THE SIGNATURE OF A SPLICE
ALEX DEGTYAREV, VINCENT FLORENS, AND ANA G. LECUONA

Abstract. We consider the signature of a colored link in an integral homology sphere and study its behavior under the splice operation. We show that the signature is almost additive, with a correction term independent of the links. We interpret this correction term as the signature of a generalized Hopf link and give a simple closed formula to compute it.

1. Introduction

The splice of two links is an operation defined by Eisenbud and Neumann in [EN85], which generalizes several other operations on links such as connected sum, cabling, and disjoint union. The precise definition is given in Section 2.1 (see Definition 2.1), but the rough idea is as follows: the splice of two links $K' \cup L' \subset S'$ and $K'' \cup L'' \subset S''$ along the distinguished components $K'$ and $K''$ is the link $L' \cup L''$ in the 3-manifold $S$ obtained by an appropriate gluing of the exteriors of the components $K'$ and $K''$. There has been much interest in understanding the behavior of various link invariants under the splice operation. For example, the genus and the fiberability of a link are additive, in a suitable sense, under splicing [EN85]. The behavior of the Conway polynomial has been studied in [Cim05], and more recently the relation between the $L$-spaces in Heegaard–Floer homology and splicing has been addressed in [HL12]. The goal of this paper is obtaining a similar (non-)additivity statement for the multivariate signature of oriented colored links. As a consequence, we show that the conventional univariate Levine–Tristram signature of a splice depends on the multivariate signatures of the summands; this result may account for the fact that the computation of the Levine–Tristram signature even for iterated torus links was not known before.

In Section 3.2 we define the signature of a colored link in an integral homology sphere. This is a natural generalization of the multivariate extension of the Levine–Tristram signature of a link in the 3-sphere, considered in [Flo05, CF08]. The principal result of the paper is Theorem 2.2 expressing the signature of the splice of two links in terms of the signatures of the summands. We show that the signature is almost additive: there is a defect, but it depends only on some combinatorial data of the links (linking numbers), and not on the links themselves. Geometrically, this defect term appears as the multivariate signature of a certain generalized Hopf link, which is computed in Theorem 2.6. At the end of Section 2 we discuss a few applications of Theorem 2.2 and relate it to some previously known results: namely, we compute the signature of a satellite knot (see Section 2.5 and Theorem 2.8) and that of an iterated torus link (see Section 2.6 and Theorem 2.9), and we relate the multivariate signature of a link to the conventional Levine–Tristram signature of an obvious auxiliary link (see Section 2.7 and Theorem 2.11): in other words, the signature can be computed by means of “Seifert surfaces” with multiple boundary components.

The paper is organized as follows. Section 2 is devoted to the detailed statement of main results, and the computation of the defect. In Section 3 we introduce the necessary background material on twisted intersection forms and construct the signature of colored links in...
integral homology spheres. The proofs of the main theorems are carried out in Section 4 and Section 5 where the signature of generalized Hopf links are computed.

Acknowledgements. We would like to thank S. Orevkov, who brought the problem to our attention. This work was partially completed during the first and third authors’ visits to the University of Pau, supported by the CNRS, and the first author’s visit to the Abdus Salam International Centre for Theoretical Physics. Also partially supported by the ANR Project Interlow JCJC-0097-01 and the Spanish GEOR MTM2011-22435.

2. Principal results

2.1. The set-up. A \( \mu \)-colored link is an oriented link \( L \) in an integral homology sphere \( S \) equipped with a surjective function \( \pi_0(L) \to \{1, \ldots, \mu\} \), referred to as the coloring. The union of the components of \( L \) given the same color \( i = 1, \ldots, \mu \) is denoted by \( L_i \).

The signature of a \( \mu \)-colored link \( L \) is a certain \( \mathbb{Z} \)-valued function \( \sigma_L \) defined on the character torus

\[
\mathcal{T}^\mu := \{(\omega_1, \ldots, \omega_\mu) \in (S^1)^\mu \subset \mathbb{C}^\mu \mid \omega_j = \exp(2\pi i \theta_j), \ \theta_j \in \mathbb{Q}\},
\]

see Definition 3.5 below for details. We let \( \mathcal{T}^1 := \{1\} \subset \mathbb{C} \). Note that \( \mathcal{T}^\mu \) is an abelian group. If \( \mu = 1 \), \( L \) is monochrome and \( \sigma_L \) coincides with the Levine–Tristram signature [Tri69] (whose definition in terms of Seifert form extends naturally to links in homology spheres).

Often, the components of \( L \) are split naturally into two groups, \( L = L' \cup L'' \), on which the coloring takes, respectively, \( \mu' \) and \( \mu'' \) values, \( \mu' + \mu'' = \mu \). In this case, we regard \( \sigma_L \) as a function of two "vector" arguments \( (\omega', \omega'') \in \mathcal{T}^{\mu'} \times \mathcal{T}^{\mu''} \). We use this notation freely, hoping that each time its precise meaning is clear from the context.

Clearly, in the definition of colored link, the precise set of colors is not very important; sometimes, we also admit the color 0. As a special case, we define a \((1, \mu)\)-colored link

\[ K \cup L = K \cup L_1 \cup \ldots \cup L_\mu \]

as a \((1 + \mu)\)-colored link in which \( K \) is the only component given the distinguished color 0. Here, we assume \( K \) connected; this component, considered distinguished, plays a special rôle in a number of operations.

In the following definition, for a \((1, \mu^*)\)-colored link \( K^* \cup L^* \subset S^* \), \( \ast = t \) or \( \nu \), we denote by \( T^* \subset S^* \) a small tubular neighborhood of \( K^* \) disjoint from \( L^* \) and let \( m^*, \ell^* \subset \partial T^* \) be, respectively, its meridian and longitude. (The latter is well defined as \( S^* \) is a homology sphere.)

**Definition 2.1.** Given two \((1, \mu^*)\)-colored links \( K^* \cup L^* \subset S^* \), \( \ast = t \) or \( \nu \), their splice is the \((\mu^t + \mu''\)\)-colored link \( L' \cup L'' \) in the integral homology sphere

\[ S := (S' \smallsetminus \text{int } T') \cup_\varphi (S'' \smallsetminus \text{int } T''), \]

where the gluing homeomorphism \( \varphi : \partial T' \to \partial T'' \) takes \( m' \) and \( \ell' \) to \( m'' \) and \( \ell'' \), respectively.

2.2. Notations. Throughout the paper, we are using several functions, some of which are not quite common or do not have a common notation.

Given a list (vector, etc.) \( a_1, \ldots, a_n \), the notation \( a_1, \ldots, \hat{a}_i, \ldots, a_n \) designates that the \( i \)-th element (component, etc.) has been removed.

The complex conjugation is denoted by \( \eta \mapsto \bar{\eta} \). The same notation applies to the elements of the character torus \( \mathcal{T}^\mu \), where we have \( \bar{\omega} = \omega^{-1} \).
The linking number of two disjoint oriented circles \( K, L \) in an integral homology sphere \( S \) is denoted by \( \ell k_S(K, L) \), with \( S \) omitted whenever understood. For a \((1, \mu)\)-colored link \( K \cup L \), we also define the linking vector \( \mathcal{L}(K, L) = (\lambda_1, \ldots, \lambda_\mu) \in \mathbb{Z}^\mu \), where \( \lambda_i := \ell k(K, L_i) \).

The signature formula is the map \( \text{sg}: \mathbb{R} \to \{\pm 1\} \) defined via

\[
\text{sg} x := \begin{cases} 
+1, & \text{if } x > 0, \\
0, & \text{if } x = 0, \\
-1, & \text{if } x < 0.
\end{cases}
\]

The index function is the map \( \text{ind}: \mathbb{R} \to \mathbb{Z} \) defined via

\[
\text{ind} x := \begin{cases} 
2x, & \text{if } x \in \mathbb{Z}, \\
2p + 1, & \text{if } x \in (p, p + 1), p \in \mathbb{Z}.
\end{cases}
\]

The Log-function \( \text{Log}: \mathcal{T}^1 \to [0, 1) \) sends \( \exp(2\pi it) \) to \( t \in [0, 1) \). This function extends to \( \text{Log}: \mathcal{T}^\mu \to [0, \mu) \) via \( \text{Log} \omega = \sum_{i=1}^\mu \text{Log} \omega_i \); in other words, we specialize each argument to the interval \([0, 1)\) and add the arguments as real numbers afterwards. Interchanging the two operations, we define the width \( \text{wd} \omega := \sum_{i=1}^\mu \text{ind}(\text{Log} \omega_i) \) of a character \( \omega \in \mathcal{T}^\mu \) as the number of components of \( \omega \) distinct from 1. Combining, we obtain the defect function

\[
\delta: \mathcal{T}^\mu \to \mathbb{Z} \quad \omega \mapsto \text{ind}(\text{Log} \omega) - \text{wd} \omega = \text{ind}(\sum_{i=1}^\mu \text{Log} \omega_i) - \sum_{i=1}^\mu \text{ind}(\text{Log} \omega_i).
\]

Finally, consider an integral vector \( \lambda \in \mathbb{Z}^\mu, \mu \geq 0 \), and let \( |\lambda| := \sum_i |\lambda_i| \). We have two maps: the weighted product

\[
\mathcal{T}^\mu \to \mathcal{T}^1, \quad \omega \mapsto \omega \uparrow \lambda := \prod_{i=1}^\mu \omega_i^{\lambda_i},
\]

and the \( \lambda \)-diagonal

\[
\mathcal{T}^\mu \to \mathcal{T}^{|\lambda|} = \mathcal{T}^{\lambda_1} \times \ldots \times \mathcal{T}^{\lambda_\mu}, \quad \omega \mapsto \omega \star \lambda,
\]
sending each component \( \omega_i \) of \( \omega \) to \( |\lambda_i| \) consecutive copies of \( \omega_i^{\text{sg} \lambda_i} \). For example,

\[
(\omega_1, \omega_2, \omega_3, \omega_4) \star (0, 1, -2, 3) = (\omega_2, \omega_3, \omega_3, \omega_4, \omega_4, \omega_4) \in \mathcal{T}^6 = \mathcal{T}^0 \times \mathcal{T}^1 \times \mathcal{T}^2 \times \mathcal{T}^3.
\]

For an integer \( p \), let \( [p]_\mu := (p, \ldots, p) \in \mathbb{Z}^\mu \). Then, clearly,

\[
(2.2) \quad \omega \uparrow \lambda = \prod_{i=1}^{|\lambda|} (\omega \star \lambda)_i = (\omega \star \lambda) \uparrow [1]_{|\lambda|}.
\]

Note also that, if \( \mu = 0 \) (and \( \lambda = 0 \in \mathbb{Z}^0 \)), both maps are constants equal to 1 in \( \mathcal{T}^0 \subset \mathcal{T}^1 \).

2.3. The signature formula. The following statement is the principal result of the paper.

**Theorem 2.2.** For \( * = t \) or \( \mu \), consider a \((1, \mu^*)\)-colored link \( K^* \cup L^* \subset S^* \), and let \( L \subset S \) be the splice of the two links. For characters \( \omega^* \in \mathcal{T}^{\mu^*} \), introduce the notation

\[
\lambda^* := \mathcal{L}(K^*, L^*) \in \mathbb{Z}^{\mu^*}, \quad \nu^* := \omega^* \uparrow \lambda^* \in \mathcal{T}^1.
\]

Then, assuming that \( (\nu', \nu'') \neq (1, 1) \), one has

\[
\sigma_L(\omega', \omega'') = \sigma_{K \cup L'}(\nu', \omega') + \sigma_{K' \cup L''}(\nu', \omega'') - \delta(\omega' \star \lambda') \delta(\omega'' \star \lambda'').
\]

As an immediate consequence, we see that the Levine–Tristram signature of a splice cannot be expressed in terms of the Levine–Tristram signature of its summands: in general, a certain multivariate extension is required.
Corollary 2.3. Let $L$ be the splice of $(1,1)$-colored links $K' \cup L'$ and $K'' \cup L''$, and denote $\lambda' = \ell k(K', L')$ and $\lambda'' = \ell k(K'', L'')$. Then, for a character $\xi \in \mathcal{T}^1$ such that $\xi^{\text{g.c.d.}}(\lambda', \lambda'') \neq 1$, one has
\[
\sigma_L(\xi) = \sigma_{K' \cup L'}(\xi', \xi) + \sigma_{K'' \cup L''}(\xi'', \xi) + \lambda' \lambda'',
\]
where $\sigma_L(\xi)$ is the Levine–Tristram signature of $L$.

Proof. Consider the 2-coloring on $L$ given by the splitting $L' \cup L''$. Here $\mu' = \mu'' = 1$ and $\delta(\xi * \lambda') = \delta(\xi * \lambda'') = 0$, see Lemma 2.7; hence, $\sigma_L(\xi, \xi) = \sigma_{K' \cup L'}(\xi', \xi) + \sigma_{K'' \cup L''}(\xi'', \xi)$ by Theorem 2.2. On the other hand, $\sigma_L(\xi) = \sigma_L(\xi, \xi) - \ell k(L', L'')$, see Proposition 3.7. By [ENS83 Proposition 1.2], $\ell k(L', L'') = \lambda' \lambda''$.

Theorem 2.2 is proved in Section 4.3. In the special case $L' = \emptyset$, it takes the following stronger form (we do not require that $\nu' \neq 1$); it is proved in Section 4.4.

Addendum 2.4. Let $L \subset S$ be the splice of a $(1,0)$-colored link $K' \subset S'$ and a $(1, \mu'')$-colored link $K'' \cup L'' \subset S''$, and let $\lambda'' := \ell k(K'', L'')$. Then, for any character $\omega \in \mathcal{T}^n$, one has
\[
\sigma_L(\omega) = \sigma_{K'}(\omega \uparrow \lambda'') + \sigma_{L''}(\omega).
\]

Remark 2.5. The assumption $(\nu', \nu'') \neq (1,1)$ in Theorem 2.2 is essential. If $\nu' = \nu'' = 1$, the expression for the signature acquires an extra correction term, which takes values in $\{\pm 1, 0\}$ and is related to the linkage invariants of the links involved. In many cases, this term can be computed algorithmically, and simple examples show that typically it does not vanish. (Addendum 2.4 states that the extra term does vanish whenever one of the links $L', L''$ is empty.) In more detail this issue is addressed in a forthcoming paper [DFL].

2.4. The generalized Hopf link. A generalized Hopf link is the link $H_{m,n} \subset S^3$ obtained from the ordinary positive Hopf link $H_{1,1} = U_1 \cup U_2$ by replacing its components $U_1$ and $U_2$ with, respectively, $m$ and $n$ parallel copies. This link is naturally $(m+n)$-colored; its signature plays a special rôle in the paper, and we introduce a shortcut
\[
\sigma_{m,n}(\eta, \zeta) := \sigma_{H_{m,n}}(\eta, \zeta), \quad (\eta, \zeta) \in \mathcal{T}^m \times \mathcal{T}^n.
\]

This signature is given by Theorem 2.6 below. Observe the similarity to the correction term in Theorem 2.2; a posteriori, Theorem 2.6 can be interpreted as a special case of Theorem 2.2 using the identity $\sigma_{1,n} \equiv 0$ (which is easily proved independently) and the fact that $H_{m,n}$ is the splice of $H_{1,m}$ and $H_{1,n}$. However, the Hopf links and their signatures are used essentially in the proof of Theorem 2.2.

Theorem 2.6. For any character $(\eta, \zeta) \in \mathcal{T}^m \times \mathcal{T}^n$, one has $\sigma_{m,n}(\eta, \zeta) = -\delta(\eta)\delta(\zeta)$.

For future references, we state a few simple properties of the defect function $\delta$ and, hence, of the signature $\sigma_{m,n}$. All proofs are immediate.

Lemma 2.7. The defect function $\delta : \mathcal{T}^n \rightarrow \mathbb{Z}$ has the following properties:

1. $\delta(1) = 0$; $\delta \equiv 0$ if $\mu = 0$ or 1;
2. $\delta(\omega) = -\delta(\omega)$ for all $\omega \in \mathcal{T}^n$;
3. $\delta$ is preserved by the coordinatewise action of the symmetric group $S^\mu$;
4. $\delta$ commutes with the coordinate embeddings $\mathcal{T}^\mu \hookrightarrow \mathcal{T}^{\mu+1}$, $\omega \mapsto (\omega, 1)$;
5. $\delta$ commutes with the embeddings $\mathcal{T}^\mu \hookrightarrow \mathcal{T}^{\mu+2}$, $\omega \mapsto (\omega, \eta, \bar{\eta})$ for any $\eta \in \mathcal{T}^1$. 

2.5. **Satellite knots.** As was first observed in [EN85], the splice operation generalizes many classical link constructions: connected sum, disjoint union and satellites among others.

Our first application is Litherland’s formula for the Levine–Tristram signature of a satellite knot, which is a particular case of Addendum 2.4.

Recall that an embedding of a solid torus in $S^3$ into another solid torus in another copy of $S^3$ is called faithful if the image of a canonical longitude of the first solid torus is a canonical longitude of the second one. Let $V$ be an unknotted solid torus in $S^3$, and let $k$ be a knot in the interior of $V$, with algebraic winding number $q$, i.e., $[k]$ is $q$ times the class of the core in $H_1(V)$. Given any knot $K \subset S^3$, the satellite knot $K^*$ is defined as the image $f(k)$ under a faithful embedding $f : V \to S^3$ sending the core of $V$ to $K$.

The isotopy class $K^*$ depends on course of the embedding $f$ (and even its concordance class, see [Lit84]). Nevertheless, its Levine–Tristram signature is determined by the signatures of the constituent knots and the winding number:

**Theorem 2.8 (cf. [Lit79] Theorem 2).** In the notation above, the Levine–Tristram signatures of $k$, $K$ and $K^*$ are related via

$$\sigma_{K^*}(\omega) = \sigma_K(\omega^q) + \sigma_k(\omega), \quad \omega \in \mathcal{T}.$$  

*Proof. Let $C$ be the core of the solid torus $S^3 \setminus V$. The satellite $K^*$ can be written as the splice of $K \cup \emptyset$ and $C \cup k$. By Addendum 2.4, we have

$$\sigma_{K^*}(\omega) = \sigma_K(\omega^\lambda) + \sigma_k(\omega).$$

where $\lambda := \ell k(C,k)$. By assumption, $\ell k(C,k) = q$, and the statement follows.\[\Box\]

2.6. **Iterated torus links.** Our next application is another special case of Theorem 2.2 which provides an inductive formula for the signatures of iterated torus links. In particular, this class of links contains the algebraic ones, i.e., the links of isolated singularities of complex curves in $\mathbb{C}^2$.

Iterated torus links are obtained from an unknot by a sequence of cabling operations (and maybe, reversing the orientation of some of the components). In order to define the cabling operations (see [EN85], consider two coprime integers $p$ and $q$ (in particular, if one of them is 0, the other is $\pm 1$), a positive integer $d$, a $(1,\mu')$-colored link $K' \cup L' \subset S^3$, and a small tubular neighbourhood $T'$ of $K'$ disjoint from $L'$. Let $m,l$ be the meridian and longitude of $K'$, and $K'(p,q)$ be the oriented simple closed curve in $\partial T'$ homologous to $p.l + q.m$. More generally, let $dK'(p,q)$ be the disjoint union of $d$ parallel copies of $K'(p,q)$ in $\partial T'$. We say that the link $L = L' \cup dK'(p,q) - K'$ (resp. $L = L' \cup dK'(p,q)$) is obtained from $K' \cup L'$ by a $(dp,dq)$-cabling with the core removed (resp. retained).

Let $H_{1,1} = U_1 \cup U_2$ be the ordinary Hopf link. The link $U_1 \cup dU_2(p,q)$ can be regarded as either $(1,d)$-colored or $(1,1)$-colored. We denote the corresponding multivariate and bivariate signature functions by $\tau_{dp,dq}$ and $\tilde{\tau}_{dp,dq}$, respectively. Note that, by Proposition 3.7 below,

$$\tilde{\tau}_{dp,dq}(\eta,\zeta) = \tau_{dp,dq}(\eta,\zeta) - \frac{1}{2}d(d-1)pq.$$  

In the case of core-removing, the link $L$ obtained by the cabling is nothing but the splice of $K' \cup L'$ and $U_1 \cup dU_2(p,q)$. (Similarly, in the core-retaining case, $L$ is the splice of $K' \cup L'$ and $U_1 \cup U_2 \cup dU_2(p,q)$.) Hence, the following statement is an immediate consequence of Theorem 2.2.
Theorem 2.9. Let $L$ be obtained from a $(1,\mu')$-colored link $K' \cup L'$ by a $(dp,dq)$-cabling with the core removed. For a character $\omega := (\omega',\omega'') \in \mathcal{T}^{d'} \times \mathcal{T}^{d}$, let
\[ \lambda' := \bar{\ell}k(K',L'), \quad \lambda'' := [p]_d, \quad \text{and} \quad v^* := \omega^* \uparrow \lambda^*, \quad * = t \text{ or } n. \]
Then, assuming that $(v^*,\omega'') \neq (1,1)$, one has
\[ \sigma_L(\omega) = \sigma_{K' \cup L'}(v^*,\omega') + \tau_{dp,dq}(v^*,\omega'') - \delta(\omega' \star \lambda')\delta(\omega'' \star \lambda''). \]

With the evident modifications, this last corollary can be adapted to give a formula for a $(dp,dq)$-cabling with the core retained.

The Levine–Tristram signature of the torus link $U_2(p,q)$ (which coincides with $\bar{\tau}_{p,q}(1,\zeta)$ in our notation) was computed by Hirzebruch. For the reader’s convenience, we cite this result in the next lemma. Unfortunately, we do not know any more general statement.

Lemma 2.10 (see [Bri66]). Let $M = \{1,\ldots,p-1\} \times \{1,\ldots,q-1\}$ and let $0 < \theta \leq \frac{1}{2}$.

Consider
\[ a = \#\{(i,j) \in M \mid \theta < (i/p) + (j/q) < \theta + 1\}, \]
\[ n = \#\{(i,j) \in M \mid (i/p) + (j/q) = \theta \text{ or } (i/p) + (j/q) = \theta + 1\}, \]
\[ b = |M| - a - n. \]

Then one has $\bar{\tau}_{p,q}(1,\zeta) = b - a$ for $\zeta = \exp(2\pi\theta)$.

2.7. Multivariate vs. univariate signature. The last application is the computation of the multivariate signature of a link in terms of the Levine–Tristram signature of an obvious auxiliary link. (One obvious application is the case where the latter auxiliary link is algebraic, so that its Seifert form can be computed in terms of the variation map in the homology of its Milnor fiber.) This result is similar to the computation of signature invariants of 3-manifolds by Gilmer, see [Gil81, Theorem 3.6].

Let $L = L_1 \cup \ldots \cup L_\mu$ be a $\mu$-colored link. For simplicity, we assume that the coloring is maximal, i.e., each component of $L$ is given a separate color. Let $[\lambda_{ij}]$ be the linking matrix of $L$, i.e., $\lambda_{ij} = \ell k(L_i,L_j)$ for $i \neq j$ and $\lambda_{ii} = 0$.

Consider a character $\omega \in \mathcal{T}^\mu$ and assume that $\omega_i = \xi^{n_i}$, where $\xi := \exp(2\pi i/n)$, for some integers $n > 0$ and $0 < n_i < n$. (In particular, all $\omega_i \neq 1$.) For $i = 1,\ldots,\mu$, denote
\begin{itemize}
  \item $\lambda_i := \sum_{j=1}^\mu n_j \lambda_{ij}$, the weighted linking number of $L_i$ and $L \setminus L_i$;
  \item $v_i := \omega \uparrow \lambda_i = \prod_{j=1}^\mu \omega_j^{\lambda_{ij}} = \xi^{X_i}$, where $\lambda_i$ is the $i$-th row of $[\lambda_{ij}]$.
\end{itemize}

Fix an integral vector $p := (p_1,\ldots,p_\mu) \in \mathbb{Z}^\mu$ and consider the monochrome link $\bar{L} := \bar{L}_p(\omega)$ obtained from $L$ by the $(n_i,p_i)$-cabling along the component $L_i$ for each $i = 1,\ldots,\mu$. In other words, each component $L_i$ of $L$ is regarded $n_i$-fold, and it is replaced with $n_i$ “simple” components, possibly linked (if $p_i \neq 0$).

Theorem 2.11. In the notation above, one has the identity
\[ \sigma_L(\omega) = \sigma_L(\xi) - \sum_{i=1}^\mu \bar{\tau}_{n_i,p_i}(v_i,\xi) - \sum_{i=1}^\mu (n_i - 1)\ind(\lambda_i^\mu/n) + \sum_{1 \leq i < j \leq \mu} (2n_i n_j - 1)\lambda_{ij}. \]

Corollary 2.12. If $p = 0$, the second term in Theorem 2.11 vanishes and one has
\[ \sigma_L(\omega) = \sigma_L(\xi) - \sum_{i=1}^\mu (n_i - 1)\ind(\lambda_i^\mu/n) + \sum_{1 \leq i < j \leq \mu} (2n_i n_j - 1)\lambda_{ij}. \]

For small values of $\mu$, this identity simplifies even further:
(1) if $\mu = 1$, then $\sigma_L(\omega) = \sigma_L(\xi)$;
(2) if $\mu = 2$ and $|\lambda_{12}| \leq 1$, then $\sigma_L(\omega) = \sigma_L(\xi) + (2n_1n_2 - n_1 - n_2 + 1)\lambda_{12}$.

**Proof.** If $p_i = 0$, then $U_1 \cup U_2(n_i, 0) = H_{L_{n_i}}$ is a generalized Hopf link; its signature vanishes due to Theorem 2.6 and Lemma 2.7(3). The only other statement that needs proof is item 2 where we have $\text{ind}(\lambda_{12}n_i/n) = \lambda_{12}$ whenever $|\lambda_{12}| \leq 1$ and $0 < n_i < n$, $i = 1, 2$. \hfill $\Box$

**Example 2.13.** Let $L = H_{1, 1}$ be the ordinary Hopf link, so that $\sigma_L = 0$ by Theorem 2.6 and Lemma 2.7(3). On the other hand, taking $p = 0$, we obtain $L = H_{n_1, n_2}$; by Theorem 2.6 and Proposition 3.7, we get $\sigma_L(\xi) = -(1 - n_1)(1 - n_2) - n_1n_2$, which agrees with Corollary 2.12(2).

**Proof of Theorem 2.11.** Denote $L[0] := L$ and, for $i = 1, \ldots, \mu$, let $L[i]$ be the link obtained from $L[i - 1]$ by the $(n_i, n_ip_i)$-cabling along the component $L_i$. Each link $L[i]$ is naturally $\mu$-colored; we assign to this link the character $\omega[i] := (\xi, \ldots, \xi, \omega_{i+1}, \ldots, \omega_{\mu})$. In this notation, $L$ is the monochrome version of $L[\mu]$ and, by Proposition 3.7,

\[(2.3) \quad \sigma_L(\xi) = \sigma_{L[\mu]}(\omega[\mu]) - \sum_{1 \leq i < j \leq \mu} n_in_j\lambda_{ij}.\]

Introduce the following characters:

- $\tilde{\omega}'[i] := (\xi, \ldots, \xi) \in T^{n_i}$;
- $\tilde{\omega}''[i]$, obtained from $\omega$ by replacing each $\omega_j$ with $n_j|\lambda_{ij}|$ copies of $\xi^{sg_{\lambda_{ij}}}$, if $j \leq i$, or $|\lambda_{ij}|$ copies of $\omega'^{sg_{\lambda_{ij}}}$, if $j > i$;
- $\tilde{\omega}[i]$, obtained from $\omega$ by replacing each $\omega_j$ with $n_j|\lambda_{ij}|$ copies of $\xi^{sg_{\lambda_{ij}}}$.

By definition, $L[i]$ is the splice of $L[i - 1]$ and $U_1 \cup n_i U_2(1, p_i)$. Then Theorem 2.2 applies and, for each $i = 1, \ldots, \mu$,

\[(2.4) \quad \sigma_{L[i]}(\omega[i]) = \sigma_{L[i - 1]}(\omega[i - 1]) + \tau_{n_i, n_ip_i}(v_i, \xi) - \delta(\tilde{\omega}'[i])\delta(\tilde{\omega}''[i]).\]

We have $\log \tilde{\omega}'[i] = n_i/n$; since $0 < n_i < n$, this implies

\[(2.5) \quad \delta(\tilde{\omega}'[i]) = 1 - n_i.\]

A bit more involved computation shows that $\delta(\tilde{\omega}''[i]) = \delta(\tilde{\omega}''[i]) - \sum_{j=i+1}^{\mu}(1 - n_j)\lambda_{ij}$. Indeed, $\tilde{\omega}[i]$ is obtained from $\tilde{\omega}''[i]$ by $|\lambda_{ij}|$ operations of replacement of a single copy of $\omega'^{sg_{\lambda_{ij}}}$ with $n_j$ copies of $\xi^{sg_{\lambda_{ij}}}$ for all $j > i$; as in (2.5), one such operation increases the value of $\delta$ by $(1 - n_j)\text{sg}_{\lambda_{ij}}$. The character $\tilde{\omega}[i]$ has all entries equal to $\xi$ or $\xi$, with the exponent sum equal to $L_i$. Using Lemma 2.7[5] and [9] to cancel the pairs $\xi$, $\xi$, we get $\delta(\tilde{\omega}[i]) = \text{ind}(L_i/n) - L_i$; hence,

\[(2.6) \quad \delta(\tilde{\omega}''[i]) = \text{ind}(L_i/n) - \sum_{j=1}^{i-1} n_j\lambda_{ij} - \sum_{j=i+1}^{\mu} \lambda_{ij}.\]

Applying (2.4) inductively and taking into account (2.5) and (2.6), we arrive at

\[\sigma_{L[\mu]}(\omega[\mu]) = \sigma_L(\omega) + \sum_{i=1}^{\mu} \tau_{n_i, n_ip_i}(v_i, \xi) + \sum_{i=1}^{\mu} (n_i - 1) \text{ind}(L_i/n) - \sum_{1 \leq i < j \leq \mu} (n_in_j - 1)\lambda_{ij},\]

and the statement of the theorem follows from (2.3). \hfill $\Box$
3. Signature of a link in a homology sphere

In the early sixties Trotter introduced a numerical knot invariant called the signature \[ \text{sign} \], which was subsequently extended to links by Murasugi \[ \text{Mur70} \]. This invariant was generalized to a function (defined via Seifert forms) on \( S^1 \subset \mathbb{C} \) by Levine and Tristram \[ \text{Tri69} \, \text{Lev69} \). It was then reinterpreted in terms of coverings and intersection forms of 4-manifolds by Viro \[ \text{Vir73} \, \text{Vir09} \]. Our definition of the signature of a colored link follows Viro’s approach and the \( G \)-signature theorem, see also \[ \text{GLMS1} \, \text{Flo05} \].

3.1. Twisted signature and additivity. We start with recalling the definition and some properties of the twisted signature of a 4-manifold.

Let \( N \) be a compact smooth oriented 4-manifold and \( G \) a finite abelian group. Fix a covering \( N^G \rightarrow N \), possibly ramified, with \( G \) the group of deck transformations. If the covering is ramified, we assume that the ramification locus \( F \) is a union of smooth compact surfaces \( F_i \subset N \) such that

1. \( \partial F_i = F_i \cap \partial N \);
2. each surface \( F_i \) is transversal to \( \partial N \), and
3. distinct surfaces intersect transversally, at double points, and away from \( \partial N \).

Items (1) and (2) above mean that each component \( F_i \) of \( F \) is a properly embedded surface. For short, a compact surface \( F \subset N \) satisfying all conditions (1)–(3) will be called \textit{properly immersed}. Under these assumptions, \( N^G \) is an oriented rational homology manifold and we have a well-defined Hermitian intersection index form

\[
\langle \cdot, \cdot \rangle : H_2(N^G; \mathbb{C}) \otimes H_2(N^G; \mathbb{C}) \rightarrow \mathbb{C}.
\]

Regard the homology groups \( H_*(N^G; \mathbb{C}) \) as \( \mathbb{C}[G] \)-modules and consider the form

\[
\varphi : H_2(N^G; \mathbb{C}) \otimes H_2(N^G; \mathbb{C}) \rightarrow \mathbb{C}[G], \quad \varphi(x, y) := \sum_{g \in G} \langle x, gy \rangle g.
\]

Since \( G \) is abelian, this form is sesquilinear, i.e., \( \varphi(g_1 x, g_2 y) = g_1 g_2^{-1} \varphi(x, y) \) for all \( g_1, g_2 \in G \).

Any multiplicative character \( \chi : G \rightarrow \mathbb{C}^* \) induces a homomorphism \( \mathbb{C}[G] \rightarrow \mathbb{C} \) of algebras with involution \( (zg) \mapsto \bar{z} g^{-1} \) in \( \mathbb{C}[G] \) is mapped to \( \eta \mapsto \bar{\eta} \) in \( \mathbb{C} \). This makes \( \mathbb{C} \) a \( \mathbb{C}[G] \)-module, and we can consider the \textit{twisted homology}

\[
H_\chi^*(N, F) := H_*(N^G; \mathbb{C}) \otimes_{\mathbb{C}[G]} \mathbb{C}.
\]

In this notation, the ramification locus \( F \) is omitted whenever it is empty or understood. The form \( \varphi \) above induces a \( \mathbb{C} \)-valued Hermitian form \( \varphi^\chi \) on \( H_2^\chi(N, F) \); explicitly, the latter is given by

\[
\varphi^\chi(x \otimes z_1, y \otimes z_2) = z_1 \bar{z}_2 \sum_{g \in G} \langle x, gy \rangle \chi(g).
\]

We will denote by sign\((N)\) the ordinary signature of the 4-manifold \( N \), i.e., that of the form \( \langle \cdot, \cdot \rangle \) on \( H_2(N) \). The \textit{twisted signature}, denoted by sign\(^\chi(N, F)\), is the signature of the above Hermitian form \( \varphi^\chi \).

\textbf{Remark 3.1.} One can easily see that the twisted homology \( H_\chi^*(N, F) \) and twisted signature sign\(^\chi(N, F)\) are independent of the group \( G \) used in the construction: they only depend on the pair \((N, F)\) and the multiplicative character \( \chi : H_1(N \setminus F) \rightarrow \mathbb{C}^* \), which must be assumed of finite order. In particular, we can always take for \( G \) the “smallest” cyclic group, viz. the
image of $\chi$. Indeed, there is an obvious canonical isomorphism between $H^*_\chi(N, F)$ and the $\chi$-equivil typical summand

\[ V^\chi_*(G) := \{ x \in H_*(N^G; \mathbb{C}) \mid gx = \chi(g)x \text{ for all } g \in G \}, \]

and the form $\varphi^\chi$ is $|G|$-times the restriction to $V^\chi_*(G)$ of the ordinary intersection index form $\langle \cdot, \cdot \rangle$. Now, if $G$ is replaced with a larger group $G' \to G$, the transfer map induces an isomorphism $V^\chi_*(G) \to V^\chi_*(G')$, multiplying the intersection index form by another positive factor $[G' : G]$; hence, the signature is preserved.

Of particular interest is the behavior of the signature under the gluing of manifolds. Recall that, by Novikov’s additivity, if $N_1$ and $N_2$ are two 4-manifolds such that $\partial N_1 = -\partial N_2$ and $N = N_1 \cup_\partial N_2$, then the ordinary and the twisted signatures of $N$ satisfy

\[ \text{sign}(N) = \text{sign}(N_1) + \text{sign}(N_2) \quad \text{and} \quad \text{sign}^\chi(N, F) = \text{sign}^\chi(N_1, F_1) + \text{sign}^\chi(N_2, F_2). \]

Of course, in the twisted version we assume that the ramification loci $F_1$ and $F_2$ match along the boundary, $F = F_1 \cup_\partial F_2$, and the characters on $N_1$, $N_2$ are the restrictions of a character on $N$. If $N_1$ and $N_2$ are glued along a part of their boundaries only, the above equalities may fail. This situation was completely studied by Wall in [Wal69]. For our purposes we only need a particular case of Wall’s theorem, which we state below. The result is given in terms of ordinary signatures, but, as mentioned by Wall at the end of his paper, the same conclusion holds if we consider twisted signatures.

**Theorem 3.2** (see [Wal69]). Suppose that $\partial N_1 \simeq M_1 \cup M_0$ and $\partial N_2 \simeq M_2 \cup -M_0$, where $M_0, M_1$ and $M_2$ are 3-manifolds glued along their common boundary. Let $N := N_1 \cup_\partial N_2$ and $X := \partial M_0 = \partial M_1 = \partial M_2$. Consider the $\mathbb{C}$-vector spaces $A_i := \text{Ker}[H_1(X; \mathbb{C}) \to H_1(M_i; \mathbb{C})]$, $i = 0, 1, 2$, and let

\[ K(A_0, A_1, A_2) := \frac{A_0 \cap (A_1 + A_2)}{(A_0 \cap A_1) + (A_0 \cap A_2)}. \]

If $K(A_0, A_1, A_2)$ is trivial, then we have $\text{sign}(N) = \text{sign}(N_1) + \text{sign}(N_2)$.

**Remark 3.3.** Note that the additivity in Theorem 3.2 holds if at least two of $A_0, A_1, A_2$ are equal. Moreover, Wall shows in his article that the vector space $K(A_0, A_1, A_2)$ is independent of the order of the $A_i$’s. When working with twisted signatures, we shall use the notation $A^\chi_i := \text{Ker}[H^\chi_1(X) \to H^\chi_1(M_i)]$, $i = 0, 1, 2$.

### 3.2. The signature of a link

Let $L$ be a $\mu$-colored link in an integral homology sphere $\mathbb{S}$. By Alexander duality, the group $H_1(\mathbb{S} \setminus L)$ is generated by the meridians of the components of $L$. We shall denote by $m^k_i$ the meridians of the components of the sublink $L_i$ of $L$ of color $i = 1, \ldots, \mu$.

Let $\mathbb{Z}^\mu$ be the free multiplicative group generated by $t_1, \ldots, t_\mu$. The coloring on $L$ gives rise to a homomorphism $c : H_1(\mathbb{S} \setminus L) \to \mathbb{Z}^\mu$, $m^k_i \mapsto t_i$, $i = 1, \ldots, \mu$. We consider multiplicative characters $H_1(\mathbb{S} \setminus L) \to \mathbb{C}^\ast$ that respect the coloring, i.e., factor through $c$. They are determined by their values on the generators $t_i$, and the group of such characters can be identified with $\mathcal{T}^\mu$.

Through this identification, the character $\omega \in \mathcal{T}^\mu$ assigns the meridians of the components of the sublink $L_i$ to $\omega_i$. With a certain abuse of the language, we will shortly speak about the character $\omega$ on $L$ and say that $\omega$ assigns $\omega_i$ to (each component of) $L_i$.

The next proposition asserts that $\omega : H_1(\mathbb{S} \setminus L) \to \mathbb{C}^\ast$ extends to a finite order character $\omega : H_1(N \setminus F) \to \mathbb{C}^\ast$ (also denoted by the same letter $\omega$), where $N$ is a 4-manifold bounded by $\mathbb{S}$ and $F \subset N$ is a certain properly immersed surface.
Proposition 3.4. Let $L$ be a $\mu$-colored link in an integral homology sphere $S$. Then, there exists a compact smooth oriented 4-manifold $N$ and an oriented properly immersed surface $F = F_1 \cup \ldots \cup F_\mu$ in $N$ such that

- $\partial N = S$ and $\partial F_i = L_i$ for $i = 1, \ldots, \mu$,
- the group $H_1(N \setminus F) \simeq \mathbb{Z}^\mu$ is freely generated by the meridians $\tilde{m}_i$ of $F_i$, and
- one has $[F_i, \partial F_i] = 0$ in $H_1(N, \partial N)$.

As a consequence, any character $\omega \in T^\mu$ extends to a unique character $\omega: H_1(N \setminus F) \to \mathbb{C}^*$, $\tilde{m}_i \mapsto \omega_i$.

For short, as for characters on links, we will speak about the character $\omega$ on $F$ and say that $\omega$ assigns $\omega_i$ to the component $F_i$.

We postpone the proof of this statement till Section 3.3.

Now, we are ready to define the main object of study in this paper.

Definition 3.5. The signature of a $\mu$-colored link $L \subset S$ is the map

$$\sigma_L: T^\mu \to \mathbb{Z}, \quad \omega \mapsto \text{sign}(N,F) - \text{sign}(N),$$

where $N$ and $F$ are as in Proposition 3.4.

The signature of a $\mu$-colored link in $S$ is related to invariants previously defined by Gilmer [Gil81], Smolinski [Smo89], Levine [Lev92] and the first author [Flo05]. The interested reader can find detailed history in [CF08]. In the case where $S = S^3$, the signature considered in this paper coincides with the signature defined by Cimasoni–Florens [CF08] for $\omega \in T$ with $\omega_i \neq 1$ for all $i = 1, \ldots, \mu$. In our present work we shall deal also with the case $\omega_i = 1$. The following remark should be clear from the definition of the signature of a colored link.

Remark 3.6. Let $L$ be a $\mu$-colored link in $S$, and let $\omega \in T^\mu$ be a vector such that $\omega_i = 1$. Then, the following equality holds:

$$\sigma_L(\ldots, 1_i, \ldots) = \sigma_{L_1 \cup \ldots \cup L_i \cup \ldots \cup L_\mu}(\ldots, \hat{1}_i, \ldots).$$

Another important observation is the fact that the coloring of the link is essential: it is not enough to merely assign a value of a character to each component of the link. More precisely, we have the following relation (whose proof for $S^3$ found in [CF08] extends to integral homology spheres almost literally: the extra term is due to the perturbation of the union $F_\mu \cup F_\mu+1$ of two components of the ramification locus into a single surface).

Proposition 3.7 (see [CF08] Proposition 2.5]). Let $L := L_1 \cup \ldots \cup L_{\mu+1}$ be a $(\mu + 1)$-colored link, and consider the $\mu$-colored link $L' := L_1' \cup \ldots \cup L_{\mu}'$ defined via $L_i' = L_i$ for $i < \mu$ and $L_{\mu}' = L_{\mu} \cup L_{\mu+1}$. Then, for any character $\omega \in T^\mu$, one has

$$\sigma_{L'}(\omega) = \sigma_L(\omega_1, \ldots, \omega_{\mu}, \omega_{\mu}) - \ell_k(L_{\mu}, L_{\mu+1}).$$

Corollary 3.8. The multivariate signature of a generalized Hopf link $H_{m,n}$ does not depend on the coloring, provided that linked components are given distinct colors.

In particular, Proposition 3.7 provides a relation between the restriction of the multivariate signature of a colored link to the diagonal in $T^\mu$ and the Levine–Tristram signature of the underlying monochrome link.

As asserted in the following proposition, the signature of a colored link is well defined, i.e., independent of the pair $(N,F)$ chosen to compute it. This is a consequence of Novikov’s additivity and the $G$-signature theorem.
\textbf{Proposition 3.9.} For all \( \omega \in \mathcal{T}^\mu \), the signature of \((S, L)\) at \( \omega \)
\[ \sigma_L(\omega) = \text{sign}^\omega(N, F) - \text{sign}(N) \]
does not depend on the pair \((N, F)\).

\textbf{Proof.} Given two pairs \((N', F')\) and \((N'', F'')\) as in Proposition 3.4, consider \(W := N' \cup g - N''\)
and \(F := F' \cup g - F'' \subset W\). By Novikov's additivity, the statement of the proposition would follow if we show that \(\text{sign}^\omega(W, F) = \text{sign}W\).

To compute the twisted signature, we can use the group \(G := C_{q_1} \times \cdots \times C_{q_\mu}\), where \(q_i\) is the order of \(\omega_i\), \(i = 1, \ldots, \mu\), see Remark 3.1. Crucial is the fact that, under the assumptions on \((W, F)\), this group results in a smooth closed manifold \(W^G\).

Consider the equitypical decomposition of the \(\mathbb{C}[G]\)-module
\[ (3.1) \quad H := H_2(W^G; \mathbb{C}) = \bigoplus \rho V^\rho, \]
where \(\rho\) runs over all multiplicative characters \(G \to \mathbb{C}^\ast\). Since the intersection index form \(\langle \cdot, \cdot \rangle\) is \(G\)-invariant, this decomposition is orthogonal. Denote by \(\text{sign}V^\rho\) the signature of the restriction of the form to \(V^\rho\). By Remark 3.1 we have \(\text{sign}^\omega(W, F) = \text{sign}V^\omega\).

The argument below is a slight generalization of [Roh71] (see also [CG78, Lemma 2.1]).

Each space \(V^\rho\) can further be decomposed (not canonically) into the orthogonal sum of two subspaces \(V^\rho_+\) and \(V^\rho_-\) with, respectively, positive and negative definite restriction of \(\langle \cdot, \cdot \rangle\). Summation over all characters gives us a \(G\)-invariant decomposition \(H = H_+ \oplus H_-\). Recall that the \(G\)-signature of an element \(g \in G\) is \(\text{sign}(g, W) := \text{trace} g_*|H_+ - \text{trace} g_*|H_- \in \mathbb{C}\). It is well defined; in fact, using (3.1), we have
\[ \text{sign}(g, W) = \sum \rho(g) \text{sign}V^\rho. \]

Multiplying this by \(\bar{\omega}(g)\) and summing up over all \(g \in G\), we arrive at
\[ |G| \text{sign}V^\omega = \sum_{g \in G} \bar{\omega}(g) \text{sign}(g, W) = |G| \text{sign}V^1 + \sum_{g \neq 1} (\bar{\omega}(g) - 1) \text{sign}(g, W). \]
(Recall that irreducible characters are orthogonal. For the second equality, we use the identity \(\sum_g \text{sign}(g, W) = |G| \text{sign}V^1, g \in G\), which is the first equality with \(\omega \equiv 1\).) By the usual transfer argument, \(\text{sign}V^1 = \text{sign}W\). Summarizing, we conclude that
\[ (3.2) \quad \text{sign}^\omega(W, F) - \text{sign}(W) = \frac{1}{|G|} \sum_{g \neq 1} (\bar{\omega}(g) - 1) \text{sign}(g, W) \]
is a linear combination of the \(g\)-signatures \(\text{sign}(g, W)\) with \(g \in G\) and \(g \neq 1\).

Since \(W\) is a smooth manifold, we can use the \(G\)-signature theorem [AS68, Gor86], which expresses the \(g\)-signature \(\text{sign}(g, W)\) in terms of the fixed point set of \(g\). We use repeatedly the fact that each surface \(F_i\) is connected and the covering is "uniform" along \(F_i\); hence, the extra factor appearing in the \(G\)-signature theorem depends on the element \(g \in G\) only and does not depend on a particular component of the fixed point set.

If \(1 \neq g \in C_{q_i}\) lies in one of the factors of \(G\), its fixed point set is \(F_i\) and \(\text{sign}(g, W)\) is a multiple of \([F_i]^2\). By Proposition 3.4 \([F^*_i, \partial F^*_i] = 0 \in H_2(N^*, \partial N^*)\) for \(* = i\) or \(n\); hence, \([F_i] = 0\) and \(\text{sign}(g, W) = 0\).

If \(g \in C_{q_i} \times C_{q_j}\) lies in the product of two factors (but not in either of them), the fixed point set is \(F_i \cap F_j\) and \(\text{sign}(g, W)\) is a multiple of \([F_i], [F_j]) = 0\) (since, as above, \([F_i] = [F_j] = 0\).
In all other cases, the fixed point set is empty (there are no triple intersections); hence, \( \text{sign}(g,W) = 0 \). Summarizing, \( \text{sign}(g,W) = 0 \) whenever \( g \neq 1 \); in view of (3.2), this implies that \( \text{sign}^*(W,F) = \text{sign} W \) and concludes the proof. \( \square \)

3.3. **Proof of Proposition 3.4.** Consider an integral surgery presentation for \( S \) given by a framed oriented link \( T = T_1 \cup \ldots \cup T_k \) in \( S^3 \). Since \( S \) is a homology sphere, we may assume that \( T \) is algebraically split and that the surgery coefficients of each of its components are \( \pm 1 \) [Mat87, Theorem A]. The link \( L \) can be represented by a collection of curves in \( S^3 \setminus T \).

Let \( N \) be the 4-manifold obtained by attaching 2-handles to \( B^4 \) along the components of \( T \) according to their framings. Since the linking matrix of \( T \) is diagonal with \( \pm 1 \) entries, we may slide the knots in \( L \) over the attached handles in order to obtain a presentation of \( L \) in \( S \) such that \( \ell k_S(L_i,T_j) = 0 \) for all \( i = 1, \ldots, \mu \) and \( j = 1, \ldots, k \). Since all \( L_i \) are disjoint from the attaching tori of the handles, we can consider a surface \( F \) in \( B^4 \), the 0-handle of \( N \), such that \( F \) is a union of compact connected oriented smooth surfaces \( F_1, \ldots, F_\mu \), and each \( F_i \) is smoothly embedded with \( \partial F_i = L_i \).

We have the following commutative diagram:

\[
0 = H^1(N) \longrightarrow H^1(N \setminus F) \longrightarrow H^2(N,N \setminus F) \longrightarrow H^2(N) \]

where, by Alexander and Lefschetz duality, the two vertical arrows are isomorphisms and the inclusion homomorphism \( i_* \) is trivial, as \( \ell k_S(L_i,T_j) = 0 \) and thus \( [F_i, \partial F_i] = 0 \in H_2(N, \partial N) \) for all \( i = 1, \ldots, \mu \). It follows that \( H^1(N \setminus F) \) is canonically isomorphic to \( H_2(F, \partial F) = \mathbb{Z}^\mu \), and the latter group is freely generated by the fundamental classes \( [F_i, \partial F_i] \). Repeating the same computation over the finite field \( \mathbb{F}_p \), we get \( H^1(F \setminus F; \mathbb{F}_p) = H_2(F, \partial F; \mathbb{F}_p) \) and, since the dimension of this vector space does not depend on \( p \), we conclude that the homology group \( H_1(F \setminus F) = \text{Hom}(H_1(F \setminus F), \mathbb{Z}) \) is freely generated by the elements of the dual basis, i.e., the meridians \( \bar{m}_i \) of the components \( F_i \subset N \). \( \square \)

4. **Proof of Theorem 2.2**

4.1. **Auxiliary statements.** In the proof of Theorem 2.2, it will be useful to have some control over the surface \( F \) used to compute the colored signatures; namely, sometimes we want the distinguished component \( K \) to bound a disk. The proof of the following lemma is a straightforward adaptation of the proof of Proposition 3.4.

**Lemma 4.1.** Let \( K \cup L \) be a \((1, \mu)\)-colored link in \( S \). Then, the pair \((N,F)\) in Proposition 3.4 can be chosen of the form \((N,D \cup F)\), where \( D \) is a disk, \( K = \partial D \) and \( L_i = \partial F_i \).

**Proof.** As explained in the proof of Proposition 3.4, we can consider an integral surgery presentation for \( S \) given by a framed oriented link \( T = T_1 \cup \ldots \cup T_k \) in \( S^3 \), where \( T \) is algebraically split and the surgery coefficients of each of its components are \( \pm 1 \). Moreover, the link \( K \cup L \) can be represented by a collection of curves in \( S^3 \setminus T \) such that \( \ell k(K,T_i) = \ell k(L_j,T_i) = 0 \) for all \( i, j \).

Notice that we can obtain \( K \cup L \subset S \) by starting with \( U \cup L \subset S^3 \setminus T \), where \( U \) is the unknot, and performing surgery on unknotted curves \( C_1, \ldots, C_\ell \) in \( S^3 \setminus (T \cup U \cup L) \) with framings \( \varepsilon_i = \pm 1 \) to do some crossing changes on \( U \) to obtain \( K \). It is clear that we might
Figure 1. This diagram represents the pairs \((N, D \cup F)\) and \((N, D \cup F)\). The gray band is the four ball \(N_2 = B = D \times B^2\).

assume \(\ell k(U, T_i) = 0\) for all \(i\) and that the curves \(C_i\) may be chosen such that \(\ell k(C_i, C_j) = 0\) if \(i \neq j\) and \(\ell k(C_i, T_j) = \ell k(C_i, U) = \ell k(C_i, L_j) = 0\) for all \(i\) and \(j\).

The link \(U \cup L\) in \(S^3\) bounds a properly immersed surface \(D \cup F_1 \cup \ldots\) in \(B^4\). Indeed, one has

\((1)\) \(L_i = \partial F_i = F_i \cap \partial B^4\) and \(U = \partial D = D \cap \partial B^4\);

\((2)\) \(D\) and each surface \(F_i\) are transversal to \(\partial B^4\), and

\((3)\) distinct surfaces intersect transversally, at double points, and away from \(\partial B^4\).

Consider the 4–manifold \(N\) obtained by attaching 2–handles to \(B^4\) along the components of \(T \cup C_1 \cup \ldots \cup C_t\) according to their framings. By construction we obtain the link \(K \cup L\) sitting in \(S = \partial N\) and bounding \(F\). Moreover, the above conditions on the linking numbers guarantee that the proof of Proposition 3.4 follows word by word with the manifold \(N\) and the surface \(F\) considered in this proof. □

The next lemma is straightforward; it is stated for references. Essentially, it is this lemma that accounts for the restriction \((\upsilon', \upsilon''') \neq (1, 1)\) in the statement of Theorem 2.2. Certainly, the statement on \(H^1_\chi(X)\) extends to any topological space \(X\), whereas that on \(H^0_\chi(X)\) extends to any space with abelian fundamental group.

Lemma 4.2. Let \(X \cong T^2\) be a 2-torus and \(\chi: H_1(X) \rightarrow \mathbb{C}^*\) a multiplicative character. Then

\[ H^1_\chi(X) = H_1(X; \mathbb{C}), \quad H^0_\chi(X) = H_0(X; \mathbb{C}) \] if \(\chi \equiv 1\) and \(H^1_\chi(X) = H^0_\chi(X) = 0\) otherwise.

4.2. A special case. We start by proving a special case of Theorem 2.2 which will be useful later on and whose proof contains the key ingredients used to establish the general formula. In the following lemma we study the effect on the colored signatures of changing the component \(K\) of a \((1, \mu)\)-colored link \(K \cup L \subset S\) to a collection of \(\nu\) parallel curves, i.e. of performing a \((\nu, 0)\)-cabling. This operation is equivalent to the splice of \(K \cup L \subset S\) and \(H^1_\nu(X) \subset S^3\).

Let \(K \cup L\) be the resulting \((\nu + \mu)\)-colored link. Denote \(\lambda := \ell k(K, L)\) and, for a character \(\omega \in \mathcal{T}^\mu\), let \(\nu := \omega \uparrow \lambda\). For a character \(\zeta \in \mathcal{T}^\nu\), let \(\pi := \prod_{i=1}^\nu \zeta_i = \zeta \uparrow [1]_\nu\).

Lemma 4.3. In the notation above, assuming that \((\nu, \pi) \neq (1, 1)\), one has

\[ \sigma_{K \cup L}(\zeta, \omega) = \sigma_{K \cup L}(\pi, \omega) - \delta(\zeta)\delta(\omega \star \lambda). \]
Proof. The diagram in Figure 1 might be helpful to follow the construction. Let \((N, D \cup F)\) be the pair constructed in Lemma 4.1 for the link \(K \cup L \subset S = \partial N\) and fix a tubular neighborhood \(B \cong D \times B^2\) of \(D\) in \(N\). The pair \((N, D \cup F)\) can be written as the union
\[
(N \setminus B, F \cap (N \setminus B)) \cup (B, (D \cup F) \cap B)
\]
glued along \((D \times S^1, F \cap \partial B)\). Without loss of generality, by taking the neighborhood \(B\) small enough, we may assume that the pair \((B, (D \cup F) \cap B)\) has boundary \((S^3, H_{1,m})\), where \(m\) is the number of points in \(D \cap F\). The components of \(H_{1,m} = V \cup U_1 \cup \ldots \cup U_m\) inherit an orientation from \(D \cup F\). Color the components according to the decomposition of \(D \cup F\). The character on \(H_{1,m}\) induced by the character on \(D \cup F\) assigns \(\pi\) to the component \(V\).

Remark 4.4. Formally, the \(U\)-components of \(H_{1,m}\) have "random" orientations depending on the signs of the intersection points. However, we can convert \(H_{1,m}\) to the standard positive generalized Hopf link by the following operations:

- recolor the link by assigning a separate color to each component; by Corollary 3.8 this operation does not change the signature of the link;
- whenever \(\ell \kappa(V, U_i) = -1\), change the orientation of \(U_i\) and replace the value of the character on the meridian of this component by its conjugate; this operation obviously preserves the cyclic covering and, hence, the signature.

We denote the resulting character on the \(U\)-part of the link by \(\bar{\omega}\). This character differs from \(\omega \ast \lambda\) by a number of pairs of the form \(\eta, \bar{\eta}\) with \(\eta \in \mathcal{T}^1\): these pairs correspond to pairs of points of intersection of \(F\) and \(D\) of opposite sign, which appear whenever the geometric intersection of \(F_i\) and \(D\) does not coincide with their algebraic intersection, given by the linking numbers of their boundaries. We have
\[
\delta(\bar{\omega}) = \delta(\omega \ast \lambda),
\]
see Lemma 2.7 and (3).

We use Wall’s Theorem 3.2 to relate the twisted and non-twisted signatures of \((N, D \cup F)\) and \((N \setminus B, F \cap (N \setminus B))\). To this end, define \(N_1 = N \setminus B\), \(M_1 = S \setminus T(K)\), \(N_2 = B\), \(M_2 = T(K)\) and \(M_0 = D \times S^1\), where \(T\) stands for a small tubular neighborhood and \(T\) is its interior. One has \(\partial N_1 = M_1 \cup M_0\) and \(\partial N_2 = M_2 \cup -M_0\), and in both cases the manifolds are glued along \(X := \partial D \times S^1 = K \times S^1\). Let \(m\) and \(\ell\) be the meridian and longitude of \(K\), which generate \(H_1(X)\). Following the notation of Theorem 3.2 we have \(A_0 = A_1 = (\ell)\) and \(A_2 = (m)\), which implies that \(K(A_0, A_1, A_2) = 0\) and thus
\[
\text{sign}(N) = \text{sign}(N_1 \cup N_2) = \text{sign}(N_1) + \text{sign}(N_2) = \text{sign}(N_1).
\]

We now make the corresponding computation with twisted coefficients. According to Lemma 4.1, the character \(\rho := (\pi, \omega)\) on \(K \cup L\) extends to a unique character \(\rho\) on \(D \cup N\), where \(\rho\) assigns the component \(D\) to \(\pi\) and \(F_i\) to \(\omega_i\). We need to study the relationship between \(\text{sign}^\rho(N_1 \cup N_2, D \cup F)\) and the twisted signatures of \(N_1\) and \(N_2\). The group \(H_1(X)\) is generated by \(m, \ell\) and, since \(\rho(m) = v\) and \(\rho(\ell) = \pi\) are not both trivial, we have \(H_1^\rho(X) = 0\), see Lemma 4.2. This trivially implies \(K(A_0^\rho, A_1^\rho, A_2^\rho) = 0\), and Wall’s Theorem 3.2 yields
\[
\text{sign}^\rho(N_1 \cup N_2, D \cup F) = \text{sign}^\rho(N_1, F \cap N_1) + \text{sign}^{(\pi, \bar{\omega})}(N_2, (D \cup F) \cap N_2).
\]

As observed above, the pair \((N_2, (D \cup F) \cap N_2)\) has boundary \((S^3, H_{1,m})\); since \(N_2\) is contractible as well, the second summand in equation (4.3) vanishes by Theorem 2.6 and
Combining equations (4.2) and (4.3) with Definition 3.5 of signature, we get

$$
\sigma_{K \cup L}(\rho) = \text{sign}(N, D \cup F) - \text{sign}(N) = \text{sign}(N_1, F \cap N_1) - \text{sign}(N_1).
$$

Moreover, we can compute the signature of $H_{\nu,m}$ from the pair $(B, (D \cup F) \cap B)$; thus,

$$
\sigma_{K \cup L}(\zeta, \omega) = \text{sign}(\zeta, \omega)(N, D \cup F) - \text{sign}(N)
$$

using Theorem 2.6. Using the pair $(N, D \cup F)$ to compute the signature of $K \cup L$, we have

$$
\sigma_{K \cup L}(\zeta, \omega) = \text{sign}(\zeta, \omega)(N, D \cup F) - \text{sign}(N)
$$

and the statement follows from (4.1).

\[\square\]

4.3. Proof of Theorem 2.2. The diagram in Figure 2 might be useful to follow the construction. We will use the shortcuts $\tilde{\omega}^* := \omega^* \ast \lambda^*, \ast = j$ or $m$. Let $(N', D' \cup F')$ be the pair constructed in Lemma 4.3 for the link $K' \cup L' \subset S'$ and fix a small tubular neighborhood $B' \cong D' \times B^2$ of $D'$ in $N'$. Since $(v', v'') \neq (1, 1)$, we can repeat the arguments in the proof of Lemma 4.3 involving Wall’s theorem to obtain

$$
\sigma_{K' \cup L'/(v', \omega')} = \text{sign}(v', \omega')(N' \setminus B', F' \cap (N' \setminus B')) - \text{sign}(N' \setminus B').
$$

Notice that, by construction, the surface $(D' \cup F') \cap B'$ consists of the disc $D'$ and a collection of $m'$ parallel discs transversal to $D'$ and coming from the surface $F'$. We have $m' \geq |\lambda'|$ and, to start with, let us assume for simplicity that $m' = |\lambda'|$. In this case, the
complement of the boundary of the $|\lambda'|$ parallel disks inherits the character $\omega'$. Consider now a pair $(\Lambda'', D'' \cup F'')$ given by Lemma 4.1 for $K'' \cup L'' \subset \mathbb{S}''$. Replace $K''$ with $|\lambda'|$ parallel copies to obtain the $(|\lambda'| + \mu'')$-colored link $K'' \cup L'' \subset \mathbb{S}''$, and assign the character $(\omega', \omega'') : H_1(\mathbb{S} \setminus (K'' \cup L'')) \to \mathbb{C}^*$. Accordingly, replace the disc $D''$ with $|\lambda'|$ parallel copies to obtain a pair $(N'', D'' \cup F'')$. Without loss of generality, we may assume that all the discs constituting $D''$ lie in a small neighborhood $B'' \cong D'' \times B^2$. We color the components of $D''$ in such a way that there is a colored oriented one-to-one correspondence between them and the $|\lambda'|$ parallel discs coming from the surface $F''$ in $(D' \cup F') \cap B'$.

Since $\nu' = \omega' \uparrow [1]|\lambda'|$, see (2.2), Lemma 4.3 applied to the $(|\lambda'|, 0)$-cabling of $K'' \cup L''$ along $K''$ yields

$$
\sigma_{K'' \cup L''}(\omega', \omega'') = \text{sign}(\omega', \omega'')(N'', D'' \cup F'') - \text{sign}(N'')
= \sigma_{K'' \cup L''}(\nu', \omega'') - \delta(\omega')\delta(\omega'').
$$

If $m' > |\lambda'|$, the geometric intersection between the $F'_1$ and $D'$ is not minimal. The additional intersection points come in pairs of opposite sign. We can repeat verbatim the above construction considering $m'$ parallel copies of $D''$. In this case, the restriction of the character will no longer be $\omega'$ but some $\omega \in T''$ with the property $\nu' = \omega \uparrow [1]|m'|$. Moreover, using the arguments in Remark 4.4 it is easy to see that $\delta(\omega) = \delta(\omega')$. Hence, equation (4.8) still holds.

Now, let us look at the pair $(N, F)$ obtained as the glueing

$$
(N' \setminus B', F' \cap (N' \setminus B')) \cup (N'', D'' \cup F''),
$$

where the solid torus $T'' \times \partial B^2$ in the boundary of the neighborhood $B'$ is identified with the solid torus $T'' = \partial D'' \times B^2$, which is a tubular neighborhood $T(K'')$ of $K''$ in $\mathbb{S}''$. The identification is made in such a way that the disc $D' \subset T'$ is glued to $B^2 \subset T''$. Moreover, the $|\lambda'|$ discs removed from the surfaces $F'$ in the intersection $F' \cap (N' \setminus B')$ are filled with the corresponding $|\lambda'|$ discs constituting $D''$. Notice that the boundary of $(N, F)$ is nothing but $(\mathbb{S}, L)$, i.e., the splice in question. Furthermore, by the construction, the pair $(N, F)$ can be used to compute the colored signature of $(\mathbb{S}, L)$, that is,

$$
\sigma_L(\omega', \omega'') = \text{sign}(\omega', \omega'')(N, F) - \text{sign}(N).
$$

To complete the proof we shall study the behavior of the twisted and classical signatures of $N$ with respect to the decomposition (4.9). By Theorem 3.2 the signatures will be additive with respect to this decomposition if at least two of the kernels $A_0, A_1, A_2$ coincide in the classical and in the twisted version. In the classical version, we are dealing with the group $H_1(\partial T')$, generated by $m_{K'} = \ell_{K'}$ and $\ell_{K'} = m_{K''}$, the meridian and longitude of $K'$ and $K''$ which are identified in (4.9). It is clear that the kernels of the inclusion of $H_1(\partial T')$ into both $H_1(\mathbb{S} \setminus \text{int}T(K'))$ and $H_1(T(K''))$ are generated by $\ell_{K'} = m_{K''}$, and thus, by Wall’s theorem we have

$$
\text{sign}(N) = \text{sign}(N' \setminus B') + \text{sign}(N'').
$$

In the twisted version, the space $H_1(\omega', \omega'')(\partial T') = H_1(\nu', \nu'')(\partial T')$ vanishes due to Lemma 4.2 and the assumption $(\nu', \nu'') \neq (1, 1)$. Hence, Theorem 3.2 yields

$$
\text{sign}(\omega', \omega'')(N, F) = \text{sign}(\nu', \omega')(N' \setminus B', F' \cap (N' \setminus B')) + \text{sign}(\omega', \omega'')(N'', D'' \cup F'').
$$
Putting these equations together, we obtain

\[ \sigma_L(\omega', \omega'') = \text{sign}(\nu'') \text{sign}(\nu' \wedge \omega')(N' \setminus B', F' \cap (N' \setminus B')) + \text{sign}(\omega'') \text{sign}(\omega' \wedge \omega')(N'', D'' \cup F'') - \text{sign}(N' \setminus B') - \text{sign}(N'') \]

\[ = \sigma_{K' \cup L'}(\nu', \omega') + \sigma_{K'' \cup L''}(\nu', \omega'') - \delta(\omega') \delta(\omega''). \]

4.4. Proof of Addendum 2.4. Applying Theorem 2.2 to the splice of \( K' \) and \( K'' \cup L'' \), we obtain

\[ \sigma_L(\omega) = \sigma_{K''}(\nu'') + \sigma_{K'' \cup L''}(1, \omega'') - \delta(1) \delta(\omega'' \wedge \lambda'') = \sigma_{K''}(\nu'') + \sigma_{L''}(\omega''). \]

Thus, it suffices to justify that, in this particular case, Theorem 2.2 holds even if \( \nu'' = 1 \).

Let \( \rho := (\nu', \nu'') \). In the proof of Theorem 2.2, the assumption \( \rho \neq (1, 1) \) was only used to establish that the twisted homology group \( H'_1(\partial T') \) is trivial, yielding (4.11). If \( \rho = (1, 1) \), this group is no longer trivial, but we shall see that (4.11) still holds if \( L' \) is empty.

By Remark 3.3, we only need to show that two among the three groups \( A_0^\rho, A_1^\rho \), and \( A_2^\rho \) are equal. We are dealing with the kernels of the inclusions \( H^0_1(\partial T') \to H^0_1(\tilde{M}_i) \), where \( M_0 = S' \setminus \text{int} T(K'), M_1 = S'' \setminus \text{int} T(K'') \) and \( M_2 = T(K'') \). Since \( \rho = (1, 1) \), the restriction of the covering to \( \partial T' \) is trivial and the group \( H^0_1(\partial T') \) is generated by the lifts \( \tilde{m}_{K'} \) of the meridian of \( K' \), which are identified respectively with the longitude and meridian of \( K'' \). While the generators of \( A_0^\rho \) are not evident, the groups \( A_0^\rho \) and \( A_2^\rho \) are easily seen to be equal. Indeed, since \( L' \) is empty and \( \nu'' = 1 \), the group \( H^0_1(\partial T') \) is the homology group of the trivial covering of \( M_0 \), therefore, \( \tilde{m}_{K'} \) generates \( A_0^\rho \). On the other hand, since \( L' \) is empty, \( |\lambda'| = 0 \) and we do not need to work with parallel copies of \( K'' \).

It follows that the group \( H^0_1(T(K'')) \) is the homology group of the trivial covering of \( M_2 \) and \( \tilde{m}_{K''} = \tilde{m}_{K'} \) generates \( A_2^\rho \). We conclude that \( A_0^\rho = A_2^\rho \), completing the proof.

5. The generalized Hopf link

In this section, we compute the signature of a generalized Hopf link using the \( C \)-complex approach of [CF08]. This approach works only for characters with all components distinct from one. Thus, we define the open character torus \( \mathcal{T}^\mu \), obtained from \( \mathcal{T}^\mu \) by removing all “coordinate planes” of the form \( \omega_i = 1, i = 1, \ldots, \mu \).

5.1. \( C \)-complexes and Seifert forms. We recall briefly the notion of \( C \)-complex of a \( \mu \)-colored link and its application to the computation of the signature. To avoid excessive indexation, we consider the special case of the bivariate signature of a bicolored link; for the general case and further details, see [CF08].

Thus, let \( K \cup L \) be a bicolored link, with the coloring \( K \mapsto 1, L \mapsto 2 \). (We do not assume \( K \) or \( L \) connected.) A \( C \)-complex is a pair of Seifert surfaces \( E \) for \( K \) and \( F \) for \( L \), possibly disconnected, which intersect each other transversally (in the stratified sense) and only at clasps, i.e., smooth simple arcs, each connecting a point of \( K \) to a point of \( L \). (In the general case of more than two colors, the only additional requirement is that all triple intersections of Seifert surfaces involved must be empty.) Let \( S := E \cup F \). Then, for each pair \( \varepsilon, \delta = \pm 1 \), one can consider the Seifert form

\[ \theta^{\varepsilon\delta} : H_1(S) \otimes H_1(S) \to \mathbb{Z}, \]

defined as follows. Pick a class \( \alpha \in H_1(S) \) and represent it by a simple closed curve \( a \subset S \) satisfying the following condition: each clasp \( c \subset E \cap F \) is either disjoint from \( a \) or entirely
Figure 3. This diagram represents a generalized Hopf link of type $H_{3,3}$. The link is depicted bounding a bicolored oriented $C$-complex $S$, which is the union of the disks $E_i$ and $F_j$. The red loop is $a_{11}$, whose homology class $\alpha_{11}$ is an element of $H_1(S)$.

contained in $a$. It is immediate that such a curve $a$ can be pushed off $E$ in the direction $\varepsilon$ (with respect to the coorientation of $E$, which is part of the structure) and off $F$ in the direction $\delta$, so that the resulting curve $a'$ is disjoint from $S$. Then, for another class $\beta \in H_1(S)$, the value $\theta^{\varepsilon\delta}(\alpha \otimes \beta)$ is the linking coefficient of the shift $a'$ and a cycle representing $\beta$.

Now, given a pair of complex units $(\eta, \zeta) \in \mathcal{T}_2$, consider the form

$$
H(\eta, \zeta) := (1 - \bar{\eta})(1 - \bar{\zeta})(\theta^{1,1} - \zeta \theta^{1,-1} - \eta \theta^{-1,1} + \eta \zeta \theta^{-1,-1}).
$$

Assuming that the extensions of $\theta^{\varepsilon\delta}$ to $H_1(S) \otimes \mathbb{C}$ are sesquilinear, this form is Hermitian; hence, it has a well-defined signature. It computes the signature of $K \cup L$.

**Theorem 5.1** (see [CF08]). The restriction to the open torus $\mathcal{T}^2$ of the bivariate signature of a bicolored link $K \cup L$ is given by

$$
\sigma_{K \cup L}(\eta, \zeta) \mapsto \text{sign} H(\eta, \zeta).
$$

**Remark 5.2.** Strictly speaking, the statement of Theorem 5.1 is the definition of signature in [CF08]. This definition is equivalent to the conventional one, see [CF08, Section 6.2].

In general, for a $\mu$-colored link $L$, one should consider a $\mu$-component $C$-complex $S$ and all $2^\mu$ possible shift directions, arriving at a Hermitian form $H(\omega)$, $\omega \in \mathcal{T}^\mu$, computing the signature $\sigma_L(\omega)$. The nullity $\text{null}_L(\omega) := \text{null} H(\omega)$ is also an invariant of $L$; it is given by the following theorem.

**Theorem 5.3** (see [CF08, Theorem 6.1]). For any character $\omega \in \mathcal{T}^\mu$ in the open character torus, one has $\text{null}_L(\omega) = \dim H_1^\mu(S^3 \setminus L)$. 
Proposition 5.4. Let $H := H_{m,n}$ be a generalized Hopf link. Then, for any $(\eta, \zeta) \in \hat{T}^m \times \hat{T}^n$, one has

$$\text{null}_H(\eta, \zeta) = \begin{cases} m + n - 3, & \text{if } \log \eta \in \mathbb{Z} \text{ and } \log \zeta \in \mathbb{Z}, \\ m - 1, & \text{if } \log \eta \notin \mathbb{Z}, \log \zeta \in \mathbb{Z}, \\ n - 1, & \text{if } \log \eta \in \mathbb{Z}, \log \zeta \notin \mathbb{Z}, \\ 0, & \text{otherwise.} \end{cases}$$

Proof. The generalized Hopf link $H_{m,n}$ can be thought of as the splice of the links $H_{1,m}$ and $H_{1,n}$. Since obviously $S^3 \setminus H_{1,m} \cong S^1 \times D_m$, where $D_m$ is an $m$-punctured disk, for any pair $(v, \eta) \in T^1 \times \hat{T}^m$ we have

$$\dim H_1^{(v,\eta)}(S^3 \setminus H_{1,m}) = \begin{cases} m - 1, & \text{if } v = 1, \\ 0, & \text{if } v \neq 1. \end{cases}$$

A similar relation holds for $H_{1,n}$; in view of Theorem 5.3, the statement of the proposition follows from the Mayer–Vietoris exact sequence, with Lemma 4.2 taken into account. \hfill \square

5.2. Proof of Theorem 2.6. Due to Remark 3.6 we have

$$\sigma_{m,n}(\ldots, 1, \ldots, \zeta) = \sigma_{m-1,n}(\ldots, \hat{1}, \ldots, \zeta), \quad \sigma_{m,n}(\eta, \ldots, 1, \ldots) = \sigma_{m,n-1}(\eta, \ldots, \hat{1}, \ldots).$$

These formulas agree with the statement of the theorem, see Lemma 2.7, and it suffices to compute the restriction of $\sigma_{m,n}$ to the open character torus $\hat{T}^{m+n}$.

Consider the group $G := \mathbb{Z}/m \times \mathbb{Z}/n$. We will use the cyclic indexing for the components of the link and other related objects. Let $K_i, i \in \mathbb{Z}/m$ be the first $m$ parallel components and $L_j, j \in \mathbb{Z}/n$, the last $n$ parallel components.

By an obvious semicontinuity argument, for any $\mu$-colored link $L$, the multivariate signature $\sigma_L(\omega)$ is constant on each connected component of each stratum $\{ \omega \in \hat{T}^\mu | \text{null}_L(\omega) = \text{const} \}$. If $L = H_{m,n}$, the strata are given by Proposition 5.4 they are the hyperplanes $P_p \times \hat{T}^m$ and $\hat{T}^m \times Q_q$, where

$$P_p := \{ \eta \in \hat{T}^m | \log \eta = p \}, \quad Q_q := \{ \zeta \in \hat{T}^n | \log \zeta = q \}, \quad p, q \in \mathbb{Z},$$

and all pairwise intersections thereof. It is immediate that the bi-diagonal $\eta_1 = \ldots = \eta_m, \zeta_1 = \ldots = \zeta_n$ meets each component of each stratum; hence, it suffices to compute the restriction of the signature function to this bi-diagonal. Due to Corollary 3.8 this is equivalent to computing the bivariate signature $\tilde{\sigma} : \hat{T}^2 \to \mathbb{Z}$, of the bicolored generalized Hopf link (with the coloring $K_i \mapsto 1, L_j \mapsto 2, (i, j) \in G$), and the formula to be established takes the form

$$\tilde{\sigma}(\eta, \zeta) = -\left( \text{ind}(m \log \eta - m) \right) \left( \text{ind}(n \log \zeta - n) \right), \quad (\eta, \zeta) \in \hat{T}^2.$$
Remark 5.5. If \( m \leq 1 \) or \( n \leq 1 \), then \( H_1(S) = 0 \) and the signature is trivially zero. Hence, from now on we can assume that \( m, n \geq 2 \). Note though that formally this case does agree with the statement of the theorem, as \( \delta \equiv 0 \) on \( \mathcal{T}^0 \) and \( \mathcal{T}^1 \).

In each disk \( E_i \), consider a collection of segments (simple arcs) \( e_{ij} := [e_{ij}, e_{i,j+1}], j \in \mathbb{Z}/n \), disjoint except the common boundary points and such that their union is a circle \( C_i \) parallel to \( \partial E_i = K_i \) (and the points appear in this circle in accordance with their cyclic order). Consider similar segments \( f_{ij} := [f_{ij}, f_{i+1,j}] \subset F_j, i \in \mathbb{Z}/m \), forming circles \( D_j \subset F_j \) parallel to \( \partial F_j = L_j \). Then, the group \( H_1(S) \) is generated by the classes \( \alpha_{ij} \) of the loops

\[
(i, j) \in G, \text{ connecting the points } e_{ij} \to f_{ij} \to f_{i+1,j} \to e_{i+1,j+1} \to f_{i+1,j+1} \to f_{ij+1} \to e_{ij+1} \to e_{ij},
\]

(in the order of appearance). The construction is illustrated in Figure 3. Note that we do not assert that these elements form a basis: they are linearly dependent. However, we will do the computations in the free abelian group \( \mathcal{H} := \bigoplus_{ij} \mathbb{Z} \alpha_{ij}, (i, j) \in G \); this change will increase the kernel of the form, but it will not affect the signature.

The proof of the following lemma is postponed till Section 5.3.

Lemma 5.6. Given \( \varepsilon, \delta = \pm 1 \), the only nontrivial values taken by the Seifert form \( \theta^{\varepsilon\delta} \) on the pairs of generators \( \alpha_{ij} \) as are as follows:

\[
\alpha_{ij} \otimes \alpha_{ij} \mapsto \varepsilon \delta, \quad \alpha_{ij} \otimes \alpha_{i+\varepsilon,j} \mapsto -\varepsilon \delta, \quad \alpha_{ij} \otimes \alpha_{i,j+\delta} \mapsto -\varepsilon \delta, \quad \alpha_{ij} \otimes \alpha_{i+\varepsilon,j+\delta} \mapsto \varepsilon \delta,
\]

where \( (i, j) \in G \).

Consider the Hermitian inner product \( \langle \cdot, \cdot \rangle \) on \( \mathcal{H} \otimes \mathbb{C} \) with respect to which \( \alpha_{ij} \) is an orthonormal basis, and use this inner product to identify operators \( A: \mathcal{H} \otimes \mathbb{C} \to \mathcal{H} \otimes \mathbb{C} \) and sesquilinear forms \( \alpha \otimes \beta \mapsto \langle \alpha A, \beta \rangle \). (In accordance with the contemporary right group action conventions, our matrices act on \textit{row} vectors by the \textit{right} multiplication.) Then, in order to complete the proof, we need to find the eigenvalues of the self-adjoint operator \( H(\eta, \zeta) \) as in (5.1). To this end, consider the unitary representation \( \rho: G \to U(\mathcal{H} \otimes \mathbb{C}) \) given by the index shifts of the basis elements, viz.

\[
\rho(p, q): \alpha_{ij} \mapsto \alpha_{i+p,j+q}, \quad (p, q, (i, j) \in G).
\]

This is the regular representation of \( G \), and its equitypical summands are all of dimension one; letting \( \xi_k := \exp(2\pi i/k) \), the summands are generated by the bi-eigenvectors

\[
v_{ij} := \frac{1}{mn} \sum_{(r,s) \in G} \xi_m^{-r} \xi_n^{-s} \alpha_{i+r,j+s}, \quad (i, j) \in G,
\]

so that \( v_{ij} \) is an eigenvector of \( \rho(p, q) \) with the eigenvalue \( \xi_m^p \xi_n^q \), \( (p, q) \in G \). It is immediate from Lemma 5.6 that all forms \( \theta^{\varepsilon\delta} \) are \( G \)-invariant; hence, they all have the same eigenvectors \( v_{ij} \). In fact, we have more: using Lemma 5.6 one easily concludes that

\[
\theta^{\varepsilon\delta} = \varepsilon \delta (\rho(0,0) - \rho(0,\varepsilon) - \rho(0,\delta) + \rho(\varepsilon,\delta)).
\]

Combining this with (5.1) and simplifying, we see that the spectrum of \( H(\eta, \zeta) \) consists of the \( mn \) real numbers \(-\lambda(\eta, \xi_m^\varepsilon)\lambda(\xi_n^\delta, \zeta)\), \( (i, j) \in G \), where

\[
\lambda(x, y) := i(1-\bar{x})(1-\bar{y})(1-xy).
\]
(Note that \(\lambda(x, y) \in \mathbb{R}\) whenever \(|x| = |y| = 1\), which we always assume.) Thus, the signature of \(I(\eta, \zeta)\) equals \(-\sigma_m(\eta)\sigma_n(\zeta)\), where \(\sigma_k(x)\) stands for the “signature” of the sequence of real numbers \(\lambda(x, \eta_i)\), \(i \in \mathbb{Z}/k\).

To compute \(\sigma_k(x)\), we make the following simple observations (where \(x, y \in \mathbb{C}\) are complex units, \(|x| = |y| = 1\)):

1. \(\lambda(x, 1) = \lambda(1, x) = \lambda(x, \bar{x}) = 0\);
2. \(\lambda(x, -1) = \lambda(-1, x) = -4 \text{Im}\ x;\)
3. with \(y \neq 1\) fixed, the function \(\lambda(x, y), x \neq 1\), changes sign only at \(x = \bar{y}\).

Combining items 2 and 3, we see that \(\sgn \lambda(x, y) = \sgn(\log x + \log y - 1)\) for all \(x, y \neq 1\). Consider the function \(\phi: (0, 1) \to \mathbb{Z}, t \mapsto \sigma_k(\exp(2\pi it))\). It follows that \(\phi\) is locally constant at each point \(t \in (0, 1)\) such that \(kt \notin \mathbb{Z}\), whereas \(\phi(t + 0) - \phi(t) = \phi(t) - \phi(t - 0) = 1\) for \(kt \in \mathbb{Z}\). Together with the normalization \(\phi(\frac{1}{2}) = \sigma_k(-1) = 0\) given by items 1 and 2 above, we have \(\phi(t) = \text{ind}(kt) - k\). In other words, \(\sigma_k(x) = \text{ind}(k\log x) - k\), which concludes the proof of the theorem.

5.3. Proof of Lemma 5.6. We keep the notation introduced in Section 5.2.

The cycles \(a_{ij}\) do satisfy the conditions imposed in the definition of \(\theta^{\varepsilon, \delta}\), see Section 5.1. To compute the linking coefficients, we consider the \(\Pi\)-shaped Seifert surface \(\Pi_{ij}\) for \(a_{ij}\) composed of three “squares”:

- one in \(E_i\), bounded by the loop \(c_{ij} \cdot k_{ij} \cdot c_{ij+1}^{-1} \cdot e_{ij}^{-1}\),
- one in \(E_{i+1}\), bounded by the loop \(e_{i+1,j} \cdot c_{i+1,j+1} \cdot k_{i+1,j}^{-1} \cdot c_{i+1,j}^{-1}\), and
- one bounded by \(f_{ij} \cdot k_{i+1,j} \cdot f_{ij+1}^{-1} \cdot k_{ij}^{-1}\), disjoint from \(S\) except the boundary.

Shift this surface together with the cycle, first off \(S\) in the direction \((\varepsilon, \delta)\), and then “up”, in the direction of the clasp \(c_{ij}\), i.e., from \(e_{ij}\) to \(f_{ij}\). Then, the intersection index of the shift \(\Pi_{ij}'\) and another cycle \(a_{pq}\) \((p, q) \in \mathbb{G}\), is easily seen geometrically; below, we give a simple visual description of the result.

Observe that all cycles \(a_{ij}\) lie in the graph \(S' := \bigcup_i C_i \cup \bigcup_j D_j \cup \bigcup_{i,j} c_{ij}\). Contracting each clasp to a point, we project \(S'\) to an \((m \times n)\)-grid in the torus \(T^2\), identified with \(D_0 \times C_0\). The cycle \(a_{ij}\) projects to the boundary \(\partial s_{ij}\) of the \((i, j)\)-th cell \(s_{ij}\) of the grid. (This cell can be visualized as the projection of the third square, the one not contained in \(E\), in the description of \(\Pi_{ij}\); the other two squares collapse to the two vertical edges of \(s_{ij}\).) Let \(s_{ij}' \subset T^2\) be a small shift of \(s_{ij}\) off the grid in the direction \((\varepsilon, \delta)\). Then one has

\[
\Pi_{ij}' \circ_{s_{ij}} a_{pq} = - \text{vert } s_{ij}' \circ_{s_{pq}} \text{hor } s_{pq},
\]

where \(\text{vert}\ s\) stands for the sum of the two “vertical” edges in the boundary of a (shifted) cell \(s\) (with their boundary orientation), \(\text{hor}\ s\) stands for the sum of the two “horizontal” edges in \(\partial s\), and the second intersection index is in the torus \(T^2\), oriented so that the projection of each cycle \(a_{ij}\) is the positive boundary of the respective cell \(s_{ij}\). From here, the statement of the lemma is immediate. □

References

[AS68] M. F. Atiyah and I. M. Singer, The index of elliptic operators. III, Ann. of Math. (2) 87 (1968), 546–604. MR 0236952 (38 #5245)

[Bri66] E. Brieskorn, Beispiele zur Differentialtopologie von Singularitäten, Invent. Math. 2 (1966), 1–14. MR 0206972 (34 #6788)

[CF08] D. Cimasoni and V. Florens, Generalized Seifert surfaces and signatures of colored links, Trans. Amer. Math. Soc. 360 (2008), no. 3, 1223–1264 (electronic). MR 2357695 (2009b:57009)
A. J. Casson and C. McA. Gordon, *On slice knots in dimension three*, Algebraic and geometric topology (Proc. Sympos. Pure Math., Stanford Univ., Stanford, Calif., 1976), Part 2, Proc. Sympos. Pure Math., XXXII, Amer. Math. Soc., Providence, R.I., 1978, pp. 39–53. MR 520521 (81g:57003)

D. Cimasoni, *The Conway function of a splice*, Proc. Edinb. Math. Soc. (2) 48 (2005), no. 1, 61–73. MR 2117712 (2005d:57007)

A. Degtyarev, V. Florens, and A. G. Lecuona, *Signature of a splice II*, In preparation.

D. Eisenbud and W. Neumann, *Three-dimensional link theory and invariants of plane curve singularities*, Annals of Mathematics Studies, vol. 110, Princeton University Press, Princeton, NJ, 1985. MR 817982 (87g:57007)

V. Florens, *Signatures of colored links with application to real algebraic curves*, J. Knot Theory Ramifications 14 (2005), no. 7, 883–918. MR 2187604 (2007d:57013)

P. M. Gilmer, *Configurations of surfaces in 4-manifolds*, Trans. Amer. Math. Soc. 264 (1981), no. 2, 353–380. MR 603768 (83h:57027)

C. McA. Gordon, R. A. Litherland, and K. Murasugi, *Signatures of covering links*, Canad. J. Math. 33 (1981), no. 2, 381–394. MR 617628 (83a:57006)

C. McA. Gordon, *On the G-signature theorem in dimension four*, À la recherche de la topologie perdue, Progr. Math., vol. 62, Birkhäuser Boston, Boston, MA, 1986, pp. 159–180. MR 900251

M. Hedden and A. S. Levine, *Splicing knot complements and bordered Floer homology*, preprint arXiv:1210.7055v1 [math.GT].

J. Levine, *Invariants of knot cobordism*, Invent. Math. 8 (1969), 98–110; addendum, ibid. 8 (1969), 355. MR 0253348 (40 #6563)

J. P. Levine, *Signature invariants of homology bordism with applications to links*, Knots 90 (Osaka, 1990), de Gruyter, Berlin, 1992, pp. 395–406. MR 1177436 (94g:57026)

R. A. Litherland, *Signatures of iterated torus knots*, Topology of low-dimensional manifolds (Proc. Second Sussex Conf., Chelwood Gate, 1977), Lecture Notes in Math., vol. 722, Springer, Berlin, 1979, pp. 71–84. MR 547456 (80k:57012)

S. V. Matveev, *Generalized surgeries of three-dimensional manifolds and representations of homology spheres*, Mat. Zametki 42 (1987), no. 2, 268–278, 345. MR 915115 (89g:57015)

K. Murasugi, *On the signature of links*, Topology 9 (1970), 283–298. MR 0261585 (41 #6198)

V. A. Rohlin, *Two-dimensional submanifolds of four-dimensional manifolds*, Funckional. Anal. i Priložen. 5 (1971), no. 1, 48–60. MR 0298684 (45 #7733)

L. Smolinsky, *A generalization of the Levine-Tristram link invariant*, Trans. Amer. Math. Soc. 315 (1989), no. 1, 205–217. MR 931532 (89m:57021)

A. G. Tristram, *Some cobordism invariants for links*, Proc. Cambridge Philos. Soc. 66 (1969), 251–264. MR 0248854 (40 #2104)

H. F. Trotter, *Homology of group systems with applications to knot theory*, Ann. of Math. (2) 76 (1962), 464–498. MR 0143201 (26 #761)

O. Viro, * Branched coverings of manifolds with boundary, and invariants of links. I*, Izv. Akad. Nauk SSSR Ser. Mat. 37 (1973), 1241–1258. MR 0370605 (51 #6832)

O. Viro, *Twisted acyclicity of a circle and signatures of a link*, J. Knot Theory Ramifications 18 (2009), no. 6, 729–755. MR 2542693 (2011b:57018)

C. T. C. Wall, *Non-additivity of the signature*, Invent. Math. 7 (1969), 269–274. MR 0246311 (39 #7615)