_B) admits a polynomial-time approximation algorithm with approximation ratio $\tau_1 := 2^{-\frac{3d}{2}}(n+1)^{-\frac{d-2}{2}}$.*

Proof. Let $(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d)$ be the feasible solution found in Step 2 of Algorithm 3.2 satisfying (4), and let $\boldsymbol{\eta} = (\eta_1, \eta_2, \dots, \eta_d)^T$ with all η_k 's being independent and taking values 1 and -1 such that $\mathbb{E}[\eta_k] = y_h^k$. By applying Lemma 3.6, (5) explicitly implies

$$\begin{aligned}
F(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d) &= \sum_{\boldsymbol{\beta} \in \mathbb{B}^d, \prod_{k=1}^d \beta_k = 1} \text{Prob} \{ \boldsymbol{\eta} = \boldsymbol{\beta} \} F \left(\begin{pmatrix} (\beta_1 \mathbf{y}^1) \\ 1 \end{pmatrix}, \begin{pmatrix} (\beta_2 \mathbf{y}^2) \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} (\beta_d \mathbf{y}^d) \\ 1 \end{pmatrix} \right) \\
&\quad - \sum_{\boldsymbol{\beta} \in \mathbb{B}^d, \prod_{k=1}^d \beta_k = -1} \text{Prob} \{ \boldsymbol{\eta} = \boldsymbol{\beta} \} F \left(\begin{pmatrix} (\beta_1 \mathbf{y}^1) \\ 1 \end{pmatrix}, \begin{pmatrix} (\beta_2 \mathbf{y}^2) \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} (\beta_d \mathbf{y}^d) \\ 1 \end{pmatrix} \right),
\end{aligned}$$

and (6) explicitly implies

$$\sum_{\boldsymbol{\beta} \in \mathbb{B}^d} F\left(\begin{pmatrix} \beta_1 \mathbf{y}^1 \\ 1 \end{pmatrix}, \begin{pmatrix} \beta_2 \mathbf{y}^2 \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} \beta_d \mathbf{y}^d \\ 1 \end{pmatrix}\right) = 0.$$

For any constant c , combing the above two equalities we have

$$\begin{aligned} F(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d) &= \sum_{\boldsymbol{\beta} \in \mathbb{B}^d, \prod_{k=1}^d \beta_k = -1} (c - \text{Prob}\{\boldsymbol{\eta} = \boldsymbol{\beta}\}) F\left(\begin{pmatrix} \beta_1 \mathbf{y}^1 \\ 1 \end{pmatrix}, \begin{pmatrix} \beta_2 \mathbf{y}^2 \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} \beta_d \mathbf{y}^d \\ 1 \end{pmatrix}\right) \\ &+ \sum_{\boldsymbol{\beta} \in \mathbb{B}^d, \prod_{k=1}^d \beta_k = 1} (c + \text{Prob}\{\boldsymbol{\eta} = \boldsymbol{\beta}\}) F\left(\begin{pmatrix} \beta_1 \mathbf{y}^1 \\ 1 \end{pmatrix}, \begin{pmatrix} \beta_2 \mathbf{y}^2 \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} \beta_d \mathbf{y}^d \\ 1 \end{pmatrix}\right). \end{aligned} \quad (7)$$

If we let

$$c = \max_{\boldsymbol{\beta} \in \mathbb{B}^d, \prod_{k=1}^d \beta_k = -1} \text{Prob}\{\boldsymbol{\eta} = \boldsymbol{\beta}\},$$

then the coefficients of each term in (7) will be nonnegative. Therefore we shall be able to find $\tilde{\boldsymbol{\beta}} \in \mathbb{B}^d$ (by enumerating the 2^d possible combinations if necessary, or by randomization), such that

$$F\left(\begin{pmatrix} \tilde{\beta}_1 \mathbf{y}^1 \\ 1 \end{pmatrix}, \begin{pmatrix} \tilde{\beta}_2 \mathbf{y}^2 \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} \tilde{\beta}_d \mathbf{y}^d \\ 1 \end{pmatrix}\right) \geq \tau_0 F(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d), \quad (8)$$

where

$$\begin{aligned} \tau_0 &:= \left(\sum_{\boldsymbol{\beta} \in \mathbb{B}^d, \prod_{k=1}^d \beta_k = 1} (c + \text{Prob}\{\boldsymbol{\eta} = \boldsymbol{\beta}\}) + \sum_{\boldsymbol{\beta} \in \mathbb{B}^d, \prod_{k=1}^d \beta_k = -1} (c - \text{Prob}\{\boldsymbol{\eta} = \boldsymbol{\beta}\}) \right)^{-1} \\ &\geq \left(2^{d-1} c + \sum_{\boldsymbol{\beta} \in \mathbb{B}^d, \prod_{k=1}^d \beta_k = 1} \text{Prob}\{\boldsymbol{\eta} = \boldsymbol{\beta}\} + (2^{d-1} - 1)c \right)^{-1} \\ &\geq \left(2^{d-1} + 1 + 2^{d-1} - 1 \right)^{-1} = 2^{-d}. \end{aligned}$$

Let us denote $\bar{\mathbf{z}}^k := \begin{pmatrix} \tilde{\beta}_k \mathbf{y}^k \\ 1 \end{pmatrix}$ for $k = 1, 2, \dots, d$. As $\|\mathbf{z}^k\| = \|\tilde{\beta}_k \mathbf{y}^k\| \leq 1$, we know that $(\bar{\mathbf{z}}^1, \bar{\mathbf{z}}^2, \dots, \bar{\mathbf{z}}^d)$ is a feasible solution for Problem (T_B) , and

$$F(\bar{\mathbf{z}}^1, \bar{\mathbf{z}}^2, \dots, \bar{\mathbf{z}}^d) \geq \tau_0 F(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d) \geq 2^{-d} 2^{-\frac{d}{2}} (n+1)^{-\frac{d-2}{2}} v_{\max}(T_B) = 2^{-\frac{3d}{2}} (n+1)^{-\frac{d-2}{2}} v_{\max}(T_B). \quad \square$$

As one may have noticed that our proposed algorithm for solving Problem (T_B) is very similar to Steps 2 and 3 of Algorithm 3.2, with only some minor modification at Step 3, namely we choose a solution in the set $\text{argmax}\left\{F\left(\begin{pmatrix} \beta_1 \mathbf{y}^1 \\ 1 \end{pmatrix}, \begin{pmatrix} \beta_2 \mathbf{y}^2 \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} \beta_d \mathbf{y}^d \\ 1 \end{pmatrix}\right), \boldsymbol{\beta} \in \mathbb{B}^d\right\}$, instead of choosing a solution in the set $\text{argmax}\left\{F\left(\begin{pmatrix} \beta_1 \mathbf{y}^1/d \\ 1 \end{pmatrix}, \begin{pmatrix} \beta_2 \mathbf{y}^2/d \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} \beta_d \mathbf{y}^d/d \\ 1 \end{pmatrix}\right), \boldsymbol{\beta} \in \mathbb{B}^d\right\}$. The reason to divide d at Step 3

in Algorithm 3.2 (to solve Problem (B)) will become clear later. Finally, we remark again that it is unnecessary to enumerate all possible 2^d combinations in this step, as (7) suggests that a simple randomization process will serve the same purpose, especially when d is large. In the latter case, we will end up with a *polynomial-time randomized approximation algorithm*; otherwise, the computational complexity of the procedure is deterministic and is polynomial-time (for fixed d).

3.4 Returning a solution to the inhomogeneous model

Finally we are led to the last step of the scheme. Step 4 of Algorithm 3.2 suggests a polarization formula $\bar{\mathbf{z}}(\beta) = \beta_1(d+1)\bar{\mathbf{z}}^1 + \sum_{k=2}^d \beta_k \bar{\mathbf{z}}^k$ with $\beta \in \mathbb{B}^d$ and $\beta_1 = \prod_{k=2}^d \beta_k = 1$. In fact, searching over all $\beta \in \mathbb{B}^d$ will possibly improve the solution, although the worst-case performance ratio will remain the same. Moreover, one may choose $\bar{\mathbf{z}}^1$ or any other $\bar{\mathbf{z}}^k$ to play the same role here; alternatively one may enumerate $\beta_\ell(d+1)\bar{\mathbf{z}}^\ell + \sum_{1 \leq k \leq d, k \neq \ell} \beta_k \bar{\mathbf{z}}^k$ over all $\beta \in \mathbb{B}^d$ and $1 \leq \ell \leq d$ and take the best possible solution; again, this will not change the theoretical performance ratio. The polarization formula at Step 4 of Algorithm 3.2 works for all d , and we shall complete the final stage of the proof of Theorem 3.3. That is, we shall prove that by letting $\mathbf{z} = \operatorname{argmax} \left\{ p(\mathbf{0}); p\left(\frac{\mathbf{z}(\beta)}{z_h(\beta)}\right), \beta \in \mathbb{B}^d \text{ and } \beta_1 = \prod_{k=2}^d \beta_k = 1 \right\}$ with $\bar{\mathbf{z}}(\beta) := \beta_1(d+1)\bar{\mathbf{z}}^1 + \sum_{k=2}^d \beta_k \bar{\mathbf{z}}^k$, we have

$$p(\mathbf{z}) - v_{\min}(B) \geq \tau_B (v_{\max}(B) - v_{\min}(B)). \quad (9)$$

First, the solution $(\bar{\mathbf{z}}^1, \bar{\mathbf{z}}^2, \dots, \bar{\mathbf{z}}^d)$ as established at Step 3 satisfies $\|\mathbf{z}^k\| \leq 1/d$ (recall that we divided d in each term at Step 3), and $z_h^k = 1$ for all $1 \leq k \leq d$, and

$$F(\bar{\mathbf{z}}^1, \bar{\mathbf{z}}^2, \dots, \bar{\mathbf{z}}^d) \geq d^{-d} 2^{-\frac{3d}{2}} (n+1)^{-\frac{d-2}{2}} v_{\max}(T_B) \geq 2^{-\frac{3d}{2}} d^{-d} (n+1)^{-\frac{d-2}{2}} v_{\max}(B). \quad (10)$$

It is easy to see that

$$2 \leq |z_h(\beta)| \leq 2d \text{ and } \|\mathbf{z}(\beta)\| \leq (d+1)/d + (d-1)/d = 2. \quad (11)$$

Thus $\bar{\mathbf{z}}(\beta)/z_h(\beta)$ is a feasible solution of Problem (\bar{B}) , and so $f(\bar{\mathbf{z}}(\beta)/z_h(\beta)) \geq v_{\min}(\bar{B}) = v_{\min}(B)$. Moreover, we shall argue below that

$$\beta_1 = 1 \implies f(\bar{\mathbf{z}}(\beta)) \geq (2d)^d v_{\min}(B). \quad (12)$$

If this were not the case, then $f(\bar{\mathbf{z}}(\beta)/(2d)) < v_{\min}(B) \leq 0$. Notice that $\beta_1 = 1$ implies $z_h(\beta) > 0$, and so we would have

$$f\left(\frac{\bar{\mathbf{z}}(\beta)}{z_h(\beta)}\right) = \left(\frac{2d}{z_h(\beta)}\right)^d f\left(\frac{\bar{\mathbf{z}}(\beta)}{2d}\right) \leq f\left(\frac{\bar{\mathbf{z}}(\beta)}{2d}\right) < v_{\min}(B),$$

which contradicts the feasibility of $\bar{\mathbf{z}}(\beta)/z_h(\beta)$.

Suppose $\xi_1, \xi_2, \dots, \xi_d$ are i.i.d. random variables, each taking values 1 and -1 with equal probability. By Lemma 1 of [9], noticing $f(\bar{\mathbf{z}}(-\xi)) = f(-\bar{\mathbf{z}}(\xi)) = (-1)^d f(\bar{\mathbf{z}}(\xi))$, we have

$$\begin{aligned}
d!F\left((d+1)\bar{z}^1, \bar{z}^2, \dots, \bar{z}^d\right) &= \mathbb{E}\left[\prod_{i=1}^d \xi_i f(\bar{\mathbf{z}}(\xi))\right] \\
&= \frac{1}{4} \mathbb{E}\left[f(\bar{\mathbf{z}}(\xi)) \mid \xi_1 = 1, \prod_{i=2}^d \xi_i = 1\right] - \frac{1}{4} \mathbb{E}\left[f(\bar{\mathbf{z}}(\xi)) \mid \xi_1 = 1, \prod_{i=2}^d \xi_i = -1\right] \\
&\quad - \frac{1}{4} \mathbb{E}\left[f(\bar{\mathbf{z}}(\xi)) \mid \xi_1 = -1, \prod_{i=2}^d \xi_i = 1\right] + \frac{1}{4} \mathbb{E}\left[f(\bar{\mathbf{z}}(\xi)) \mid \xi_1 = -1, \prod_{i=2}^d \xi_i = -1\right] \\
&= \frac{1}{4} \mathbb{E}\left[f(\bar{\mathbf{z}}(\xi)) \mid \xi_1 = 1, \prod_{i=2}^d \xi_i = 1\right] - \frac{1}{4} \mathbb{E}\left[f(\bar{\mathbf{z}}(\xi)) \mid \xi_1 = 1, \prod_{i=2}^d \xi_i = -1\right] \\
&\quad - \frac{1}{4} \mathbb{E}\left[f(\bar{\mathbf{z}}(-\xi)) \mid \xi_1 = 1, \prod_{i=2}^d \xi_i = (-1)^{d-1}\right] + \frac{1}{4} \mathbb{E}\left[f(\bar{\mathbf{z}}(-\xi)) \mid \xi_1 = 1, \prod_{i=2}^d \xi_i = (-1)^d\right].
\end{aligned}$$

By inserting and canceling a constant term, the above expression further leads to

$$\begin{aligned}
d!F\left((d+1)\bar{z}^1, \bar{z}^2, \dots, \bar{z}^d\right) &= \mathbb{E}\left[\prod_{i=1}^d \xi_i f(\bar{\mathbf{z}}(\xi))\right] \\
&= \frac{1}{4} \mathbb{E}\left[\left(f(\bar{\mathbf{z}}(\xi)) - (2d)^d v_{\min}(B)\right) \mid \xi_1 = 1, \prod_{i=2}^d \xi_i = 1\right] \\
&\quad - \frac{1}{4} \mathbb{E}\left[\left(f(\bar{\mathbf{z}}(\xi)) - (2d)^d v_{\min}(B)\right) \mid \xi_1 = 1, \prod_{i=2}^d \xi_i = -1\right] \\
&\quad + \frac{(-1)^{d-1}}{4} \mathbb{E}\left[\left(f(\bar{\mathbf{z}}(\xi)) - (2d)^d v_{\min}(B)\right) \mid \xi_1 = 1, \prod_{i=2}^d \xi_i = (-1)^{d-1}\right] \\
&\quad + \frac{(-1)^d}{4} \mathbb{E}\left[\left(f(\bar{\mathbf{z}}(\xi)) - (2d)^d v_{\min}(B)\right) \mid \xi_1 = 1, \prod_{i=2}^d \xi_i = (-1)^d\right] \\
&\leq \frac{1}{2} \mathbb{E}\left[\left(f(\bar{\mathbf{z}}(\xi)) - (2d)^d v_{\min}(B)\right) \mid \xi_1 = 1, \prod_{i=2}^d \xi_i = 1\right],
\end{aligned}$$

where the last inequality is due to (12). Therefore, there is a binary vector $\tilde{\beta} \in \mathbb{B}^d$ with $\tilde{\beta}_1 = \prod_{i=2}^d \tilde{\beta}_i = 1$, such that

$$f(\bar{\mathbf{z}}(\tilde{\beta})) - (2d)^d v_{\min}(B) \geq 2d!F((d+1)\bar{z}^1, \bar{z}^2, \dots, \bar{z}^d) \geq 2^{-\frac{3d}{2}+1} (d+1)! d^{-d} (n+1)^{-\frac{d-2}{2}} v_{\max}(B),$$

where the last step is due to (10).

Below we shall argue $\mathbf{z} = \operatorname{argmax}\left\{p(\mathbf{0}); p\left(\frac{\mathbf{z}(\tilde{\beta})}{z_h(\tilde{\beta})}\right), \beta \in \mathbb{B}^d \text{ and } \beta_1 = \prod_{k=2}^n \beta_k = 1\right\}$ satisfies (9). Indeed, if $-v_{\min}(B) \geq \tau_B (v_{\max}(B) - v_{\min}(B))$, then $\mathbf{0}$ trivially satisfies (9), and so does \mathbf{z} in this case. Otherwise, if $-v_{\min}(B) < \tau_B (v_{\max}(B) - v_{\min}(B))$, then we have

$$v_{\max}(B) > (1 - \tau_B) (v_{\max}(B) - v_{\min}(B)) \geq \frac{v_{\max}(B) - v_{\min}(B)}{2},$$

which implies

$$f\left(\frac{\bar{\mathbf{z}}(\tilde{\beta})}{2d}\right) - v_{\min}(B) \geq (2d)^{-d} 2^{-\frac{3d}{2}+1} (d+1)! d^{-d} (n+1)^{-\frac{d-2}{2}} v_{\max}(B) \geq \tau_B (v_{\max}(B) - v_{\min}(B)).$$

The above inequality also implies that $f\left(\frac{\bar{\mathbf{z}}(\tilde{\beta})}{2d}\right) > 0$. Recall that $\tilde{\beta}_1 = 1$ implies $z_h(\tilde{\beta}) > 0$, and thus $2d/z_h(\tilde{\beta}) \geq 1$ by (11). Therefore, we have

$$p(\mathbf{z}) \geq p\left(\frac{\mathbf{z}(\tilde{\beta})}{z_h(\tilde{\beta})}\right) = f\left(\frac{\bar{\mathbf{z}}(\tilde{\beta})}{z_h(\tilde{\beta})}\right) = \left(\frac{2d}{z_h(\tilde{\beta})}\right)^d f\left(\frac{\bar{\mathbf{z}}(\tilde{\beta})}{2d}\right) \geq f\left(\frac{\bar{\mathbf{z}}(\tilde{\beta})}{2d}\right).$$

This shows that the solution \mathbf{z} satisfies (9) in both cases. Putting all the pieces together, Theorem 3.3 is proven by construction.

4 Polynomial Optimization with Convex Quadratic Constraints

In this section, we consider an extension of Problem (B), namely

$$\begin{aligned} (Q) \quad & \max \quad p(\mathbf{x}) \\ & \text{s.t.} \quad \mathbf{x}^\top \mathbf{Q}_i \mathbf{x} \leq 1, \quad i = 1, 2, \dots, m, \\ & \quad \mathbf{x} \in \mathbb{R}^n, \end{aligned}$$

where $\mathbf{Q}_i \succeq 0$ for all $1 \leq i \leq m$, and $\sum_{i=1}^m \mathbf{Q}_i \succ 0$. By assuming that there is no constant term in the polynomial function $p(\mathbf{x})$, we know that $v_{\min}(Q) \leq 0 \leq v_{\max}(Q)$. Like in the previous section, we shall provide a polynomial-time randomized algorithm for approximately solving Problem (Q), with a worst-case relative performance ratio.

Algorithm 4.1

Input: an n -dimensional d -th degree polynomial function $p(\mathbf{x})$ with $p(\mathbf{0}) = 0$, matrices $\mathbf{Q}_i \succeq 0$ for $i = 1, 2, \dots, m$ with $\sum_{i=1}^m \mathbf{Q}_i \succ 0$.

1. Rewrite $p(\mathbf{x}) = F(\underbrace{\bar{\mathbf{x}}, \bar{\mathbf{x}}, \dots, \bar{\mathbf{x}}}_d)$ when $x_h = 1$ as in (3), where F is an $(n+1)$ -dimensional d -th order super-symmetric tensor.
2. Approximately solve the problem

$$\begin{aligned} & \max F(\bar{\mathbf{x}}^1, \bar{\mathbf{x}}^2, \dots, \bar{\mathbf{x}}^d) \\ \text{s.t.} \quad & (\bar{\mathbf{x}}^k)^\top \begin{bmatrix} \mathbf{Q}_i & \mathbf{0} \\ \mathbf{0}^\top & 1 \end{bmatrix} \bar{\mathbf{x}}^k \leq 1, \quad k = 1, 2, \dots, d, \quad i = 1, 2, \dots, m \end{aligned}$$

using Algorithm 3 of [9], and get an approximate solution $(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d)$.

3. Compute $(\bar{\mathbf{z}}^1, \bar{\mathbf{z}}^2, \dots, \bar{\mathbf{z}}^d) = \operatorname{argmax} \left\{ F\left(\left(\beta_1 \mathbf{y}_1^{1/d}\right), \left(\beta_2 \mathbf{y}_1^{2/d}\right), \dots, \left(\beta_d \mathbf{y}_1^{d/d}\right)\right), \beta \in \mathbb{B}^d \right\}$.
4. Compute $\mathbf{z} = \operatorname{argmax} \left\{ p(\mathbf{0}); p\left(\frac{\mathbf{z}(\beta)}{z_h(\beta)}\right), \beta \in \mathbb{B}^d \text{ and } \beta_1 = \prod_{k=2}^d \beta_k = 1 \right\}$, where

$$\bar{\mathbf{z}}(\beta) = \beta_1(d+1)\bar{\mathbf{z}}^1 + \sum_{k=2}^d \beta_k \bar{\mathbf{z}}^k.$$

Output: a feasible solution \mathbf{z} .

Theorem 4.2 Problem (Q) admits a polynomial-time randomized approximation algorithm (Algorithm 4.1) with relative approximation ratio τ_Q , i.e., a feasible solution \mathbf{z} can be found in polynomial-time with high probability, such that

$$p(\mathbf{z}) - v_{\min}(Q) \geq \tau_Q (v_{\max}(Q) - v_{\min}(Q)),$$

where $\tau_Q := \Omega\left(n^{-\frac{d-2}{2}} (\log m)^{-(d-1)}\right)$.

Our scheme for solving general Problem (Q) is similar to that for Problem (B) in the previous section. The main difference lies in Step 2, where a different relaxation model requires a different solution method to cope with. The method in question is Algorithm 3 of [9].

Theorem 4.3 (He, Li, and Zhang [9]) Suppose F is a d -th order multilinear function, matrices $\mathbf{Q}_{i_k}^k \succeq 0$ and $\sum_{i_k=1}^{m_k} \mathbf{Q}_{i_k}^k \succ 0$ for all $1 \leq k \leq d, 1 \leq i_k \leq m_k$. The problem

$$\begin{aligned} & \max F(\mathbf{x}^1, \mathbf{x}^2, \dots, \mathbf{x}^d) \\ \text{s.t.} \quad & (\mathbf{x}^k)^\top \mathbf{Q}_{i_k}^k \mathbf{x}^k \leq 1, \quad k = 1, 2, \dots, d, \quad i_k = 1, 2, \dots, m_k, \\ & \mathbf{x}^k \in \mathfrak{R}^{n_k}, \quad k = 1, 2, \dots, d \end{aligned}$$

admits a polynomial-time randomized approximation algorithm with approximation ratio $\Omega\left(\left(\sqrt{n_1 n_2 \cdots n_{d-2}} (\log m)^{-(d-1)}\right)^{-1}\right)$, where $m = \max_{1 \leq k \leq d} \{m_k\}$.

The proof of Theorem 4.2 is similar to that of Theorem 3.3. Here we shall only illustrate the main ideas and skip the details. By homogenizing $p(\mathbf{x})$, we may rewrite Problem (Q) as

$$\begin{aligned} (\bar{Q}) \quad & \max f(\bar{\mathbf{x}}) \\ \text{s.t.} \quad & \bar{\mathbf{x}} = \begin{pmatrix} \mathbf{x} \\ x_h \end{pmatrix}, \\ & \mathbf{x}^\top \mathbf{Q}_i \mathbf{x} \leq 1, \mathbf{x} \in \mathfrak{R}^n, i = 1, 2, \dots, m, \\ & x_h = 1, \end{aligned}$$

which can be relaxed to the inhomogeneous multilinear function problem

$$\begin{aligned} (T_Q) \quad & \max F(\bar{\mathbf{x}}^1, \bar{\mathbf{x}}^2, \dots, \bar{\mathbf{x}}^d) \\ \text{s.t.} \quad & \bar{\mathbf{x}}^k = \begin{pmatrix} \mathbf{x}^k \\ x_h^k \end{pmatrix}, k = 1, 2, \dots, d, \\ & (\mathbf{x}^k)^\top \mathbf{Q}_i \mathbf{x}^k \leq 1, \mathbf{x}^k \in \mathfrak{R}^n, k = 1, 2, \dots, d, i = 1, 2, \dots, m, \\ & x_h^k = 1, k = 1, 2, \dots, d, \end{aligned}$$

where $F(\underbrace{\bar{\mathbf{x}}^1, \bar{\mathbf{x}}^2, \dots, \bar{\mathbf{x}}^d}_d) = f(\bar{\mathbf{x}})$ with \mathbf{F} being super-symmetric. We then further relax Problem (T_Q)

to the homogeneous multilinear function Problem (T_Q(√2)), with

$$\begin{aligned} (T_Q(t)) \quad & \max F(\bar{\mathbf{x}}^1, \bar{\mathbf{x}}^2, \dots, \bar{\mathbf{x}}^d) \\ & (\bar{\mathbf{x}}^k)^\top \hat{\mathbf{Q}}_i \bar{\mathbf{x}}^k \leq t^2, k = 1, 2, \dots, d, i = 1, 2, \dots, m, \\ & \bar{\mathbf{x}}^k \in \mathfrak{R}^{n+1}, k = 1, 2, \dots, d, \end{aligned}$$

where $\hat{\mathbf{Q}}_i = \begin{bmatrix} \mathbf{Q}_i & \mathbf{0} \\ \mathbf{0}^\top & 1 \end{bmatrix}$ for $i = 1, 2, \dots, m$.

By Theorem 4.3, for any $t > 0$, Problem (T_Q(t)) admits a polynomial-time randomized algorithm with approximation ratio τ_Q , and $v_{\max}(T_Q(t)) = t^d v_{\max}(T_Q(1))$. Thus the approximate solution $(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d)$ found by step 2 of Algorithm 4.1 satisfies

$$F(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d) \geq \tau_Q v_{\max}(T_Q(1)) = (\sqrt{2})^{-d} \tau_Q v_{\max}(T_Q(\sqrt{2})) \geq \tau_Q v_{\max}(T_Q).$$

By noticing that $(y_h^k)^2 \leq (\bar{\mathbf{y}}^k)^\top \hat{\mathbf{Q}}_1 \bar{\mathbf{y}}^k \leq 1$, we may again apply Lemma 3.6 to $(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d)$, and use the same argument as in the proof of Theorem 3.7.

Let $c = \max_{\beta \in \mathbb{B}^d, \prod_{k=1}^d \beta_k = -1} \text{Prob}\{\boldsymbol{\eta} = \beta\}$, where $\boldsymbol{\eta} = (\eta_1, \eta_2, \dots, \eta_d)^\top$ and its components are independent random variables, each takes values 1 and -1 with $\mathbb{E}[\eta_k] = y_h^k$ for $k = 1, 2, \dots, d$. Then we are able to find $\tilde{\beta} \in \mathbb{B}^d$, such that

$$F\left(\begin{pmatrix} \tilde{\beta}_1 \mathbf{y}^1 \\ 1 \end{pmatrix}, \begin{pmatrix} \tilde{\beta}_2 \mathbf{y}^2 \\ 1 \end{pmatrix}, \dots, \begin{pmatrix} \tilde{\beta}_d \mathbf{y}^d \\ 1 \end{pmatrix}\right) \geq \tau_0 F(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d) \geq 2^{-d} F(\bar{\mathbf{y}}^1, \bar{\mathbf{y}}^2, \dots, \bar{\mathbf{y}}^d) \geq \tau_Q v_{\max}(T_Q).$$

This proves the following theorem as a byproduct.

Theorem 4.4 *Problem (T_Q) admits a polynomial-time randomized approximation algorithm with approximation ratio τ_Q .*

To prove the main theorem in this section (Theorem 4.2), we only need to check the feasibility of \mathbf{z} generated by Algorithm 4.1, while the worst-case performance ratio can be proven by the similar argument in Section 3.4. Indeed, $(\bar{\mathbf{z}}^1, \bar{\mathbf{z}}^2, \dots, \bar{\mathbf{z}}^d)$ at Step 3 of Algorithm 4.1 satisfies

$$(\mathbf{z}^k)^\top \mathbf{Q}_i \mathbf{z}^k \leq 1/d^2, \quad \forall 1 \leq i \leq m, 1 \leq k \leq d.$$

For any binary vector $\beta \in \mathbb{B}^d$, as $\bar{\mathbf{z}}(\beta) = \beta_1(d+1)\bar{\mathbf{z}}^1 + \sum_{k=2}^d \beta_k \bar{\mathbf{z}}^k$, we have $2 \leq |z_h(\beta)| \leq 2d$. Noticing by Cauchy-Schwarz inequality,

$$|(\mathbf{z}^j)^\top \mathbf{Q}_i \mathbf{z}^k| \leq \|\mathbf{Q}_i^{1/2} \mathbf{z}^j\| \cdot \|\mathbf{Q}_i^{1/2} \mathbf{z}^k\| \leq 1/d^2, \quad \forall 1 \leq i \leq m, 1 \leq j, k \leq d,$$

it follows that

$$(\mathbf{z}(\beta))^\top \mathbf{Q}_i \mathbf{z}(\beta) \leq 2d \cdot 2d \cdot 1/d^2 = 4, \quad \forall 1 \leq i \leq m.$$

Thus $\mathbf{z}(\beta)/z_h(\beta)$ is a feasible solution to Problem (Q) , which implies \mathbf{z} is also feasible.

We remark here that Problem (Q) includes as a special case the optimization of a general polynomial function over a central-symmetric polytope:

$$\begin{aligned} \max \quad & p(\mathbf{x}) \\ \text{s.t.} \quad & -1 \leq (\mathbf{a}^i)^\top \mathbf{x} \leq 1, \quad i = 1, 2, \dots, m, \\ & \mathbf{x} \in \mathfrak{R}^n, \end{aligned}$$

with $\text{rank}(\mathbf{a}^1, \mathbf{a}^2, \dots, \mathbf{a}^m) = n$.

Before concluding this section, let us embark on a treatment for a special low degree case of Problem (Q) , where an *absolute* approximation ratio is possible instead of a mere *relative* one as stipulated in Theorem 4.2. In fact, for Problem (Q) , when $d = 2$, an $\Omega(1/\log m)$ -approximation ratio was easily derived from the homogenous relaxation problem by Nemirovski et al. [26]. The following result presents a very useful case when $d = 3$. However for $d \geq 4$, Proposition 3.1 has ruled out such approximation ratios, even for the case $m = 1$.

Theorem 4.5 *If $d = 3$ and the quadratic form in $p(\mathbf{x})$ is positive semidefinite, then Problem (Q) admits a polynomial-time randomized approximation algorithm with approximation ratio $\Omega\left(\frac{1}{\sqrt{n} \log^2 m}\right)$.*

Proof. Denote the cubic, quadratic and linear forms in $p(\mathbf{x})$ to be $f_3(\mathbf{x})$, $f_2(\mathbf{x})$ and $f_1(\mathbf{x})$ respectively, with $f_2(\mathbf{x})$ being positive semidefinite. By homogenization as (3), we have

$$p(\mathbf{x}) = f_3(\mathbf{x}) + f_2(\mathbf{x}) + f_1(\mathbf{x}) = F \left(\begin{pmatrix} \mathbf{x} \\ 1 \end{pmatrix}, \begin{pmatrix} \mathbf{x} \\ 1 \end{pmatrix}, \begin{pmatrix} \mathbf{x} \\ 1 \end{pmatrix} \right) = f \left(\begin{pmatrix} \mathbf{x} \\ 1 \end{pmatrix} \right),$$

where tensor $\mathbf{F} \in \mathbb{R}^{(n+1)^3}$ is super-symmetric and its last component is 0. As before, Problem (Q) can be relaxed to the multilinear form optimization Problem $(T_Q(\sqrt{2}))$ when $d = 3$. By Theorem 4.3, we may find a feasible solution $\left(\begin{pmatrix} \mathbf{y}^1 \\ y_h^1 \end{pmatrix}, \begin{pmatrix} \mathbf{y}^2 \\ y_h^2 \end{pmatrix}, \begin{pmatrix} \mathbf{y}^3 \\ y_h^3 \end{pmatrix}\right)$ of Problem $(T_Q(1/3))$ in polynomial-time, satisfying $(\mathbf{y}^k)^\top \mathbf{Q}_i \mathbf{y}^k \leq \frac{1}{9}$ and $|y_h^k| \leq \frac{1}{3}$ for $k = 1, 2, 3$ and $i = 1, 2, \dots, m$, such that

$$\begin{aligned} F\left(\begin{pmatrix} \mathbf{y}^1 \\ y_h^1 \end{pmatrix}, \begin{pmatrix} \mathbf{y}^2 \\ y_h^2 \end{pmatrix}, \begin{pmatrix} \mathbf{y}^3 \\ y_h^3 \end{pmatrix}\right) &\geq \Omega\left(\frac{1}{\sqrt{n} \log^2 m}\right) v(T_Q(1/3)) \\ &= \Omega\left(\frac{1}{\sqrt{n} \log^2 m}\right) \frac{v(T_Q(\sqrt{2}))}{54\sqrt{2}} \\ &\geq \Omega\left(\frac{1}{\sqrt{n} \log^2 m}\right) v(Q). \end{aligned}$$

Then by Lemma 3.6 and (8), we may adjust $\left(\begin{pmatrix} \mathbf{y}^1 \\ y_h^1 \end{pmatrix}, \begin{pmatrix} \mathbf{y}^2 \\ y_h^2 \end{pmatrix}, \begin{pmatrix} \mathbf{y}^3 \\ y_h^3 \end{pmatrix}\right)$ to $\left(\begin{pmatrix} \mathbf{z}^1 \\ 1 \end{pmatrix}, \begin{pmatrix} \mathbf{z}^2 \\ 1 \end{pmatrix}, \begin{pmatrix} \mathbf{z}^3 \\ 1 \end{pmatrix}\right)$, satisfying $(\mathbf{z}^k)^\top \mathbf{Q}_i \mathbf{z}^k \leq \frac{1}{9}$ for $k = 1, 2, 3$ and $i = 1, 2, \dots, m$, such that

$$F\left(\begin{pmatrix} \mathbf{z}^1 \\ 1 \end{pmatrix}, \begin{pmatrix} \mathbf{z}^2 \\ 1 \end{pmatrix}, \begin{pmatrix} \mathbf{z}^3 \\ 1 \end{pmatrix}\right) \geq 2^{-3} F\left(\begin{pmatrix} \mathbf{y}^1 \\ y_h^1 \end{pmatrix}, \begin{pmatrix} \mathbf{y}^2 \\ y_h^2 \end{pmatrix}, \begin{pmatrix} \mathbf{y}^3 \\ y_h^3 \end{pmatrix}\right) \geq \Omega\left(\frac{1}{\sqrt{n} \log^2 m}\right) v(Q).$$

It is easy to verify the following link identity (see also Lemma 1 of [9])

$$\begin{aligned} &f\left(\begin{matrix} \mathbf{z}^1 + \mathbf{z}^2 + \mathbf{z}^3 \\ 3 \end{matrix}\right) + f\left(\begin{matrix} \mathbf{z}^1 - \mathbf{z}^2 - \mathbf{z}^3 \\ -1 \end{matrix}\right) + f\left(\begin{matrix} -\mathbf{z}^1 + \mathbf{z}^2 - \mathbf{z}^3 \\ -1 \end{matrix}\right) + f\left(\begin{matrix} -\mathbf{z}^1 - \mathbf{z}^2 + \mathbf{z}^3 \\ -1 \end{matrix}\right) \\ &= 24F\left(\begin{pmatrix} \mathbf{z}^1 \\ 1 \end{pmatrix}, \begin{pmatrix} \mathbf{z}^2 \\ 1 \end{pmatrix}, \begin{pmatrix} \mathbf{z}^3 \\ 1 \end{pmatrix}\right) \geq \Omega\left(\frac{1}{\sqrt{n} \log^2 m}\right) v(Q). \end{aligned} \quad (13)$$

Therefore, the largest term of $f(\cdot)$ in (13) is at least in order of $\Omega\left(\frac{1}{\sqrt{n} \log^2 m}\right) v(Q)$. If $f\left(\begin{matrix} \mathbf{z}^1 + \mathbf{z}^2 + \mathbf{z}^3 \\ 3 \end{matrix}\right)$ is this largest term, then $\mathbf{y} := \frac{\mathbf{z}^1 + \mathbf{z}^2 + \mathbf{z}^3}{3}$ satisfies the constraint of Problem (Q), and

$$p(\mathbf{y}) = f\left(\begin{matrix} \mathbf{y} \\ 1 \end{matrix}\right) = \frac{f\left(\begin{matrix} 3\mathbf{y} \\ 3 \end{matrix}\right)}{27} \geq \Omega\left(\frac{1}{\sqrt{n} \log^2 m}\right) v(Q).$$

Otherwise by symmetricity, we may without loss of generality assume that $f\left(\begin{matrix} \mathbf{z}^1 - \mathbf{z}^2 - \mathbf{z}^3 \\ -1 \end{matrix}\right)$ is this largest term, then $\mathbf{z}^1 - \mathbf{z}^2 - \mathbf{z}^3$ satisfies the constraint of Problem (Q), and

$$\begin{aligned} p(\mathbf{z}^1 - \mathbf{z}^2 - \mathbf{z}^3) &= f_3(\mathbf{z}^1 - \mathbf{z}^2 - \mathbf{z}^3) + f_2(\mathbf{z}^1 - \mathbf{z}^2 - \mathbf{z}^3) + f_1(\mathbf{z}^1 - \mathbf{z}^2 - \mathbf{z}^3) \\ &\geq f_3(\mathbf{z}^1 - \mathbf{z}^2 - \mathbf{z}^3) - f_2(\mathbf{z}^1 - \mathbf{z}^2 - \mathbf{z}^3) + f_1(\mathbf{z}^1 - \mathbf{z}^2 - \mathbf{z}^3) \\ &= f\left(\begin{matrix} \mathbf{z}^1 - \mathbf{z}^2 - \mathbf{z}^3 \\ -1 \end{matrix}\right) \geq \Omega\left(\frac{1}{\sqrt{n} \log^2 m}\right) v(Q), \end{aligned}$$

where the first inequality is due to the fact that $f_2(\mathbf{x})$ is positive semidefinite. Finally,

$$\operatorname{argmax} \{p(\mathbf{y}), p(\mathbf{z}^1 - \mathbf{z}^2 - \mathbf{z}^3), p(-\mathbf{z}^1 + \mathbf{z}^2 - \mathbf{z}^3), p(-\mathbf{z}^1 - \mathbf{z}^2 + \mathbf{z}^3)\}$$

is the approximate solution with approximation ratio $\Omega\left(\frac{1}{\sqrt{n} \log^2 m}\right)$. \square

5 Polynomial Optimization over a Convex Compact Set

In this section we consider polynomial optimization model in a generic constraint format:

$$(G) \quad \begin{aligned} & \max && p(\mathbf{x}) \\ & \text{s.t.} && \mathbf{x} \in S, \end{aligned}$$

where $S \subseteq \mathbb{R}^n$ is a general convex compact set. We are concerned with *polynomial-time approximation algorithms* for solving Problem (G). Our approach makes use of the famous *Löwner-John ellipsoids* (see e.g. [4, 25]):

Theorem 5.1 (Löwner-John) *Let $S \subseteq \mathbb{R}^n$ be a bounded convex set with non-empty interior. Then:*

1. *There exists a unique largest volume full-dimensional ellipsoid E_{in} contained in S . The concentric to E_{in} n times larger (in linear sizes) ellipsoid contains S ; if S is central-symmetric, then \sqrt{n} times larger ellipsoid concentric to E_{in} already contains S .*
2. *There exists a unique smallest volume full-dimensional ellipsoid E_{out} containing S . The concentric to E_{out} n times smaller (in linear sizes) ellipsoid is contained in S ; if S is central-symmetric, then \sqrt{n} times smaller ellipsoid concentric to E_{out} is already contained in S .*

Armed with the above theorem, if we are able to find the Löwner-John ellipsoid (either E_{in} or E_{out}) of the feasible region S in polynomial-time, then the following algorithm approximately solves Problem (G) with a worst-case performance ratio.

Algorithm 5.2

Input: an n -dimensional d -th degree polynomial function $p(\mathbf{x})$ and a set $S \subseteq \mathbb{R}^n$.

1. *Find a scalar $t \in \mathbb{R}$, a vector $\mathbf{b} \in \mathbb{R}^n$, and a matrix $\mathbf{A} \in \mathbb{R}^{n \times m}$ with $\text{rank}(\mathbf{A}) = m \leq n$, such that two co-centered ellipsoids $E_1 = \{\mathbf{A}\mathbf{u} + \mathbf{b} \mid \|\mathbf{u}\| \leq 1, \mathbf{u} \in \mathbb{R}^m\}$ and $E_2 = \{\mathbf{A}\mathbf{u} + \mathbf{b} \mid \|\mathbf{u}\| \leq t, \mathbf{u} \in \mathbb{R}^m\}$ satisfy $E_1 \subseteq S \subseteq E_2$.*
2. *Compute polynomial function $p_0(\mathbf{u}) = p(\mathbf{A}\mathbf{u} + \mathbf{b})$, where $\mathbf{u} \in \mathbb{R}^m$.*
3. *Apply Algorithm 3.2 with input $p_0(\mathbf{x}) - p_0(\mathbf{0})$ and output $\mathbf{z} \in \mathbb{R}^m$.*

Output: a feasible solution $\mathbf{A}\mathbf{z} + \mathbf{b}$.

The key result in this section is the following theorem.

Theorem 5.3 *Let $B(t) := \{\mathbf{x} \in \mathbb{R}^n, \|\mathbf{x}\| \leq t\}$. Suppose that $B(1) \subseteq S \subseteq B(t)$ for some $t \geq 1$. Then, Problem (G) admits a polynomial-time approximation algorithm with relative approximation ratio $\tau_G(t)$, i.e., a feasible solution $\mathbf{z} \in S$ can be found in polynomial-time, satisfying*

$$p(\mathbf{z}) - v_{\min}(G) \geq \tau_G(t) (v_{\max}(G) - v_{\min}(G)), \quad (14)$$

where $\tau_G(t) := (d+1)!(2d)^{-2d}(n+1)^{-\frac{d-2}{2}}(t^2+1)^{-\frac{d}{2}}$.

Proof. By homogenizing the object function of Problem (G), we get the equivalent problem

$$\begin{aligned} (\bar{G}) \quad & \max f(\bar{\mathbf{x}}) \\ \text{s.t.} \quad & \bar{\mathbf{x}} = \begin{pmatrix} \mathbf{x} \\ x_h \end{pmatrix}, \\ & \mathbf{x} \in S, x_h = 1, \end{aligned}$$

where $f(\bar{\mathbf{x}}) = p(\mathbf{x})$ if $x_h = 1$, and $f(\bar{\mathbf{x}})$ is an $(n+1)$ -dimensional homogeneous polynomial function of degree d .

If we write $f(\bar{\mathbf{x}}) = F(\overbrace{\bar{\mathbf{x}}, \bar{\mathbf{x}}, \dots, \bar{\mathbf{x}}}^d)$ with \mathbf{F} being super-symmetric, Problem (\bar{G}) can be relaxed to the inhomogeneous multilinear function problem

$$\begin{aligned} \max \quad & F(\bar{\mathbf{x}}^1, \bar{\mathbf{x}}^2, \dots, \bar{\mathbf{x}}^d) \\ \text{s.t.} \quad & \bar{\mathbf{x}}^k = \begin{pmatrix} \mathbf{x}^k \\ x_h^k \end{pmatrix}, k = 1, 2, \dots, d, \\ & \mathbf{x}^k \in S, x_h^k = 1, k = 1, 2, \dots, d. \end{aligned}$$

Recall that we have previously defined

$$\begin{aligned} (T_B(t)) \quad & \max F(\bar{\mathbf{x}}^1, \bar{\mathbf{x}}^2, \dots, \bar{\mathbf{x}}^d) \\ \text{s.t.} \quad & \|\bar{\mathbf{x}}^k\| \leq t, \bar{\mathbf{x}}^k \in \mathfrak{R}^{n+1}, k = 1, 2, \dots, d. \end{aligned}$$

As $\mathbf{x}^k \in S \subseteq B(t)$, it follows $\|\bar{\mathbf{x}}^k\| \leq \sqrt{t^2+1}$. Thus Problem $(T_B(\sqrt{t^2+1}))$ is a relaxation of Problem (\bar{G}) and $v_{\max}(T_B(\sqrt{t^2+1})) \geq v_{\max}(\bar{G}) = v_{\max}(G)$. The rest of the proof follows similarly as that in Section 3.4. \square

Observe that any ellipsoid can be linearly transformed into the Euclidean ball, by a variable transformation if necessary, we are led to the main result in this section.

Corollary 5.4 *Let $S \subseteq \mathfrak{R}^n$ be a given compact set. Suppose two co-centered ellipsoids $E_1 = \{\mathbf{A}\mathbf{u} + \mathbf{b} \mid \|\mathbf{u}\| \leq 1, \mathbf{u} \in \mathfrak{R}^n\}$ and $E_2 = \{\mathbf{A}\mathbf{u} + \mathbf{b} \mid \|\mathbf{u}\| \leq t, \mathbf{u} \in \mathfrak{R}^n\}$ can be found in polynomial-time, satisfying $E_1 \subseteq S \subseteq E_2$. Then Problem (G) admits a polynomial-time approximation algorithm (Algorithm 5.2) with relative approximation ratio $\tau_G(t)$.*

We would like to remark that the set S in Theorem 5.3 and Corollary 5.4 does not need to be convex, as long as the two required ellipsoids are in place. Therefore, Problem (G) generally includes cases of non-convex set S . However, the famous Löwner-John theorem guarantees the existence of such inner and outer ellipsoids required in Corollary 5.4 for any bounded convex set, with $t = n$ for S being non-central-symmetric, and $t = \sqrt{n}$ for S being central-symmetric. Thus, if we are able to find a pair of ellipsoids (E_1, E_2) in polynomial-time for S , then Problem (G) can be solved by

a polynomial-time approximation algorithm with relative approximation ratio $\tau_G(t)$. Indeed, it is possible to compute in polynomial-time the Löwner-John ellipsoids in several interesting cases. Below is a list of such cases (assuming S is bounded); for the details one is referred to [4, 25]:

- $S = \{\mathbf{x} \in \mathfrak{R}^n \mid (\mathbf{a}^i)^\top \mathbf{x} \leq b_i, i = 1, 2, \dots, m\}$;
- $S = \text{conv}\{\mathbf{x}^1, \mathbf{x}^2, \dots, \mathbf{x}^m\}$, where $\mathbf{x}^i \in \mathfrak{R}^n, i = 1, 2, \dots, m$;
- $S = \bigcap_{i=1}^m E_i$, where E_i is an ellipsoid in $\mathfrak{R}^n, i = 1, 2, \dots, m$;
- $S = \text{conv}\{\bigcup_{i=1}^m E_i\}$, where E_i is an ellipsoid in $\mathfrak{R}^n, i = 1, 2, \dots, m$;
- $S = \sum_{i=1}^m E_i := \{\sum_{i=1}^m \mathbf{x}^i \mid \mathbf{x}^i \in E_i, i = 1, 2, \dots, m\}$, where E_i is an ellipsoid in $\mathfrak{R}^n, i = 1, 2, \dots, m$.

By Corollary 5.4, and the computability of the Löwner-John ellipsoids ([4, 25]) as we discussed above, we conclude that for Problem (G) with the constraint set S belonging to any of the above cases, then there is a polynomial-time approximation algorithm with a relative approximation quality assurance. In particular, the ratio is $\tau_G(\sqrt{m}) = \Omega\left(n^{-\frac{d-2}{2}} m^{-\frac{d}{2}}\right)$ for the last case, and $\tau_G(n) = \Omega\left(n^{-\frac{3d-2}{2}}\right)$ for the other cases.

We shall also remark that Problem (Q) : $\max_{\mathbf{x}^\top \mathbf{Q}_i \mathbf{x} \leq 1, i=1,2,\dots,m} p(\mathbf{x})$, discussed in Section 4, may in principle be solved by directly applying Corollary 5.4 as well. If we adopt that approach (Algorithm 5.2), then the relative approximation ratio will be $\tau_G(\sqrt{n}) = \Omega\left(n^{-\frac{2d-2}{2}}\right)$, which will prevail if m is exceedingly large. By taking the best of the two, the quality ratio in Theorem 4.2 can be improved to $\Omega\left(\max\left\{n^{-\frac{d-2}{2}} (\log m)^{-(d-1)}, n^{-\frac{2d-2}{2}}\right\}\right)$.

Our investigation quite naturally leads to a question which is of a general geometric interest itself. Consider the intersection of m co-centered ellipsoids in \mathfrak{R}^n as a geometric structure to be considered. Let $\mathcal{E}_{m,n}$ be the collection of all such ellipsoids, or more specifically

$$\mathcal{E}_{m,n} := \left\{ \bigcap_{i=1}^m E_i \mid E_i = \{\mathbf{x} \in \mathfrak{R}^n \mid \mathbf{x}^\top \mathbf{Q}_i \mathbf{x} \leq 1\} \text{ with } \mathbf{Q}_i \succeq 0, i = 1, 2, \dots, m, \text{ and } \sum_{i=1}^m \mathbf{Q}_i \succ 0 \right\}.$$

For any central-symmetric, convex and compact set S centered at \mathbf{b} , there exist $E_{m,n} \in \mathcal{E}_{m,n}$ and $t \geq 1$, such that $\mathbf{b} + E_{m,n} \subseteq S \subseteq \mathbf{b} + tE_{m,n}$. Obviously, one can naturally define

$$\begin{aligned} t(S; m, n) &:= \inf \{t \mid E_{m,n} \in \mathcal{E}_{m,n} \text{ such that } \mathbf{b} + E_{m,n} \subseteq S \subseteq \mathbf{b} + tE_{m,n}\} \\ \theta(m, n) &:= \sup \{t(S; m, n) \mid S \text{ is any central-symmetric convex compact set in } \mathfrak{R}^n\}. \end{aligned}$$

The famous Löwner-John theorem states that $\theta(1, n) = \sqrt{n}$. Naturally, $\theta(\infty, n) = 1$, because any central-symmetric convex set can be expressed by the intersection of an infinite number of co-centered ellipsoids. It is interesting to compute $\theta(m, n)$ for general m and n . It is of

course trivial to observe that $\theta(m, n)$ is monotonically decreasing in m for any fixed n . Anyway, if we were able to compute $\theta(m, n)$, then Theorem 4.2 suggests a polynomial-time randomized approximation algorithm of Problem (G) with relative approximation ratio $(\theta(m, n))^{-d} \tau_Q = \Omega\left((\theta(m, n))^{-d} n^{-\frac{d-2}{2}} (\log m)^{-(d-1)}\right)$.

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