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# Sparse and structured decomposition of audio signals on hybrid dictionaries using musical priors

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This paper investigates the use of musical priors for sparse expansion of audio signals of music, on an overcomplete dual-resolution dictionary taken from the union of two orthonormal bases that can describe both transient and tonal components of a music audio signal. More specifically, chord and metrical structure information are used to build a structured model that takes into account dependencies between coefficients of the decomposition, both for the tonal and for the transient layer. The denoising task application is used to provide a proof of concept of the proposed musical priors. Several configurations of the model are analyzed. Evaluation on monophonic and complex polyphonic excerpts of real music signals shows that the proposed approach provides results whose quality measured by the signal-to-noise ratio is competitive with state-of-the-art approaches, and more coherent with the semantic content of the signal. A detailed analysis of the model in terms of sparsity and in terms of interpretability of the representation is also provided, and shows that the model is capable of giving a relevant and legible representation of Western tonal music audio signals.

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## I. INTRODUCTION

We describe in this paper a novel approach for *structured sparse* decomposition of a music signal in an overcomplete time-frequency hybrid dictionary. Within a Bayesian framework, we propose to incorporate musical priors in order to build signal representations that take into account some “structural” information and that are more suitable to music than existing methods that are based on physical signal properties. For this, we take advantage of the recent work that have been done on chord estimation and beat tracking in the context of music content indexing. The model we propose is inspired from previously proposed Bayesian models for time-frequency inverse modeling of non-stationary signals (Wolfe *et al.*, 2004) or sparse linear regression in unions of bases (Févotte *et al.*, 2008), but presents an essential difference in the way dependencies between coefficients of the representation are modeled, using the newly introduced musical priors. One of the goal of this work is to show that ideas that have emerged in two related but distinct communities, *Sparsity* and *Music Information Retrieval*, can be exploited jointly to open new perspective for audio signal processing. Sparse representations have been used as a basis for extracting high-level information for MIR applications, such as note extraction in (Davies and Daudet, 2006), or beat tracking, chord recognition and musical genre classification in (Ravelli *et al.*, 2010). Our approach is somewhat different: we propose to incorporate music content information in order to build structured sparse representations that are tailored to the analyzed music signal and legible from a musical point of view.

## A. Structured sparse representation

The problem of representing an audio signal using a time-frequency dictionary has been given a lot of attention these last few years. The specific problem we consider here is finding an approximation of a music audio signal as a linear combination of elementary waveforms (also called *atoms*) of a suitably chosen dictionary.

Musical signals are intrinsically structured. A particularity of musical signals is that, very often, several types of components are superimposed such as, among other features, tonal components (the partials of the notes, that are characterized by sinusoids with slowly varying amplitude and frequency) and transients (the attacks of the notes, that correspond to events well-localized in time). This is illustrated in Figure 1 that represents the spectrogram of a glockenspiel signal. The tonals appear as thin horizontal lines whereas the transients appear as sharp vertical lines. These various components may have significantly different behaviors in terms of time-frequency localization. For instance, fast varying transients require short analysis window length, whereas low varying tonals require long windows. Thus, they cannot be optimally represented within the same basis. The Balian-Low theorem (Low, 1985) states that redundancy is necessary for having well-localized functions both in time and frequency for transforms based on local Fourier analysis. This is why *hybrid* models, allowing a simultaneous representation of different components have been proposed (Hamdy *et al.*, 1996; Verma and Meng, 2000; Daudet and Torrèsani, 2002; Molla and Torrèsani, 2005). These models consider redundant (or overcomplete) dictionaries that are constructed by the concatenation of several families or bases (usually time-frequency atoms, such as Gabor atoms or local cosines; or time-scale atoms, such

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3 as wavelets). Typically, the resulting dictionaries contain 40  
 4 elements with various time-frequency characteristics and 41  
 5 are more flexible than orthonormal bases (Chen *et al.*, 42  
 6 1998).

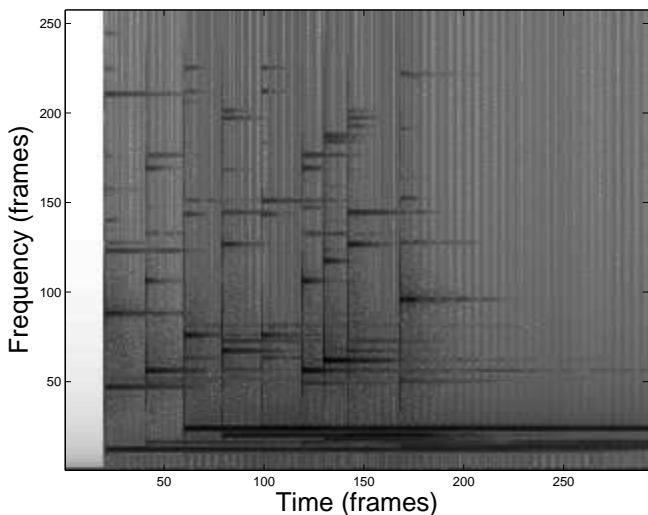


FIG. 1. Time-frequency representation of a recording of a glockenspiel excerpt. The vertical lines correspond to the attacks of the notes and the horizontal lines correspond to the partials.

7 Among the various existing transforms, lapped trans- 68  
 8 forms such as the Modified Discrete Cosine Transform 69  
 9 (MDCT) (Mallat, 1998; Malvar, 1990) is a standard 70  
 10 choice for the bases (Févotte *et al.*, 2006; Kowalski and 71  
 11 Torrèsani, 2008). This transform is very popular, in par- 72  
 12 ticular in high quality audio coding and signal compression 73  
 13 applications, because it allows an orthogonal time- 74  
 14 frequency transform without blocking effects. Following 75  
 15 these approaches, we consider in this work a dictionary 76  
 16 built as the union of two MDCT bases with different 77  
 17 time-frequency resolutions. The narrow band basis – 78  
 18 with long time resolution – is used to estimate the tonal 79  
 19 parts of the signal, and the wide band basis – with short 80  
 20 time resolution – is used to estimate the transient parts. 81  
 21 Such a dictionary is overcomplete since the number of el- 82  
 22 ements of the dictionary is greater than the length of the 83  
 23 signal. The expansion of the signal with respect to the 84  
 24 dictionary is thus not unique. *Sparsity* may be used as a 85  
 25 selection criterion for finding the expansion coefficients, 86  
 26 in the sense that only a few coefficients of the decompo- 87  
 27 sition of the signal on the bases are significantly nonzero. 88  
 28 The signal can thus be well approximated by a limited 89  
 29 number of coefficients. This problem is often referred to 90  
 30 as *sparse regression*. Sparsity has become a fundamental 91  
 31 concept in diverse areas of modern signal processing. It 92  
 32 is, for instance, an essential ingredient of popular cod- 93  
 33 ing standards such as the MPEG-1 layer III (“MP3”) or 94  
 34 the MPEG-2 AAC. A review of sparse representations 95  
 35 for musical signals and their applications can be found in 96  
 36 (Daudet and Torrèsani, 2006; Plumbley *et al.*, 2010). 97

37 A common approach to find a sparse expansion of sig- 98  
 38 nals in overcomplete dictionaries consists of minimizing 1  
 39 the  $\ell_1$  norm of the expansion, and is known as *basis pur-* 2

*suit* (Chen *et al.*, 1998), or LASSO (Tibshirani, 1996). Other methods include variational approaches (Kowalski, 2009), probabilistic approaches (Kowalski and Torrèsani, 2008), greedy methods, such as the Matching Pursuit algorithm (Mallat and Zhang, 1993; Daudet, 2010) and its variants (the Orthogonal Matching Pursuit (Mallat, 1998; Pati *et al.*, 1993), the Molecular Matching Pursuit (Daudet, 2006b)), or Bayesian formulations as for instance EM-based algorithms (Figueiredo, 2003). In the framework of Bayesian variable selection, MCMC (Markov chain Monte Carlo) type approaches have been proposed (Févotte and Godsill, 2006; Févotte *et al.*, 2008). One of the main advantages of the MCMC techniques is their robustness because they scan the whole of the posterior distribution and thus are unlikely to fall into local minima. However, this is done at the expense of high computational cost.

The concept of *structured approximation* has been introduced from the observation that significant coefficients are not isolated but tend to form “clusters” in the index space. As mentioned above, audio music signals are well-structured. In the time-frequency plane, the partials of the notes will generate horizontal lines localized in frequency, whereas the attacks of the notes and the percussive sounds will generate vertical lines localized in time. Ideally, this structure should be reflected in the signal decomposition, so that the coefficients have physical interpretability and are more meaningful than isolated coefficients from an analysis perspective. Interpretability is a key concept in sparsity<sup>1</sup>. A signal representation where coefficients can be explained from a theoretical or a physical point of view can help assessing the model accuracy, and provides a suitable representation for higher-level tasks. For instance in music signal analysis, a time-frequency representation where coefficients can be physically interpretable as being part of the tonal layer may be very useful to the multi-f<sub>0</sub> estimation task (Yeh *et al.*, 2010). This is why we are interested in finding a signal approximation that is not only sparse, but also *structured*, by considering dependencies between significant coefficients. Previous approaches that use unstructured priors, such as Bernoulli models have shown that they generate isolated coefficients with high amplitude in both bases (Févotte and Godsill, 2006; Kowalski and Torrèsani, 2008). These components do not have any physical or musical meaning and are usually perceived as “musical artifacts” or “musical noise” in the reconstructed signal. Considering dependencies between atoms coefficients and using structured priors allows reducing the number of such undesirable components. Various approaches have been proposed for introducing dependencies between coefficients in the time-frequency domain. These approaches aim at exploiting the fact that significant coefficients tend to be organized into clusters, which results from persistence properties of time-frequency representations. Structures can be modeled directly in the coefficients themselves, such as in (Kowalski, 2009). However, dependencies are often introduced in the time-frequency indices, rather than directly in the coefficients. This results into hierarchical models in which both the coefficients and the addresses of the significant

Among existing approaches, physical properties resulting in persistency over frequency of the transient layer can be modeled using structured hierarchical Bernoulli models on a dictionary built as the union of two MDCT bases with different time-frequency resolutions (Kowalski and Torrésani, 2008), binary Markov trees (Crouse *et al.*, 1998; Molla and Torrésani, 2005), or dyadic trees of wavelet coefficients used with wavelet bases (Daudet and Torrésani, 2002); persistency of the tonal layer can be favored using Markov chains, as proposed in (Molla and Torrésani, 2005) in the case of a MDCT base; in (Févotte *et al.*, 2008), structural constraints on the coefficients that rely on physical properties of the signal are imposed for both layers. Persistencies of time-frequency coefficients of musical signal are modeled using two types of Markov chains. It results in a “horizontal structure” for the tonal layer and a “vertical structure” for the transient layer.

Enforcing structure between expansion coefficients can be managed using sequential approaches (Daudet and Torrésani, 2002; Daudet, 2004; Molla and Torrésani, 2005) that first identify the tonal layer using the first basis, and then estimate the transient components from the residual, using the second basis. In (Daudet and Torrésani, 2002; Daudet, 2004), tonal and transient components are expanded sequentially into local cosine and dyadic wavelets bases respectively. The method does not rely on any prior segmentation of the signal. For each layer, only the largest coefficients in each time frame are retained based on threshold values that are estimated adaptively in a quantization stage. In the framework of audio coding, (Molla and Torrésani, 2005) describes a hybrid model for the expansion of audio signals considering a redundant dictionary made out of the union of local cosine and wavelet bases. A recursive scheme is proposed to estimate the two layers, that relies on the assumption that the cardinalities of the significance maps have to be known. A priori estimates for the relative sizes of the tonal and transient layers are obtained based on an algorithm that determines local transientness of audio signals (Molla and Torrésani, 2004). The approach is used to develop an hybrid audio coder that does not rely on prior (time) segmentation of the signal.

As stressed in (Daudet, 2006a), sequential approaches suffer from two limitations. First, errors in a step are systematically propagated into the next estimation stage and thus bias the estimates of the other components. Second, the choice of a threshold that allows discriminating large significant from small residual coefficients is difficult. An alternative to sequential approaches is the simultaneous approach of both layers, as proposed in (Févotte *et al.*, 2008).

Starting from this approach, we build a structured model for sparse signal decomposition within a Bayesian framework. The originality of our work is that we model dependencies between the expansion coefficients by using priors that are based on musical information.

Up to now, additional structure constraints that have been added rely on physical properties of the signal. The recent advances in automatic extraction of content information from audio music signals in the field of Music Information Retrieval (MIR) offers an interesting alternative. Content-based music information retrieval deals with the extraction and processing of meaningful information from musical audio. Techniques developed for searching, retrieving, organizing and interacting in a personalized way with large databases of music signals are often based on the use of musical descriptors that are extracted from the signal, such as the key, the chord progression, the melody or the instrumentation. Musical content information can be used to build structured priors that reflect the content of the signal. For instance, as we propose in this paper, the chord progression provides information about the notes that are present in the signal and can be used to build a prior for the tonal layer. Similarly, the position of the beats is related to the transients and can be used to build a prior for the transient layer. These concepts are introduced in what follows.

### 1. Chord estimation

The chord progression of a piece of music is a very important descriptor because it characterizes its harmonic structure. Here, we want to work directly on audio. The symbolic transcription (the score) of a piece of music is not always available, especially in music genres such as jazz music where there is a large part devoted to improvisation. In addition, algorithms that extract a transcription from an audio signal, such as multi-f0 estimation algorithms (Yeh *et al.*, 2010), are still limited and costly. However, numbers of recent work have shown that it is possible to accurately extract a robust representation of the harmonic content without the use of transcription algorithms. Estimating the chord progression of an audio signal has thus become a very popular task in MIR (Sheh and Ellis, 2003; Bello and Pickens, 2005; Harte and Sandler, 2005; Papadopoulos and Peeters, 2011).

The output of a chord estimation algorithm consists in a progression of chords chosen among a given chord lexicon, that is very often limited to the 24 major and minor triads. Chord estimation on real signals has been favored by the use of the *chroma* features (Wakefield, 1999) or Pitch Class Profiles (Fujishima, 1999), which are traditionally 12-dimensional vectors, with each dimension corresponding to the intensity associated with one of the 12 semitone pitch classes (chroma) of the Western tonal music scale, regardless of octave. The temporal sequence of chroma vectors over time is known as *chromagram*. Conceptually, the chromagram is a frequency spectrum folded into a single octave. Pooling the spectrum into twelve bins that correspond to the twelve pitch classes of the equal-tempered scale results in a signal representation that allows identifying pitches by an octave. Each chord may be characterized by the semitone pitch classes

3 or chroma that correspond to the notes it is composed 58  
4 of. The use of such a mid-level representation overcomes 59  
5 the problem of automatic transcription. 60

6 Various approaches for chroma computation exist. Al- 61  
7 though they present some variances in the implementa- 62  
8 tion, they follow in general the same guideline that con- 63  
9 sists of two main steps: 64

- 10 1. First, a semitone pitch class spectrum (SPS), that 65  
11 is a log-frequency representation of the spectral 66  
12 content of the music audio signal, is constructed. 67  
13 It is expressed in a MIDI-note scale and is in gen- 68  
14 eral either computed from the Fourier transform or 69  
15 from the constant-Q transform (Brown, 1991). 70  
71
- 16 2. Secondly, the semitone pitch spectrum is mapped 72  
17 to the chroma vectors. For this, the semitones in 73  
18 octave distance are added up to pitch classes. 74  
75

19 The chromagram computation may include some other 76  
20 steps such as a pre-processing step that separates har- 77  
21 monic and noise components, a filtering step that 78  
22 smoothes the chromagram or a post-processing normal- 79  
23 ization step that makes the chromagram invariant to dy- 80  
24 namics.

25 We rely in this paper on a chromagram computation 81  
26 method, described in (Papadopoulos and Peeters, 2011), 82  
27 that is based on a constant-Q transform applied on a 83  
28 downsampled signal.

29 For chord estimation, we rely on the model proposed in 84  
30 (Papadopoulos and Peeters, 2007, 2011), that is based on 85  
31 chord templates and hidden Markov models. We briefly 86  
32 described here the concepts that are used in the rest of 87  
33 the paper. The front-end of our model is based on the 88  
34 extraction of a chromagram that represents the audio 89  
35 signal. The chord progression is then modeled as an 90  
36 ergodic 24-states HMM, each hidden state correspond- 91  
37 ing a chord of a the chord lexicon (CM, . . . , BM, Cm, 92  
38 . . . , Bm), and the observations being the chroma vec- 93  
39 tors. The observation chord symbol probabilities are ob- 94  
40 tained by computing the correlation between the obser- 95  
41 vation vectors (the chroma vectors) and a set of chord 96  
42 templates which are the theoretical chroma vectors corre- 97  
43 sponding to the  $I = 24$  major and minor triads. A state- 98  
44 transition matrix based on musical knowledge (Noland 99  
45 and M., 2006) is used to model the rules from which 100  
46 the transitions between chords result. The chord pro- 101  
47 gression over time is estimated in a maximum likelihood 102  
48 sense by decoding the underlying sequence of hidden 103  
49 chords  $S = (s_1, s_2, \dots, s_N)$  from the sequence of observed 104  
50 chroma vectors using the Viterbi decoding algorithm. 105  
106

## 51 2. Beat tracking 107

52 Beat tracking is a challenging problem that has been 1  
53 addressed in a large number of works because beat in- 2  
54 formation is used in many applications in music signal 3  
55 processing, such as music analysis, score alignment or 4  
56 cover version identification. Numerous good overviews 5  
57 on the problem of beat tracking are available, such as 6

for instance (Dixon, 2007; Scheirer, 1998; Klapuri *et al.*,  
2006; Davies and Plumbley, 2007). In the present work,  
we use the beat tracker proposed in (Peeters and Pa-  
padopoulos, 2011) as a front end of the system. Briefly,  
this approach aims at simultaneously estimating beat lo-  
cations with downbeat locations from an audio file. A  
probabilistic framework in which the time of the beats  
and their associated beat-positions-inside-a-measure role,  
hence the downbeats, are considered as hidden states  
and are estimated simultaneously using signal observa-  
tions. For this, a reverse Viterbi algorithm that decodes  
hidden states over beat-numbers is proposed. A beat-  
template is used to derive the beat observation probabil-  
ities. A machine-learning method, the Linear Discrimi-  
nant Analysis, allows estimating the most discrimina-  
tive beat-templates. Two kinds of observations are pro-  
posed to derive the beat-position-inside-a-measure ob-  
servation probability: the variation over time of chroma  
vectors and the spectral balance. This methods was  
ranked first for the McKinney Collection test-set dur-  
ing the MIREX 2009 beat tracking contest. We refer  
the reader to (Peeters and Papadopoulos, 2011) for more  
details.

## 52 C. Contributions 108

Sparse representations of signals have recently proved  
to be useful for a wide range of applications in signal  
processing, such as denoising (Févotte *et al.*, 2006), cod-  
ing and compression (Daudet *et al.*, 2004; Ravelli *et al.*,  
2008), source separation (Benaroya *et al.*, 2006; Févotte  
and Godsill, 2006) or music transcription (Blumensath  
and Davies, 2004). Here, we focus on the task of denois-  
ing an excerpt of musical audio. The approach we pro-  
pose is in many respects related to previously proposed  
MCMC schemes for nonlinear approximation in hybrid  
dictionaries of waveforms. However, a main difference is  
that we aim at providing a multilayered signal decom-  
position that fits the music signal, in which the layers  
can well explain the signal and reflect its music content  
and can provide more relevant semantic information. By  
incorporating musical priors, we built a model that is  
particularly well adapted to music and fits the intrinsic  
nature of Western tonal music. The denosing application  
is used as a proof of concept for the description of new  
musical priors introduced in the paper, and we thus focus  
on assessing the relevance of the new priors rather than  
demonstrating the superiority of the method in terms of  
denoising results (although it is competitive with respect  
to signal to noise ratio to the state-of-the-art). In this  
context, we systematically compare our model, in which  
structural constraints on the coefficients are based on mu-  
sical prior, to the model proposed (Févotte *et al.*, 2008),  
and in which structural constraints on the coefficients  
rely on physical properties of the signal are imposed for  
both layers, reaching the state-of-the-art in terms of SNR  
results.

Preliminary results of the proposed approach can be  
found in (Papadopoulos and Kowalski, 2011). In this ar-  
ticle, we propose significant improvements to the signal

7 model, in particular by presenting a structured model for  
 8 the transient layer; we include the result of new experi-  
 9 ments; finally we present a detailed analysis of the model  
 10 and case-study examples.

11 The remainder of this paper is structured as follows. In  
 12 Section II, we present our model for sparse signal decom-  
 13 position on hybrid dictionaries that incorporates musical  
 14 priors; our main contribution is described in part II.C  
 15 where we specify our formulation of prior dependence  
 16 structures in the time-frequency plane. We briefly ad-  
 17 dress the problem of parameters estimation in Section III.  
 18 In Sections IV and V, we present and discuss the simula-  
 19 tion results of our model. Conclusions and perspectives  
 20 for future work are given in Section VI.

## 21 II. SIGNAL MODEL

22 This section introduces first the mathematical model  
 23 used to represent the audio signal, and then defines the  
 24 priors chosen in a Bayesian context. Particularly, the  
 25 new musical priors based on the *chromagram* and the  
 26 beat locations are exposed in Section II.C.

### 27 A. Model

28 In this part, we describe our model for signal decom-  
 29 position with sparse constraint on a *hybrid* dictionary  
 30 of elementary waveforms (Daudet and Torr sani, 2002).  
 31 The dictionary is constructed as the union of two or-  
 32 thogonal bases with different time-frequency resolution  
 33 that account respectively for the tonal and the transient  
 34 parts of the signal. We consider a tree-layer signal model  
 35 of the form:

$$36 \quad \text{signal} = \text{tonals} + \text{transients} + \text{residual} .$$

37 Let  $V = \{v_n, n = 1, \dots, N\}$  and  $U = \{u_m, m =$   
 38  $1, \dots, N\}$  be two MDCT bases of  $\mathbb{R}^N$  with respectively  
 39 long frame  $\ell_{ton}$  to achieve good frequency resolution for  
 40 tonals and short frame  $\ell_{tran}$  to achieve good time res-  
 41 olution for transients. The MDCT is a bijective linear  
 42 transform and we note  $n_{ton} = \frac{N}{\ell_{ton}}$  and  $n_{tran} = \frac{N}{\ell_{tran}}$  the  
 43 number of frames for each basis (see Figure 2). Here,  
 44  $n$  and  $m$  are time-frequency indexes and will be de-  
 45 noted in the following  $n = (q, \nu) \in [1, n_{ton}] \times [1, \ell_{ton}]$   
 46 or  $m = (q, \nu) \in [1, n_{tran}] \times [1, \ell_{tran}]$ .

47 The signal is decomposed as a linear combination of  
 48 atoms of the two basis  $V$  and  $U$  that account for the  
 49 tonal and transient layers plus a residual part that ac-  
 50 counts for the noise and that is not sparse with respect  
 51 to the two considered bases. We denote  $D = V \cup U$  the  
 52 dictionary made as the union of these two bases.  $D$  is  
 53 overcomplete in  $\mathbb{R}^N$ , and any  $x \in \mathbb{R}^N$  admits infinitely  
 54 many expansions in the form:

$$55 \quad x = \sum_{n \in I} \alpha_n v_n + \sum_{m \in I} \beta_m u_m + r , \quad (1)$$

56 where  $I = \{1, \dots, N\}$ ,  $\alpha_n$  and  $\beta_m$  are the expansion co-  
 57 efficients and  $r$  represents the noise term.

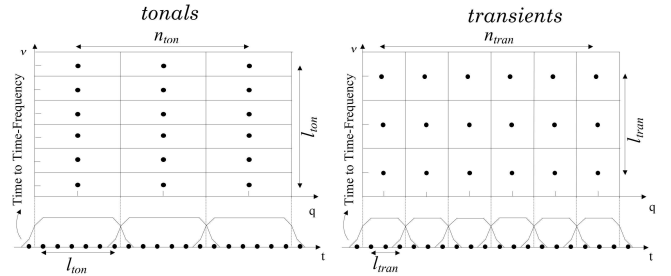


FIG. 2. Illustration of the two MDCT bases that account for the tonal part (long time resolution) and the transient part (short time resolution) of the signal.

We are interested in sparse signals, i.e. signals that may be written as:

$$x = \sum_{\lambda \in \Lambda} \alpha_\lambda v_\lambda + \sum_{\delta \in \Delta} \beta_\delta u_\delta + r , \quad (2)$$

57 where  $\Lambda$  and  $\Delta$  are small subsets of the index set  $I =$   
 58  $\{1, \dots, N\}$  that account for the significant coefficients,  
 1 i.e they identify which coefficient of the expansion are  
 2 significantly non-zero. In what follows, they will be re-  
 3 ferred to as *significance maps*.

4 In order to model sparseness in the time-frequency co-  
 5 efficients, we introduce two indicator random variables  
 6 corresponding to the significance maps  $\Lambda$  and  $\Delta$ ,  $\gamma_{ton,n}$   
 7 and  $\gamma_{tran,m} \in \{0, 1\}$  that control the sparsity of the ex-  
 8 pansion:

$$\gamma_{ton,n} = \begin{cases} 1 & \text{if } n \in \Lambda \\ 0 & \text{otherwise} \end{cases} \quad \gamma_{tran,m} = \begin{cases} 1 & \text{if } m \in \Delta \\ 0 & \text{otherwise} \end{cases} . \quad (3)$$

We can therefore rewrite Eq. (2) as:

$$x = \sum_{n \in I} \gamma_{ton,n} \alpha_n v_n + \sum_{m \in I} \gamma_{tran,m} \beta_m u_m + r . \quad (4)$$

The hybrid model is defined by two components: a discrete probability model for the significance maps, and a probability model for the expansion coefficients conditional upon the significance maps. Both of them are described below.

### 14 B. Coefficient priors

15 The sparseness of the expansion is conceptualized in  
 16 a hierarchical manner as it is not directly modeled in  
 17 the coefficients but through the binary indicator random  
 18 variables  $\gamma_{ton,n}$  and  $\gamma_{tran,m}$  that are attached to each  
 19 coefficient. As a result, hierarchical priors are given to  
 20 the coefficients. We assume that, conditional upon the  
 21 significance maps  $\Lambda$  and  $\Delta$ , the coefficients  $\alpha_n$  and  $\beta_m$

22 are independent zero-mean normal random variables:

$$\begin{aligned}
 p(\alpha_n | \gamma_{ton,n}, \sigma_{ton,n}) &= (1 - \gamma_{ton,n}) \delta_0(\alpha_n) + & (5) \\
 &\quad \gamma_{ton,n} \mathcal{N}(\alpha_n | 0, \sigma_{ton,n}^2) \\
 p(\beta_m | \gamma_{tran,m}, \sigma_{tran,m}) &= (1 - \gamma_{tran,m}) \delta_0(\beta_m) + \\
 &\quad \gamma_{tran,m} \mathcal{N}(\beta_m | 0, \sigma_{tran,m}^2),
 \end{aligned}$$

23 where  $\delta_0$  is the Dirac delta distribution and, following  
 24 (Wolfe *et al.*, 2004; Févotte *et al.*, 2008), the variances  
 25  $\sigma_{ton,n}$  and  $\sigma_{tran,m}$  are given an inverse-Gamma conjugate  
 26 prior distribution:

$$\begin{aligned}
 p(\sigma_{ton,n}^2 | \gamma_{ton,n} = 1, f_{ton,n}) &= & (6) \\
 &\quad \mathcal{IG}(\sigma_{ton,n}^2 | 1, f_{ton,n}) \\
 p(\sigma_{tran,m}^2 | \gamma_{tran,m} = 1, f_{tran,m}) &= \\
 &\quad \mathcal{IG}(\sigma_{tran,m}^2 | 1, f_{tran,m}),
 \end{aligned}$$

where the scale parameters  $f_{ton,n}$  and  $f_{tran,m}$  are para-  
 metric frequency profiles that aim at taking into account  
 the decrease of the energy of the signal when the fre-  
 quency increases (Févotte *et al.*, 2008, Eq. (8)):

$$f_{ton,n} = \frac{\lambda_{ton}}{1 + \left(\frac{q-1}{\ell_{ton}/3}\right)} \quad f_{tran,m} = \frac{\lambda_{tran}}{1 + \left(\frac{q-1}{\ell_{tran}/3}\right)}. \quad (7)$$

27 The parameters  $\lambda_{ton}$  and  $\lambda_{tran}$  are given a non-  
 28 informative *Gamma* conjugate prior.

29 Sparsity is enforced when  $\gamma_{ton,n} = 0$  (resp.  $\gamma_{tran,m} =$   
 30 0). In this case, the coefficients  $\alpha_n$  (resp.  $\beta_m$ ) are set to  
 31 zero.

### 32 C. Indicator variable priors

33 In order to enforce structure between expansion coef-  
 34 ficients, the significance maps  $\Lambda$  and  $\Delta$  are given struc-  
 35 tured priors. We design priors that are tailored to the  
 36 music signal. The one corresponding to the tonal basis  
 37 encodes musical information based on harmonic content  
 38 information using a chord transcription of the analyzed  
 39 excerpt. The one corresponding to the transient basis is  
 40 based on metrical content information using the sequence  
 41 of beats corresponding to the analyzed excerpt.

42 To show the relevance of the proposed priors, the  
 43 proposed approach will be systematically compared with  
 44 a closely related state-of-the art approach described in  
 45 Section II.C.3.

46  
 47 In what follows, some results will be illustrated  
 48 through the representation of the significance maps that  
 49 are defined by the two binary indicator random vari-  
 50 ables  $\gamma_{ton,n}$  and  $\gamma_{tran,m}$ . In Figure 2, the MDCT bases  
 51 are illustrated by a tiling of the time-frequency plane,  
 52 where each tile represents a particular atom. The signif-  
 53 icance maps in the time-frequency plane are represented  
 54 through the binary indicator random variable  $\gamma$ . To  
 55 each atom corresponds an indicator variable that controls  
 56 whether this atom is selected ( $\gamma = 1$ ) or not ( $\gamma = 0$ )<sup>2</sup>.

### 57 1. Model for tonals

For the significance map corresponding to the tonals,  
 we propose to model dependencies between indicator  
 variables using information about the harmonic content  
 of the audio signal. Ideally, we would assume that we  
 know the score corresponding to the musical excerpt and  
 that, for each time frame  $q \in \{1, \dots, n_{ton}\}$ , we know  
 which notes the signal is composed of.

However, here, we want to work directly on audio, for  
 which an exact transcription is usually not available. A  
 number of recent work have shown that it is possible to  
 accurately extract robust mid-level representation of the  
 music, such as the chord progression (Papadopoulos and  
 Peeters, 2011), that characterizes its harmonic content.

We propose to give a musical prior to the indica-  
 tor variables using musical information obtained from  
 a chord progression estimated from the audio file. The  
 output of a chord estimation algorithm consists in a pro-  
 gression of chords chosen among a given chord lexicon  
 that, in general, does not distinguish between any possi-  
 ble combination of simultaneous notes, but is typically  
 reduced to a set of chords of 3 or 4 notes. The number  
 of notes composing the chords will be denoted by  $N_c$   
 in the following. Here, we limit our chord lexicon to the  
 24 major and minor triads ( $N_c = 3$ ). The method we  
 propose could be extended to larger dictionaries.

Each chord is characterized by a set of semitone pitch  
 classes or chroma that correspond to the notes it is com-  
 posed of. The chord progression does not provide an  
 exact transcription of the music. For instance, passing  
 notes are in general ignored, missing notes in the har-  
 mony may be added. Moreover, the chords are estimated  
 regardless of octave. However, experiments show that the  
 provided music content information is sufficient enough  
 to build musically meaningful priors.

We consider two methods for building the structured  
 significance maps for the tonal layer. In the first case,  
 denoted as *Method Chord*, we use chord information. In  
 the second case, denoted as *Method Chroma*, the priors  
 are built relying directly on chromagram information.

*a. Mapping between MDCT bins and chroma:* In order  
 to select atoms of the MDCT base that correspond to  
 the harmonic content of the signal, we first perform  
 a mapping between the MDCT bins and the 12 semi-  
 tone pitch classes. Given a fixed frame index  $q$ , let  
 $\{p_\nu^{MDCT}\}_{\nu=1, \dots, \ell_{ton}}$  denote the semitone pitch classes cor-  
 responding to each frequency MDCT bin.

Assuming a perfect tuning of  $A = 440\text{Hz}$ , a MDCT bin  
 of frequency  $\nu$  is converted to a chroma  $p_\nu^{MDCT}$  by the  
 following equation:

$$p_\nu^{MDCT} = (12 \log_2 \frac{\nu}{440} + 69) \pmod{12}^3. \quad (8)$$

Note that, a single semitone pitch-class corresponds to  
 several consecutive bins of the MDCT. Because of the  
 logarithmic scale of Western tonal music, the higher the  
 frequency, the larger the number of MDCT bins corre-  
 spond to a single pitch class.

7 *b. Method Chords:* Given a fixed frame index  $q$ ,<sup>39</sup>  
 8 let  $\{p_k^{chord}\}_{k=1,\dots,N_c}$  denote the semitone pitch-classes  
 9 (chroma) corresponding to the estimated chord  $c_q$ . All  
 10 bins of the MDCT that correspond to a note belonging to  
 11 the estimated chord are selected. The indicator variables  
 12  $\{\gamma_{ton,(q,\nu)}\}_{\nu=1,\dots,\ell_{ton}}$  are given the following membership  
 13 probabilities:

$$P_{\Lambda}\{\gamma_{ton,(q,\nu)} = 1\} \quad (9)$$

$$= \begin{cases} p_{ton} & \text{if } \exists k \in [1, N_c] \mid p_{\nu}^{MDCT} = p_k^{chord} \\ 1 - p_{ton} & \text{otherwise,} \end{cases}$$

14 where  $0 \leq p_{ton} \leq 1$ . The significance maps corresponding  
 15 to the tonal layer should reflect the harmonic content of  
 16 the audio signal. In practice, the value  $p_{ton}$  will be close  
 17 to 1 (in our experiments,  $p_{ton} = 0.9$ ) so that atoms cor-  
 18 responding to the notes that are played are given high  
 19 prior. The significant map for the tonal layer corre-  
 20 sponding to the *Glockenspiel* monophonic audio signal  
 21 of our test-set is illustrated in Figure 3. A set of atoms  
 22 is selected at each frame according to the notes of the  
 23 (note) transcription, regardless of octave. For instance  
 24 all atoms  $\{B1, B2, \dots\}$  corresponding to the semitone B  
 25 are selected when the first B note of the *Glockenspiel* is  
 26 sounded.

27 The significance maps are given structures of “tubes”  
 28 that have a musical meaning. Note also that we provide  
 29 here a “vertical structure” for tonals.

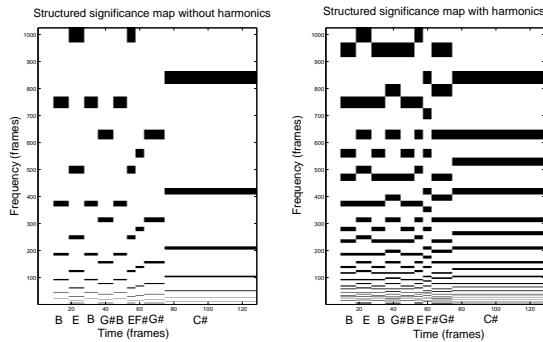


FIG. 3. Structured significance map for tonals for a *Glockenspiel* excerpt using chord information. Left: only notes composing the chords are considered. Right: higher harmonics are considered. The note transcription is indicated in the bottom.

30 *c. Method Chroma:* Given a fixed frame index  $q$ ,  
 31 let  $\{a_k\}_{k=1,\dots,12}$  denote the amplitude of each bin<sup>48</sup>  
 32  $\{p_k^{chroma}\}_{k=1,\dots,12}$  of the computed chroma vector. Note<sup>49</sup>  
 33 that, according to (Papadopoulos and Peeters, 2011), the<sup>50</sup>  
 34 chromagram has been normalized so that  $\sum_{k=1}^{12} a_k = 1$ . For<sup>51</sup>  
 35 each chroma bin, all MDCT bins that correspond to this<sup>52</sup>  
 36 chroma are selected and given a weighted contribution<sup>53</sup>  
 37 according to the amplitude in the chroma vector. The<sup>54</sup>  
 38 indicator variables  $\{\gamma_{ton,(q,\nu)}\}_{\nu=1,\dots,\ell_{ton}}$  are given the fol-<sup>55</sup>

lowing membership probabilities:

$$P_{\Lambda}\{\gamma_{ton,(q,\nu)} = 1\} \quad (10)$$

$$= a_k \text{ if } \exists k \in [1, 12] \mid p_{\nu}^{MDCT} = p_k^{chroma} .$$

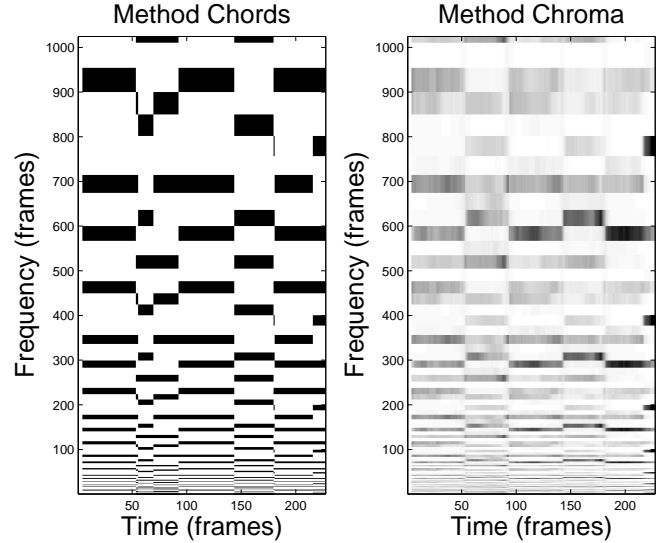


FIG. 4. Structured significance map for tonals for a *Beethoven String Quartet Op.127* excerpt using chroma information.

40 Figure 4 shows the significant maps for the tonal layer  
 41 corresponding to the *Beethoven String Quartet Op.127*  
 42 audio signal of our test-set obtained with *Method Chord*  
 43 [left] and *Method Chroma* [right].

44 Two additional components may be added to improve  
 45 the model.

*d. Tuning:* The instruments may have been tuned ac-  
 cording to a reference pitch different from the standard  
 $A4 = 440\text{Hz}$ . In this case it is necessary to estimate the  
 tuning of the track and Eq. (8) becomes:

$$p_{\nu}^{MDCT} = (12 \log_2 \frac{\nu}{A_{est}} + 69) \pmod{12} , \quad (11)$$

46 where  $A_{est}$  denotes the estimated tuning, here obtained  
 47 with the method proposed in (Peeters, 2006).

*e. Harmonics:* Higher harmonics may be considered in  
 the model. Each note produces a set of harmonics, whose  
 frequencies are whole number multiples of the fundamen-  
 tal frequency<sup>4</sup>, that results in a mixture of non-zero val-  
 ues in the chroma vector corresponding to the chord. For  
 instance a C1 note will produce the set of harmonics  
 $\{C1 - C2 - G2 - C3 - E3 - G3 - \dots\}$ . They can be  
 considered in the significance maps, as illustrated in the  
 right part of Figure 3. Here we take into account the first  
 6 harmonics of the notes<sup>5</sup>



## 5 2. Model for transients

6 For the significance map corresponding to the tran- 40  
7 sients, we propose to model dependencies between in- 41  
8 dicator variables using information about the metrical 42  
9 structure of the audio signal. The idea is that, in a piece 43  
10 of music, most of the transient sounds will occur on beats 44  
11 or beat subdivisions. For instance, drum sounds are gen- 45  
12 erally used to underline the metrical structure (beats, 46  
13 downbeats); in a string quartet piece, bow changes will 47  
14 generally occur on note changes, which are related to the 48  
15 metrical structure.

16 The structured prior corresponding to the significance 49  
17 map for tonals is built as follows. The beat positions 50  
18 are estimated from the signal using the beat tracker pro- 51  
19 posed in (Peeters and Papadopoulos, 2011), described in 52  
20 Section I.B.2. Let  $\{b_k\}_{k=1,\dots,N_b}$  denote the  $N_b$  beat 53  
21 positions (in frames) of the track (subdivisions of beats 54  
22 as quarter notes or eighth notes can be considered as 55  
23 well). The indicator variables  $\{\gamma_{tran,(q,\nu)}\}_{\nu=1,\dots,\ell_{tran}}$  56  
24 are given the following membership probabilities:

$$\begin{aligned} \forall \nu = 1, \dots, \ell_{tran} \quad P_{\Delta}\{\gamma_{tran,(q,\nu)} = 1\} & \quad (12) \quad 49 \\ & = \begin{cases} p_{tran} & \text{if } \exists k \in [1, N_b] \mid q = k \\ 1 - p_{tran} & \text{otherwise,} \end{cases} \quad 50 \end{aligned}$$

25 where  $0 \leq p_{tran} \leq 1$ . The significance maps correspond- 53  
26 ing to the transient layer should reflect the metrical con- 54  
27 tent of the audio signal. In practice, the value  $p_{tran}$  55  
28 will be close to 1 (in our experiments,  $p_{tran} = 0.9$ ) so 56  
29 that atoms corresponding to beat locations are given high 57  
30 prior. The significant map for the transient layer corre- 58  
31 sponding to the *Glockenspiel* audio signal of our test-set 59  
32 is illustrated in Figure 5. For each beat location, all fre- 60  
33 quency bins are retained, resulting in vertical lines that 61  
34 are sparse in time but cover all the frequencies, in the 62  
35 significance map. It may be noticed that the duration 63  
36 between two consecutive lines is not constant, as there 64  
37 may be variations in the tempo.

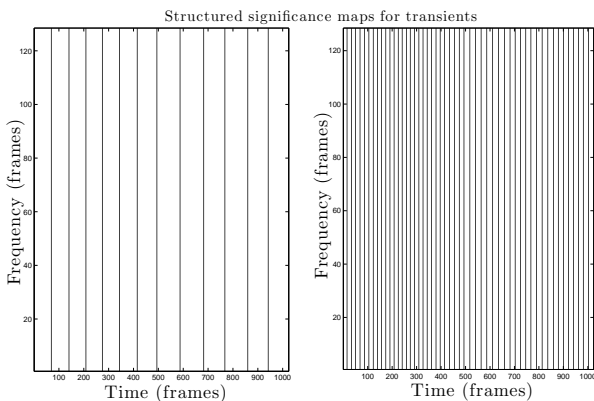


FIG. 5. Structured significance map for transients for a *Glock-*  
*enspiel* excerpt using beat location information, resulting in  
vertical lines in the time-frequency plane. Left: considering  
beat locations. Right: considering eight-notes locations.

38 **Remark 1** As underlined in (Kowalski and Torr esani,  
39 2008; F evotte et al., 2008), the window lengths for each  
layer must be significantly different enough to discrim-  
40 inate between tonals and transients. Better results are  
41 obtained using a very short window length for the tran-  
42 sients ( $\approx 3ms$ ) that is shorter than the duration of a short  
43 attack. In this case, several frames may be needed to de-  
44 scribe a transient. In practice, we also select vertical lines  
45 surrounding the theoretical (or estimated) beat locations  
46 in the transient layer prior. Eq. (12) thus becomes:

$$\begin{aligned} \forall \nu = 1, \dots, \ell_{tran} \quad P_{\Delta}\{\gamma_{tran,(q,\nu)} = 1\} & \quad (13) \\ & = \begin{cases} p_{tran} & \text{if } \exists k \in [1, N_b] \mid q = k \\ p_{tran} & \text{if } \exists k \in [1, N_b] \mid q = k - 1 \\ p_{tran} & \text{if } \exists k \in [1, N_b] \mid q = k + 1 \\ 1 - p_{tran} & \text{otherwise.} \end{cases} \end{aligned}$$

## 48 3. Baseline approach for comparison

In this article, we compare our approach, in which  
structural constraints on the coefficients are based on mus-  
ical prior, to the baseline model (F evotte et al., 2008),  
in which structural constraints on the coefficients relying  
on physical properties of the signal are imposed for both  
layers. Structure between significant coefficients of the  
decomposition is introduced to model persistence prop-  
erties of time-frequency representations of audio signals,  
so that a horizontal prior structure is given to the in-  
dicator variables corresponding to the tonal layer, while  
vertical prior structure is given to the indicator variables  
corresponding to the transient layer.

For the tonal layer, persistency in time of the time-  
frequency coefficients is modeled. Given a fixed frequency  
index  $\nu$ , the sequence  $\{\gamma_{ton,(q,\nu)}\}_{q=1,\dots,n_{ton}}$  is modeled by  
a two-state first-order Markov chain with transition prob-  
abilities  $P_{ton,00}$  and  $P_{ton,11}$ , assumed equal for all fre-  
quency indices and initial distribution  $\pi_{ton}$  of each chain  
taken to be its stationary distribution.

For the transient layer, persistency in frequency of the  
time-frequency coefficients is modeled. Given a fixed  
frame index  $q$ , the sequence  $\{\gamma_{tran,(q,\nu)}\}_{\nu=1,\dots,\ell_{tran}}$  is  
modeled by a two-state first-order Markov chain with  
probabilities  $P_{tran,00}$  and  $P_{tran,11}$ , assumed equal for all  
frames, and with learned initial probability  $\pi_{tran}$ .

The tonal and transient models are illustrated in Fig-  
ure 6. We refer the reader to (F evotte et al., 2008) for  
more details.

## 7 D. Residual

The residual signal  $r$  is modeled as an independent,  
identically distributed (i.i.d) Gaussian white noise, with  
variance  $\sigma^2$ , which is given an inverse-Gamma conjugate  
prior <sup>6</sup>.

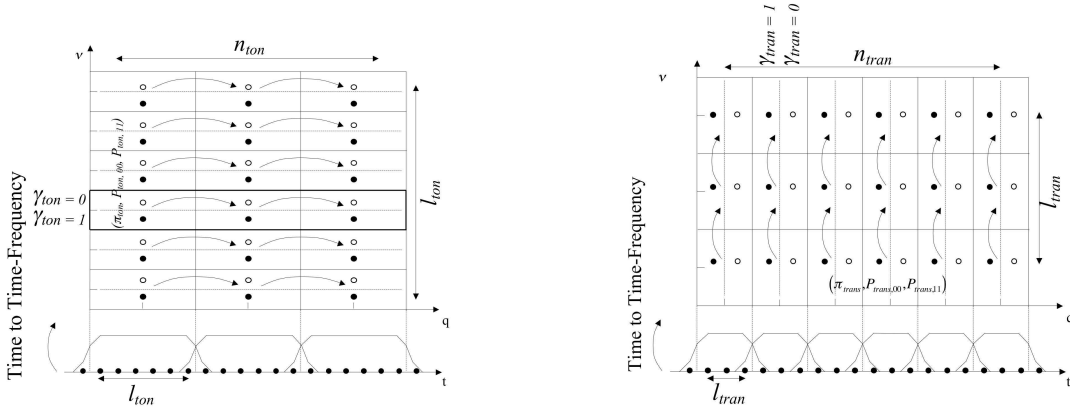


FIG. 6. Structured horizontal model for tonals and vertical model for transients based on time-frequency persistency properties. Adapted from (Févotte *et al.*, 2008).

### 12 III. MCMC INFERENCE

13 In the spirit of some previous work on Bayesian variable selection (Geweke, 1996; George and McCulloch, 1997), and following (Wolfe *et al.*, 2004; Févotte *et al.*, 2008), the posterior distribution of the set of parameters and hyperparameters of the model, denoted by  $\theta = \{\alpha, \beta, \sigma_{ton}, \sigma_{tran}, \nu_{ton}, \nu_{tran}\} \cup \sigma$ , is sampled from using a Gibbs sampler (Geman and Geman, 1984; Casella and George, 1992). Gibbs sampler is a standard Markov Chain Monte Carlo (MCMC) technique that simply requires to iteratively sample from the posterior distribution of each parameter, conditionally upon the data  $x$  and the remaining parameters.

25 The MCMC inference scheme we use is similar to the one described in (Wolfe *et al.*, 2004; Févotte and Godsill, 2006; Févotte *et al.*, 2008), the main difference being the new musical priors considered for the indicator variables we have introduced in Section II.C. For the sake of completeness, we provide in this section its general outline, using the notations we adopted in this paper. Further details about derivation of the expression for the update steps of the parameters, can be found in (Geweke, 1996; George and McCulloch, 1997; Wolfe *et al.*, 2004; Févotte *et al.*, 2008).

Let  $\theta_{-k}$  denote the set of parameters in  $\theta$  except the parameter  $k$ . Using Bayes'rule, the conditional distribution of each parameter  $k$  conditional upon the other parameters and the data can be written as:

$$p(k|\theta_{-k}, x) \propto p(x|\theta)p(\theta). \quad (14)$$

36 The conditional distributions are thus proportional to the likelihood of the data times the priors on the parameters.

In order to avoid a nonconvergent Markov chain in the Gibbs sampler,  $(\gamma_{ton}, \alpha)$  and  $(\gamma_{tran}, \beta)$  need to be sampled jointly (Geweke, 1996). As pointed out in (Févotte *et al.*, 2008), the structure of the dictionary  $D = [VU]$  and the gaussian noise assumption allows alternative

block sampling of  $(\gamma_{ton}, \alpha)$  and  $(\gamma_{tran}, \beta)$ , with the benefit of avoiding any matrix inversion at each iteration of the Gibbs sampler. Indeed, with the gaussian noise assumption, the likelihood of the observations can be written as:

$$p(x|\theta) = (2\pi\sigma^2)^{-N/2} \exp\left(-\frac{1}{2\sigma^2} \|x - V\alpha - U\beta\|_2^2\right). \quad (15)$$

Because the Euclidian norm is invariant under rotation, Eq. (15) can be written as:

$$\begin{aligned} p(x|\theta) &= (2\pi\sigma^2)^{-N/2} \exp\left(-\frac{1}{2\sigma^2} \|\underbrace{U^T(x - V\alpha)}_{x_{tran|ton}} - \beta\|_2^2\right) \\ &= (2\pi\sigma^2)^{-N/2} \exp\left(-\frac{1}{2\sigma^2} \|\underbrace{V^T(x - U\beta)}_{x_{ton|tran}} - \alpha\|_2^2\right). \end{aligned} \quad (16)$$

According to Eq. (16), conditionally upon  $\beta$  (resp.  $\alpha$ ) and the other parameters, inferring  $\alpha$  (resp.  $\beta$ ) is thus a simple regression problem with data  $x_{ton|tran}$  (resp.  $x_{tran|ton}$ ), variable  $\alpha$  (resp.  $\beta$ ) modeled as i.i.d. conditionally upon  $\gamma_{ton}$  (resp.  $\gamma_{tran}$ ), and i.i.d. noise, that does not require any matrix inversion.

Briefly,  $(\gamma_{ton}, \alpha)$  and  $(\gamma_{tran}, \beta)$  are jointly sampled from by 1) sampling  $\gamma_{ton}$  (resp.  $\gamma_{tran}$ ) from the posterior conditional distribution  $p(\gamma_{ton,n}|\sigma_{ton,n}, \sigma, x_{ton|tran})$  (resp.  $p(\gamma_{tran,m}|\sigma_{tran,m}, \sigma, x_{tran|ton})$ ), and 2) sampling  $\alpha$  (resp.  $\beta$ ) from the posterior conditional distribution  $p(\alpha_n|\gamma_{ton,n}, \sigma_{ton,n}, \sigma, x_{ton|tran})$  (resp.  $p(\beta_m|\gamma_{tran,m}, \sigma_{tran,m}, \sigma, x_{tran|ton})$ ). The detailed posterior distributions are given in Appendix A, and we refer the reader to (Févotte *et al.*, 2008; Geweke, 1996) for more details.

The posterior distribution of the other parameters  $\sigma_{ton}, \sigma_{tran}, \nu_{ton}$  and  $\nu_{tran}$  are easy to sample from since they have conjugate prior distributions and thus the corresponding posterior will have the same form.

The principal steps of the Gibbs sampler are summarized in Table I, where  $K$  is the total number of iterations

of the Gibbs sampler and  $K_{Burnin}$  is the burn-in length, corresponding to the number of iterations required before the Markov chain  $\{\theta^{(1)}, \theta^{(2)}, \dots\}$  reaches its stationary distribution. We provide the full posterior distributions in Appendix A.

TABLE I. Gibbs sampler steps for parameters inference.

```

Initialize  $\theta^{(0)}$ 
for  $k = 1 : K + K_{Burnin}$  do
  Update tonals
  Update  $\gamma_{ton}$  and  $\alpha$ 
   $\gamma_{ton}^{(k)} \sim p(\gamma_{ton} | \sigma_{ton}^{(k-1)}, \sigma^{(k-1)}, x_{ton|tran}^{(k-1)})$  (Eq. (A1))
   $\alpha^{(k)} \sim p(\alpha | \gamma_{ton}^{(k)}, \sigma_{ton}^{(k-1)}, \sigma^{(k-1)}, x_{ton|tran}^{(k-1)})$  (Eq. (A5))
  Update hyperparameters
   $\sigma_{ton}^{(k)} \sim p(\sigma_{ton} | \alpha^{(k)}, \lambda_{ton}^{(k-1)})$  (Eq. (A7))
   $\lambda_{ton}^{(k)} \sim p(\lambda_{ton} | \sigma_{ton}^{(k)})$  (Eq. (A9))
  Update transients
  Update  $\gamma_{tran}$  and  $\beta$ 
   $\gamma_{tran}^{(k)} \sim p(\gamma_{tran} | \sigma_{tran}^{(k-1)}, \sigma^{(k-1)}, x_{tran|ton}^{(k-1)})$  (Eq. (A3))
   $\beta^{(k)} \sim p(\beta | \gamma_{tran}^{(k)}, \sigma_{tran}^{(k-1)}, \sigma^{(k-1)}, x_{tran|ton}^{(k-1)})$  (Eq. (A6))
  Update hyperparameters
   $\sigma_{tran}^{(k)} \sim p(\sigma_{tran} | \beta^{(k)}, \lambda_{tran}^{(k-1)})$  (Eq. (A8))
   $\lambda_{tran}^{(k)} \sim p(\lambda_{tran} | \sigma_{tran}^{(k)})$  (Eq. (A10))
  Update noise
   $\sigma^{(k)} \sim p(\sigma | \alpha^{(k)}, \beta^{(k)}, x)$  (Eq. (A11))
end for

```

The Minimum Mean Square Estimates (MMSE) of the parameters  $\theta$  can then be computed from the Gibbs samples  $\{\theta^{(K_{Burnin})}, \theta^{(K_{Burnin}+1)}, \dots, \theta^{(K)}\}$  of the posterior distribution  $p(\theta|x)$ :

$$\hat{\theta}_{MMSE} = \int \theta p(\theta|x) d\theta \quad (17)$$

$$\approx \frac{1}{K - K_{Burnin}} \sum_{k=K_{Burnin}+1}^K \theta^{(k)}. \quad (18)$$

Time-domain source estimates are reconstructed by inverse transform of the estimated coefficients (inverse MDCT in our case). The denoised estimation is constructed by  $\hat{x} = \alpha V + \beta U$ .

## IV. EXPERIMENTS PROTOCOL AND EVALUATION MEASURES

In this Section, we describe the test-set and measures we use for the evaluation of the proposed model.

### A. Experimental setup

We present simulation results on 5 musical excerpts of various music styles that are described in Table II. These signals have been chosen because they have diverse characteristics: the *Glockenspiel* signal is a monophonic signal of a tuned percussion instrument, the *Misery* and *Love Me Do* signals are two complex polyphonic excerpts of Beatles songs containing voice and drum sounds, the

*Beethoven String Quartet* signal is an excerpt of a string quartet and the *Mozart Piano Sonata* signal is an excerpt of polyphonic piano music.

TABLE II. Sound excerpts used for evaluation of the model. SR: sampling rate.

| Name                                | SR (Hz) | Duration |
|-------------------------------------|---------|----------|
| Glockenspiel                        | 44100   | 2s       |
| Misery (Beatles)                    | 11025   | 11s      |
| Love Me Do (Beatles)                | 11025   | 5s       |
| Beethoven String Quartet Op.127 - 1 | 11025   | 11s      |
| Mozart Piano Sonata KV310 - 1       | 11025   | 11s      |

*a. Parameters* : The length of the two MDCT bases are set to 1024 samples for the tonal layer and 128 samples for the transient layer, at a sampling rate of 44100Hz, and respectively to 256 and 32 samples at a sampling rate of 11025Hz. The MDCT of the clean and noisy signals, with input  $SNR = 10dB$  are represented in Figure 7. The MMSE and MAP estimates of the parameters are computed by averaging the last 100 samples of the Gibbs sampler, run for 500 iterations.

We compare a semi-automatic model (denoted as version *SA*), assuming that the transcription is known (notes for the monophonic signal, chords for the polyphonic signals, and beat locations) with a fully-automatic model where the music content is directly estimated from the input signal (denoted as version *A*). Our approach that incorporates musical priors is compared with the one presented in (Févotte *et al.*, 2008), described in Section II.C.3, in which the priors for both the tonal and transient layers are based on time-frequency persistency properties (version (Févotte *et al.*, 2008)).

## B. Evaluation measures

### 1. Audio denoising:

In the context of audio denoising task, artificial noisy signals are created by adding Gaussian white noise to the clean signal with various input SNRs. The case without additional noise *WN* (without noise) corresponds to a separation into two layers *transient + tonal*. Partials are expected to be recovered in the tonal layer while attacks or percussive sounds will be recovered in the transient layer. The results in terms of output SNR provide an objective evaluation measure. However, although widely used for assessing algorithm performances, the SNR is not a completely relevant measure of distortion for audio signals and is insufficient to measure the quality or intelligibility of the reconstructed signals. Indeed, it does not reflect exactly the perceived audio quality that includes distortion of the reconstructed signal, musical noise or other artifacts. Subjective evaluation by listening to the signals is also required. Subjective quality assessment of signal reconstruction in source separation or denoising tasks is an active ongoing topic of re-

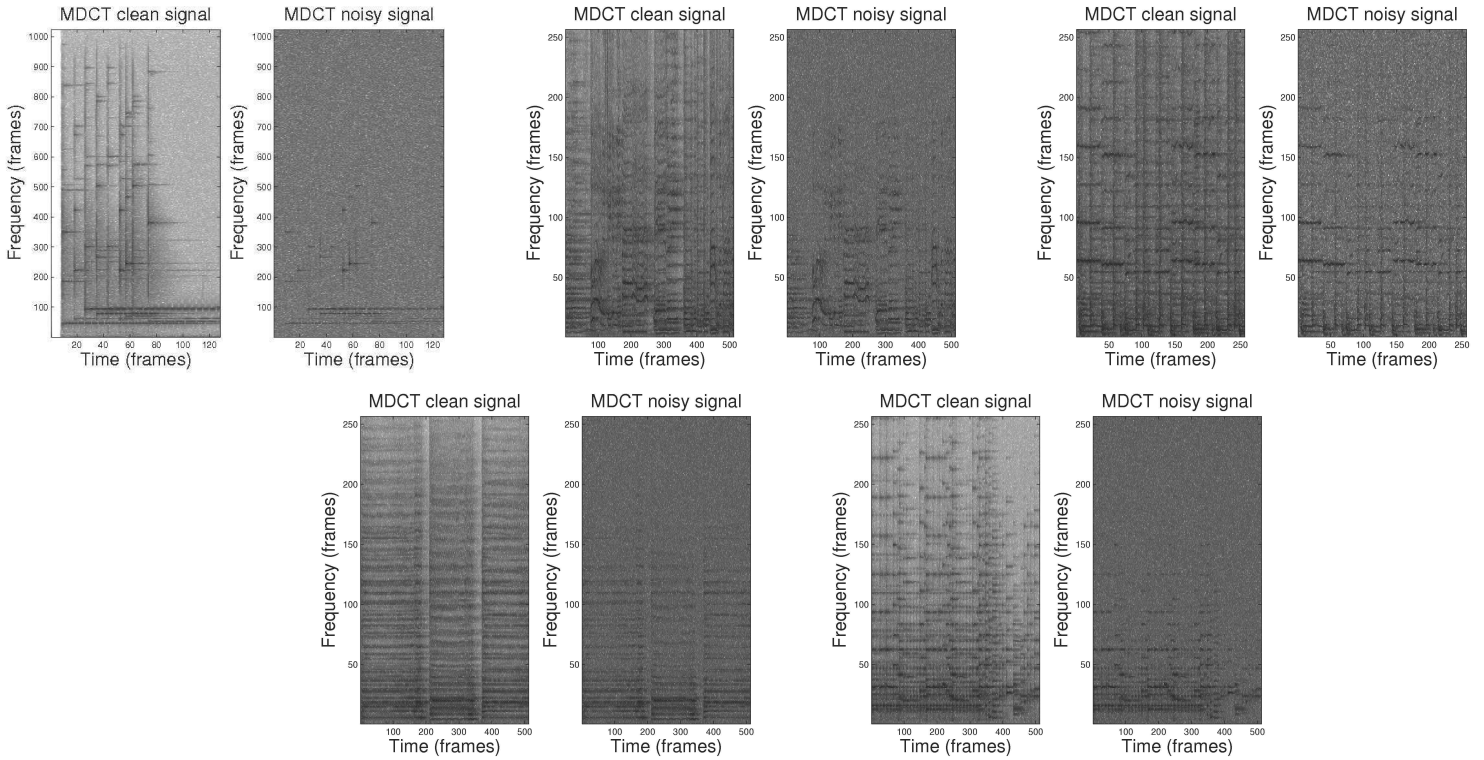


FIG. 7. MDCT of the clean and noisy signals, with input  $SNR = 10dB$ . Form top top bottom : Glockenspiel, Misery, Love Me Do, Beethoven and Mozart excerpts.

4 search (Vincent *et al.*, 2006; Emiya *et al.*, 2010; Rohden- 30  
5 burg *et al.*, 2005). It has been found that statistically 31  
6 significant results can be obtained from listening tests 32  
7 with less than ten non-expert subjects (Vincent *et al.*, 33  
8 2006). However, conducting large-scale listening tests  
9 is out of scope of this work, and the subjective assess-  
10 ment of the results is limited here to an analysis and  
11 description by the authors of the audio excerpts obtained  
12 by the proposed algorithm. All the audio excerpts are  
13 available at [http://webpages.lss.supelec.fr/perso/](http://webpages.lss.supelec.fr/perso/matthieu.kowalski/jasa/jasa.htm) 34  
14 [matthieu.kowalski/jasa/jasa.htm](http://webpages.lss.supelec.fr/perso/matthieu.kowalski/jasa/jasa.htm) (date last viewed  
15 01/20/13).

## 16 2. Sparsity:

17 In this work, we aim at obtaining a dual representa- 42  
18 tion of the signal that is sparse, but that is also struc- 43  
19 tured and is meaningful according to the music content  
20 of the analyzed audio excerpt. A number of criteria for  
21 measuring the sparsity of an expansion have been pro- 44  
22 posed. Among them, Rényi entropies (Rényi, 1961), a  
23 generalization of the Shannon entropy, have been intro- 45  
24 duced in (Baraniuk *et al.*, 2001) as measures for estimat- 46  
25 ing the complexity and information content of a signal 47  
26 through its time-frequency representation. It has been 48  
27 shown that minimizing the complexity or information of 49  
28 a time-frequency representation of a signal is equivalent 50  
29 to maximizing its concentration, peakiness, and resolu-

tion. Let  $\Phi \in \mathcal{L}^2(\mathbb{R}^2)$  be a time-frequency representation  
of a unit-energy signal  $s \in \mathcal{L}^2(\mathbb{R})$  (for instance, in this arti-  
cle  $\Phi$  is the MDCT transform of the signal). The Rényi  
entropies of  $\Phi$ , defined as:

$$R_\alpha(\Phi(t, f)_s) = \frac{1}{1-\alpha} \log_2 \int \int \Phi(t, f)_s^\alpha dt df, \quad \alpha \in [0, 1], \quad (19)$$

may be interpreted as sparsity measures and have thus  
been used as a criterion for obtaining a sparse expan-  
sion of an audio signal (Jaillet and Torr sani, 2004; Li-  
uni *et al.*, 2011). In the present work, we use a R nyi  
entropy criteria as an evaluation measure to compare the  
sparsity of the significance maps. We present here results  
with  $\alpha = 0.9$ , similar results were obtained with different  
criteria.

Sparsity is also measured in terms of the percentage of  
atoms selected in the significance maps.

## C. Computational performances

The algorithms are implemented in MATLAB and per-  
formed on a MacBook Pro Intel Core 2 Duo clocked at  
2.4GHz with 2GB RAM. The computation time of the  
proposed method is similar to the one obtained with  
(F votte *et al.*, 2008),  $\approx 270$  s for processing the *Glock-*  
*enspiel* signal for instance. Note that the use of MCMC  
schemes generates high computational costs.

## V. RESULTS AND DISCUSSION

The aim of this section is to provide an analysis of the proposed approach for sparse and structured expansion of audio signals on overcomplete dictionaries. In order to compare our approach to previous work, we evaluate the performance of the proposed approach for the task of audio denoising. Our purpose is to show how expert music knowledge can be used to build priors to obtain a relevant signal decomposition. The main contribution of the article is the design of new musical priors. In order to evaluate the impact of the prior itself, we compare our results with (Févotte *et al.*, 2008), that specifically differs from the proposed method in the priors. The impact of the various parameters (tuning, harmonics, and priors settings) is studied. We also provide a detailed analysis of our model in terms of sparsity and in terms of interpretability of the representation. We wish to show that the use of priors built on music content information allows making the structure of the signal legible and leads to a representation that has a musical/physical meaning.

### A. Structured representation

Our aim here is to provide a structured representation of the signal that is meaningful from a musical point of view, in the sense that it highlights characteristics of the signal that are of interest. Such a relevant representation may be very useful for extracting higher-level information for a given MIR application. For instance, having a clear representation of the partials of the notes may be useful for removing the drum from a polyphonic excerpt.

The use of musical priors yields a structure that better reflects the music content of the signal compared to the approach that uses physical priors. Figure 8 shows the significance maps of the selected atoms (MMSE estimates) for the *Glockenspiel* signal, in the *WN* case, obtained with the (Févotte *et al.*, 2008) approach [left-top], using musical priors for the transient layer [left-bottom], using musical priors for the tonal layer [right-top], using musical priors for both the tonal and transient layers [right-bottom]. When using musical priors for the tonal layer, the resolution of the tonal significance map is sharper. The partials of the notes clearly appear as thin horizontal lines and are better discriminated, especially in low frequencies. The beginning of the notes is also clearer. The structure of the significance maps is even sharper and legible when we also use musical priors for the transient layer.

However, it should be noticed that, especially under low-input SNRs conditions, one may perceive artifacts in the reconstructed signal with the method we propose. These artifacts may be due, on the one hand, to the fact that some high frequencies are captured by the transient basis rather than by the tonal basis. On the other hand, the construction of the significance map corresponding to the transient layer leads to some regular “clicks” that are audible in low frequencies. But, in spite of these artifacts, one can find by listening to the reconstructed signals that results obtained relying on musical priors are generally

“richer” than the ones obtained with the approach used in (Févotte *et al.*, 2008). This is very clear for instance in the case of the *Beethoven* excerpt, with  $SNR_{in} = 10\text{dB}$ . The chords (especially those on beats 2 and 3) sound more “round”, and the notes are better held. It should be noticed that listening tests in general do not reveal noticeable improvement when using musical prior also for the transient layer, even though the reconstructed signal in the case of the *Mozart* excerpt with  $SNR_{in} = 0\text{db}$  sounds a little “flatter” without musical prior for the transient layer.

### B. Semi-automatic versus automatic approach

#### 1. Tonal layer

Table III shows that the SNR results obtained with an automatic approach (*A*), where the tonal content is directly estimated from the audio (using a chord estimation algorithm), are similar to the ones obtained with a semi-automatic approach (*SA*), where the transcription (chord ground-truth) is given as an input of the model. Results are similar at the same time in terms of SNR, in terms of legibility of the significance maps, and in terms of listening tests. The results of chord estimation are indicated in Table III and show that the chord estimation is not perfect. Two scores are considered: *Exact Estimation EE* corresponds to the rate of chords correctly detected; *Exact + Neighbor E+N* corresponds to the rate of correctly detected chords including neighboring chords<sup>7</sup>. It can be seen that the exact chord estimation results may be low, especially in low input SNR conditions (for instance  $EE = 28.35\%$  for the *Love Me Do* excerpt, with  $SNR_{in} = 0$ ). However, most errors correspond to neighboring chords (high  $E + N$  results), which indicates that most of the notes present in the signal are correctly taken into account. A rough estimation of the tonal content is thus sufficient to build relevant prior for the significance map corresponding to the tonal layer.

#### 2. Transient layer

The difference between the SNR results obtained with an automatic approach, where the beats are directly estimated from the audio (using a beat tracking algorithm) and a semi-automatic approach where the beat locations are given as an input of the model, was in each case  $\leq 0.1\text{dB}$  (For conciseness, detailed results are not reported here). Here again, the transcription does not need to be perfect to build relevant prior for the significance map corresponding to the transient layer.

### C. Influence of musical priors for the transient layer only

Table IV shows the effect of using musical priors for the transient layer only (and using frequency persistency-based priors for the tonal layer, as in (Févotte *et al.*, 2008)), denoted as case *Method tr*. In terms of SNR,

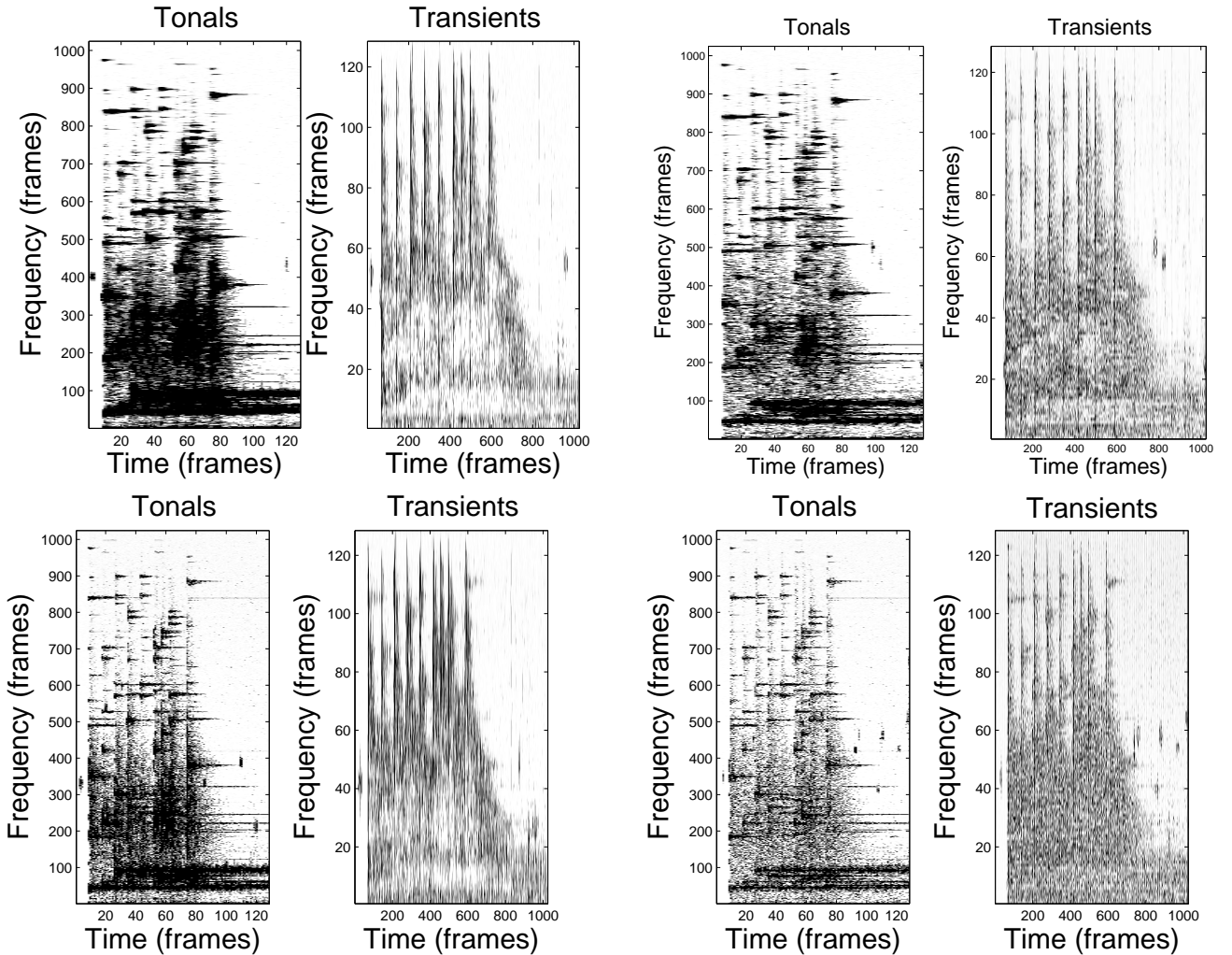


FIG. 8. Significance maps of the tonal and transient bases (MMSE estimates) for the *Glockenspiel* excerpt, case *WN*. Left-top: approach (Févotte *et al.*, 2008); Left-bottom: proposed approach using musical priors for the transient layer only; Right-top: proposed approach using musical priors for the tonal layer; Right-bottom: proposed approach using musical priors for both the tonal and transient layers.

1 musical priors for the transient layer yield results that 8  
2 are equivalent to state-of-the-art results, except for poly- 9  
3 phonic clean signals. For monophonic and polyphonic 10  
4 noisy signals, the use of musical priors for transients re-  
5 sults in a tonal layer that may be more consistent with  
6 the music content: the partials of the notes are more 11  
7 distinguishable, as illustrated in Figure 8 [Left-bottom].  
8 However, for clean polyphonic signals, the use of beat po- 12  
9 sitions as prior information for building the transit layer 13  
10 is too restrictive for having a satisfying decomposition.  
11 When listening to the results on the *Mozart* excerpt, one 14  
12 can hear that the residual part obtained with *Method* 15  
1 *tr.* is non-negligible compared to the one obtained with 16  
2 *Method* (Févotte *et al.*, 2008), although it should be zero.  
3 For the Beethoven excerpt, some high frequencies are 17  
4 captured by the transient basis rather than by the tonal 18  
5 basis, as it is illustrated Figure 9. Using musical prior 19  
6 for transients based on the metrical structure thus shows 20  
7 some potential, as it is adapted to the semantic content 21

of the signal, but it should be refined, for instance by  
using onset positions instead of beat positions. This is  
also discussed in Section V.E.

#### D. Comparison between chromagram versus chords

We have proposed two methods for building priors for  
the significance map corresponding to the tonal layer.

1. In the first case (*Method Chord*), the map is built  
using information about the tonal content from the  
estimated chords.
2. In the second case (*Method Chroma*), the map is  
built using information about the tonal content di-  
rectly from the chromagram.

Table V shows that *Method Chord* outperforms *Method  
Chroma* in terms of SNR in the case without noise added

TABLE III. SNR results (in dB), and chord estimation results (*EE*: Exact Estimation, *E+N*: Exact + Neighbor) for various input SNRs and without additional Gaussian noise (*WN*), for comparison between a semi-automatic (estimated chords) and an automatic (given chords) approach.

|            | $SNR_{in}$   | <i>WN</i> |           | 0        |           | 10       |           | 20       |           |
|------------|--------------|-----------|-----------|----------|-----------|----------|-----------|----------|-----------|
|            |              | <i>A</i>  | <i>SA</i> | <i>A</i> | <i>SA</i> | <i>A</i> | <i>SA</i> | <i>A</i> | <i>SA</i> |
| <i>Gl.</i> | <i>EE</i>    | 14.39     |           | 14.39    |           | 14.39    |           | 14.39    |           |
|            | <i>E + N</i> | 72.27     |           | 72.27    |           | 72.27    |           | 72.27    |           |
|            | $SNR_{out}$  | 71.07     | 71.36     | 14.15    | 14.13     | 21.31    | 21.37     | 28.58    | 28.59     |
| <i>Mi.</i> | <i>EE</i>    | 79.22     |           | 79.02    |           | 79.22    |           | 78.77    |           |
|            | <i>E + N</i> | 82.00     |           | 88.1     |           | 82.00    |           | 81.54    |           |
|            | $SNR_{out}$  | 42.28     | 42.73     | 6.36     | 6.35      | 13.02    | 13.02     | 20.91    | 20.87     |
| <i>Lo.</i> | <i>EE</i>    | 95.29     |           | 28.35    |           | 60.58    |           | 96.27    |           |
|            | <i>E + N</i> | 100       |           | 92.62    |           | 100      |           | 100      |           |
|            | $SNR_{out}$  | 29.12     | 28.31     | 6.44     | 6.42      | 12.44    | 12.44     | 19.24    | 19.21     |
| <i>Be.</i> | <i>EE</i>    | 87.22     |           | 86.56    |           | 86.77    |           | 86.77    |           |
|            | <i>E + N</i> | 100       |           | 100      |           | 100      |           | 100      |           |
|            | $SNR_{out}$  | 55.15     | 54.72     | 7.17     | 7.15      | 13.56    | 13.54     | 21.63    | 21.62     |
| <i>Mo.</i> | <i>EE</i>    | 75.69     |           | 70.26    |           | 75.25    |           | 75.69    |           |
|            | <i>E + N</i> | 90.26     |           | 88.70    |           | 90.26    |           | 90.26    |           |
|            | $SNR_{out}$  | 62.13     | 62.33     | 8.20     | 8.19      | 15.47    | 15.47     | 23.40    | 23.42     |

TABLE IV. SNRs results (in dB), for various input SNRs and without additional Gaussian noise (*WN*), for comparison between using musical priors for the transient layer only, case *tr*, and with the baseline approach (Févotte *et al.*, 2008) (*F2008*).

| $SNR_{in}$ | <i>WN</i> |              | 0         |              | 10        |              | 20        |              |
|------------|-----------|--------------|-----------|--------------|-----------|--------------|-----------|--------------|
|            | <i>tr</i> | <i>F2008</i> | <i>tr</i> | <i>F2008</i> | <i>tr</i> | <i>F2008</i> | <i>tr</i> | <i>F2008</i> |
| <i>Gl.</i> | 70.01     | 70.22        | 15.54     | 15.74        | 22.14     | 22.45        | 29.16     | 29.22        |
| <i>Mi.</i> | 33.38     | 44.41        | 6.89      | 6.90         | 13.13     | 13.29        | 20.43     | 21.08        |
| <i>Lo.</i> | 27.30     | 29.61        | 6.72      | 6.77         | 12.77     | 12.72        | 19.49     | 19.35        |
| <i>Be.</i> | 39.60     | 54.64        | 7.71      | 7.71         | 13.90     | 14.03        | 21.44     | 21.99        |
| <i>Mo.</i> | 54.47     | 60.96        | 8.98      | 8.97         | 15.87     | 15.94        | 23.59     | 23.88        |

22 to the clean signal, and in the case of the monophonic signal. *Method Chroma* slightly outperforms *Method Chord* in terms of SNR in the case of polyphonic music and when noise is added to the clean signal. Experiments reveal that the significance maps obtained with *Method Chroma* are sharper and sparser than those obtained with *Method Chord*, as illustrated in Figure 10. Moreover, listening tests reveal that the noise induced by the proposed method in the case of *Method Chord*, is considerably reduced when using *Method Chroma*, especially when musical priors are used both for the tonal and the transient layers (see for instance the *Beethoven* excerpt, case  $SNR_{in} = 10$ dB).

35 However, reconstructed signals using *Method Chroma* are not systematically more pleasant to listen too. A drawback of *Method Chroma* is that, because the hierarchy between the 12 pitch classes is less strong than with *Method Chord* when building the prior for the tonal layer (because all pitch classes are given a non-zero contribution, whereas in the case of *Method Chord*, only 3 pitch classes are considered at each time-instant), the reconstructed signal may select notes that do not

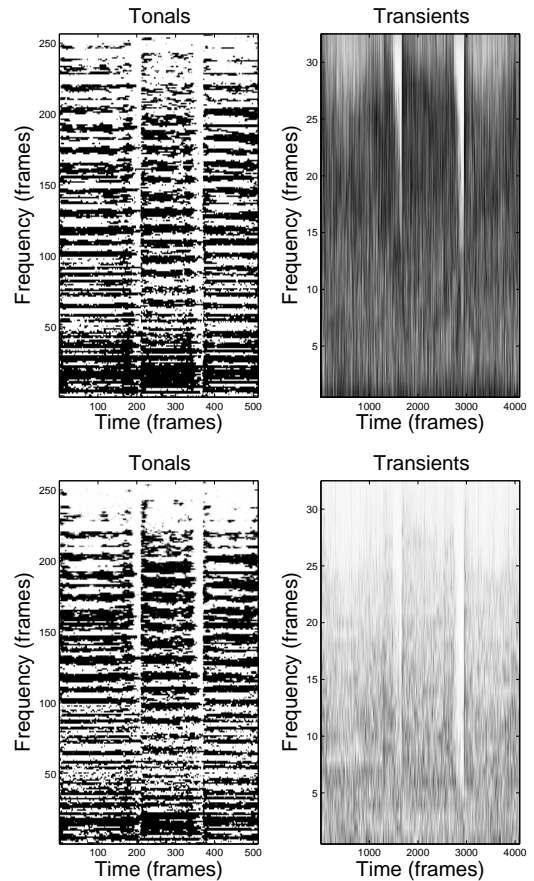


FIG. 9. Significance maps of the tonal and transient bases (MMSE estimates) for the *Beethoven* excerpt, case *WN*. Top: approach (Févotte *et al.*, 2008); Bottom: proposed approach using musical priors for the transient layer only.

TABLE V. SNRs results (in dB), for various input SNRs and without additional Gaussian noise (*WN*), for comparison between *Method Chord* (*Cho*) and *Method Chroma* (*Chr*).

| $SNR_{in}$ | <i>WN</i>  |            | 0          |            | 10         |            | 20         |            |
|------------|------------|------------|------------|------------|------------|------------|------------|------------|
|            | <i>Cho</i> | <i>Chr</i> | <i>Cho</i> | <i>Chr</i> | <i>Cho</i> | <i>Chr</i> | <i>Cho</i> | <i>Chr</i> |
| <i>Gl.</i> | 71.35      | 69.90      | 14.13      | 13.27      | 21.37      | 20.70      | 28.59      | 27.87      |
| <i>Mi.</i> | 42.73      | 37.09      | 6.35       | 7.04       | 13.02      | 13.35      | 20.87      | 20.89      |
| <i>Lo.</i> | 28.32      | 26.19      | 6.42       | 6.80       | 12.44      | 12.85      | 19.21      | 19.27      |
| <i>Be.</i> | 54.72      | 54.62      | 7.15       | 8.63       | 13.53      | 14.52      | 21.62      | 22.05      |
| <i>Mo.</i> | 62.33      | 60.1       | 8.19       | 9.45       | 15.47      | 16.28      | 23.42      | 23.96      |

fit the harmonic content, similarly to the one obtained with approach (Févotte *et al.*, 2008). In this case, one may perceive “wrong” notes in the reconstructed signal, especially in high frequencies, as it can be heard, for instance, when listening to the *Mozart* excerpt, case  $SNR_{in} = 10$ dB. This blurry phenomenon has especially an impact in the case on clean and monophonic signals.

TABLE VI. SNR results for comparison between the proposed method that uses musical priors and the approach proposed in (Févotte *et al.*, 2008) (*F2008*). Case *A*: musical priors only for the tonal layer (automatic approach). Case *A + tr*: musical priors for the tonal and the transient layer.

| $SNR_{in}$ | <i>WN</i> |          |               | 0            |          |               | 10           |          |               | 20           |          |               |
|------------|-----------|----------|---------------|--------------|----------|---------------|--------------|----------|---------------|--------------|----------|---------------|
|            | Method    | <i>A</i> | <i>A + tr</i> | <i>F2008</i> | <i>A</i> | <i>A + tr</i> | <i>F2008</i> | <i>A</i> | <i>A + tr</i> | <i>F2008</i> | <i>A</i> | <i>A + tr</i> |
| Gl.        | 71.35     | 71.49    | 70.22         | 14.13        | 13.86    | 15.74         | 21.37        | 20.98    | 22.45         | 28.59        | 28.24    | 29.22         |
| Mi.        | 42.73     | 32.72    | 44.41         | 7.03         | 7.04     | 6.9           | 13.35        | 13.34    | 13.29         | 20.89        | 20.60    | 21.08         |
| Lo.        | 28.32     | 27.14    | 29.61         | 6.80         | 6.72     | 6.77          | 12.85        | 12.95    | 12.72         | 19.27        | 19.72    | 19.35         |
| Be.        | 54.72     | 35.97    | 54.64         | 8.63         | 8.65     | 7.71          | 14.52        | 14.54    | 14.03         | 22.05        | 21.49    | 21.99         |
| Mo.        | 62.33     | 57.07    | 60.96         | 9.45         | 9.37     | 8.97          | 16.28        | 16.12    | 15.94         | 23.96        | 23.73    | 23.88         |

## E. Denoising quality

Table VI compares results obtained with the proposed method that uses musical priors with the approach proposed in (Févotte *et al.*, 2008). As underlined in the previous section, *Method Chroma* has a negative “blurry” effect on clean and monophonic signals. Ideally, the method should be selected according to the type of test signal. For the sake of legibility, we do not report results with both methods in Table Table VI. Our purpose here is to demonstrate the potential of the proposed musical priors, compared to existing approaches. We thus present the best results, obtained with *Method Chroma* in the case of polyphonic music and when noise is added to the clean signal and *Method Chord* otherwise. Concerning the quality of denoising, our model provides results that are comparable to state-of-the-art algorithms in terms of SNR: the difference between our method and method (Févotte *et al.*, 2008) are in general lower than 1 dB. The method proposed in (Févotte *et al.*, 2008) slightly outperforms our method in the case of monophonic music, whereas our method performs slightly better in the case of polyphonic music. Our explanation is that, by relying on chord information, too many notes are considered when building the prior corresponding to the tonal significance map of the monophonic excerpt. A polyphonic/monophonic detection step could be added to improve the proposed model.

Differences between the two approaches may be perceived while listening to the sound files. As said before, the proposed approach induces some artifacts. In particular, the quality of denoising obtained with the proposed prior for the transient layer is disappointing. Indeed, the construction of the significance map corresponding to the transient layer leads to some regular “click” sounds that are superimposed to the signal of interest. As indicated in Table VII and illustrated in Figure 10 and 11, compared to (Févotte *et al.*, 2008), our approach selects much less atoms in the transient layer. Although the idea seems “natural”, the use of beat position information for building the prior for the transient layer may be too restrictive for denoising purpose.

When we build the tonal significance map, we select at each time instant all the MDCT bins that correspond to the notes of the estimated chord, regardless of octaves. Because the estimation of the tonal content is rough (we do not have an exact transcription and ignore for instance passing tones), some of the “tubes” that result from this

selection in the tonal significance map may correspond to added notes that are not actually in the signal and thus not completely relevant. However, these atoms are musically coherent with the music content (they are coherent with the underlying harmony) and are not as disturbing as if they were atoms randomly selected. Figure 11 shows the significance maps (MMSE estimates) for the *Mozart* signal, in the case  $SNR_{in} = 10$ dB. It can be seen that in the case of (Févotte *et al.*, 2008) approach, many atoms that do not fit the tonal content are selected, especially in high frequencies. When listening to the reconstructed signal, one may perceive some notes that seem “wrong”. When listening to the signal obtained with the proposed approach, one may also perceive some added notes, but they are coherent with the harmonic content. This is important when extracting higher-level information from the reconstructed signal. For instance, in the case of key estimation, the algorithm will be less affected by notes that belong to the tonal content than by notes that seem randomly selected.

## F. Sparsity

In the case of polyphonic music, the proposed approach provides a representation that is sparser than the one proposed in (Févotte *et al.*, 2008). Indeed, the number of remaining non-zero coefficients in contrast to the total numbers of atoms of the initial redundant dictionary is usually lower when using musical priors, as well as Renyi entropy, as it can be seen in Table VII. Figures 8, 10 and 11 illustrate the fact that the energy density of the significance map corresponding to the tonal layer is concentrated into thin horizontal lines, and Figures 8, 10 and 12 clearly illustrate that the energy density of the significance map corresponding to the transient layer is concentrated into thin vertical lines. In the case of monophonic music, figures in Table VII indicate that our representation is less sparse than the one provided in (Févotte *et al.*, 2008). This is because our method induces some artifacts resulting from undesirable selected atoms (see Figure 12, [middle]). The representation may become sparser by increasing the value of  $p_{ton}$  in Eq. (9), as explained in Section V.G.1. Note that, as illustrated in Figure 8, in the case of running the algorithm on a clean signal (case *WN*), our approach provides a representation that is sparser than the one obtained with (Févotte *et al.*, 2008), where a small noise is needed to obtain a



TABLE VII. Percentage of remaining non-zero coefficients selected for the tonal layer (% *ton.*) and the transient layer (% *tran.*) and value of Renyi entropy for tonal layer (*Renyi ton.*) and the transient layer (*Renyi tran.*) (MAP estimates). Case: *F2008*: approach in (Févotte *et al.*, 2008). Case *A*: musical priors only for the tonal layer (using estimated chords). Case *A + tr*: musical priors for the tonal and the transient layer.

| Method     | $SNR_{in}$         | $WN$     |               |              | 0          |               |              | 10         |               |              | 20         |               |              |
|------------|--------------------|----------|---------------|--------------|------------|---------------|--------------|------------|---------------|--------------|------------|---------------|--------------|
|            |                    | <i>A</i> | <i>A + tr</i> | <i>F2008</i> | <i>A</i>   | <i>A + tr</i> | <i>F2008</i> | <i>A</i>   | <i>A + tr</i> | <i>F2008</i> | <i>A</i>   | <i>A + tr</i> | <i>F2008</i> |
| <i>Gl.</i> | % <i>ton.</i>      | 26.1482  | 19.7510       | 30.3772      | 2.0317     | 1.9966        | 1.5022       | 2.5848     | 2.4879        | 1.5518       | 3.3974     | 3.2333        | 3.3745       |
|            | % <i>tran.</i>     | 29.0039  | 33.0078       | 24.6094      | 0          | 8.9844        | 0            | 0          | 6.8359        | 0            | 0          | 5.9570        | 0            |
|            | <i>Renyi ton.</i>  | 15.0604  | 14.6550       | 15.2776      | 11.3662    | 11.3403       | 10.9392      | 11.7111    | 11.6559       | 10.9812      | 12.1047    | 12.0313       | 12.0875      |
|            | <i>Renyi tran.</i> | 15.2006  | 15.3874       | 14.9631      | <i>NaN</i> | 13.5122       | <i>NaN</i>   | <i>NaN</i> | 13.1180       | <i>NaN</i>   | <i>NaN</i> | 12.9194       | <i>NaN</i>   |
| <i>Mi.</i> | % <i>ton.</i>      | 23.1979  | 14.7957       | 50.7500      | 3.0151     | 3.0815        | 15.7799      | 5.2574     | 5.5031        | 25.5539      | 9.0256     | 9.4261        | 37.4146      |
|            | % <i>tran.</i>     | 58.3740  | 32.6172       | 44.8242      | 11.8164    | 16.2109       | 12.3047      | 21.5820    | 19.3359       | 48.9014      | 46.1914    | 23.3398       | 67.8223      |
|            | <i>Renyi ton.</i>  | 14.8886  | 14.2306       | 16.0161      | 11.9396    | 11.9697       | 14.3331      | 12.7418    | 12.8048       | 15.0260      | 13.5188    | 13.5808       | 15.5774      |
|            | <i>Renyi tran.</i> | 16.1770  | 15.3702       | 15.7958      | 13.9016    | 14.3637       | 13.9315      | 14.7733    | 14.6180       | 15.9218      | 15.8713    | 14.8896       | 16.3935      |
| <i>Lo.</i> | % <i>ton.</i>      | 16.6702  | 12.2955       | 45.8679      | 2.6535     | 2.8152        | 11.4395      | 4.8920     | 5.0903        | 20.6650      | 8.7173     | 8.7738        | 32.9956      |
|            | % <i>tran.</i>     | 74.0723  | 37.5000       | 27.0020      | 31.2500    | 20.3125       | 10.2051      | 45.7031    | 26.5625       | 19.4824      | 51.9531    | 32.2266       | 24.6582      |
|            | <i>Renyi ton.</i>  | 13.4112  | 12.9614       | 14.8705      | 10.7474    | 10.8349       | 12.8587      | 11.6348    | 11.6909       | 13.7200      | 12.4686    | 12.4759       | 14.3943      |
|            | <i>Renyi tran.</i> | 15.5207  | 14.5736       | 14.0640      | 14.3106    | 13.6891       | 12.6616      | 14.8560    | 14.0761       | 13.5926      | 15.0413    | 14.3550       | 13.9329      |
| <i>Be.</i> | % <i>ton.</i>      | 30.2101  | 19.2009       | 44.4839      | 3.1097     | 3.0518        | 8.9005       | 5.6511     | 5.9242        | 18.5188      | 9.5741     | 10.3973       | 32.7576      |
|            | % <i>tran.</i>     | 57.5195  | 31.2500       | 61.3037      | 2.9297     | 6.8359        | 13.4033      | 23.4375    | 6.7383        | 82.7148      | 80.0781    | 15.8203       | 99.8779      |
|            | <i>Renyi ton.</i>  | 15.2689  | 14.6063       | 15.8275      | 11.9828    | 11.9540       | 13.5067      | 12.8449    | 12.9090       | 14.5619      | 13.6028    | 13.7216       | 15.3836      |
|            | <i>Renyi tran.</i> | 16.1560  | 15.3084       | 16.2482      | 11.8713    | 13.1180       | 14.0549      | 14.8926    | 13.0972       | 16.6802      | 16.6664    | 14.3285       | 16.9521      |
| <i>Mo.</i> | % <i>ton.</i>      | 36.0977  | 21.1670       | 42.2409      | 2.9648     | 2.9938        | 8.1978       | 4.6402     | 4.8706        | 12.5305      | 7.4661     | 7.5645        | 18.7614      |
|            | % <i>tran.</i>     | 39.4287  | 54.6875       | 33.2764      | 4.1992     | 14.7461       | 14.4043      | 39.3555    | 15.8203       | 47.2656      | 79.9805    | 28.8086       | 92.5049      |
|            | <i>Renyi ton.</i>  | 15.5174  | 14.7432       | 15.7447      | 11.9101    | 11.9226       | 13.3835      | 12.5500    | 12.6164       | 13.9843      | 13.2364    | 13.2536       | 14.5687      |
|            | <i>Renyi tran.</i> | 15.6106  | 16.1180       | 15.3662      | 12.4149    | 14.2271       | 14.1588      | 15.6433    | 14.3285       | 15.8731      | 16.6655    | 15.1933       | 16.8414      |

77 good decomposition.

23 using tuning information allows selecting atoms within  
24 the correct frequency regions.

## 78 G. Impact of parameters

### 79 1. Indicator variable prior set-up:

1 The values  $p_{ton}$  in Eq. (9) and Eq. (10) and  $p_{tran}$  in  
2 Eq. (13) have an effect on the above-mentioned artifacts  
3 produced by our model in low-input SNRs conditions.  
4 For instance, setting  $p_{ton}$  and  $p_{tran}$  to 0.99 instead of  
5 0.9 in the case of the *Glockenspiel* signal allows reducing  
6 the artifacts for  $SNR_{in} = 10dB$ , as it can be seen in  
7 Figure 12. However, our experiments show that indicator  
8 variables corresponding to atoms that do not belong to  
9 the chord must not be set to 0. Setting  $p_{ton}$  or  $p_{tran}$  to 1  
10 results in reconstructed signals of very “poor” sound, as it  
11 can be assessed by listening tests. Output SNRs are also  
12 degraded. Setting  $p_{ton} < 1$  allows taking into account  
13 imperfections of the chromagram given as input of the  
14 hybrid model (temporal imperfections due to windowing,  
15 discrepancy between the ideal model and reality, *etc.*).

### 16 2. Impact of tuning:

17 Integrating tuning information in the model does not  
18 lead to improvement in terms of output SNR values (de-  
19 tailed results are not reported here to avoid overfill of the  
20 article), but yields to estimated significance maps that  
21 are more coherent with our model. Indeed, the “tubes”  
22 depend on the tuning and thus, in case of “bad” tuning,

### 25 3. Impact of harmonics:

26 We did not find any improvement when adding har-  
27 monics in our model: the difference between the SNR  
28 results obtained with and without considering the har-  
29 monics was systematically  $\leq 0.3dB$  (detailed results are  
30 not reported here to avoid overfill of the article). This  
31 may be explained by the fact that, in the polyphonic  
32 case, the contribution of a large part of the first 6 higher  
33 harmonics of a note is already taken into account in the  
34 significance map by the other notes. For instance, let us  
35 consider C major chord (C-E-G). The C note generates  
36 harmonics E and G. E and G are thus both actual played  
37 notes and harmonics. Their contribution is already par-  
38 tially taken into account in the significance map in the  
39 case of the model “without harmonics” .

## 40 VI. CONCLUSION AND FUTURE WORK

41 In this article, we have presented a new approach for  
42 sparse decomposition of audio signals of music on an over-  
43 complete dictionary made as the union of two MDCT  
44 bases. The originality of our model is that, within a  
45 Bayesian framework, we introduce musical priors that  
46 aim at modeling dependencies between the coefficients of  
47 the expansion in a more realistic way than what has been  
48 proposed before. The main contribution of the article is

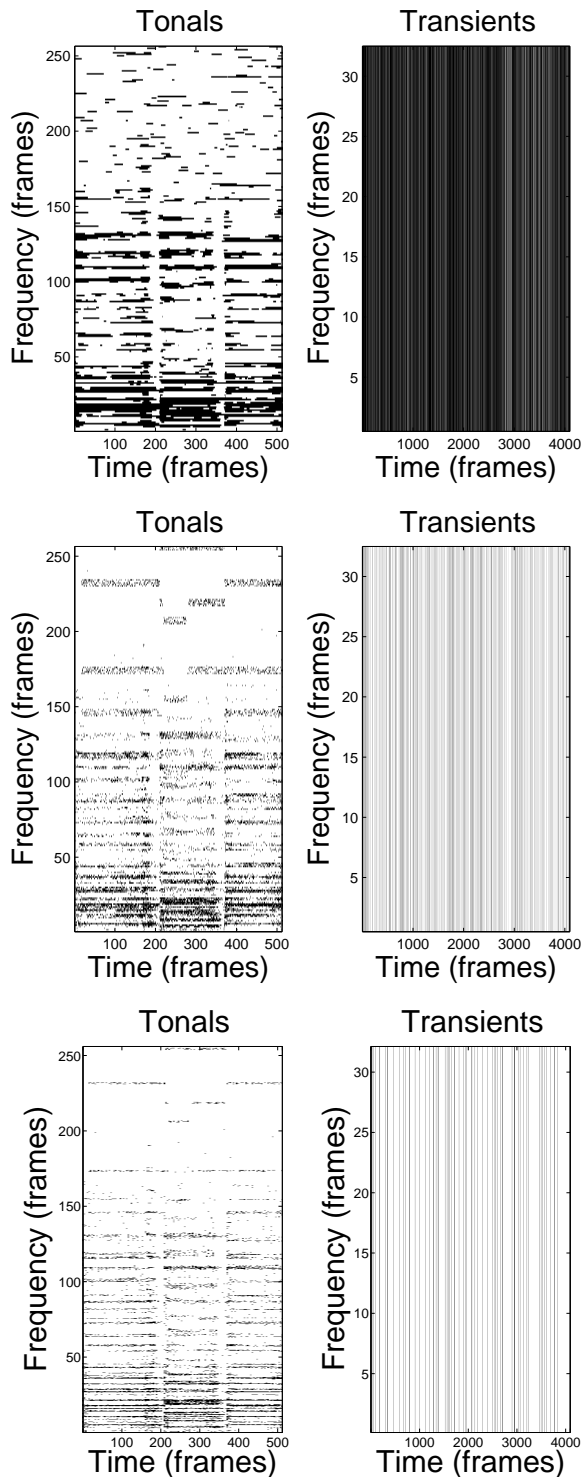


FIG. 10. Significance maps of the tonal and transient bases (MAP estimates) for the *Beethoven* excerpt, case  $SNR_{in} = 10\text{dB}$ . Top: approach (Févotte *et al.*, 2008); middle: proposed approach using musical priors for both layers, *Method Chord*; bottom: proposed approach using musical priors for both layers, *Method Chroma*.

1 to show that the musical prior based on musical knowl- 8  
 2 edge performs as well as more sophisticate prior as HMM 9

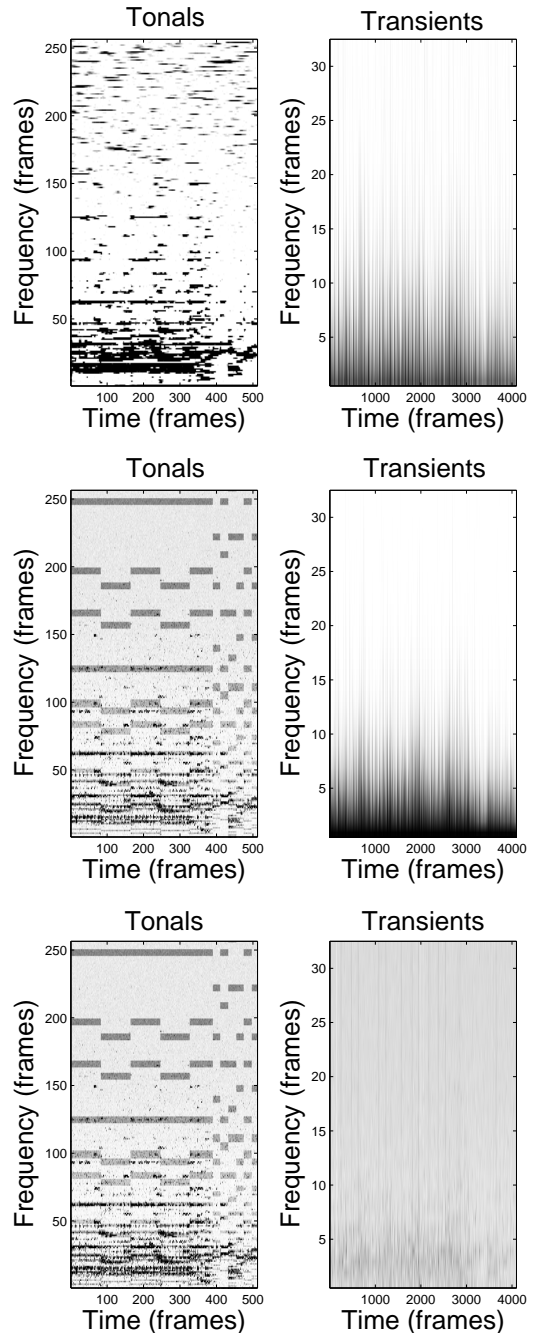


FIG. 11. Significance maps of each basis (MMSE estimates) for the *Mozart* excerpt, case  $SNR_{in} = 10\text{dB}$ . Top: approach (Févotte *et al.*, 2008); middle: proposed approach using a musical prior for the tonal layer; bottom: proposed approach using musical priors for both the tonal and transient layers.

3 and appears to be more “natural”. The significance maps  
 4 corresponding to the tonal and transient layers are coher-  
 5 ent with the intrinsic content of music audio.

6 We have provided numerical results and a number of  
 7 case study examples that assess that our model is ade-  
 8 quate to fairly represent audio signals of music. The de-  
 9 noising task has been used as a “proof of concept” of the

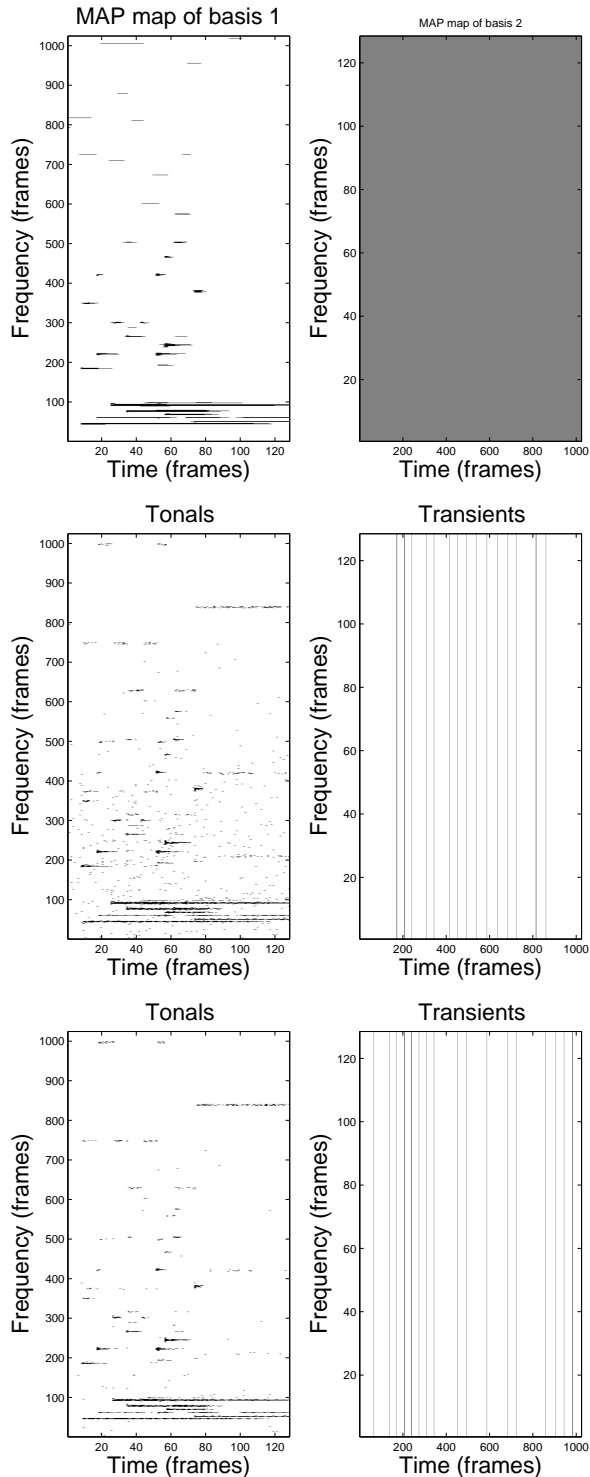


FIG. 12. Significance maps of each basis (MAP estimates) for the *Glockenspiel* excerpt, case  $SNR_{in} = 10\text{dB}$ . Top: approach (Févotte *et al.*, 2008); middle: proposed approach using musical priors with  $p_{ton} = 0.9$  and  $p_{tran} = 0.9$ ; bottom: proposed approach using musical priors with  $p_{ton} = 0.99$  and  $p_{tran} = 0.99$ .

newly introduced musical priors. Concerning the quality of denoising, all the configurations of the model we

propose provide results whose quality in terms of SNR results outperforms or, at least, corresponds to state-of-the-art approaches. Moreover, the content of reconstructed signal is more coherent with the underlying harmony and metrical structure, and thus musically meaningful.

A well-structured representation may be very useful to provide access to higher level information about the audio signal, whereas relevant music content information should help providing a “good” representation. Future work will concentrate on fully integrating in the model chord and beat estimation in an interactive fashion. For instance the chromagram could be updated with the other parameters during MCMC inference in order to possibly improve the chord estimation.

The priors we propose have a great potential of improvement in the future (for example, by using a time segmentation, a larger chord lexicon, using onsets combined with beat positions etc.). The model could also be extended so that dependencies between layers are taken into account. For this, musical information such as the fact that chord changes usually occur on beat subdivisions (which are related to transient locations) could be used. This should help reducing musical noise and artifacts.

As far as we know, the introduction of musical priors in hybrid models for sparse decomposition is novel. The use of mid-level representation of audio – such as the chromagram, as proposed in this paper – or scores, if available, could be extended to many applications such as denoising, source separation, compression, coding and many others. Usually, only physical and mathematical criteria are taken into account. We believe that the use of musical content information opens new interesting perspectives.

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## APPENDIX A: POSTERIOR DISTRIBUTIONS USED IN THE GIBBS SAMPLER

### 1. Indicator variables

#### a. Tonal layer

$$\begin{aligned}
 p(\gamma_{ton,n} = 0 | \sigma_{ton,n}, \sigma, x_{ton|tran}) &= \frac{1}{1 + \tau_{ton,n}} \\
 p(\gamma_{ton,n} = 1 | \sigma_{ton,n}, \sigma, x_{ton|tran}) &= \frac{\tau_{ton,n}}{1 + \tau_{ton,n}},
 \end{aligned}
 \tag{A1}$$

with

### 50 3. Hyperparameters

#### 51 a. Scale parameters of coefficients

$$\begin{aligned} \tau_{ton,n} &= \sqrt{\frac{\sigma^2}{\sigma^2 + \sigma_{ton,n}}} \exp\left(\frac{x_{ton|tran}^2 \sigma_{ton,n}}{2\sigma^2(\sigma^2 + \sigma_{ton,n})}\right) \\ &\times p\left(\frac{\gamma_{ton,n} = 1 | \gamma_{ton,-n}}{\gamma_{ton,n} = 0 | \gamma_{ton,-n}}\right). \end{aligned} \quad (A2)$$

42 The ratio  $p\left(\frac{\gamma_{ton,n}=1|\gamma_{ton,-n}}{\gamma_{ton,n}=0|\gamma_{ton,-n}}\right)$  is  $\frac{P_\Lambda\{\gamma_{ton,n}=1\}}{1-P_\Lambda\{\gamma_{ton,n}=1\}}$ , where  
 43  $P_\Lambda\{\gamma_{ton,n} = 1\}$  is defined in Eq. (9) for *Method Chord*  
 44 and in Eq. (10) for *Method Chroma*.

#### 45 b. Transient layer

$$\begin{aligned} p(\gamma_{tran,m} = 0 | \sigma_{tran,m}, \sigma, x_{tran|ton}) &= \frac{1}{1 + \tau_{tran,m}} \\ p(\gamma_{tran,m} = 1 | \sigma_{tran,m}, \sigma, x_{tran|ton}) &= \frac{\tau_{tran,m}}{1 + \tau_{tran,m}}, \end{aligned} \quad (A3)$$

46 with

$$\begin{aligned} \tau_{tran,m} &= \sqrt{\frac{\sigma^2}{\sigma^2 + \sigma_{tran,m}}} \exp\left(\frac{x_{tran|ton}^2 \sigma_{tran,m}}{2\sigma^2(\sigma^2 + \sigma_{tran,m})}\right) \\ &\times p\left(\frac{\gamma_{tran,m} = 1 | \gamma_{tran,-m}}{\gamma_{tran,m} = 0 | \gamma_{tran,-m}}\right). \end{aligned} \quad (A4)$$

47 The ratio  $p\left(\frac{\gamma_{tran,m}=1|\gamma_{tran,-m}}{\gamma_{tran,m}=0|\gamma_{tran,-m}}\right)$  is  $\frac{P_\Delta\{\gamma_{tran,m}=1\}}{1-P_\Delta\{\gamma_{tran,m}=1\}}$ ,  
 48 where  $P_\Delta\{\gamma_{tran,m} = 1\}$  is defined in Eq. (13).

### 49 2. Coefficients

$$\begin{aligned} p(\alpha_n | \gamma_{ton,n}, \sigma_{ton,n}, \sigma, x_{ton|tran}) &= (1 - \gamma_{ton,n}) \delta_0(\alpha_n) \\ &+ \gamma_{ton,n} \mathcal{N}\left(\alpha_n \left| \frac{u_n^T r \sigma_{ton,n}^2}{\sigma_{ton,n}^2 + \sigma^2}, \frac{\sigma^2 \sigma_{ton,n}^2}{\sigma^2 + \sigma_{ton,n}^2} \right.\right) \end{aligned} \quad (A5)$$

$$\begin{aligned} p(\beta_m | \gamma_{tran,m}, \sigma_{tran,m}, \sigma, x_{tran|ton}) &= (1 - \gamma_{tran,m}) \delta_0(\beta_m) \\ &+ \gamma_{tran,m} \mathcal{N}\left(\beta_m \left| \frac{v_m^T r \sigma_{tran,m}^2}{\sigma_{tran,m}^2 + \sigma^2}, \frac{\sigma^2 \sigma_{tran,m}^2}{\sigma^2 + \sigma_{tran,m}^2} \right.\right) \end{aligned} \quad (A6)$$

$$\begin{aligned} p(\sigma_{ton,n}^2 | \gamma_{ton,n}, f_{ton,n}) &= (1 - \gamma_{ton,n}) \mathcal{IG}(\sigma_{ton,n} | 1, f_{ton,n}) \\ &+ \gamma_{ton,n} \mathcal{IG}\left(\sigma_{ton,n} \left| 3/2, \frac{\alpha_{ton,n}^2}{2} + f_{ton,n} \right.\right) \end{aligned} \quad (A7)$$

$$\begin{aligned} p(\sigma_{tran,m}^2 | \gamma_{tran,m}, f_{tran,m}) &= (1 - \gamma_{tran,m}) \mathcal{IG}(\sigma_{tran,m} | 1, f_{tran,m}) \\ &+ \gamma_{tran,m} \mathcal{IG}\left(\sigma_{tran,m} \left| 3/2, \frac{\alpha_{tran,m}^2}{2} + f_{tran,m} \right.\right) \end{aligned} \quad (A8)$$

#### 52 b. Scale parameters of frequency profiles

$$p(\lambda_{ton} | \sigma_{ton}) = \gamma \left( \lambda_{ton} \left| N, \sum_n \frac{1}{1 + \frac{q-1}{\ell_{ton}/3} \sigma_{ton,n}} \right. \right) \quad (A9)$$

$$p(\lambda_{tran} | \sigma_{tran}) = \gamma \left( \lambda_{tran} \left| N, \sum_m \frac{1}{1 + \frac{q-1}{\ell_{tran}/3} \sigma_{tran,m}} \right. \right) \quad (A10)$$

#### 53 c. Variance of the noise

$$p(\sigma^2 | x_{ton}, x_{tran}, x) = \mathcal{IG}\left(\sigma^2 \left| \frac{N}{2}, \frac{\|x - V\alpha - U\beta\|^2}{2} \right.\right) \quad (A11)$$

- 54 1. See e.g. <https://sites.google.com/site/nips10sparsews/>.
- 55 2. Here  $\gamma$  is used to refer indifferently to  $\gamma_{ton,n}$  or  $\gamma_{tran,m}$ .
- 56 3.  $a \pmod b$  denotes the mathematical operator *modulo*, the
- 57 remainder when  $a$  is divided by  $b$ .
- 58 4. In general, the harmonics of harmonic music sounds do not
- 59 have frequencies that are *exact* multiples of its fundamental
- 60 frequency, but are nearly harmonically related.
- 61 5. We limit the number of considered harmonics to 6 because
- 62 many of the higher harmonics, which are theoretically whole
- 63 number multiples of the fundamental frequency, are far from
- 64 any note of the Western chromatic scale. This is especially
- 65 true for the 7th and the 11th harmonics.
- 66 6. As stressed in (Févotte *et al.*, 2008), colored or non-Gaussian
- 67 noise could also be considered as well and embedded into the
- 68 same framework, but this would lead to an increase in the
- 69 computational efficiency of the algorithm because of some
- 70 matrix inversion, which is out of the scope of this paper.
- 71 7. Neighboring chords considered here are harmonically close
- 72 triads: parallel Major/ minor (EM being confused with Em),
- 73 relative (Am being confused with CM), dominant (CM being
- 74 confused with GM) or subdominant (CM being confused
- 75 with FM).

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