Factoring linear trellises

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Factoring linear trellises

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Abstract—Koetter/Vardy proved in [9] the remarkable result that any linear trellis can be factored into elementary trellises. We prove that the spans (and their multiplicities) of the elementary factors of a linear trellis are uniquely determined, extending a known result for minimal trellises ([4], [8], [11]). In doing so, we give a graphical method to compute all the spans and their multiplicities. We also show how to determine all the possible edge-labelings of the factors of a linear trellis, and give exact conditions for their uniqueness. These results can help to compute and classify all trellises for a given code.

I. INTRODUCTION

Linear trellises are amongst the most important graph representations of linear codes, both for theoretical and practical reasons. Towards the end of last millennium, due to the observation of striking low complexity achieved by nonconventional trellises ([11]), the interest expanded to the whole class of tail-biting trellises (of which conventional trellises can be seen as a particular case). As a consequence, in the recent years, linear tail-biting trellises has been the subject of major research within trellis theory ([9], [8], [4], [5], [10], [7]). The most important achievement is probably the factorization theorem proven in [9], which states that every linear trellis is a product of elementary trellises. This fundamental theorem opened the road to other central works concerning minimal linear trellis representations of codes ([8], [4]).

In this paper we investigate further linear trellis factorizations and give graphical/combinatorial methods to compute such factorizations. We first prove that if we forget about edge-labels then unique factorization holds, which means that all the spans of factors and their multiplicities are uniquely determined. Our proof yields at the same time a method for computing all the spans and multiplicities. This result was proven before for minimal trellises ([11]), and the striking fact is that this holds true for any linear trellis and that edge-labels play no role. We then show how to find all the possible labelings of the elementary factors of a linear trellis, once the spans’ multiplicities are known. As a corollary, we get precise conditions under which such labelings are uniquely determined. Finally, we mention how these results help us to compute and classify all trellises representing a fixed code, which is important for the search of trellis representations that perform well under iterative or LP decoding.

II. BASICS ON TRELLISES

All trellises considered will be over a fixed finite field \( \mathbb{F} \equiv \mathbb{F}_q \) and have a fixed length \( n \). Also, we want to do modular arithmetic on the coordinate indices of \( \mathbb{F}^n \), so \( \mathbb{Z}_n \equiv \mathbb{Z}/n\mathbb{Z} \) will be the index set of coordinates. A trellis (over \( \mathbb{F} \), and of length \( n \)) is a directed graph \( T = (V, E) \) together with a partition \( V = \sqcup_{i \in \mathbb{Z}_n} V_i \) indexed over \( \mathbb{Z}_n \), such that the edges are \( \mathbb{F} \)-labeled and can only go from \( V_i \) to \( V_{i+1} \), so that \( E \) has also a partition \( E = \sqcup_{i \in \mathbb{Z}_n} E_i \), where \( E_i \subseteq V_i \times \mathbb{F} \times V_{i+1} \). For formal reasons we also allow multiple edges in a trellis, i.e. each edge \( e \in E \) also has a multiplicity \( m(e) \geq 1 \). A trellis is conventional if \( |V_0| = 1 \).

Two trellises \( T = (V, E) \), \( T' = (V', E') \) are isomorphic if there exists a bijection \( f : V \to V' \) such that \( e = (v, a, w) \in E \) if and only if \( f(v) = (f(v), a, f(w)) \in E' \), \( m(e) = m(f(e)) \) for all \( e \in E \), and \( f(V_0) = V'_0 \). If by forgetting their labels \( T \) and \( T' \) are isomorphic as directed multigraphs, then we say that \( T \) and \( T' \) are structurally isomorphic (again, we require \( V_0 \) to be sent to \( V'_0 \)) and write \( T \cong T' \).

By a cycle of a trellis \( T \) we mean a closed directed path in \( T \) of length \( n \) starting and ending at \( V_0 \). The subset \( C(T) := \{ \text{edge-label sequences of cycles of } T \} \subseteq \mathbb{F}^n \) is the code represented by \( T \). A trellis is reduced if every edge and every vertex belongs to a cycle. A trellis is linear if it is reduced, the multiplicity function \( m : E \to \mathbb{N} \) on each \( E_i \) is a constant of the form \( q^j \) for some \( j \geq 0 \), and all \( V_i \)'s have an \( \mathbb{F} \)-vector space structure such that \( E_i \) is an \( \mathbb{F} \)-subspace of \( V_i \times \mathbb{F} \times V_{i+1} \) for all \( i \). If \( T \) and \( T' \) are isomorphic then \( T \) is linear if and only if \( T' \) is linear. Also, if \( T \) is linear then so is \( C(T) \). In this paper we will consider only linear trellises, so, to simplify the terminology, from now on by a trellis we will always mean a linear trellis.

We will denote by \( \mathbb{T} \) the set of trellises up to isomorphism, and by \( \mathbb{T} \) the set of unlabeled trellises, i.e. trellises up to structural isomorphism. Clearly \( \mathbb{T} \) can be identified with the subset of all trellises having all edge-labels equal to 0, so, we see \( \mathbb{T} \subseteq \mathbb{T} \). We have a projection map \( \mathbb{T} \to \mathbb{T} \), which to each trellis \( T \) associates its underlying unlabeled trellis \( \mathbb{T} \) (equivalently, putting all edge-labels of \( T \) equal to 0).

For \( 0 \leq h \leq n \) and \( i \in \mathbb{Z}_n \), \( (i, i+h) := \{ i+1, i+2, \ldots, i+h \} \subseteq \mathbb{Z}_n \) is a span of length \( h \) of \( v \in \mathbb{F}^n \) if \( \text{supp}(v) \subseteq [i, i+h] := \{ i \} \cup \{ i+h \} \). If \( h < n \) we say that the span \( (i, i+h) \) is proper, and that it starts at \( i \) and ends at \( j = i+h \).
The degenerate span $Z_n$ is a span of any $v \in \mathbb{F}^n$. Now, let $s$ be a span of $v \in \mathbb{F}^n$. Let $V_t := \mathbb{F}$ for all $t \in s$ and else $V_t := 0$. Choose $w_t \in V_t \setminus \{0\}$ for all $t \in s$, while for all $t \notin s$ put $w_t := 0$. Let then $E_t := \mathbb{F}(w_{t1}, v_t, w_{t+1})$, i.e. $E_t$ is the subspace of $V_t \times \mathbb{F} \times V_{t+1}$ generated by the vector $(w_t, v_t, w_{t+1})$. We also put $m(e) := 1$ for all $e \in E$, except in the case $v|s = 0 ([i, j]$ where we put $m(e) = q$ for the (only) edge $e = (0, 0, 0) \in E_i$ (i.e. $e$ is repeated $q$ times). This gives the elementary trellis $T|v(i)$ (up to trellis isomorphism, it doesn’t depend on the choice of the $w_i$’s). It is clearly a (linear) trellis, and it satisfies $v|s = \lambda v|s$ for $\lambda \neq 0$, $C(v|s) = \mathbb{F}v$. Notice also that $v|s = v'|s'$ if and only if $s = s'$, and that since $F$ is finite, the set $T_{F}^{\mathbb{N}}$ of elementary trellises is finite too.

**B. Trellis products**

$T$ benefits from a natural monoid structure $(T, \otimes)$ given as follows. Let $T, T' \in T$ be two trellises. For $e = (v_t, a, v_{t+1}) \in E_i$, $e' = (v'_t, a', v'_{t+1}) \in E'_i$ define $e \otimes e' := ((v_t, v'_t), a + a', (v_{t+1}, v'_{t+1}))$ for each $i$ let $V^0 := V_i \times V'_i$ and let $E^0 := \{ e \otimes e' | e \in E_i, e' \in E_i' \}$. Then the trellis $T \otimes T' := (\cup V^0, \cup E^0)$ is called the trellis product of $T$ and $T'$. This is the usual definition of trellis product as given for example in [8], [9]. Since we also allow multiple edges in a trellis, we naturally define the multiplicity of $e' \in E'^0$ as $m(e') := \sum_{e \in \mathcal{E}_F} m(e)m(e')$. It’s easy to see that if $T$ is a product of elementary trellises then $T$ has no multiple edges if and only if no factor of span length 0 is repeated and no factor is of the form $0([i, i])$

The operation $\otimes$ is associative, commutative, and has an identity, the zero trellises $\mathbf{0} \rightarrow \mathbf{0} \rightarrow \mathbf{0} \rightarrow \cdots \rightarrow \mathbf{0} \rightarrow \mathbf{0}$, i.e. $(T, \otimes)$ is a commutative monoid. Note that the only invertible element of $(T, \otimes)$ is the zero trellis, that the subset $T$ is a submonoid of $(T, \otimes)$, and $T \otimes T' = T \otimes T'$

Also, a fundamental property of the trellis product is the identity $C(T \otimes T') = C(T) + C(T')$, from which follows that any linear code can be represented by a product of elementary trellises. That any trellis is a product of elementary trellises is the following famous factorization theorem (see [9]):

**Theorem 1 (KV).** Any (linear) trellis is a product of elementary trellises.

II. Unique factorization in $T$

Knowing that every trellis can be factored into elementary trellises, a natural following question is whether the factorization must be unique or not. The answer is that in general it does not. For example, $111|\{0, 2\} \otimes 010|\{1, 1\} = 101|\{0, 2\} \otimes 010|\{1, 1\}$, but the two factorizations are different, as $111|\{0, 2\} \neq 101|\{0, 2\}$. Nevertheless, one sees here that the two factorizations have precisely the same set of spans, i.e. up to labels the two factorizations are equal. This is no coincidence, as it is a well known result that different factorizations of the minimal conventional trellis for a linear code must have the same set of spans (for details on minimal and conventional trellises see [11], [8]), a result that is proved only as a byproduct of the minimality assumption. More recently the same result was also proven for minimal nonconventional trellises (see [8], [4]), again by exploiting the minimality assumption. We show that this holds actually for any trellis, and that the edge-labels really play no role in determining the spans of factors. The structure alone determines the spans. Here is our main result of this section:

**Theorem 2.** In $(T, \otimes)$ unique factorization holds, that is, if $T_1 \otimes T_2 \otimes \cdots \otimes T_r = T'_1 \otimes T'_2 \otimes \cdots \otimes T'_r$, with $T_i, T'_i \in T_{EI}$, then $r = r'$ and, up to order, $T_i = T'_i$ for all $i$. In other words, the spans (along with their multiplicities) appearing in a factorization of a trellis $T$ are uniquely determined.

It is easy to see that the multiplicity of the degenerate span $Z_n$ is uniquely determined and is equal to the number of connected components of $T$, so, the real problem is understanding what happens with proper spans. In what follows we will tackle this problem by a graph-theoretical approach, which yields also a method to compute the structural factorization.

Before going on to prove Theorem 2, we also inform the reader that we were recently told by Heide Gluesing-Luerssen that her PhD student Elizabeth Weaver has independently obtained uniqueness of spans of factors in the particular case of one-to-one trellises.

A. Graph-theoretical approach

The graph-theoretical approach involves studying the earliest intersections of paths starting along different edges from a fixed vertex. Not only does this enable to prove unique factorization in $(T, \otimes)$, but from the same intersection data one also is able to determine precisely all the spans of the factors.

Now, let us give some notation. Given a multiset $S$, we write $m(x, S)$ for the multiplicity of $x$ in $S$ (in particular $m(x, S) > 0$ if and only if $x \in S$). If $T$ is a trellis and $e = (v, a, v')$ is an edge of $T$, then $h(e) := v'$ is the head of $e$, and $t(e) := v$ is its tail. A path $p = p_0p_1 \cdots p_r$ in $T$ is a sequence of edges $p_0, p_1, \ldots, p_r$ in $T$ such that $h(p_i) = t(p_{i+1}), i = 0, \ldots, r - 1$.

Now, let $e \neq e'$ be two different edges of $T$ such that $t(e) = t(e')$. Define $l(e, e')$ to be the smallest $r \geq 0$ such that there exist two directed paths $p = p_0 \cdots p_r = p_0' \cdots p'_r$ in $T$ satisfying $p_0 = e, p_0' = e'$, and $h(p_i) = h(p'_i)$ if there exist no directed paths satisfying those conditions then we put $l(e, e') = \infty$. Define then the multiset $I(e) := \{ l(e, e') | e' \neq e, t(e') = t(e) \}$.

**Example 1.** Consider the unlabeled trellis

```
  e
  |   |
  |   |
  v   v
  |   |
  e'  e'
```

Then $I(e) = \{\{1\}\}, I(e') = \{\{2\}\}$, and $I(e'') = \{\{1, 1\}\}$.

Now, let $T$ be a trellis and let $e, e'$ be two edges with same tail. A priori, to compute $I(e, e')$ one needs to compute the set of all possible couples of paths $p, p'$ starting along
e, e′, and look for the earliest possible intersection. But in fact, by linearity (we are only considering trellises with linear structure) one can fix p and let only p′ vary:

**Observation 1.** Let T be a trellis and let e, e′ be two edges such that ℓ(e) = ℓ(e′). Fix a path p such that p₀ = e. Then ℓ(e, e′) = min{r | ∃ p′ = p₀...p'r such that p₀ = e′, h(p') = h(p₀)}.

The highly symmetrical structure of (linear) trellises is further reflected in the following fundamental lemma:

**Lemma 1.** Let T be a trellis of length n. Then:
- ℓ(e, e′) ≤ n − 1 for any edges e, e′.
- I(e) = I(e′) if ℓ(e), ℓ(e′) ∈ Vᵢ for some i.

In sight of this result, for a trellis T and i ∈ Ζₙ it is legitimate to define Iᵢ(T) := I(e), where e is any edge such that ℓ(e) ∈ Vᵢ.

The next lemma tells us that Iᵢ(T) is determined only by those factors of T whose spans start at i.

**Lemma 2.** Let T be a trellis, and let T' ∈ Tₑ surviv be an elementary trellis with span not starting at i or degenerate span. Then Iᵢ(T ⊗ T') = Iᵢ(T).

The above lemma is crucial for the following theorem, which is the key result:

**Theorem 3.** Let T = T₁ ⊗...⊗ Tᵣ, with T₁, ..., Tᵣ ∈ Tₑ surviv. Fix i ∈ Ζₙ, and let Lᵢ(T) be the multiset of span lengths of those Tᵢ's with (proper) span starting at i. Then for l = 0, ..., n − 1

\[
\log_q \left(1 + \sum_{j=0}^{l} m(j, Lᵢ(T))\right) = \sum_{j=1}^{l} m(0, Lᵢ(T))
\]

The above equations can be recursively solved for m(j, Lᵢ(T)), j = 0, ..., n − 1, and the solution is unique. Therefore, since the left-hand side depends only on T, we conclude that Theorem 2 holds. Moreover, by computing all Iᵢ(T)'s we are able to determine all the (proper) spans and their multiplicities in any factorization of T.

**Example 2.** Let T be the unlabeled connected trellis

![Diagram of an unlabeled connected trellis]

This trellis is F₂-linear, its linear structure given by the shown F₂-labels of vertices. Then one easily computes
- I₀(T) = I(e₀) = ∅
- I₁(T) = I(e₁) = \{ \{2\}\}
- I₂(T) = I(e₂) = ∅
- I₃(T) = I(e₃) = \{ \{3, 4, 4\}\}

But, by linearity (we are only considering trellises with linear structure) one can fix p and let only p′ vary:

**Theorem 3.** Let T be a trellis and let e, e′ be two edges such that ℓ(e) = ℓ(e′). Fix a path p such that p₀ = e. Then ℓ(e, e′) = min{r | ∃ p′ = p₀...p'r such that p₀ = e′, h(p') = h(p₀)}.

We have already pointed out that in (Tₑ, ⊗) unique factorization doesn’t hold, since the labels are not necessarily uniquely determined. Nevertheless, we give a method to find a legitimate labeling of a structural factorization of a trellis.

In sight of this result, for a trellis T and i ∈ Ζₙ, it is legitimate to define Iᵢ(T) := I(e), where e is any edge such that ℓ(e) ∈ Vᵢ.

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- I₃(T) = I(e₃) = \{ \{3, 4, 4\}\}

Thus labeled, T is again F₂-linear. Then one gets:
- C₁₂₃₄(T) = \{0000, 01010\}

**III. Factorization in T**

We have already pointed out that in (Tₑ, ⊗) unique factorization doesn’t hold, since the labels are not necessarily uniquely determined. Nevertheless, we give a method to find a legitimate labeling of a structural factorization of a trellis.

In sight of this result, for a trellis T and i ∈ Ζₙ, it is legitimate to define Iᵢ(T) := I(e), where e is any edge such that ℓ(e) ∈ Vᵢ.

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Thus labeled, T is again F₂-linear. Then one gets:
- C₁₂₃₄(T) = \{0000, 01010\}
Theorem 4 tells us the precise relations that hold among all the possible lists of vectors that give the same trellis. More precisely, if the given spans are \( \mathbf{s}_1, \ldots, \mathbf{s}_r \) with respective multiplicities \( m_1, \ldots, m_r \), and \( \{ \mathbf{v}_{ij} \}_{1 \leq i \leq r, 1 \leq j \leq m_i} \), \( \{ \mathbf{w}_{ij} \}_{1 \leq i \leq r, 1 \leq j \leq m_i} \) are lists of vectors associated to the spans, then it is easy to see from Theorem 4 that the corresponding trellises are isomorphic if and only if for all \( i = 1, \ldots, r \) the equation
\[
\sum_{h \in \mathbf{v}_{ij}} \sum_{1 \leq j \leq m_h} F_h \mathbf{v}_{ij} = \sum_{h \in \mathbf{w}_{ij}} \sum_{1 \leq j \leq m_h} F_h \mathbf{w}_{ij}
\]
holds.

**Remark 1.** It is easy to show that if a trellis \( T \) for a given code is optimal with respect to iterative or LP decoding (in the sense that it yields few bad pseudocodewords) then it must be one-to-one, i.e. the list of generating vectors of \( T \) must be a basis of the code. So, for iterative or LP decoding purposes, it is actually sufficient to do a complete classification of one-to-one trellises.

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