

# BOUNDING THE BETTI NUMBERS AND COMPUTING THE EULER-POINCARÉ CHARACTERISTIC OF SEMI-ALGEBRAIC SETS DEFINED BY PARTLY QUADRATIC SYSTEMS OF POLYNOMIALS

SAUGATA BASU, DMITRII V. PASECHNIK, AND MARIE-FRANÇOISE ROY

ABSTRACT. Let  $R$  be a real closed field,  $\mathcal{Q} \subset R[Y_1, \dots, Y_\ell, X_1, \dots, X_k]$ , with  $\deg_Y(Q) \leq 2, \deg_X(Q) \leq d, Q \in \mathcal{Q}, \#(\mathcal{Q}) = m$ , and  $\mathcal{P} \subset R[X_1, \dots, X_k]$  with  $\deg_X(P) \leq d, P \in \mathcal{P}, \#(\mathcal{P}) = s$ , and  $S \subset R^{\ell+k}$  a semi-algebraic set defined by a Boolean formula without negations, with atoms  $P = 0, P \geq 0, P \leq 0, P \in \mathcal{P} \cup \mathcal{Q}$ . We prove that the sum of the Betti numbers of  $S$  is bounded by

$$\ell^2(O(s + \ell + m)\ell d)^{k+2m}.$$

This is a common generalization of previous results in [4] and [3] on bounding the Betti numbers of closed semi-algebraic sets defined by polynomials of degree  $d$  and 2, respectively.

We also describe an algorithm for computing the Euler-Poincaré characteristic of such sets, generalizing similar algorithms described in [4, 12]. The complexity of the algorithm is bounded by  $(\ell s m d)^{O(m(m+k))}$ .

## 1. INTRODUCTION AND MAIN RESULTS

Let  $R$  be a real closed field and  $S \subset R^k$  a semi-algebraic set defined by a Boolean formula with atoms of the form  $P > 0, P < 0, P = 0$  for  $P \in \mathcal{P} \subset R[X_1, \dots, X_k]$ . We call  $S$  a  $\mathcal{P}$ -semi-algebraic set and the Boolean formula defining  $S$  a  $\mathcal{P}$ -formula. If, instead, the Boolean formula has atoms of the form  $P = 0, P \geq 0, P \leq 0, P \in \mathcal{P}$ , and additionally contains no negation, then we will call  $S$  a  $\mathcal{P}$ -closed semi-algebraic set, and the formula defining  $S$  a  $\mathcal{P}$ -closed formula. Moreover, we call a  $\mathcal{P}$ -closed semi-algebraic set  $S$  basic if the  $\mathcal{P}$ -closed formula defining  $S$  is a conjunction of atoms of the form  $P = 0, P \geq 0, P \leq 0, P \in \mathcal{P}$ .

For any closed semi-algebraic set  $X \subset R^k$ , and any field of coefficients  $K$ , we denote by  $b_i(X, K)$  the dimension of the  $K$ -vector space,  $H_i(X, K)$ , which is the  $i$ -th homology group of  $X$  with coefficients in  $K$ . We refer to [9] for the definition of homology in the case of  $R$  being an arbitrary real closed field, not necessarily the field of real numbers, and  $K = \mathbb{Q}$ . The definition for a more general  $K$  is similar. We denote by  $b(X, K)$  the sum  $\sum_{i \geq 0} b_i(X, K)$ . We write  $b_i(X)$  for  $b_i(X, \mathbb{Z}/2\mathbb{Z})$  and  $b(X)$  for  $b(X, \mathbb{Z}/2\mathbb{Z})$ . Note that the mod-2 Betti numbers  $b_i(X)$  are an upper bound on the Betti numbers  $b_i(X, \mathbb{Q})$  (as a consequence of the Universal Coefficient Theorem for homology (see [19] for example)).

---

1991 *Mathematics Subject Classification*. Primary 14P10, 14P25; Secondary 68W30.

*Key words and phrases*. Betti numbers, Quadratic inequalities, Semi-algebraic sets.

The first author was supported in part by an NSF grant CCF-0634907. The second author was supported by an NTU startup grant. Part of this work was done when the authors were visiting the Institute of Mathematics and Its Application, Minneapolis, IRMAR (Rennes) and the Nanyang Technological University, Singapore.

The following result appeared in [4].

**Theorem 1.1.** [4] *For a  $\mathcal{P}$ -closed semi-algebraic set  $S \subset \mathbb{R}^k$ ,  $b(S, \mathbb{K})$  is bounded by  $(O(sd))^k$ , where  $s = \#\mathcal{P}$ , and  $d = \max_{P \in \mathcal{P}} \deg(P)$ .  $\square$*

It is a generalization of the results due to Oleinik, Petrovsky [21], Thom [23], and Milnor [20] on bounding the Betti numbers of real varieties. It provides an upper bound on the sum of the Betti numbers of  $\mathcal{P}$ -closed semi-algebraic sets in terms of the number and degrees of the polynomials in  $\mathcal{P}$  (see also [13] for a slightly more precise bound, and [16] for an extension of this result to arbitrary semi-algebraic sets with a slight worsening of the bound). Notice that this upper bound has singly exponential dependence on  $k$ , and this dependence is unavoidable (see Example 1.2 below).

In another direction, a restricted class of semi-algebraic sets - namely, semi-algebraic sets defined by quadratic inequalities - has been considered by several researchers [2, 3, 18, 8]. As in the case of general semi-algebraic sets, the Betti numbers of such sets can be exponentially large in the number of variables, as can be seen in the following example.

**Example 1.2.** The set  $S \subset \mathbb{R}^\ell$  defined by

$$Y_1(Y_1 - 1) \geq 0, \dots, Y_\ell(Y_\ell - 1) \geq 0$$

satisfies  $b_0(S) = 2^\ell$ .

However, it turns out that for a semi-algebraic set  $S \subset \mathbb{R}^\ell$  defined by  $m$  quadratic inequalities, it is possible to obtain upper bounds on the Betti numbers of  $S$  which are polynomial in  $\ell$  and exponential only in  $m$ . The first such result is due to Barvinok [3], who proved the following theorem.

**Theorem 1.3.** [3] *Let  $S \subset \mathbb{R}^\ell$  be defined by  $Q_1 \geq 0, \dots, Q_m \geq 0$ ,  $\deg(Q_i) \leq 2$ ,  $1 \leq i \leq m$ . Then  $b(S, \mathbb{K}) \leq \ell^{O(m)}$ .*

A tighter bound appears in [8].

Even though Theorem 1.1 [4] and Theorem 1.3 [3] are stated and proved in the case  $\mathbb{K} = \mathbb{Q}$  in the original papers, the proofs can be extended without any difficulty to a general  $\mathbb{K}$ .

*Remark 1.4.* Notice that the bound in Theorem 1.3 is polynomial in the dimension  $\ell$  for fixed  $m$ , and this fact depends crucially on the assumption that the degrees of the polynomials  $Q_1, \dots, Q_m$  are at most two. For instance, the semi-algebraic set defined by a *single* polynomial of degree 4 can have Betti numbers exponentially large in  $\ell$ , as exhibited by the semi-algebraic subset of  $\mathbb{R}^\ell$  defined by

$$\sum_{i=0}^{\ell} Y_i^2 (Y_i - 1)^2 \leq 0.$$

The above example illustrates the delicate nature of the bound in Theorem 1.3, since a single inequality of degree 4 is enough to destroy the polynomial nature of the bound. In contrast to this, we show in this paper (see Theorem 1.5 below) that a polynomial bound on the Betti numbers of  $S$  continues to hold, even if we allow a few (meaning any constant number) of the variables to occur with degrees larger than two in the polynomials used to describe the set  $S$ .

We now state the main results of this paper.

**1.1. Bounds on the Betti Numbers.** We consider semi-algebraic sets defined by polynomial inequalities, in which the dependence of the polynomials on a *subset of the variables* is at most quadratic. As a result we obtain common generalizations of the bounds stated in Theorems 1.1 and 1.3. Given any polynomial  $P \in \mathbb{R}[X_1, \dots, X_k, Y_1, \dots, Y_\ell]$ , we will denote by  $\deg_X(P)$  (resp.  $\deg_Y(P)$ ) the total degree of  $P$  with respect to the variables  $X_1, \dots, X_k$  (resp.  $Y_1, \dots, Y_\ell$ ).

*Notation 1.* Throughout the paper we fix a real closed field  $\mathbb{R}$ , and denote by

- $\mathcal{Q} \subset \mathbb{R}[Y_1, \dots, Y_\ell, X_1, \dots, X_k]$ , a family of polynomials with

$$\deg_Y(Q) \leq 2, \deg_X(Q) \leq d, Q \in \mathcal{Q}, \#(\mathcal{Q}) = m,$$

- $\mathcal{P} \subset \mathbb{R}[X_1, \dots, X_k]$ , a family of polynomials with

$$\deg_X(P) \leq d, P \in \mathcal{P}, \#(\mathcal{P}) = s.$$

We prove the following theorem.

**Theorem 1.5.** *Let  $S \subset \mathbb{R}^{\ell+k}$  be a  $(\mathcal{P} \cup \mathcal{Q})$ -closed semi-algebraic set. Then*

$$b(S) \leq \ell^2(O(s + \ell + m)\ell d)^{k+2m}.$$

*In particular, for  $m \leq \ell$ , we have  $b(S) \leq \ell^2(O(s + \ell)\ell d)^{k+2m}$ .*

Notice that Theorem 1.5 can be seen as a common generalization of Theorems 1.1 and 1.3, in the sense that we recover similar bounds (that is bounds having the same shape) as in Theorem 1.1 (respectively, Theorem 1.3) by setting  $\ell$  and  $m$  (respectively,  $s$ ,  $d$  and  $k$ ) to  $O(1)$ . Since we use Theorem 1.1 in the proof of Theorem 1.5 (more precisely in the proof of Theorem 2.3 which is a key step in the proof of Theorem 1.5), our proof does not give a new proof of Theorem 1.1. However, our methods do give a new proof of the known bound on Betti numbers in the quadratic case (Theorem 1.3), and this new proof is quite different from those given in [3, 8, 17]. The techniques used in [3, 17, 8] do not appear to generalize easily to the parametrized situation considered in this paper.

Note also that as a special case of Theorem 1.5 we obtain a bound on the sum of the Betti numbers of a semi-algebraic set defined over a quadratic map. Such sets have been considered from an algorithmic point of view in [18], where an efficient algorithm is described for computing sample points in every connected component, as well as testing emptiness, of such sets.

More precisely, we show the following.

**Corollary 1.6.** *Let  $Q = (Q_1, \dots, Q_k) : \mathbb{R}^\ell \rightarrow \mathbb{R}^k$  be a map where each  $Q_i \in \mathbb{R}[Y_1, \dots, Y_\ell]$  and  $\deg(Q_i) \leq 2$ . Let  $V \subset \mathbb{R}^k$  be a  $\mathcal{P}$ -closed semi-algebraic set for some family  $\mathcal{P} \subset \mathbb{R}[X_1, \dots, X_k]$ , with  $\#(\mathcal{P}) = s$  and  $\deg(P) \leq d, P \in \mathcal{P}$ . Let  $S = Q^{-1}(V)$ . Then*

$$b(S) \leq \ell^2(O(s + \ell + k)\ell d)^{3k}.$$

*Remark 1.7.* Note that the Morse theoretic techniques developed in [17] give a possible alternative approach for proving Corollary 1.6.

**1.2. Algorithmic Implications.** The algorithmic problem of computing topological invariants of semi-algebraic sets (such as the Betti numbers, Euler-Poincaré characteristic) is very well studied. We refer the reader to a recent survey [5] for a detailed account of the recent progress and open problems in this field.

The techniques developed in this paper for obtaining tight bounds on the Betti numbers of semi-algebraic sets defined by partly quadratic systems of polynomials also pave the way towards designing more efficient algorithms for computing the Euler-Poincaré characteristic as well as the Betti numbers of such sets. These algorithms have better complexity than the ones known before.

**Definition 1.8** (Complexity). By complexity of an algorithm we will mean the number of arithmetic operations (including comparisons) performed by the algorithm in  $\mathbb{R}$ . We refer the reader to [9, Chapter 8] for a full discussion about the various measures of complexity.

We prove the following theorem.

**Theorem 1.9.** *There exists an algorithm that takes as input the description of a  $(\mathcal{P} \cup \mathcal{Q})$ -closed semi-algebraic set  $S$  (following the same notation as in Theorem 1.5) and outputs its the Euler-Poincaré characteristic  $\chi(S)$ . The complexity of this algorithm is bounded by  $(\ell \text{smd})^{O(m(m+k))}$ . In the case when  $S$  is a basic closed semi-algebraic set the complexity of the algorithm is  $(\ell \text{smd})^{O(m+k)}$ .*

The algorithm for computing all the Betti numbers has complexity  $(\ell \text{smd})^{2^{O(m+k)}}$  and is much more technical. We omit its description in this paper. It will appear in full detail separately in a subsequent paper.

While the complexity of both the algorithms discussed above is *polynomial* for fixed  $m$  and  $k$ , the complexity of the algorithm for computing the Euler-Poincaré characteristic is significantly better than that of the algorithm for computing all the Betti numbers.

1.2.1. *Significance from the computational complexity theory viewpoint.* The problem of computing the Betti numbers of semi-algebraic sets in general is a PSPACE-hard problem. We refer the reader to [6] and the references contained therein, for a detailed discussion of these hardness results. In particular, the problem of computing the Betti numbers of a real algebraic variety defined by a single quartic equation is also PSPACE-hard, and the same is true for semi-algebraic sets defined by many quadratic inequalities. On the other hand, as shown in [6] (see also [7]), the problem of computing the Betti numbers of semi-algebraic sets defined by a constant number of quadratic inequalities is solvable in polynomial time. The results mentioned above indicate that the problem of computing the Betti numbers of semi-algebraic sets defined by a constant number of polynomial inequalities is solvable in polynomial time, even if we allow a small (constant sized) subset of the variables to occur with degrees larger than two in the polynomials defining the given set. Note that such a result is not obtainable directly from the results in [6] by the naive method of replacing the monomials having degrees larger than two by a larger set of quadratic ones (introducing new variables and equations in the process).

For general semi-algebraic sets, the algorithmic problem of computing all the Betti numbers is notoriously difficult and only doubly exponential time algorithm is known for this problem. Very recently, singly exponential time algorithms [10, 11] have been found for computing the first few Betti numbers of such sets, but the problem of designing singly exponential time algorithm for computing all the Betti numbers remains open. Singly exponential time algorithm is also known for computing the Euler-Poincaré characteristic of general semi-algebraic sets [4].

The rest of the paper is organized as follows. In Section 2 we prove Theorem 1.5. In Section 3 we describe our algorithm for computing the Euler-Poincaré characteristic of sets defined by partly quadratic system of polynomials and prove Theorem 1.9.

## 2. PROOF OF THEOREM 1.5

One of the main ideas behind our proof of Theorem 1.5 is to parametrize a construction introduced by Agrachev in [1] while studying the topology of sets defined by (purely) quadratic inequalities (that is without the parameters  $X_1, \dots, X_k$  in our notation). In *loc. cit.* Agrachev constructs a spectral sequence converging to the cohomology of the set being studied. However, it is assumed that the initial quadratic polynomials are generic. In this paper we do not make any genericity assumptions on our polynomials. In order to prove our main theorem we follow another approach based on infinitesimal deformations which avoids the construction of a spectral sequence as done in [1].

We first need to fix some notation and a few preliminary results needed later in the proof.

### 2.1. Mathematical Preliminaries.

2.1.1. *Some Notation.* For all  $a \in R$  we define

$$\begin{aligned} \text{sign}(a) &= 0 \text{ if } a = 0, \\ &= 1 \text{ if } a > 0, \\ &= -1 \text{ if } a < 0. \end{aligned}$$

Let  $\mathcal{A}$  be a finite subset of  $R[X_1, \dots, X_k]$ . A *sign condition* on  $\mathcal{A}$  is an element of  $\{0, 1, -1\}^{\mathcal{A}}$ . The *realization of the sign condition*  $\sigma$ ,  $\mathcal{R}(\sigma, R^k)$ , is the basic semi-algebraic set

$$\{x \in R^k \mid \bigwedge_{P \in \mathcal{A}} \text{sign}(P(x)) = \sigma(P)\}.$$

A *weak sign condition* on  $\mathcal{A}$  is an element of  $\{\{0\}, \{0, 1\}, \{0, -1\}\}^{\mathcal{A}}$ . The *realization of the weak sign condition*  $\rho$ ,  $\mathcal{R}(\rho, R^k)$ , is the basic semi-algebraic set

$$\{x \in R^k \mid \bigwedge_{P \in \mathcal{A}} \text{sign}(P(x)) \in \rho(P)\}.$$

We often abbreviate  $\mathcal{R}(\sigma, R^k)$  by  $\mathcal{R}(\sigma)$ , and we denote by  $\text{Sign}(\mathcal{A})$  the set of realizable sign conditions  $\text{Sign}(\mathcal{A}) = \{\sigma \in \{0, 1, -1\}^{\mathcal{A}} \mid \mathcal{R}(\sigma) \neq \emptyset\}$ .

More generally, for any  $\mathcal{A} \subset R[X_1, \dots, X_k]$  and a  $\mathcal{A}$ -formula  $\Phi$ , we denote by  $\mathcal{R}(\Phi, R^k)$ , or simply  $\mathcal{R}(\Phi)$ , the semi-algebraic set defined by  $\Phi$  in  $R^k$ .

2.1.2. *Use of Infinitesimals.* Later in the paper, we extend the ground field  $R$  by infinitesimal elements. We denote by  $R\langle\zeta\rangle$  the real closed field of algebraic Puiseux series in  $\zeta$  with coefficients in  $R$  (see [9] for more details). The sign of a Puiseux series in  $R\langle\zeta\rangle$  agrees with the sign of the coefficient of the lowest degree term in  $\zeta$ . This induces a unique order on  $R\langle\zeta\rangle$  which makes  $\zeta$  infinitesimal:  $\zeta$  is positive and smaller than any positive element of  $R$ . When  $a \in R\langle\zeta\rangle$  is bounded from above and below by some elements of  $R$ ,  $\lim_{\zeta} a$  is the constant term of  $a$ , obtained by substituting 0 for  $\zeta$  in  $a$ . We denote by  $R\langle\zeta_1, \dots, \zeta_n\rangle$  the field  $R\langle\zeta_1\rangle \cdots \langle\zeta_n\rangle$  and in this case  $\zeta_1$  is positive and infinitesimally small compared to 1, and for  $1 \leq i \leq n-1$ ,

$\zeta_{i+1}$  is positive and infinitesimally small compared to  $\zeta_i$ , which we abbreviate by writing  $0 < \zeta_n \ll \dots \ll \zeta_1 \ll 1$ .

Let  $R'$  be a real closed field containing  $R$ . Given a semi-algebraic set  $S$  in  $R^k$ , the *extension* of  $S$  to  $R'$ , denoted  $\text{Ext}(S, R')$ , is the semi-algebraic subset of  $R'^k$  defined by the same quantifier free formula that defines  $S$ . The set  $\text{Ext}(S, R')$  is well defined (i.e. it only depends on the set  $S$  and not on the quantifier free formula chosen to describe it). This is an easy consequence of the transfer principle (see for instance [9]).

We will need a few results from algebraic topology, which we state here without proofs, referring the reader to papers where the proofs appear.

**2.1.3. Mayer-Vietoris Inequalities.** The following inequalities are consequences of the Mayer-Vietoris exact sequence.

**Proposition 2.1** (Mayer-Vietoris inequalities). *Let the subsets  $W_1, \dots, W_t \subset R^n$  be all closed. Then for each  $i \geq 0$  we have*

$$(2.1) \quad b_i \left( \bigcup_{1 \leq j \leq t} W_j \right) \leq \sum_{J \subset \{1, \dots, t\}} b_{i - \#(J) + 1} \left( \bigcap_{j \in J} W_j \right),$$

$$(2.2) \quad b_i \left( \bigcap_{1 \leq j \leq t} W_j \right) \leq \sum_{J \subset \{1, \dots, t\}} b_{i + \#(J) - 1} \left( \bigcup_{j \in J} W_j \right).$$

*Proof.* See for instance [9]. □

**2.1.4. Topology of Sphere Bundles.** Given a closed and bounded semi-algebraic set  $B$ , a semi-algebraic  $\ell$ -sphere bundle over  $B$  is given by a continuous semi-algebraic map  $\pi : E \rightarrow B$ , such that for each  $b \in B$ ,  $\pi^{-1}(b)$  is homeomorphic to  $\mathbf{S}^\ell$  (the  $\ell$ -dimensional unit sphere in  $R^{\ell+1}$ ).

We need the following proposition that relates the Betti numbers of  $B$  with that of  $E$ .

**Proposition 2.2.** *Let  $B \subset R^k$  be a closed and bounded semi-algebraic set and let  $\pi : E \rightarrow B$  be a semi-algebraic  $\ell$ -sphere bundle with base  $B$ . Then*

$$(2.3) \quad b(E) \leq 2 \cdot b(B).$$

*Proof.* In case  $\ell > 0$ , the proposition follows from the inequality (2.4) proved in [15, page 252 (4.1)]

$$(2.4) \quad P_E(t) \leq P_{\mathbf{S}^\ell}(t) P_B(t),$$

where  $P_X(t) = \sum_{i \geq 0} b_i(X) t^i$  denotes the Poincaré polynomial of a topological space  $X$ , and the inequality holds coefficient-wise. The inequality (2.3) holds for the Betti numbers with coefficients in  $\mathbb{Q}$ , as well.

For  $\ell = 0$ , inequality (2.4) is no longer true for the ordinary Betti numbers, as can be observed from the example of the two-dimensional torus, which is a double cover of the Klein bottle. But inequality (2.3) holds for Betti numbers with  $\mathbb{Z}/2\mathbb{Z}$ -coefficients. This follows from the Leray-Serre spectral sequence of the projection map  $\pi$ , since the homology with coefficients in a local system in this case are the same as ordinary homology (an elementary proof is given in [8]). □

We now return to the proof of Theorem 1.5.

## 2.2. Homogeneous Case.

*Notation 2.* We denote by

- $\mathcal{Q}^h$  the family of polynomials obtained by homogenizing  $\mathcal{Q}$  with respect to the variables  $Y$ , i.e.

$$\mathcal{Q}^h = \{Q^h \mid Q \in \mathcal{Q}\} \subset \mathbb{R}[Y_0, \dots, Y_\ell, X_1, \dots, X_k],$$

where  $Q^h = Y_0^2 Q(Y_1/Y_0, \dots, Y_\ell/Y_0, X_1, \dots, X_k)$ ,

- $\Phi$  a formula defining a  $\mathcal{P}$ -closed semi-algebraic set  $V$ ,
- $A^h$  the semi-algebraic set

$$(2.5) \quad A^h = \bigcup_{Q \in \mathcal{Q}^h} \{(y, x) \mid |y| = 1 \wedge Q(y, x) \leq 0 \wedge \Phi(x)\},$$

- $W^h$  the semi-algebraic set

$$(2.6) \quad W^h = \bigcap_{Q \in \mathcal{Q}^h} \{(y, x) \mid |y| = 1 \wedge Q(y, x) \leq 0 \wedge \Phi(x)\}.$$

We are going to prove

**Theorem 2.3.**

$$(2.7) \quad b(A^h) \leq \ell^2(O((s + \ell + m)\ell d))^{m+k}.$$

and

**Theorem 2.4.**

$$(2.8) \quad b(W^h) \leq \ell^2(O((s + \ell + m)\ell d))^{m+k}.$$

Before proving Theorem 2.3 and Theorem 2.4 we need a few preliminary results.

Let

$$(2.9) \quad \Omega = \{\omega \in \mathbb{R}^m \mid |\omega| = 1, \omega_i \leq 0, 1 \leq i \leq m\}.$$

Let  $\mathcal{Q} = \{Q_1, \dots, Q_m\}$  and  $\mathcal{Q}^h = \{Q_1^h, \dots, Q_m^h\}$ . For  $\omega \in \Omega$  we denote by  $\langle \omega, \mathcal{Q}^h \rangle \in \mathbb{R}[Y_0, \dots, Y_\ell, X_1, \dots, X_k]$  the polynomial defined by

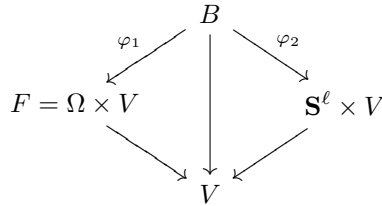
$$(2.10) \quad \langle \omega, \mathcal{Q}^h \rangle = \sum_{i=1}^m \omega_i Q_i^h.$$

For  $(\omega, x) \in \Omega \times V$ , we denote by  $\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)$  the quadratic form in  $Y_0, \dots, Y_\ell$  obtained from  $\langle \omega, \mathcal{Q}^h \rangle$  by specializing  $X_i = x_i, 1 \leq i \leq k$ .

Let  $B \subset \Omega \times \mathbf{S}^\ell \times V$  be the semi-algebraic set defined by

$$(2.11) \quad B = \{(\omega, y, x) \mid \omega \in \Omega, y \in \mathbf{S}^\ell, x \in V, \langle \omega, \mathcal{Q}^h \rangle(y, x) \geq 0\}.$$

We denote by  $\varphi_1 : B \rightarrow F$  and  $\varphi_2 : B \rightarrow \mathbf{S}^\ell \times V$  the two projection maps (see diagram below).



The following key proposition was proved by Agrachev [1] in the unparametrized situation, but as we see below it works in the parametrized case as well. Note that the proposition is quite general and does not require quadratic dependence on the variables  $Y$  (i.e. the polynomials  $Q_i$  need not be quadratic in  $Y$ ).

**Proposition 2.5.** *The semi-algebraic set  $B$  is homotopy equivalent to  $A^h$ .*

*Proof.* We first prove that  $\varphi_2(B) = A^h$ . If  $(y, x) \in A^h$ , then there exists some  $i, 1 \leq i \leq m$ , such that  $(Q_i^h(y, x) \leq 0) \wedge \Phi(x)$ . Then for  $\omega = (-\delta_{1,i}, \dots, -\delta_{m,i})$  (where  $\delta_{ij} = 1$  if  $i = j$ , and 0 otherwise), we see that  $(\omega, y, x) \in B$ . Conversely, if  $(y, x) \in \varphi_2(B)$ , then there exists  $\omega \in \Omega$  such that  $\langle \omega, \mathcal{Q}^h \rangle(y, x) \geq 0$ . Since  $\omega \leq 0$  and  $\omega \neq 0$ , we have that  $(Q_i^h(y, x) \leq 0) \wedge \Phi(x)$  for some  $i, 1 \leq i \leq m$ . This shows that  $(y, x) \in A^h$ .

For  $(y, x) \in \varphi_2(B)$ , the fibre

$$\varphi_2^{-1}(y, x) = \{(\omega, y, x) \mid \omega \in \Omega \text{ such that } \langle \omega, \mathcal{Q}^h \rangle(y, x) \geq 0\},$$

is a non-empty subset of  $\Omega$  defined by a single linear inequality. Thus, each fiber is an intersection of a non-empty closed convex cone with  $\mathbf{S}^{m-1}$ . The proposition now follows from the well-known Vietoris-Smale theorem [22] since by the above observation each fiber is a closed, bounded and contractible semi-algebraic set.  $\square$

We will use the following notation.

*Notation 3.* For a quadratic form  $Q \in \mathbf{R}[Y_0, \dots, Y_\ell]$ , we denote by  $\text{index}(Q)$  the number of negative eigenvalues of the symmetric matrix of the corresponding bilinear form, i.e. of the matrix  $M$  such that  $Q(y) = \langle My, y \rangle$  for all  $y \in \mathbf{R}^{\ell+1}$  (here  $\langle \cdot, \cdot \rangle$  denotes the usual inner product). We also denote by  $\lambda_i(Q), 0 \leq i \leq \ell$  the eigenvalues of  $Q$  in non-decreasing order, i.e.

$$\lambda_0(Q) \leq \lambda_1(Q) \leq \dots \leq \lambda_\ell(Q).$$

For  $F = \Omega \times V$  as above we denote

$$F_j = \{(\omega, x) \in F \mid \text{index}(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)) \leq j\}.$$

It is clear that each  $F_j$  is a closed semi-algebraic subset of  $F$  and we get a filtration of the space  $F$  given by

$$F_0 \subset F_1 \subset \dots \subset F_{\ell+1} = F.$$

**Lemma 2.6.** *The fibre of the map  $\varphi_1$  over a point  $(\omega, x) \in F_j \setminus F_{j-1}$  has the homotopy type of a sphere of dimension  $\ell - j$ .*

*Proof.* Denote  $\lambda_i(\omega, x) = \lambda_i(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x))$  the eigenvalues of  $\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)$  in increasing order. First notice that for  $(\omega, x) \in F_j \setminus F_{j-1}$ ,

$$\lambda_0(\omega, x) \leq \dots \leq \lambda_{j-1}(\omega, x) < 0.$$

Moreover, letting  $W_0(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)), \dots, W_\ell(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x))$  be the co-ordinates with respect to an orthonormal basis consisting of eigenvectors of  $\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)$ , we have that  $\varphi_1^{-1}(\omega, x)$  is the subset of  $\mathbf{S}^\ell = \{\omega\} \times \mathbf{S}^\ell \times \{x\}$  defined by

$$\begin{aligned} \sum_{i=0}^{\ell} \lambda_i(\omega, x) W_i(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x))^2 &\geq 0, \\ \sum_{i=0}^{\ell} W_i(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x))^2 &= 1. \end{aligned}$$

Since  $\lambda_i(\omega, x) < 0$  for all  $0 \leq i < j$ , it follows that for  $(\omega, x) \in F_j \setminus F_{j-1}$ , the fiber  $\varphi_1^{-1}(\omega, x)$  is homotopy equivalent to the  $(k - j)$ -dimensional sphere defined by setting

$$W_0(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)) = \cdots = W_{j-1}(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)) = 0$$

on the sphere defined by

$$\sum_{i=0}^{\ell} W_i(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x))^2 = 1.$$

□

For each  $(\omega, x) \in F_j \setminus F_{j-1}$ , let  $L_j^+(\omega, x) \subset \mathbb{R}^{\ell+1}$  denote the sum of the non-negative eigenspaces of  $\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)$ . Since  $\text{index}(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)) = j$  stays invariant as  $(\omega, x)$  varies over  $F_j \setminus F_{j-1}$ ,  $L_j^+(\omega, x)$  varies continuously with  $(\omega, x)$ .

We denote by  $C$  the semi-algebraic set defined by the following. We first define for  $0 \leq j \leq \ell + 1$

$$(2.12) \quad C_j = \{(\omega, y, x) \mid (\omega, x) \in F_j \setminus F_{j-1}, y \in L_j^+(\omega, x), |y| = 1\},$$

and finally we define

$$(2.13) \quad C = \bigcup_{j=0}^{\ell+1} C_j.$$

The following proposition relates the homotopy type of  $B$  to that of  $C$ .

**Proposition 2.7.** *The semi-algebraic set  $C$  defined by (2.13) is homotopy equivalent to  $B$ .*

Before proving the Proposition we give an illustrative example.

**Example 2.8.** In this example  $m = 2, \ell = 3, k = 0$ , and  $\mathcal{Q}^h = \{Q_1^h, Q_2^h\}$  with

$$\begin{aligned} Q_1^h &= -Y_0^2 - Y_1^2 - Y_2^2, \\ Q_2^h &= Y_0^2 + 2Y_1^2 + 3Y_2^2. \end{aligned}$$

The set  $\Omega$  is the part of the unit circle in the third quadrant of the plane, and  $F = \Omega$  in this case (since  $k = 0$ ). In the following Figure 1, we display the fibers of the map  $\varphi_1^{-1}(\omega) \subset B$  for a sequence of values of  $\omega$  starting from  $(-1, 0)$  and ending at  $(0, -1)$ . We also show the spheres,  $C \cap \varphi_1^{-1}(\omega)$ , of dimensions 0, 1, and 2, that these fibers retract to. At  $\omega = (-1, 0)$ , it is easy to verify that  $\text{index}(\langle \omega, \mathcal{Q}^h \rangle) = 3$ , and the fiber  $\varphi_1^{-1}(\omega) \subset B$  is empty. Starting from  $\omega = (-\cos(\arctan(1)), -\sin(\arctan(1)))$  we have  $\text{index}(\langle \omega, \mathcal{Q}^h \rangle) = 2$ , and the fiber  $\varphi_1^{-1}(\omega)$  consists of the union of two spherical caps, homotopy equivalent to  $\mathbf{S}^0$ . Starting from  $\omega = (-\cos(\arctan(1/2)), -\sin(\arctan(1/2)))$  we have  $\text{index}(\langle \omega, \mathcal{Q}^h \rangle) = 1$ , and the fiber  $\varphi_1^{-1}(\omega)$  is homotopy equivalent to  $\mathbf{S}^1$ . Finally, starting from  $\omega = (-\cos(\arctan(1/3)), -\sin(\arctan(1/3)))$ ,  $\text{index}(\langle \omega, \mathcal{Q}^h \rangle) = 0$ , and the fiber  $\varphi_1^{-1}(\omega)$  stays equal to  $\mathbf{S}^2$ .

*Proof of Proposition 2.7.* We construct a deformation retraction of  $B$  to  $C$  as follows. Let

$$(2.14) \quad B_j = \bigcup_{i=j}^{\ell+1} C_i \cup \varphi_1^{-1}(F_{j-1}),$$



FIGURE 1. Type change:  $\emptyset \rightarrow \mathbf{S}^0 \rightarrow \mathbf{S}^1 \rightarrow \mathbf{S}^2$ .  $\emptyset$  is not shown.

and note that  $B_{\ell+1} = B, \dots, B_0 = C$ .

We construct a sequence of homotopy equivalences from  $B_{j+1}$  to  $B_j$  for every  $j = \ell, \dots, 0$  as follows.

Let  $0 \leq j \leq \ell$ . For each  $(\omega, x) \in F_j \setminus F_{j-1}$ , we retract the fiber  $\varphi_1^{-1}(\omega, x)$  to the  $(\ell - j)$ -dimensional sphere,  $L_j^+(\omega, x) \cap \mathbf{S}^\ell$  as follows. Let

$$W_0(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)), \dots, W_\ell(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x))$$

be the co-ordinates with respect to an orthonormal basis consisting of eigenvectors

$$e_0(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)), \dots, e_\ell(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x))$$

of  $\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)$  corresponding to the non-decreasing sequence of eigenvalues of  $\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)$ . Then  $\varphi_1^{-1}(\omega, x)$  is the subset of  $\mathbf{S}^\ell$  defined by

$$\sum_{i=0}^{\ell} \lambda_i(\omega, x) W_i(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x))^2 \geq 0,$$

$$\sum_{i=0}^{\ell} W_i(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x))^2 = 1.$$

and  $L_j^+(\omega, x)$  is defined by  $W_0(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)) = \dots = W_{j-1}(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)) = 0$ . We retract  $\varphi_1^{-1}(\omega, x)$  to the  $(\ell - j)$ -dimensional sphere,  $L_j^+(\omega, x) \cap \mathbf{S}^\ell$  by the retraction sending,  $(w_0, \dots, w_\ell) \in \varphi_1^{-1}(\omega, x)$ , at time  $t$  to  $(tw_0, \dots, tw_{j-1}, t'w_j, \dots, t'w_\ell)$ ,

where  $0 \leq t \leq 1$ , and  $t' = \left( \frac{1 - t^2 \sum_{i=0}^{j-1} w_i^2}{\sum_{i=j}^{\ell} w_i^2} \right)^{1/2}$ . Notice that even though the local

co-ordinates  $W_0(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)), \dots, W_\ell(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x))$  in  $\mathbf{R}^{\ell+1}$  with respect to the orthonormal basis  $(e_0(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)), \dots, e_\ell(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)))$  of eigenvectors may not be uniquely defined at the point  $(\omega, x)$  (for instance, if the quadratic form  $\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)$  has multiple eigen-values), the retraction is still well-defined since it only depends on the decomposition of  $\mathbf{R}^{\ell+1}$  into orthogonal complements  $\text{span}(e_0, \dots, e_{j-1})$  and  $\text{span}(e_j, \dots, e_\ell)$  which is well defined.

We can thus retract simultaneously all fibers over  $F_j \setminus F_{j-1}$  continuously, to obtain  $B_j \subset B$ , which is moreover homotopy equivalent to  $B_{j+1}$ .  $\square$

Notice that the semi-algebraic set  $C_j$  is a  $\mathbf{S}^{\ell-j}$ -bundle over  $F_j \setminus F_{j-1}$  under the map  $\varphi_1$ , and  $C$  is a union of these sphere bundles. Since we have good bounds on the number as well as the degrees of polynomials used to define the bases,  $F_j \setminus F_{j-1}$ , we can bound the Betti numbers of each  $C_j$  using Proposition 2.2. However, the  $C_j$  could be possibly glued to each other in complicated ways, and thus knowing upper bounds on the Betti numbers of each  $C_j$  does not immediately produce a bound on Betti numbers of  $C$ . In order to get around this difficulty, we consider

certain closed subsets,  $F'_j$  of  $F$ , where each  $F'_j$  is an infinitesimal deformation of  $F_j \setminus F_{j-1}$ , and form the base of a  $\mathbf{S}^{\ell-j}$ -bundle  $C'_j$ . Additionally, the  $C'_j$  are glued to each other along sphere bundles over  $F'_j \cap F'_{j-1}$ , and their union,  $C'$ , is homotopy equivalent to  $C$ . Since the  $C'_j$  are closed and bounded semi-algebraic sets, and we have good bounds on their Betti numbers as well as the Betti numbers of their non-empty intersections, we can use Mayer-Vietoris inequalities (Proposition 2.1) to bound the Betti numbers of  $C'$ , which in turn are equal to the Betti numbers of  $C$ .

We now make precise the argument outlined above.

Let  $\Lambda \in \mathbf{R}[Z_1, \dots, Z_m, X_1, \dots, X_k, T]$  be the polynomial defined by

$$\begin{aligned} \Lambda &= \det(T \cdot \text{Id}_{\ell+1} - M_{Z \cdot \mathcal{Q}^h}), \\ &= T^{\ell+1} + C_\ell T^\ell + \dots + C_0, \end{aligned}$$

where  $Z \cdot \mathcal{Q}^h = \sum_{i=1}^m Z_i Q_i^h$ , and each  $C_i \in \mathbf{R}[Z_1, \dots, Z_m, X_1, \dots, X_k]$ .

Note that for  $(\omega, x) \in \Omega \times \mathbf{R}^k$ , the polynomial  $\Lambda(\omega, x, T)$ , being the characteristic polynomial of a real symmetric matrix, has all its roots real. It then follows from Descartes' rule of signs (see for instance [9]), that for each  $(\omega, x) \in \Omega \times \mathbf{R}^k$ ,  $\text{index}(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x))$  is determined by the sign vector

$$(\text{sign}(C_\ell(\omega, x)), \dots, \text{sign}(C_0(\omega, x))).$$

More precisely, the number of sign variations in the sequence

$$\text{sign}(C_0(\omega, x)), \dots, (-1)^i \text{sign}(C_i(\omega, x)), \dots, (-1)^\ell \text{sign}(C_\ell(\omega, x)), +1$$

is equal to  $\text{index}(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x))$ . Hence, denoting

$$(2.15) \quad \mathcal{C} = \{C_0, \dots, C_\ell\} \subset \mathbf{R}[Z_1, \dots, Z_m, X_1, \dots, X_k],$$

we have

**Lemma 2.9.**  $F_j$  is the intersection of  $F$  with a  $\mathcal{C}$ -closed semi-algebraic set  $D_j \subset \mathbf{R}^{m+k}$ , for each  $0 \leq j \leq \ell + 1$ .  $\square$

*Notation 4.* let

$$0 < \varepsilon_0 \ll \dots \ll \varepsilon_{\ell+1} \ll 1.$$

be infinitesimals. For  $0 \leq j \leq \ell + 1$ , we denote by  $\mathbf{R}_j$  the field  $\mathbf{R}\langle \varepsilon_{\ell+1} \dots \varepsilon_j \rangle$ .

Let

$$\mathcal{C}'_j = \{P \pm \varepsilon_j, P \in \mathcal{C}\}.$$

Given  $\rho \in \text{Sign}(\mathcal{C})$ , and  $0 \leq j \leq \ell + 1$ , we denote by  $\mathcal{R}(\rho_j^\varepsilon) \subset \mathbf{R}_j^{m+k}$  the  $\mathcal{C}'_j$ -semi-algebraic set defined by the formula  $\rho_j^\varepsilon$  obtained by taking the conjunction of

$$\begin{aligned} -\varepsilon_j \leq P \leq \varepsilon_j &\text{ for each } P \in \mathcal{C} \text{ such that } \rho(P) = 0, \\ P \geq -\varepsilon_j, &\text{ for each } P \in \mathcal{C} \text{ such that } \rho(P) = 1, \\ P \leq \varepsilon_j, &\text{ for each } P \in \mathcal{C} \text{ such that } \rho(P) = -1. \end{aligned}$$

Similarly, we denote by  $\mathcal{R}(\rho_j^o) \subset \mathbf{R}_j^{m+k}$  the  $\mathcal{C}'_j$ - semi-algebraic set defined by the formula  $\rho^o$  obtained by taking the conjunction of

$$\begin{aligned} -\varepsilon_j < P < \varepsilon_j &\text{ for each } P \in \mathcal{C} \text{ such that } \rho(P) = 0, \\ P > -\varepsilon_j, &\text{ for each } P \in \mathcal{C} \text{ such that } \rho(P) = 1, \\ P < \varepsilon_j, &\text{ for each } P \in \mathcal{C} \text{ such that } \rho(P) = -1. \end{aligned}$$

Since the semi-algebraic sets  $D_j$  defined above in Lemma 2.9 are  $\mathcal{C}$ -semi-algebraic sets, each  $D_j$  is defined by a disjunction of sign conditions on  $\mathcal{C}$ . More precisely, for each  $0 \leq j \leq \ell + 1$  let  $D_j$  be defined by the formula

$$D_j = \bigcup_{\rho \in \Sigma_j} \mathcal{R}(\rho),$$

where  $\Sigma_j \subset \text{Sign}(\mathcal{C})$ .

For each  $j, 0 \leq j \leq \ell + 1$ , let

$$\begin{aligned} D_j^o &= \bigcup_{\rho \in \Sigma_j} \mathcal{R}(\rho_j^o), \\ D_j^c &= \bigcup_{\rho \in \Sigma_j} \mathcal{R}(\rho_j^c), \\ D_j' &= \text{Ext}(D_j^c, \mathbf{R}_{j-1}) \setminus D_{j-1}^o, \\ F_j' &= \text{Ext}(F, \mathbf{R}_{j-1}) \cap D_j', \end{aligned}$$

where we denote by  $D_{-1}^o = \emptyset$ .

**Lemma 2.10.** *For  $0 \leq j + 1 < i \leq \ell + 1$ ,*

$$\text{Ext}(D_i', \mathbf{R}_{j-1}) \cap D_j' = \emptyset.$$

*Proof.* The inclusions

$$\begin{aligned} D_{j-1} &\subset D_j \subset D_{i-1} \subset D_i, \\ D_{j-1}^o &\subset \text{Ext}(D_j^c, \mathbf{R}_{j-1}) \subset \text{Ext}(D_{i-1}^o, \mathbf{R}_{j-1}) \subset \text{Ext}(D_i^c, \mathbf{R}_{j-1}) \end{aligned}$$

follow directly from the definitions of the sets

$$D_i, D_j, D_{j-1}, D_i^c, D_j^c, D_{i-1}^o, D_{j-1}^o,$$

and the fact that

$$\varepsilon_i \gg \varepsilon_{i-1} \gg \varepsilon_j \gg \varepsilon_{j-1}.$$

It follows immediately that

$$D_i' = \text{Ext}(D_i^c, \mathbf{R}_{j-1}) \setminus \text{Ext}(D_{i-1}^o, \mathbf{R}_{j-1})$$

is disjoint from  $\text{Ext}(D_j^c, \mathbf{R}_{j-1})$ , and hence also from  $D_j'$ .  $\square$

We now associate to each  $F_j'$  an  $\mathbf{S}^{\ell-j}$ -bundle as follows.

For each  $(\omega, x) \in F_j'' = \text{Ext}(F_j, \mathbf{R}_{j-2}) \setminus F_{j-1}'$ , let  $L_j^+(\omega, x) \subset \mathbf{R}_{j-2}^{\ell+1}$  denote the sum of the non-negative eigenspaces of  $\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)$  (i.e.  $L_j^+(\omega, x)$  is the largest linear subspace of  $\mathbf{R}_{j-2}^{\ell+1}$  on which  $\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)$  is positive semi-definite). Since  $\text{index}(\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)) = j$  stays invariant as  $(\omega, x)$  varies over  $F_j''$ ,  $L_j^+(\omega, x)$  varies continuously with  $(\omega, x)$ .

Let

$$\lambda_0(\omega, x) \leq \cdots \leq \lambda_{j-1}(\omega, x) < 0 \leq \lambda_j(\omega, x) \leq \cdots \leq \lambda_\ell(\omega, x)$$

be the eigenvalues of  $\langle \omega, \mathcal{Q}^h \rangle(\cdot, x)$  for  $(\omega, x) \in F_j''$ . There is a continuous extension of the map sending  $(\omega, x) \mapsto L_j^+(\omega, x)$  to  $(\omega, x) \in \text{Ext}(F_j', \mathbf{R}_{j-2})$ . To see this observe that for  $(\omega, x) \in F_j''$  the block of the first  $j$  (negative) eigenvalues,  $\lambda_0(\omega, x) \leq \cdots \leq \lambda_{j-1}(\omega, x)$ , and hence the sum of the eigenspaces corresponding to them can be

extended continuously to any infinitesimal neighborhood of  $F_j''$ , and in particular to  $\text{Ext}(F_j', \mathbf{R}_{j-2})$ . Now  $L_j^+(\omega, x)$  is the orthogonal complement of the sum of the eigenspaces corresponding to the block of negative eigenvalues,  $\lambda_0(\omega, x) \leq \dots \leq \lambda_{j-1}(\omega, x)$ .

We denote by  $C_j' \subset F_j' \times \mathbf{R}_{j-1}^{\ell+1}$  the semi-algebraic set defined by

$$C_j' = \{(\omega, y; x) \mid (\omega, x) \in F_j', y \in L_j^+(\omega, x), |y| = 1\}.$$

Abusing notation, we denote by  $\varphi_1$  the projection  $C_j' \rightarrow F_j'$ , which makes  $C_j'$  the total space of a  $\mathbf{S}^{\ell-j}$ -bundle over  $F_j'$ .

The following proposition, expressing in precise terms the fact that  $C_j' \cap C_{j-1}'$  is a  $\mathbf{S}^{\ell-j}$ -bundle over  $F_j' \cap F_{j-1}'$  under the map  $\varphi_1$ , follows directly from the definition of the sets  $C_j'$  and  $F_j'$ .

**Proposition 2.11.** *For every  $j$  from  $\ell$  to 1,  $C_{j-1}' \cap \text{Ext}(C_j', \mathbf{R}_{j-2})$  is a  $\mathbf{S}^{\ell-j}$ -bundle over  $\text{Ext}(F_j', \mathbf{R}_{j-2}) \cap F_{j-1}'$  under the map  $\varphi_1$ .  $\square$*

We also have the following.

**Proposition 2.12.** *The semi-algebraic set*

$$C' = \bigcup_{j=0}^{\ell+1} \text{Ext}(C_j', \mathbf{R}_0)$$

*is homotopy equivalent to  $\text{Ext}(C, \mathbf{R}_0)$ .*

*Proof.* First observe that  $C = \lim_{\varepsilon_{\ell+1}} C'$  where  $C$  is the semi-algebraic set defined in (2.13) above.

Now let

$$C_0 = \lim_{\varepsilon_0} C',$$

$$C_i = \lim_{\varepsilon_i} C_{i-1}, 1 \leq i \leq \ell + 1.$$

Notice that each  $C_i$  is a closed and bounded semi-algebraic set. Also, let  $C_{i-1,t} \subset \mathbf{R}_{i-1}^{\ell+k}$  be the semi-algebraic set obtained by replacing  $\varepsilon_i$  in the definition of  $C_{i-1}$  by the variable  $t$ . Then there exists  $t_0 > 0$ , such that for all  $0 < t_1 < t_2 \leq t_0$ ,  $C_{i-1,t_1} \subset C_{i-1,t_2}$ .

It follows (see [9, Lemma 16.17]) that for each  $i$ ,  $0 \leq i \leq \ell + 1$ ,  $\text{Ext}(C_i, \mathbf{R}_i)$  is homotopy equivalent to  $C_{i-1}$  (where  $C_{-1} = C'$ ).

The proposition is now a consequence of Proposition 2.7.  $\square$

*Proof of Theorem 2.3.* In light of Propositions 2.7 and 2.12, it suffices to bound the Betti numbers of the semi-algebraic set  $C'$ . Now,

$$C' = \bigcup_{j=0}^{\ell+1} \text{Ext}(C_j', \mathbf{R}_0).$$

By (2.1) it suffices to bound the Betti numbers of the various intersections amongst the sets  $\text{Ext}(C_j', \mathbf{R}_0)$ 's. However, by Lemma 2.10, the only non-empty intersections among  $\text{Ext}(C_j', \mathbf{R}_0)$ 's are of the form  $\text{Ext}(C_j', \mathbf{R}_0) \cap \text{Ext}(C_{j+1}', \mathbf{R}_0)$ . Using Proposition 2.2 and Proposition 2.11 we have that  $b(C_j')$  (resp.  $b(C_j' \cap C_{j+1}')$ ) is bounded by  $2b(F_j')$  (resp.  $2b(\text{Ext}(F_j', \mathbf{R}_0) \cap \text{Ext}(F_{j+1}', \mathbf{R}_0))$ ).

Finally, each  $F'_j$  (resp.  $\text{Ext}(F'_j, \mathbb{R}_0) \cap \text{Ext}(F'_{j+1}, \mathbb{R}_0)$ ) is a bounded  $\mathcal{P}'_j$ -closed semi-algebraic set, where  $\mathcal{P}'_j = \mathbb{R}[Z_1, \dots, Z_m, X_1, \dots, X_k]$  is defined by

$$\mathcal{P}'_j = \mathcal{P} \cup \mathcal{C}'_j \cup \bigcup_{i=1}^m \{Z_i\}.$$

Note that

$$\begin{aligned} \deg(P) &\leq d, P \in \mathcal{P}, \\ \deg(P) &\leq d(\ell + 1), P \in \mathcal{C}'_j, \\ \#(\mathcal{P}) &= s, \\ \#(\mathcal{C}'_j) &= 2(\ell + 1). \end{aligned}$$

Now applying Theorem 1.1 we obtain that

$$(2.16) \quad b(F'_j), b(\text{Ext}(F'_j, \mathbb{R}_0) \cap \text{Ext}(F'_{j+1}, \mathbb{R}_0)) \leq (O((s + \ell + m)\ell d))^{m+k}.$$

Applying Proposition 2.2 and (2.16) we obtain immediately that

$$(2.17) \quad b(\mathcal{C}'_j), b(\text{Ext}(\mathcal{C}'_j, \mathbb{R}_0) \cap \text{Ext}(\mathcal{C}'_{j+1}, \mathbb{R}_0)) \leq (O((s + \ell + m)\ell d))^{m+k}.$$

Finally, using inequality (2.1) and Lemma 2.10 we get that

$$(2.18) \quad b(C') = b\left(\bigcup_{j=0}^{\ell} \mathcal{C}'_j\right) \leq \ell^2 (O((s + \ell + m)\ell d))^{m+k}.$$

The theorem now follows from Propositions 2.12, 2.5 and 2.7.  $\square$

*Proof of Theorem 2.4.* Apply (2.2) together with Theorem 2.3.  $\square$

**2.3. General Case.** We now prove the general version of Theorem 2.3. We follow Notation 2.

**Theorem 2.13.** *Let  $W \subset \mathbb{R}^\ell \times \mathbb{R}^k$  be semi-algebraic set defined by*

$$W = \bigcap_{Q \in \mathcal{Q}} \{(y, x) \mid Q(y, x) \leq 0 \wedge \Phi(x)\},$$

where  $\Phi(x)$  is a  $\mathcal{P}$ -closed formula defining a bounded  $\mathcal{P}$ -closed semi-algebraic set  $V \subset \mathbb{R}^k$ .

Then

$$(2.19) \quad b(W) \leq \ell^2 (O((s + \ell + m)\ell d))^{m+k}.$$

*Proof.* Let  $1 \gg \varepsilon > 0$  be an infinitesimal and let  $B_\ell(0, 1/\varepsilon)$  denote the closed ball in  $\mathbb{R}\langle\varepsilon\rangle^\ell$  centered at the origin and of radius  $1/\varepsilon$ .

Let  $W_\varepsilon \subset \mathbb{R}^{\ell+k}$  be the set defined by

$$W_\varepsilon = W \cap \left( B_\ell(0, 1/\varepsilon) \times \mathbb{R}^k \right)$$

It follows from the local conical structure of semi-algebraic sets at infinity [14, Theorem 9.3.6] that  $W_\varepsilon$  has the same homotopy type as  $\text{Ext}(W, \mathbb{R}\langle\varepsilon\rangle)$ .

Let

$$Q_0 = \varepsilon^2(Y_1^2 + \dots + Y_\ell^2) - 1,$$

and  $W_\varepsilon^h \subset \mathbb{S}^\ell \times \mathbb{R}\langle\varepsilon\rangle^k$  be the semi-algebraic set defined by

$$W_\varepsilon^h = \bigcap_{i=0}^m \{(y, x) \mid |y| = 1 \wedge Q_i^h(y, x) \leq 0 \wedge \Phi(x)\}.$$

It is clear that  $W_\varepsilon^h$  is a union of two disjoint, closed and bounded semi-algebraic sets, each homeomorphic to  $W_\varepsilon$ . Hence, for every  $i = 0, \dots, k + \ell - 1$

$$(2.20) \quad b_i(W_\varepsilon^h) = 2b_i(W_\varepsilon) = 2b_i(W).$$

The theorem is proved by applying Theorem 2.4 to  $W_\varepsilon^h$ .  $\square$

**2.4. Proof of Theorem 1.5.** We are now in a position to prove Theorem 1.5. We first need a few preliminary results.

Given a list of polynomials  $\mathcal{A} = \{A_1, \dots, A_t\}$  with coefficients in  $\mathbb{R}$ , we introduce  $t$  infinitesimals,  $1 \gg \delta_1 \gg \dots \gg \delta_t > 0$ .

We define  $\mathcal{A}_{>i} = \{A_{i+1}, \dots, A_t\}$  and

$$\begin{aligned} \Sigma_i &= \{A_i = 0, A_i = \delta_i, A_i = -\delta_i, A_i \geq 2\delta_i, A_i \leq -2\delta_i\}, \\ \Sigma_{\leq i} &= \{\Psi \mid \Psi = \bigwedge_{j=1, \dots, i} \Psi_j, \Psi_j \in \Sigma_j\}. \end{aligned}$$

If  $\Phi$  is any  $\mathcal{A}$ -closed formula, we denote by  $\mathcal{R}_i(\Phi)$  the extension of  $\mathcal{R}(\Phi)$  to  $\mathbb{R}\langle \delta_1, \dots, \delta_i \rangle^k$ . For  $\Psi \in \Sigma_{\leq i}$ , we denote by  $\mathcal{R}_i(\Psi)$  the realization of  $\Psi$  and by  $b(\Psi)$  the sum of the Betti numbers of  $\mathcal{R}_i(\Psi)$ .

**Proposition 2.14.** *For every  $\mathcal{A}$ -closed formula  $\Phi$ ,*

$$b(\Phi) \leq \sum_{\Psi \in \Sigma_{\leq t}} b(\Psi).$$

*Proof.* See [9, Proposition 7.39].  $\square$

*Proof of Theorem 1.5.* First note that we can assume (if necessary by adding to  $\mathcal{Q}$  an extra quadratic inequality) that the set  $S$  is bounded.

Denoting  $\mathcal{P} = \{P_1, \dots, P_s\}$ , define  $\mathcal{B} = \{B_1, \dots, B_{s+m}\}$ , where

$$B_i = \begin{cases} Q_i, & 1 \leq i \leq m, \\ P_{i-m}, & m+1 \leq i \leq m+s. \end{cases}$$

It follows from Proposition 2.14 that in order to bound  $b(S)$ , it suffices to bound  $b(T)$ , where  $T$  is defined by

$$\bigwedge_{i=1}^{s+m} B_i^2 (B_i^2 - \delta_i^2)^2 (B_i^2 - 4\delta_i^2) \geq 0.$$

We now introduce  $m$  new variables,  $Z_1, \dots, Z_m$  and let

$$\mathcal{A} = \{A_1, \dots, A_{s+m}\} \subset \mathbb{R}[Y_1, \dots, Y_\ell, X_1, \dots, X_k, Z_1, \dots, Z_m]$$

be defined by

$$A_i = \begin{cases} Z_i, & 1 \leq i \leq m, \\ P_{i-m}, & m+1 \leq i \leq m+s. \end{cases}$$

Consider the semi-algebraic set  $T' \subset \mathbb{R}^{m+k+l}$  defined by

$$\bigwedge_{i=1}^{s+m} A_i^2 (A_i^2 - \delta_i^2)^2 (A_i^2 - 4\delta_i^2) \geq 0 \wedge \bigwedge_{i=1}^m (Z_i - Q_i = 0).$$

Clearly,  $T$  is homeomorphic to  $T'$ . Notice that the number of polynomials in the definition of  $T'$ , which depend only on  $X$  and  $Z$  is  $s + m$ , and the degrees of these polynomials are bounded by  $6d$ . The number of polynomials depending on  $X, Y$  and  $Z$  is  $m$  and these are of degree at most 2 in  $Y$  and at most  $d$  in the remaining variables. Thus, we are in a position to apply Theorem 2.13 to obtain that

$$b(S) \leq b(T') \leq \ell^2(O(s + \ell + m)\ell d)^{k+2m}.$$

This proves the theorem.  $\square$

*Proof of Corollary 1.6.* Introduce  $k$  new variables,  $Z_1, \dots, Z_k$ , and let  $\tilde{Q}_i = Z_i - Q_i$  for  $1 \leq i \leq k$ .

Define the semi-algebraic set  $\tilde{S} \subset \mathbb{R}^{\ell+k}$  by

$$\tilde{S} = \{(y, x) \mid \bigwedge_{i=1}^k \tilde{Q}_i(y, x) = 0 \wedge \Phi(x)\}.$$

It is clear that  $\tilde{S}$  is semi-algebraically homeomorphic to  $S$ . Applying Theorem 1.5 to  $\tilde{S}$ , we obtain the desired bound.  $\square$

### 3. ALGORITHM FOR COMPUTING THE EULER-POINCARÉ CHARACTERISTIC

We first need a few preliminary definitions and results.

**3.1. Some Algorithmic and Mathematical Preliminaries.** Recall that for a closed and bounded semi-algebraic set  $S \subset \mathbb{R}^k$ , the Euler-Poincaré characteristic of  $S$ , denoted by  $\chi(S)$ , is defined by

$$\chi(S) = \sum_{i=0}^k (-1)^i b_i(S).$$

Moreover, we have the following additivity property which is classical.

**Proposition 3.1.** *Let  $X_1$  and  $X_2$  be closed and bounded semi-algebraic sets. Then*

$$\chi(X_1 \cap X_2) = \chi(X_1) + \chi(X_2) - \chi(X_1 \cup X_2).$$

Recall also that for a locally closed semi-algebraic set  $S$ , the Borel-Moore Euler-Poincaré characteristic of  $S$ , denoted by  $\chi^{BM}(S)$ , is defined by

$$\chi^{BM}(S) = \sum_{i=0}^k (-1)^i b_i^{BM}(S),$$

where  $b_i^{BM}(S)$  denotes the dimension of the  $i$ -th Borel-Moore homology group  $H_i^{BM}(S, \mathbb{Z}/2\mathbb{Z})$  of  $S$ . Note that  $\chi^{BM}(S) = \chi(S)$  for  $S$  closed and bounded.

Note that  $\chi^{BM}(S)$  has the following classically known (see e.g. [9] for a proof) additivity property.

**Proposition 3.2.** *Let  $X_1$  and  $X_2$  be locally closed semi-algebraic sets such that  $X_1 \cap X_2 = \emptyset$ . Then*

$$\chi^{BM}(X_1 \cup X_2) = \chi^{BM}(X_1) + \chi^{BM}(X_2),$$

*provided that  $X_1 \cup X_2$  is locally closed as well.*

Let  $Z \subset \mathbb{R}^k$  and  $Q \in \mathbb{R}[X_1, \dots, X_k]$ . We define

$$\begin{aligned}\mathcal{R}(Q = 0, Z) &= \{x \in Z \mid Q(x) = 0\}, \\ \mathcal{R}(Q > 0, Z) &= \{x \in Z \mid Q(x) > 0\}, \\ \mathcal{R}(Q < 0, Z) &= \{x \in Z \mid Q(x) < 0\}.\end{aligned}$$

**Corollary 3.3.** *Let  $Z \subset \mathbb{R}^k$  be a locally closed semi-algebraic set. Then*

$$\chi^{BM}(Z) = \chi^{BM}(\mathcal{R}(Q = 0, Z)) + \chi^{BM}(\mathcal{R}(Q > 0, Z)) + \chi^{BM}(\mathcal{R}(Q < 0, Z)).$$

*Notation 5.* Let  $Z \subset \mathbb{R}^k$  be a locally closed semi-algebraic set and let  $\mathcal{A}$  be a finite subset of  $\mathbb{R}[X_1, \dots, X_k]$ .

The realization of the sign condition  $\rho \in \{0, 1, -1\}^{\mathcal{A}}$  on  $Z$  is

$$\mathcal{R}(\rho, Z) = \{x \in Z \mid \bigwedge_{A \in \mathcal{A}} \text{sign}(A(x)) = \rho(A)\},$$

and its Borel-Moore Euler-Poincaré characteristic is denoted  $\chi^{BM}(\rho, Z)$ .

We denote by  $\text{Sign}(\mathcal{A}, Z)$  the list of  $\rho \in \{0, 1, -1\}^{\mathcal{A}}$  such that  $\mathcal{R}(\rho, Z)$  is non-empty. We denote by  $\chi^{BM}(\mathcal{A}, Z)$  the list of Euler-Poincaré characteristics  $\chi^{BM}(\rho, Z) = \chi^{BM}(\mathcal{R}(\rho, Z))$  for  $\rho \in \text{Sign}(\mathcal{A}, Z)$ .

Finally, given two finite families of polynomials,  $\mathcal{A} \subset \mathcal{A}'$ , and  $\rho \in \{0, 1, -1\}^{\mathcal{A}}$ ,  $\rho' \in \{0, 1, -1\}^{\mathcal{A}'}$ , we define  $\rho \prec \rho'$  by: for all  $P \in \mathcal{A}$ ,  $\rho(P) = \rho'(P)$ .

We will use the following algorithm for computing the list  $\chi^{BM}(\mathcal{A}, Z)$  described in [9]. We recall here the input, output and complexity of the algorithm.

ALGORITHM 1 (Euler-Poincaré Characteristic of Sign Conditions).

INPUT A finite list  $\mathcal{A} = \{A_1, \dots, A_t\}$  of polynomials in  $\mathbb{R}[X_1, \dots, X_k]$ .

OUTPUT The list  $\chi^{BM}(\mathcal{A})$ .

COMPLEXITY: Let  $d$  be a bound on the degrees of the polynomials in  $\mathcal{A}$ , and  $t = \#\mathcal{A}$ . The number of arithmetic operations is bounded by

$$t^{k+1}O(d)^k + t^k((k \log_2(s) + k \log_2(d))d)^{O(k)}.$$

The algorithm also involves the inversion of matrices of size  $t^k O(d)^k$  with integer coefficients.

**3.2. Algorithms for the Euler-Poincaré characteristic.** We first deal with the special case of polynomials which are homogeneous and of degree two in the variables  $Y_0, \dots, Y_\ell$ , and in this case we describe algorithms (Algorithms 2 and 3 below) for computing the Euler-Poincaré characteristic of the sets  $A^h$  and  $W^h$  respectively. We then use Algorithm 3 to derive algorithms for computing the Euler-Poincaré characteristic in the general case (Algorithms 4 and 5 below).

**3.2.1. Homogeneous quadratic polynomials.**

ALGORITHM 2 (Euler-Poincaré characteristic, homogeneous union case).

INPUT

- A family of polynomials,  $\mathcal{Q}^h \subset \mathbb{R}[Y_0, \dots, Y_\ell, X_1, \dots, X_k]$ , with  $\deg_Y(Q) \leq 2$ ,  $\deg_X(Q) \leq d$ ,  $Q \in \mathcal{Q}^h$ ,  $\#\mathcal{Q}^h = m$ , homogeneous with respect to  $Y$ ,
- another family,  $\mathcal{P} \subset \mathbb{R}[X_1, \dots, X_k]$  with  $\deg_X(P) \leq d$ ,  $P \in \mathcal{P}$ ,  $\#\mathcal{P} = s$ ,

- a formula  $\Phi$  defining a bounded  $\mathcal{P}$ -closed semi-algebraic set  $V$ .

OUTPUT the Euler-Poincaré characteristic  $\chi(A^h)$ , where  $A^h$  is the semi-algebraic set defined by

$$A^h = \bigcup_{Q \in \mathcal{Q}^h} \{(y, x) \mid |y| = 1 \wedge Q(y, x) \leq 0 \wedge \Phi(x)\}.$$

PROCEDURE

Step 1. Let  $Z = (Z_1, \dots, Z_m)$  be variables and let  $M$  be the symmetric matrix with entries in  $\mathbb{R}[Z_1, \dots, Z_m, X_1, \dots, X_k]$  associated to the quadratic form  $\langle Z, \mathcal{Q}^h \rangle$ . Obtain  $C_i \in \mathbb{R}[Z_1, \dots, Z_m, X_1, \dots, X_k]$  by computing the following determinant.

$$\det(T \cdot \text{Id}_{\ell+1} - M) = T^{\ell+1} + C_\ell T^\ell + \dots + C_0.$$

Step 2. Compute  $\chi^{BM}(\mathcal{C}, F)$  as follows. Call Algorithm 1 with input  $\mathcal{C}' = \mathcal{C} \cup \mathcal{P}$ . Compute from the output the list  $\chi^{BM}(\mathcal{C}, F)$ , using the additivity property of the Borel-Moore Euler-Poincaré characteristic (Proposition 3.2). For each  $\rho \in \{0, +1, -1\}^{\mathcal{C}}$ , such that there exists  $\rho' \in \text{Sign}(\mathcal{C}', F)$  with  $\rho \prec \rho'$  (see Notation 5) and  $\rho'(Z_j) \in \{0, -1\}$  for  $1 \leq j \leq m$ , compute

$$\chi^{BM}(\rho, F) = \sum_{\substack{\rho', \rho \prec \rho', \\ \rho'(Z_j) \in \{0, -1\}, 1 \leq j \leq s}} \chi^{BM}(\rho', F).$$

Step 3. Output

$$\chi(A^h) = \sum_{\rho \in \text{Sign}(\mathcal{C}, F)} \chi^{BM}(\mathcal{R}(\rho, F)) \cdot (1 + (-1)^{(k-n(\rho))}),$$

where  $n(\rho)$  denotes the number of sign variations in the sequence,

$$\rho(C_0), \dots, (-1)^i \rho(C_i), \dots, (-1)^\ell \rho(C_\ell), +1.$$

PROOF OF CORRECTNESS: It follows from Lemma 2.6 that for any  $\rho \in \text{Sign}(\mathcal{C}, F)$

$$\chi^{BM}(\varphi_1^{-1}(\mathcal{R}(\rho))) = \chi^{BM}(\mathcal{R}(\rho)) \cdot (1 + (-1)^{(k-n(\rho))}).$$

Also, by virtue of Proposition 2.5 we have that

$$\chi^{BM}(B) = \chi(A^h), \quad \text{where } B = \bigcup_{\rho \in \text{Sign}(\mathcal{C}, F)} \varphi^{-1}(\mathcal{R}(\rho)).$$

The correctness of the algorithm is now a consequence of the additivity property of the Borel-Moore Euler Poincaré characteristic (Proposition 3.2) and the correctness of Algorithm 1.  $\square$

COMPLEXITY ANALYSIS: The complexity of the algorithm is  $(\ell s m d)^{O(m+k)}$  using the complexity of Algorithm 1.  $\square$

We are now in a position to describe the algorithm for computing the Euler-Poincaré characteristic in the homogeneous intersection case.

ALGORITHM 3 (Euler-Poincaré characteristic, homogeneous intersection case).

INPUT

- A family of polynomials,  $\mathcal{Q}^h = \{Q_1^h, \dots, Q_m^h\} \subset \mathbb{R}[Y_0, \dots, Y_\ell, X_1, \dots, X_k]$ , with  $\deg_Y(Q) \leq 2, \deg_X(Q) \leq d, Q \in \mathcal{Q}^h$ , homogeneous with respect to  $Y$ ,
- another family,  $\mathcal{P} \subset \mathbb{R}[X_1, \dots, X_k]$  with  $\deg_X(P) \leq d, P \in \mathcal{P}, \#(\mathcal{P}) = s$ ,

- a formula  $\Phi$  defining a bounded  $\mathcal{P}$ -closed semi-algebraic set  $V$ .

OUTPUT

the Euler-Poincaré characteristic  $\chi(W^h)$ , where  $W^h$  is the semi-algebraic set defined by

$$W^h = \bigcap_{Q \in \mathcal{Q}^h} \{(y, x) \mid |y| = 1 \wedge Q(y, x) \leq 0 \wedge \Phi(x)\}.$$

PROCEDURE

Step 1. For each subset  $J \subset [m]$  do the following.

Compute  $\chi(A^J)$  using Algorithm 2, where

$$A^J = \bigcup_{Q \in J} \{(y, x) \mid |y| = 1 \wedge Q(y, x) \leq 0 \wedge \Phi(x)\}.$$

Step 2. Output

$$(3.1) \quad \chi(W^h) = \sum_{J \subset \mathcal{Q}} (-1)^{\#(J)+1} \chi(A^J).$$

PROOF OF CORRECTNESS: First note that the equality 3.1 can be easily deduced from Proposition 3.1 by induction. The correctness of the algorithm is now a consequence of the correctness of Algorithm 2.  $\square$

COMPLEXITY ANALYSIS: There are  $2^m$  calls to Algorithm 2. Using the complexity analysis of Algorithm 2, the complexity of the algorithm is bounded by  $(\ell s m d)^{O(m+k)}$ .  $\square$

### 3.2.2. The Case of Intersections.

ALGORITHM 4 (Euler-Poincaré Characteristic, Intersection Case).

INPUT

- A family of polynomials,  $\mathcal{Q} \subset \mathbb{R}[Y_1, \dots, Y_\ell, X_1, \dots, X_k]$ , with  $\deg_Y(Q) \leq 2, \deg_X(Q) \leq d, Q \in \mathcal{Q}, \#(\mathcal{Q}) = m$
- another family of polynomials,  $\mathcal{P} \subset \mathbb{R}[X_1, \dots, X_k]$  with  $\deg_X(Q) \leq d, P \in \mathcal{P}, \#(\mathcal{P}) = s$ ,
- a  $\mathcal{P}$ -closed formula  $\Phi$  defining a  $\mathcal{P}$ -closed semi-algebraic set  $V \subset \mathbb{R}^k$ .

OUTPUT the Euler-Poincaré characteristic  $\chi(W)$ , where  $W$  is the semi-algebraic set defined by

$$W = \bigcap_{Q \in \mathcal{Q}} \{(y, x) \mid Q(y, x) \leq 0 \wedge \Phi(x)\}.$$

PROCEDURE

Step 1. Replace  $\mathcal{Q}^h$  by  $\mathcal{Q}^h \cup \{Q_0^h\}$ , with  $Q_0 = \varepsilon^2(Y_1^2 + \dots + Y_\ell^2) - 1$ . Define

$$W_\varepsilon^h = \bigcap_{Q^h \in \mathcal{Q}^h} \{(y, x) \mid |y| = 1 \wedge Q^h(y, x) \leq 0 \wedge \Phi(x)\}.$$

Step 2. Using Algorithm 3 compute  $\chi(W_\varepsilon^h)$ .

Step 3. Output  $\chi(W) = \frac{1}{2} \chi(W_\varepsilon^h)$ .

PROOF OF CORRECTNESS: The correctness of Algorithm 4 follows from (2.20) and the correctness of Algorithm 3.  $\square$

COMPLEXITY ANALYSIS: The complexity of the algorithm is clearly  $(\ell smd)^{O(m+k)}$  arithmetic operations in  $\mathbb{R}\langle\varepsilon\rangle$  from the complexity analysis of Algorithm 3. Moreover the maximum degree in  $\varepsilon$  is bounded by  $(\ell md)^{O(m+k)}$ . Finally the complexity of the algorithm is  $(\ell smd)^{O(m+k)}$  arithmetic operations in  $\mathbb{R}$ .  $\square$

3.2.3. *The case of a  $\mathcal{Q} \cup \mathcal{P}$ -closed semi-algebraic set.* Since we want to deal with a general  $\mathcal{Q} \cup \mathcal{P}$ -closed semi-algebraic set, we shall need a property similar to Corollary 3.3 in a context where all the sets considered are closed and bounded.

We need a few preliminary definitions and results. Let  $\mathcal{Q} = \{Q_1, \dots, Q_m\}$  and

$$0 < \varepsilon_m \ll \dots \ll \varepsilon_1 \ll \varepsilon_0 \ll 1$$

be infinitesimals. For every  $j \in [m] = \{1, \dots, m\}$ , denote  $\mathbb{R}_j = \mathbb{R}\langle\varepsilon_0, \dots, \varepsilon_j\rangle$ . Let

$$\begin{aligned} \Psi_i^0 &= (Q_i = 0), \\ \Psi_i^1 &= (Q_i \geq \varepsilon_i), & \Psi_i^{-1} &= (Q_i \leq -\varepsilon_i), \\ \Psi_i^2 &= (Q_i = \varepsilon_i), & \Psi_i^{-2} &= (Q_i = -\varepsilon_i). \end{aligned}$$

The following Lemma 3.4 plays a role similar to Corollary 3.3.

**Lemma 3.4.** *Let  $S$  be a  $\mathcal{Q} \cup \mathcal{P}$ -closed bounded semi-algebraic set. For every  $j \in [m]$*   
 $\chi(S) = \chi(\mathcal{R}(\Psi_j^0, S)) + \chi(\mathcal{R}(\Psi_j^1, S)) + \chi(\mathcal{R}(\Psi_j^{-1}, S)) - \chi(\mathcal{R}(\Psi_j^2, S)) - \chi(\mathcal{R}(\Psi_j^{-2}, S))$

*Proof.* The claims follow from the additivity property of the Euler-Poincaré characteristic, and the fact that

$$\chi(\mathcal{R}(\Psi_j^0, S)) = \chi(\{(x, y) \in S \mid -\varepsilon_j \leq Q_j(x, y) \leq \varepsilon_j\}),$$

since  $\mathcal{R}(\Psi_j^0, S)$  is a deformation retract of  $\{(x, y) \in S \mid -\varepsilon_j \leq Q_j(x, y) \leq \varepsilon_j\}$ .  $\square$

We define  $\Sigma_m = \{-2, -1, 0, 1, 2\}^{[m]}$ . Given  $\rho \in \Sigma_m$  we define

$$\mathcal{R}(\rho, S) = \{(x, y) \in \text{Ext}(S, \mathbb{R}_m) \mid \bigwedge_{i=1}^m \Psi_i^{\rho(i)}(x, y)\}.$$

For any  $\rho \in \Sigma_m$  and  $\sigma$  a weak sign condition on  $\mathcal{Q} \cup \mathcal{P}$ , we say that  $\rho \prec \sigma$ , if for each  $i \in [m]$ ,  $\text{sign}(\rho(i)) \in \sigma(Q_i)$  and  $\mathbb{R}(\sigma) \subset S$ .

Notice that an alternative description of  $\mathcal{R}(\rho, S)$  is given by

$$(3.2) \quad \mathcal{R}(\rho, S) = \left\{ (x, y) \in \mathbb{R}_m^{\ell+k} \mid \bigwedge_{i=1}^m \Psi_i^{\rho(i)}(x, y) \wedge \left( \bigvee_{\rho \prec \sigma} \bigwedge_{P \in \mathcal{P}} (\text{sign}(P(x)) \in \sigma(P)) \right) \right\}.$$

ALGORITHM 5 (Euler-Poincaré, the general case).

INPUT

- A family of polynomials,  $\mathcal{Q} = \{Q_1, \dots, Q_m\} \subset \mathbb{R}[Y_1, \dots, Y_\ell, X_1, \dots, X_k]$ , with  $\deg_Y(Q) \leq 2$ ,  $\deg_X(Q) \leq d$ ,
- another family of polynomials,  $\mathcal{P} \subset \mathbb{R}[X_1, \dots, X_k]$  with  $\deg_X(P) \leq d$ ,  $P \in \mathcal{P}$ ,  $\#\mathcal{P} = s$ ,
- a  $\mathcal{Q} \cup \mathcal{P}$ -closed formula defining a  $\mathcal{Q} \cup \mathcal{P}$ -closed semi-algebraic set  $S$ .

OUTPUT the Euler-Poincaré characteristic  $\chi(S)$ .

PROCEDURE

- Step 1. Define  $Q_0 = \varepsilon_0^2(Y_1^2 + \dots + Y_\ell^2) - 1$ ,  $P_0 = \varepsilon_0^2(X_1^2 + \dots + X_k^2) - 1$ . Replace  $\mathcal{P}$  by  $\mathcal{P} \cup \{P_0\}$  and  $S$  by  $\mathcal{R}(S, \mathbf{R}(\varepsilon)) \cap (\mathcal{R}(Q_0 \leq 0) \times \mathcal{R}(P_0 \leq 0))$ .
- Step 2. For every generalized sign condition  $\rho \in \Sigma_m$  compute  $\chi(\mathcal{R}(\rho, S))$  using 3.2 and Algorithm 4.
- Step 3. Denoting by  $n(\rho) = \#\{i \in [m] \mid |\rho(i)| = 2\}$ , output

$$\chi(S) = \sum_{\rho} (-1)^{n(\rho)} \chi(\mathcal{R}(\rho, S)).$$

**PROOF OF CORRECTNESS:** It follows from the local conic structure of semi-algebraic sets at infinity [14, Theorem 9.3.6] that replacing  $S$  by  $\mathcal{R}(S, \mathbf{R}(\varepsilon)) \cap (\mathcal{R}(Q_0 \leq 0) \times \mathcal{R}(P_0 \leq 0))$  does not modify the Euler-Poincaré characteristic. The proof is now based on the following lemma.

**Lemma 3.5.** *Let  $S$  be a  $\mathcal{Q} \cup \mathcal{P}$ -closed and bounded semi-algebraic set. Denoting by  $n(\rho) = \#\{i \in [m] \mid |\rho(i)| = 2\}$ , for  $\rho \in \Sigma_m$ ,*

$$\chi(S) = \sum_{\rho \in \Sigma_m} (-1)^{n(\rho)} \chi(\mathcal{R}(\rho, S)).$$

*Proof.* The proof is by induction on  $m$ . The induction hypothesis  $H_j$  states that denoting by  $n(\rho) = \#\{i \in [j] \mid |\rho(i)| = 2\}$  for  $\rho \in \Sigma_j$ ,

$$\chi(S) = \sum_{\rho \in \Sigma_j} (-1)^{n(\rho)} \chi(\mathcal{R}(\rho, S)).$$

The base case  $H_1$  is exactly Lemma 3.4 applied to  $S$ . Suppose now that  $H_{j-1}$  holds for some  $1 < j \leq m$ , i.e.

$$(3.3) \quad \chi(S) = \sum_{\rho \in \Sigma_{j-1}} (-1)^{n(\rho)} \chi(\mathcal{R}(\rho, S))$$

and let us prove  $H_j$ . Define  $\mathcal{Q}_j = \mathcal{Q} \cup \{Q_i \pm \varepsilon_i, i = 1, \dots, j\}$ .

For every  $\rho \in \Sigma_{j-1}$ ,  $\mathcal{R}(\rho, S)$  is a  $\mathcal{Q}_{j-1} \cup \mathcal{P}$ -closed semi-algebraic set. Denoting by  $\rho_i \in \Sigma_j$ , for  $\rho \in \Sigma_{j-1}$ ,  $i \in \{-2, -1, 0, 1, 2\}$ , the generalized sign condition defined by  $\rho_i(u) = \rho(u)$ ,  $u = 1, \dots, j-1$ ,  $\rho_i(j) = i$ , notice that  $\mathcal{R}(\rho_i, S) = \mathcal{R}(\Psi_j^i, \mathcal{R}(\rho, S))$ . Using Lemma 3.4 applied to  $\mathcal{R}(\rho, S)$ , we obtain

$$\begin{aligned} \chi(\mathcal{R}(\rho, S)) &= \chi(\mathcal{R}(\rho_0, S)) + \chi(\mathcal{R}(\rho_1, S)) + \chi(\mathcal{R}(\rho_{-1}, S)) \\ &\quad - \chi(\mathcal{R}(\rho_2, S)) - \chi(\mathcal{R}(\rho_{-2}, S)). \end{aligned}$$

Substituting each  $\chi(\mathcal{R}(\rho, S))$  by its value in (3.3) one gets  $H_j$ , since every element of  $\Sigma_j$  is of the form  $\rho_i$  for some  $\rho \in \Sigma_{j-1}$ ,  $i \in \{-2, -1, 0, 1, 2\}$ .  $\square$

The correctness of Algorithm 5 now follows directly from the previous lemma.  $\square$

**COMPLEXITY ANALYSIS:** There are  $5^m$  calls to Algorithm 4. The complexity of the algorithm is clearly  $(lsm d)^{O(m+k)}$  arithmetic operations in  $\mathbf{R}_m$  from the complexity analysis of Algorithm 4. Moreover the maximum degree in  $\varepsilon_0, \dots, \varepsilon_m$  is bounded by  $(lmd)^{O(m+k)}$ . Finally the complexity of the algorithm is  $(lsm d)^{O(m(m+k))}$  arithmetic operations in  $\mathbf{R}$ .  $\square$

*Proof of Theorem 1.9.* The proof of correctness and the complexity analysis of Algorithm 5 also proves Theorem 1.9.  $\square$

## REFERENCES

1. A.A. Agrachev, *Topology of quadratic maps and Hessians of smooth maps*, Algebra, Topology, Geometry, Itogi Nauki i Tekhniki, Akad. Nauk SSSR, Vsesoyuz. Inst. Nauchn. Tekhn. Inform., vol. 26, VINITI, Moscow, 1988, Translated in J. Soviet Mathematics. 49 (1990), no. 3, 990-1013., pp. 85–124 (Russian, English).
2. A. I. Barvinok, *Feasibility testing for systems of real quadratic equations*, Discrete Comput. Geom. **10** (1993), no. 1, 1–13. MR **94f**:14051
3. ———, *On the Betti numbers of semialgebraic sets defined by few quadratic inequalities*, Math. Z. **225** (1997), no. 2, 231–244. MR **98f**:14044
4. S. Basu, *On bounding the Betti numbers and computing the Euler characteristic of semi-algebraic sets*, Discrete Comput. Geom. **22** (1999), no. 1, 1–18.
5. ———, *Algorithmic semi-algebraic geometry and topology – recent progress and open problems*, Surveys on Discrete and Computational Geometry: Twenty Years Later, Contemporary Mathematics, vol. 453, American Mathematical Society, 2008, pp. 139–212.
6. ———, *Computing the top few Betti numbers of semi-algebraic sets defined by quadratic inequalities in polynomial time*, Found. Comput. Math. **8** (2008), no. 1, 45–80.
7. ———, *Errata for computing the top few Betti numbers of semi-algebraic sets defined by quadratic inequalities in polynomial time*, Found. Comput. Math. **8** (2008), no. 1, 81–95.
8. S. Basu and M. Kettner, *A sharper estimate on the Betti numbers of sets defined by quadratic inequalities*, Discrete Comput. Geom. (to appear), preprint at arXiv:math.AG/0610954.
9. S. Basu, R. Pollack, and M.-F. Roy, *Algorithms in real algebraic geometry*, Algorithms and Computation in Mathematics, vol. 10, Springer-Verlag, Berlin, 2006 (second edition). MR **1998i47** (**2004g**:14064)
10. ———, *Computing the first Betti number of a semi-algebraic set*, Found. Comput. Math. **8** (2008), no. 1, 97–136.
11. Saugata Basu, *Computing the first few Betti numbers of semi-algebraic sets in single exponential time*, J. Symbolic Comput. **41** (2006), no. 10, 1125–1154. MR **2262087** (**2007k**:14120)
12. ———, *Efficient algorithm for computing the Euler-Poincaré characteristic of a semi-algebraic set defined by few quadratic inequalities*, Comput. Complexity **15** (2006), no. 3, 236–251. MR **2268404** (**2007k**:14119)
13. Saugata Basu, Richard Pollack, and Marie-Françoise Roy, *On the Betti numbers of sign conditions*, Proc. Amer. Math. Soc. **133** (2005), no. 4, 965–974 (electronic). MR **2117195** (**2006a**:14096)
14. J. Bochnak, M. Coste, and M.-F. Roy, *Géométrie algébrique réelle*, Ergebnisse der Mathematik und ihrer Grenzgebiete (3) [Results in Mathematics and Related Areas (3)], vol. 12, Springer-Verlag, Berlin, 1987. MR **949442** (**90b**:14030)
15. Shiing-shen Chern and E. Spanier, *The homology structure of sphere bundles*, Proc. Nat. Acad. Sci. U. S. A. **36** (1950), 248–255. MR 0035994 (12,42h)
16. Andrei Gabrielov and Nicolai Vorobjov, *Betti numbers of semialgebraic sets defined by quantifier-free formulae*, Discrete Comput. Geom. **33** (2005), no. 3, 395–401. MR **2121987** (**2005i**:14075)
17. D. Grigoriev and D. Pasechnik, *On Betti numbers of semi-algebraic sets over quadratic maps*, Manuscript, 2004.
18. Dima Grigoriev and Dmitrii V. Pasechnik, *Polynomial-time computing over quadratic maps. I. Sampling in real algebraic sets*, Comput. Complexity **14** (2005), no. 1, 20–52. MR **2134044** (**2005m**:68262)
19. Allen Hatcher, *Algebraic topology*, Cambridge University Press, Cambridge, 2002. MR **1867354** (**2002k**:55001)
20. J. Milnor, *On the Betti numbers of real varieties*, Proc. Amer. Math. Soc. **15** (1964), 275–280. MR 0161339 (28 #4547)
21. I. G. Petrovskii and O. A. Oleĭnik, *On the topology of real algebraic surfaces*, Izvestiya Akad. Nauk SSSR. Ser. Mat. **13** (1949), 389–402. MR 0034600 (11,613h)
22. Stephen Smale, *A Vietoris mapping theorem for homotopy*, Proc. Amer. Math. Soc. **8** (1957), 604–610. MR 0087106 (19,302f)
23. René Thom, *Sur l’homologie des variétés algébriques réelles*, Differential and Combinatorial Topology (A Symposium in Honor of Marston Morse), Princeton Univ. Press, Princeton, N.J., 1965, pp. 255–265. MR 0200942 (34 #828)

SCHOOL OF MATHEMATICS, GEORGIA INSTITUTE OF TECHNOLOGY, ATLANTA, GA 30332, U.S.A.  
*E-mail address:* `saugata.basu@math.gatech.edu`

MAS DIVISION, SCHOOL OF PHYSICAL AND MATHEMATICAL SCIENCES, NANYANG TECHNOLOGICAL UNIVERSITY, 21 NANYANG LINK, SINGAPORE 637371.  
*E-mail address:* `dima@ntu.edu.sg`

IRMAR (URA CNRS 305), UNIVERSITÉ DE RENNES I, CAMPUS DE BEAULIEU 35042 RENNES CEDEX FRANCE.  
*E-mail address:* `marie-francoise.roy@univ-rennes1.fr`