Estimating Arbitrary Measures on the Torus from Moments

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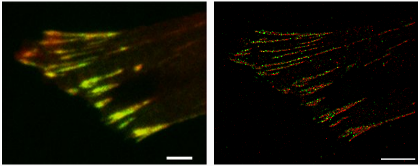
University of Osnabrück.

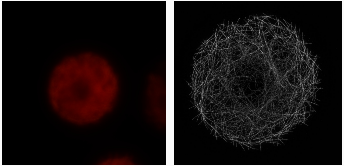
Recovering Algebraic Structures in Imaging & Signal Processing, SIAM 2022, 23.03.22

Motivation

Super-resolution. Estimate a signal from coarse measurements

- Recover pointwise sources or more complex structures





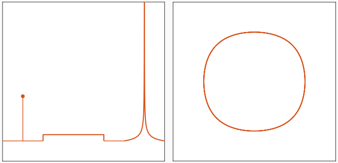
- Ubiquitous problem in imaging and data science, *e.g.* fluorescence microscopy, X-ray crystallography, mixture model estimation.

[0] images from the cell image library (http://cellimagelibrary.org/)

Data model

- **Borel measures**
  $d \in \mathbb{N} \setminus \{0\}$, $\mathbb{T} \overset{\text{def.}}{=} \mathbb{R}/\mathbb{Z}$ Torus,

$$\mu \in \mathcal{M}(\mathbb{T}^d)$$



Singular measures μ

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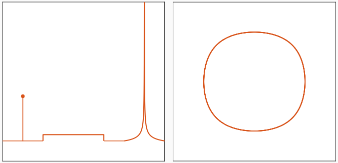
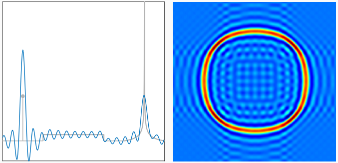


Singular measures μ

- **Trigonometric moments**
  $k \in \mathbb{Z}^d$,

$$\hat{\mu}(k) \overset{\text{def.}}{=} \int_{\mathbb{T}^d} e^{-2\imath\pi\langle k, x\rangle} \mathrm{d}\mu(x)$$



Fourier partial sum $S_n\mu$ $(n = 20)$

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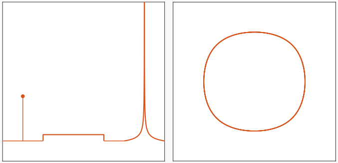

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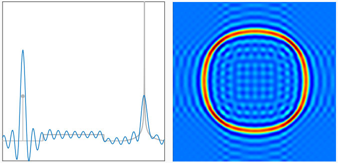
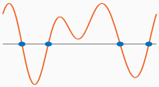


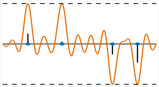
Fourier partial sum $S_n\mu$ $(n = 20)$

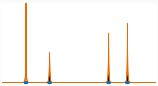
How "well" can we recover μ from $\{\hat{\mu}(k)\}$, $k \in \{-n, \ldots, n\}^d$?

Previous works

- For discrete measures,
  - Prony's method[1]; ESPRIT[2] , MUSIC[3] , matrix pencils[4] .
  - Variational methods, *e.g.* TV-minimization[5] .
- For general measures,
  - FRI approaches[6] .
  - Christoffel functions[7] .


Prony


Variational


Approximation

- Our work shares similarities with [Mhaskar 2019], use another metric on measures

[1] *R. de Prony, 1795,* Essai Expérimental et Analytique: Sur les Lois de la Dilatabilité des Fluides Élastiques ...

[2] *Roy and Kailath, 1989,* ESPRIT-Estimation of Signal Parameters via Rotational Invariance Techniques

[3] *Schmidt, 1986,* Multiple Emitter Location and Signal Parameter Estimation

[4] *Hua and Sarkar, 1989,* Generalized Pencil-of-Function Method for Extracting Poles of an EM System from its Transient Response

[5] *Candès and Fernandez-Granda, 2014,* Towards a Mathematical Theory of Super-Resolution

[6] *Pan, Blu, and Dragotti, 2014,* Sampling Curves With Finite Rate of Innovation

[7] *Pauwels, Putinar, and Lasserre, 2020,* Data Analysis From Empirical Moments and the Christoffel Function

[8] *Mhaskar, 2019,* Super-Resolution Meets Machine Learning: Approximation of Measures

Overview

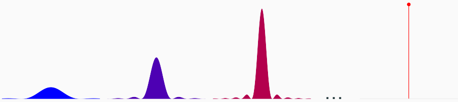
1. **Preliminaries**
2. **Polynomial Approximations in Wasserstein**-1
    - Lower bound for best approximation in the worst case
    - Upper bound for $F_n * \mu$
    - Upper bound for $J_n * \mu$
    - Sharpness
3. **Polynomial Interpolation**
    - Pointwise convergence
    - The discrete case
4. **Numerical illustrations**
5. **Conclusion**

Preliminaries

Wasserstein-1 distance

- The quality of an approximation depends on the metric over $\mathcal{M}(\mathbb{T}^d)$[1]
- Examples include f-divergences, MMD, and Wasserstein distances
- Wasserstein distances metrize the weak* topology (on compact sets), *i.e.*

$$\mu_n \rightharpoonup \mu \iff \mathcal{W}_p(\mu_n, \mu) \to 0$$



- Wasserstein-1 further admits the practical (dual) formulation

$$\mathcal{W}_1(\mu, \nu) = \sup_{f \in \mathscr{C}(\mathbb{T}^d), \mathrm{Lip}(f) \leqslant 1} \int f \mathrm{d}(\mu - \nu)$$

$\rightarrow$ requires no positivity, only $\mu(\mathbb{T}^d) = \nu(\mathbb{T}^d)$

$\rightarrow$ $\mathrm{Lip}(f) \leqslant 1$ means $|f(x) - f(y)| \leqslant \min_{k \in \mathbb{Z}^d} \|x - y + k\|_1, \forall x, y$

[1] *Mhaskar, 2019,* Super-Resolution Meets Machine Learning: Approximation of Measures

Moment Matrix

Definition (Moment matrix). Given $\{\hat{\mu}(k)\}$, $k \in \{-n, \dots, n\}^d$, we define the moment matrix

$$T_n \stackrel{\text{def.}}{=} \left[\hat{\mu}(k-l)\right]_{k,l \in \{0,\dots,n\}^d}.$$

- Singular value decomposition

$$T_n = \sum_{j=1}^{r} \sigma_j u_j^{(n)} v_j^{(n)*}$$

- When $\mu = \sum_{j=1}^r \lambda_j \delta_{x_j}$, T_n admits the Vandermonde decomposition

$$T_n = A \Lambda A^*$$

where $A = \left[e^{-2i\pi\langle k, x_j\rangle}\right]_{k \in \{0,\dots,n\}^d, j \in [\![1,r]\!]}$ and $\Lambda = \mathrm{Diag}(\lambda)$.

Polynomial Approximations

Best Polynomial Approximation

- Assume μ is of finite total variation, $\|\mu\|_{TV} = 1$
- We make no further assumptions

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Theorem (Worst-case bound). For every $d, n \in \mathbb{N}$, for every $\mu \in \mathcal{M}(\mathbb{T}^d)$, there exists a polynomial of best approximation in the Wasserstein-1 distance. Moreover, it holds that

$$\sup_{\mu \in \mathcal{M}} \min_{\deg(p) \leqslant n} \mathcal{W}_1(p, \mu) \geqslant \frac{1}{4(n+1)}.$$

Idea of the proof

$$\begin{aligned}
\sup_{\mu} \min_{p} \mathcal{W}_1(p, \mu) &\geqslant \min_{p} \mathcal{W}_1(p, \delta_0) \\
&= \min_{p} \sup_{\mathrm{Lip}(f) \leqslant 1} \|f - \check{p} * f\|_\infty \qquad (\check{p}(x) = p(-x)) \\
&\geqslant \sup_{\mathrm{Lip}(f) \leqslant 1} \min_{p} \|f - p\|_\infty
\end{aligned}$$

$\rightarrow$ worst-case error for best polynomial approximation of Lipschitz functions

$\rightarrow$ generalize a univariate argument of [Fisher 1977] to the multivariate case

[1] *Fisher, 1977,* Best Approximation by Polynomials

Fejér approximation

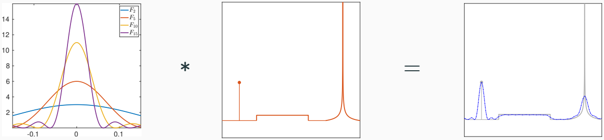
- Consider the Fejér kernel F_n

$$F_n(x) \stackrel{\text{def.}}{=} \frac{1}{(n+1)^d} \prod_{i=1}^{d} \frac{\sin^2((n+1)\pi x_i)}{\sin^2(\pi x_i)}$$

- Consider the polynomial $p_n \stackrel{\text{def.}}{=} F_n * \mu$
  - alternatively

$$p_n(x) = \frac{1}{(n+1)^d} e_n(x)^* T_n e_n(x) = \frac{1}{(n+1)^d} \sum \sigma_j u_j^{(n)}(x) v_j^{(n)}(x)^*$$

  - computed from $\hat{\mu}(k)$ using fast Fourier transforms



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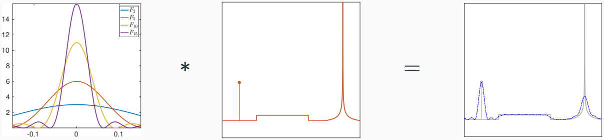


Theorem (Weak* convergence). We have that $p_n \rightharpoonup \mu$. More precisely,

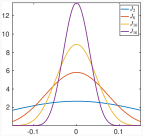
$$\mathcal{W}_1(p_n, \mu) \leqslant \frac{d}{\pi^2} \frac{\log(n+1) + 3}{n}$$

Jackson approximation

- Consider the Jackson kernel J_n

$$J_{2m}(x) \stackrel{\text{def.}}{=} \alpha(m) \prod_{i=1}^{d} \frac{\sin^4((m+1)\pi x_i)}{\sin^4(\pi x_i)}$$

- Consider the polynomial $q_n(x) \stackrel{\text{def.}}{=} J_n * \mu$
  - also computed with FFT



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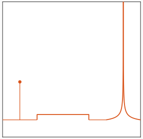

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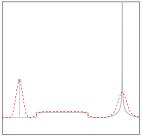

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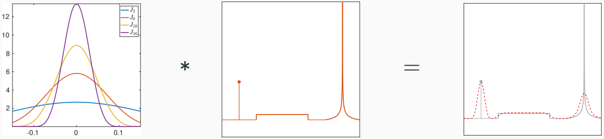

Theorem. (Weak* convergence) We have that $q_n \rightharpoonup \mu$. More precisely,

$$\mathcal{W}_1(q_n, \mu) \leqslant \frac{3}{2} \frac{d}{n+2}$$

Sharpness

- For the worst-case bound, sharpness is revealed in the univariate case

Lemma. For $\mu, \nu \in \mathcal{M}(\mathbb{T})$, we have

$$\mathcal{W}_1(\mu,\nu) = \int_{\mathbb{T}} |\mathcal{B}_1 * \mu(t) - \mathcal{B}_1 * \nu(t)| \mathrm{d}t, \quad \text{where} \quad \mathcal{B}_1(t) \stackrel{\text{def.}}{=} \sum_{k=1}^{\infty} \frac{\sin 2\pi k t}{\pi k} = \frac{1}{2} - t$$

- Periodic analog of the cumulative distribution formulation of $\mathcal{W}_1$ on $\mathbb{R}$
- If μ is absolutely continuous, leads to unicity of the best approximation
- If $\mu = \delta_0$, then $\mathcal{W}_1(p^*, \delta_0) = \frac{1}{4}(n+1)^{-1}$, matching our lower bound

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- For the Fejér approximation

Theorem (Saturation). For every measure $\mu \in \mathcal{M}(\mathbb{T}^d)$ not being the Lebesgue measure, there exists a constant c such that

$$\mathcal{W}_1(p_n, \mu) \geqslant \frac{c}{n+1}$$

- For instance $\mathrm{d}\mu/\mathrm{d}x = 1 + \cos(2\pi x) := w(x)$ yields $\mathcal{W}_1(p_n, w) \geqslant (4\pi)^{-1}(n+1)^{-1}$
- However, $\mathcal{W}_1(p_n, \delta_0) \geqslant \frac{d}{\pi^2}\left(\frac{\log(n+2)}{n+1} + \frac{1}{n+3}\right)$

Polynomial Interpolation

Interpolating Polynomial

- The singular value decomposition: $T_n = \sum_{j=1}^{r} \sigma_j u_j^{(n)} v_j^{(n)*}$ allows to define

$$p_{1,n}(x) = \frac{1}{(n+1)^d} \sum_{j=1}^{r} |u_j^{(n)}(x)|^2$$

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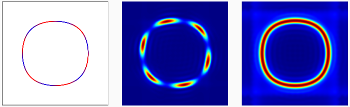
- Let $V \overset{\text{def.}}{=} \overline{\operatorname{Supp}\mu}^Z$ be the Zariski closure of $\operatorname{Supp}\mu$, and $V(\operatorname{Ker} T_n)$ be the set of common roots of all polynomials in $\operatorname{Ker} T_n$.

Theorem. We have $0 \leqslant p_{1,n} \leqslant 1$. If $V(\operatorname{Ker} T_n) = V$, then $p_{1,n}(x) = 1$ iff $x \in V$.

μ $\quad$ $F_{20} * \mu$ $\quad$ $p_{1,20}(\mu)$



$\rightarrow$ $V(\operatorname{Ker} T_n) = V$ always holds for sufficiently large n if μ discrete[1] or $\mu \in \mathcal{M}_+$[2]

$\rightarrow$ generalizes a result of [Ongie and Jacob 2016] to varieties of arbitrary dimension

1 *Kunis et al., 2016,* A Multivariate Generalization of Prony's Method

2 *Wageringel, 2022,* Truncated moment problems on positive-dimensional algebraic varieties

3 *Ongie and Jacob, 2016,* Off-the-grid recovery of piecewise constant images from few Fourier samples

Pointwise convergence

- We assume that $\overline{\operatorname{Supp}\mu}^Z \neq \mathbb{T}^d$

Theorem. Let $y \in \mathbb{T}^d \setminus \overline{\operatorname{Supp}\mu}^Z$, and let g be a polynomial of max-degree m such that $g(y) \neq 0$ and g vanishes on $\operatorname{Supp}\mu$. Then, for all $n \geqslant m$,

$$p_{1,n+m}(y) \leqslant \frac{\|g\|_{L^2}^2}{|g(y)|} \frac{m(4m+2)^d}{n+1} + \frac{dm}{n+m+1}$$

- In combination with the interpolation property, this proves pointwise convergence to the characteristic function of the support, with rate $O(n^{-1})$.

The Discrete Case

- If $\mu = \sum_{j=1}^{r} \lambda_j \delta_{x_j}$, stronger results are derived with the help of the Vandermonde decomposition of T_n

Theorem (Pointwise convergence). Let $x \neq x_j$ for all j. If $n+1 > \frac{4d}{\min_{j \neq l} \|x_j - x_l\|_\infty}$, then

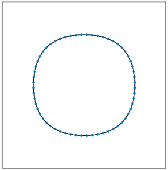
$$p_{1,n}(x) \leqslant \frac{1}{3(n+1)^2} \frac{\lambda_{\max}}{\lambda_{\min}} \sum \frac{1}{\|x - x_j\|_\infty^2}$$

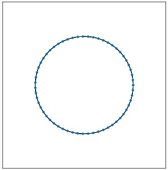
Theorem (Weak* convergence). We have

$$\frac{p_{1,n}}{\|p_{1,n}\|_{L^1}} \rightharpoonup \frac{1}{r} \sum_{j=1}^{r} \delta_{x_j}$$

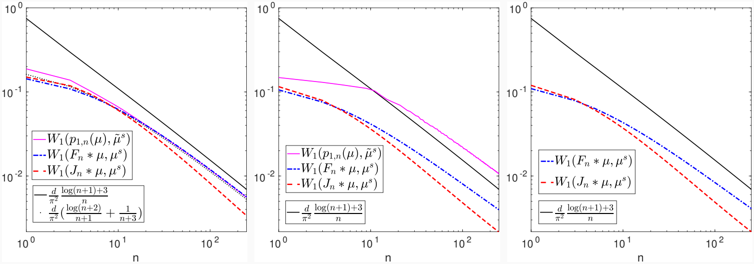
Numerical Illustrations

- We consider three synthetic examples
  - discrete, $r = 15$ points, λ random moments analytical
  - algebraic curve, $r = 3000$ points, λ uniform numerical integration
  - circle, $r = 3000$ points, λ uniform analytical





- We compute the semidiscrete optimal transport between the discretized approximation μ^r and the density p_n



Conclusion

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Summary.

- New insights on Waaserstein-1 approximation of measures
- Computationally efficient polynomial approximations
- Pointwise convergence towards the characteristic function of the support

Outlook.

- Extension to the noisy regime

Preprint available: arXiv.2203.10531

Thank you for your attention!

References

- Candès, E.J. and C. Fernandez-Granda (2014). "Towards a Mathematical Theory of Super-Resolution". In: *Comm. Pure Appl. Math.* 67.6, pp. 906–956.
- Fisher, Stephen D. (1977). "Best Approximation by Polynomials". In: *J. Approx. Th.* 21.1, pp. 43–59.
- Hua, Y. and T.K. Sarkar (1989). "Generalized Pencil-of-Function Method for Extracting Poles of an EM System from its Transient Response". In: *IEEE Trans. Antennas Propagation* 37.2.
- Kunis, S. et al. (2016). "A Multivariate Generalization of Prony's Method". In: *Linear Algebra Appl.* 490, pp. 31–47.
- Mhaskar, H. N. (2019). "Super-Resolution Meets Machine Learning: Approximation of Measures". In: *J. Fourier Anal. Appl.* 25.6, pp. 3104–3122.
- Ongie, G. and M. Jacob (2016). "Off-the-grid recovery of piecewise constant images from few Fourier samples". In: *SIAM J. Imaging Sci.* 9.3, pp. 1004–1041.
- Pan, H., T. Blu, and P.L. Dragotti (2014). "Sampling Curves With Finite Rate of Innovation". In: *IEEE Trans. Signal Process.* 62.2, pp. 458–471.
- Pauwels, E., M. Putinar, and J.B. Lasserre (2020). "Data Analysis From Empirical Moments and the Christoffel Function". In: *F. Comp. Math.*
- R. de Prony, G. (1795). "Essai Expérimental et Analytique: Sur les Lois de la Dilatabilité des Fluides Élastiques ...". In: *Journal de l'École Polytechnique Floréal et Plairial* 1.cahier 22, pp. 24–76.

Roy, R. and T. Kailath (1989). "ESPRIT-Estimation of Signal Parameters via Rotational Invariance Techniques". In: *IEEE Trans. Acoustics Speech Signal Process.* 37.7, pp. 984–995.

Schmidt, R. (1986). "Multiple Emitter Location and Signal Parameter Estimation". In: *IEEE Trans. Antennas Propagation* 34.3, pp. 276–280.

Wageringel, M. (2022). "Truncated moment problems on positive-dimensional algebraic varieties".