EPFL

COM-500 Throughput optimization for 5G networks

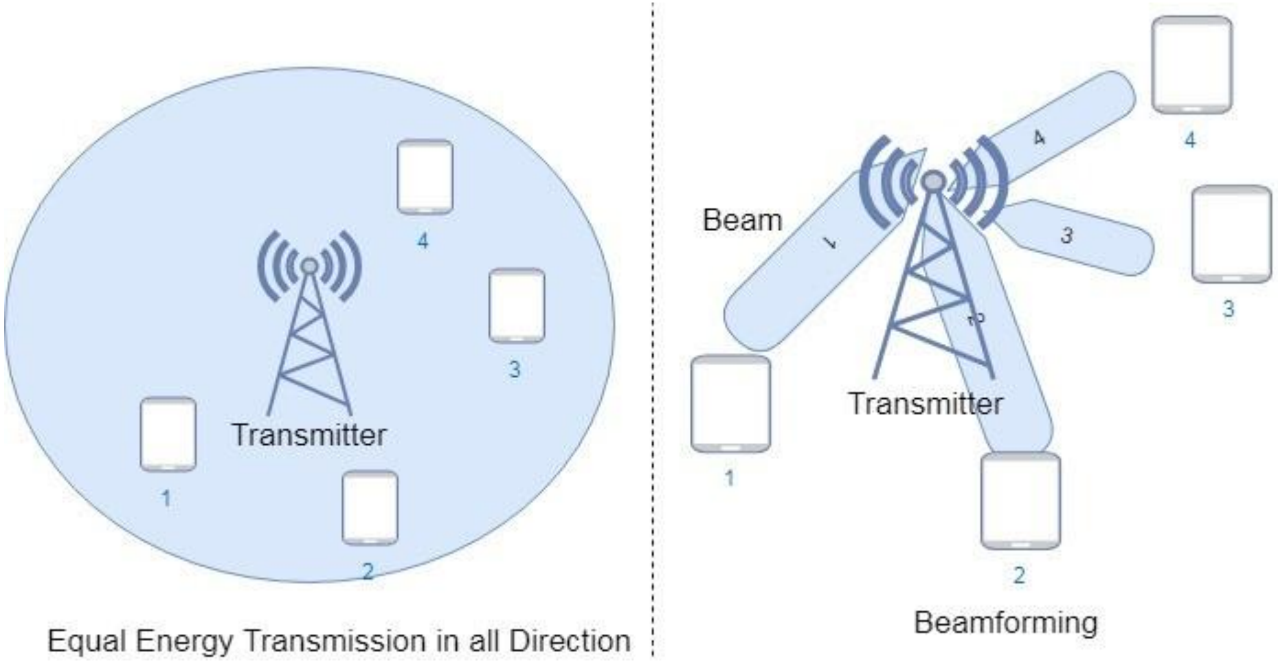
Saged Bounekhel
Franck Khayat
Salim Najib

June 2023

Introduction - Beamforming in 5G

Saged Bounekhel, Franck Khayat, Salim Najib

Motivation : Short Transmission Distance, Increased Throughput and Energy Efficiency



Introduction - Beamforming in 5G

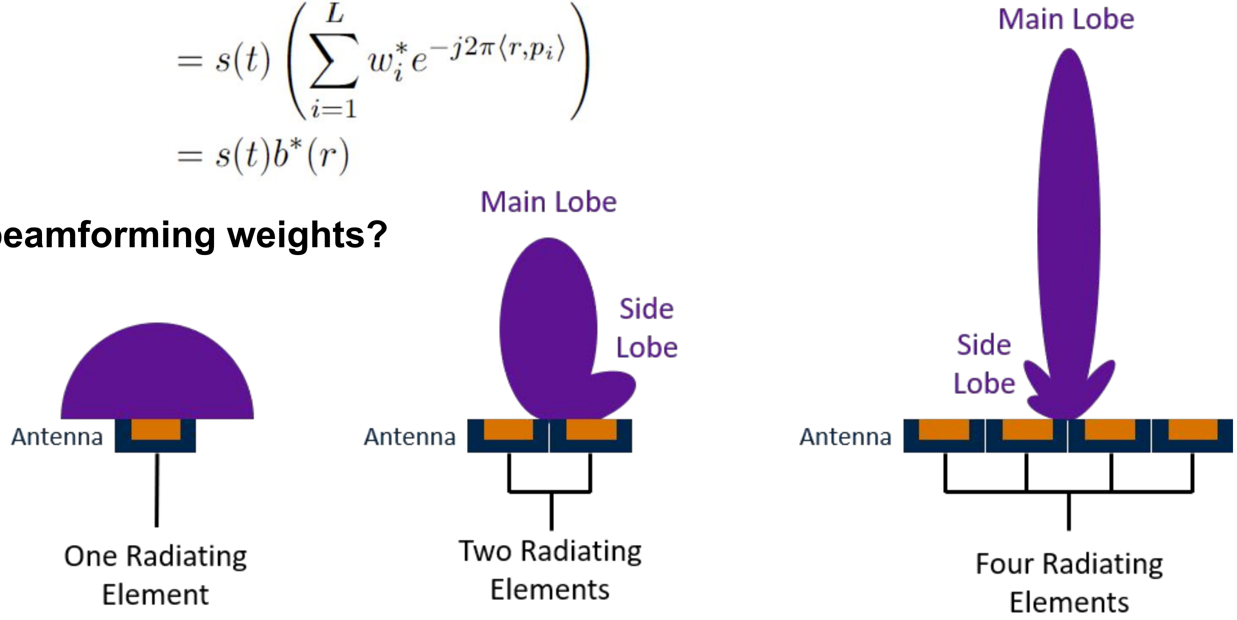
Saged Bounekhel, Franck Khayat, Salim Najib

Motivation : Short Transmission Distance, Increased Throughput and Energy Efficiency

Noiseless Signal :

$$
\begin{aligned}
y(t,r) &= s(t)\left(\sum_{i=1}^{L} \gamma_i e^{j\phi_i} e^{-j2\pi\langle r, p_i\rangle}\right) \\
&= s(t)\left(\sum_{i=1}^{L} w_i^* e^{-j2\pi\langle r, p_i\rangle}\right) \\
&= s(t) b^*(r)
\end{aligned}
$$

How to design beamforming weights?



Matched beamforming

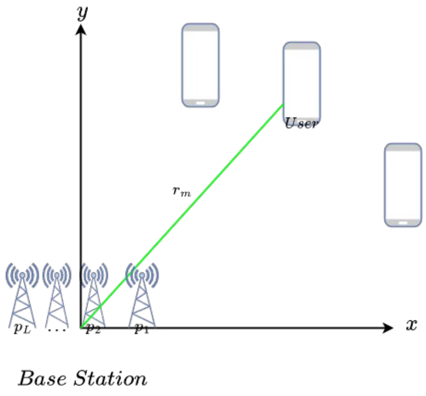
Array Beam Shape : $b(r) = \sum_{i=1}^{L} w_i e^{j2\pi\langle r, p_i\rangle}$

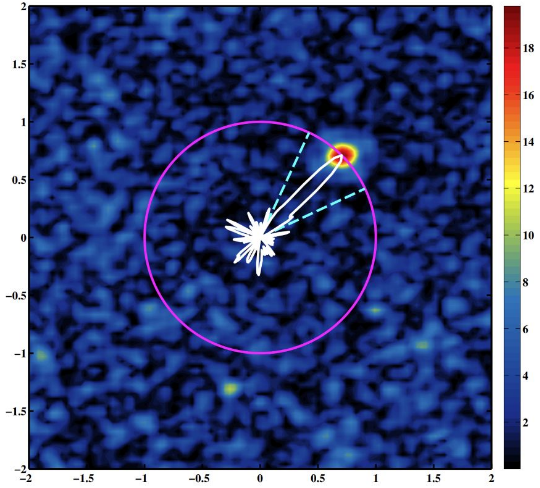
Emitted Signal : $x_i(t) = b_i s(t) = \gamma_i e^{j\phi_i} s(t), \ \forall i = 1, 2, ..., L.$

Noiseless Signal : $$\begin{aligned} y(t,r) &= s(t)\left(\sum_{i=1}^{L} \gamma_i e^{j\phi_i} e^{-j2\pi\langle r, p_i\rangle}\right) \\ &= s(t)\left(\sum_{i=1}^{L} w_i^* e^{-j2\pi\langle r, p_i\rangle}\right) \\ &= s(t) b^*(r) \end{aligned}$$

Matched weights : $w_i = e^{-j2\pi\langle r_0, p_i\rangle}$

r_0 being the steering direction estimated by MUSIC.





Saged Bounekhel, Franck Khayat, Salim Najib

Flexibeam

Notion of a continuum of antennas in $\mathbb{R}^2$

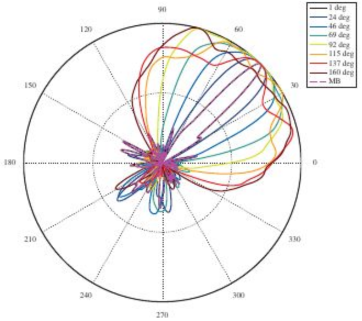
More flexible beam-shape

Sensor function : $x(t,p) = \int_{\mathbb{S}^1} s(t) e^{-j2\pi\langle r,p\rangle} dr \in \mathbb{C}$

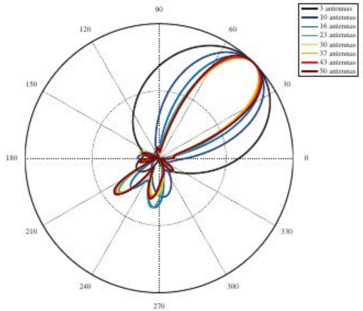
Noiseless transmitted signal :

$$\begin{aligned} z(t) &= \langle x(t,.), w\rangle_{\mathcal{L}^2(\mathbb{R}^2)} \\ &= \int_{\mathbb{R}^2} x(t,p) w^*(p) dp \\ &= \int_{\mathbb{R}^2} dp\ w^*(p) \int_{\mathbb{S}^1} s(t) e^{-j2\pi\langle r,p\rangle} dr \\ &= \int_{\mathbb{S}^1} dr\ s(t) \underbrace{\int_{\mathbb{R}^2} dp\ w^*(p) e^{-j2\pi\langle r,p\rangle}}_{=b^*(r)} \\ &= s(t) \int_{\mathbb{S}^1} b^*(r) dr \end{aligned}$$

Observed signal : $y(t,r) = s(t) b^*(r)$



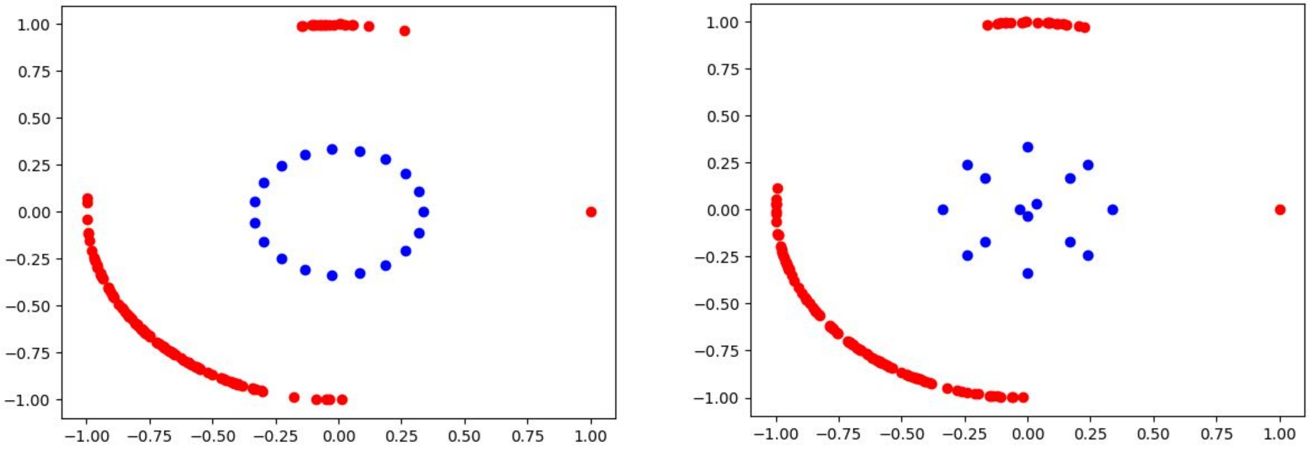
(a) Filtering a range of directions with flexibeam for various angles and 96 antennas.



(b) Filtering a range of directions with flexibeam for $\Theta = 40^\circ$ with varying number of antennas.

Saged Bounekhel, Franck Khayat, Salim Najib

Throughput estimations - Setup

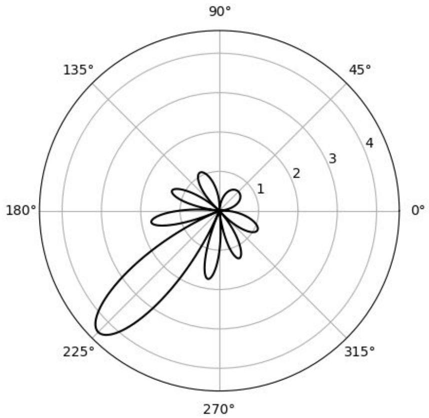


Antenna and transmitter positions, data 1 (left) and 2 (right). Antennas are denoted as blue dots and user positions as red dots.

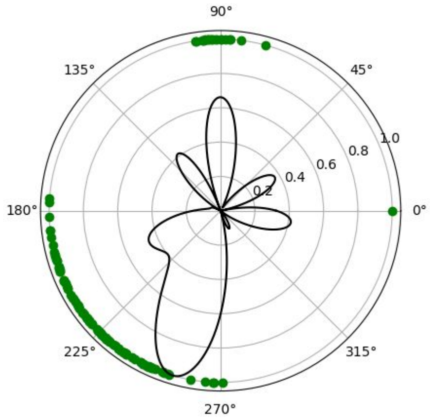
$$\mathrm{Bitrate}(r) = B \log_2 \left(1 + C_0 \frac{|b(r)|^2}{\sigma^2} \right)$$

With B being the bandwidth, C_0 a scaling constant and σ the white noise variance

Throughput estimations



Beamshape generated by matched beamforming
Dataset 1



Beamshape evaluated by flexibeam
Dataset 1

Green dots denote user positions

	Dataset 1	Dataset 2
Matched beamforming	7.27 Mb/s	6.87 Mb/s
Flexibeam	8.77 Mb/s	10.86 Mb/s

Saged Bounekhel, Franck Khayat, Salim Najib

Collaborative beamforming with flexibeam

Saged Bounekhel, Franck Khayat, Salim Najib

Received signal at a station: $v_s(t) = A_s s(t) + n(t) \in C^L$

with steering matrix: $A_s \in \mathbb{C}^{L \times Q}$

Autocorrelation of received signal: $R_{v_s} = \mathbb{E}\left(v_s(t)v_s(t)^H\right) = A_s \Sigma A_s^H + \Sigma_n$

Cross-correlation: $R_{y_s} := R_s = \mathbb{E}\left(y_s(t)y_s(t)^*\right) = \sum_{q=1}^{Q} \sigma_q^2 |w_s^H a_{s,q}|^2 + \sigma_n^2 ||w_s||_2^2$

Cross-correlation is a sufficient statistic of the users' density!

LASSO Problem Formulation for user density estimation $\hat{f}$

$$\arg\min_{\hat{f}, \hat{\sigma}_n^2} \left|\left| \hat{R} - W^H \left(\mathrm{Adiag}\left(\hat{f}\right) A^H - \hat{\sigma}_n^2 I_{SL} \right) W \right|\right|_F^2 + \lambda ||\hat{f}||_1$$

Implemented using PYCSOU

Collaborative beamforming with flexibeam

Received signal at a station: $v_s(t) = A_s s(t) + n(t) \in C^L$

with steering matrix: $A_s \in \mathbb{C}^{L \times Q}$

Autocorrelation of received signal: $R_{v_s} = \mathbb{E}\left(v_s(t) v_s(t)^H\right) = A_s \Sigma A_s^H + \Sigma_n$

Cross-correlation: $R_{s_1,s_2} = \mathbb{E}\left(y_{s_1}(t) y_{s_2}(t)^*\right) = \sum_{q=1}^{Q} \sigma_q^2 w_{s_1}^H a_{s_1,q} w_{s_2}^H a_{s_2,q} \in \mathbb{C}$

Cross-correlation is a sufficient statistic of the users' density!

LASSO Problem Formulation for user density estimation $\hat{f}$

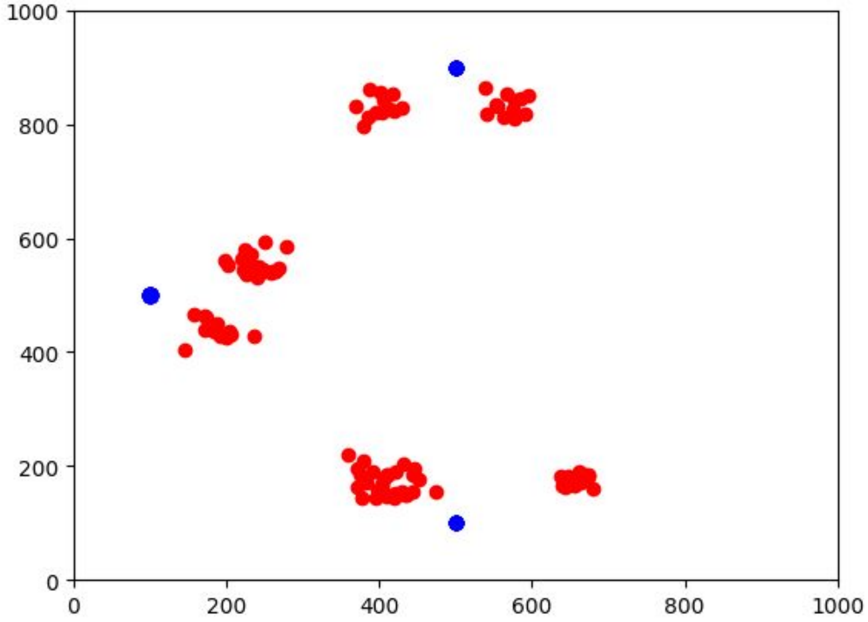
$$\arg\min_{\hat{f}, \hat{\sigma}_n^2} \left|\left| \hat{R} - W^H \left(\mathrm{Adiag}\left(\hat{f}\right) A^H - \hat{\sigma}_n^2 I_{SL} \right) W \right|\right|_F^2 + \lambda ||\hat{f}||_1$$

Implemented using PYCSOU

Saged Bounekhel, Franck Khayat, Salim Najib

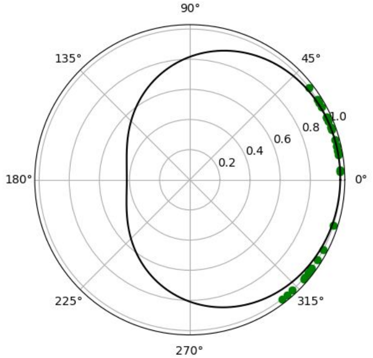
Testing collaborative beamforming with flexibeam

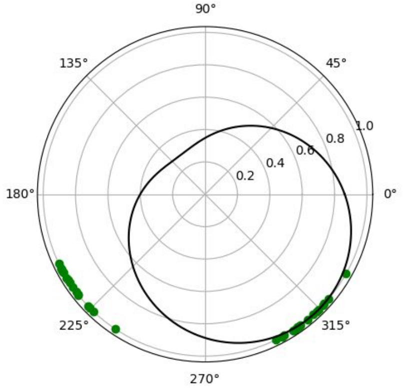
Saged Bounekhel, Franck Khayat, Salim Najib



Test setup: 3 stations of 20 antennas, 100 users in 6 GMMs - 3000 iterations of PGD

Beamshapes of leftmost then topmost stations

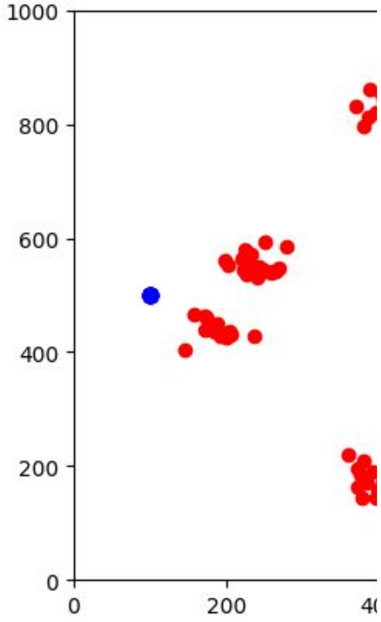


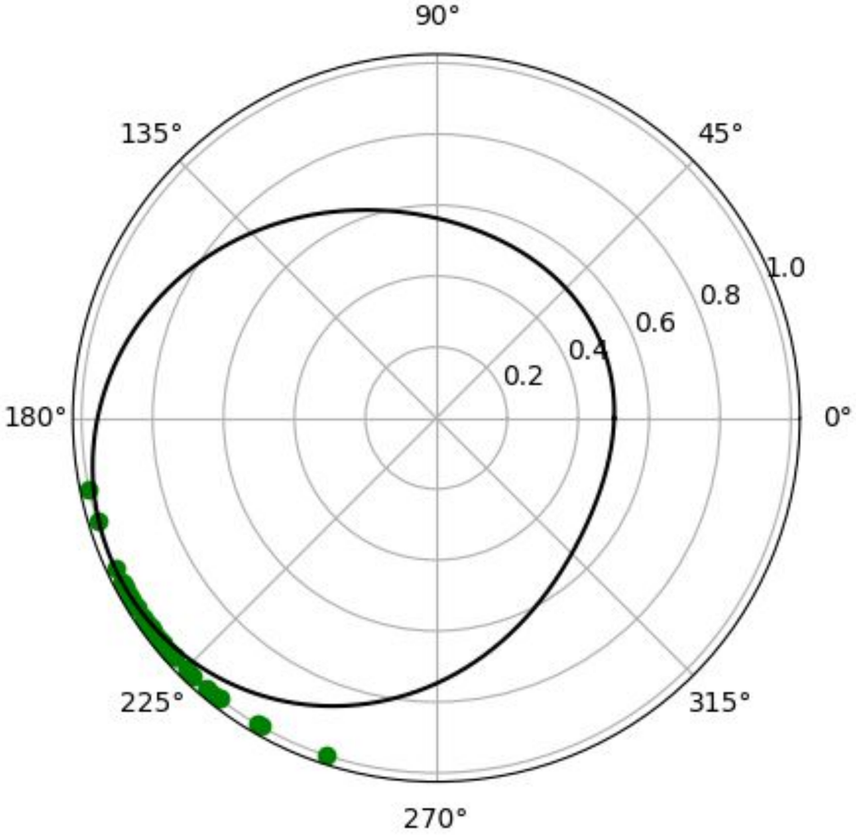


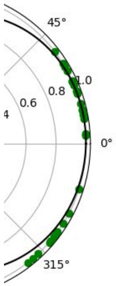
Testing collaborative beamforming with flexibeam

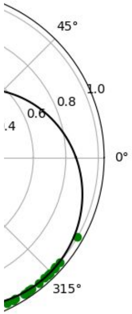
Saged Bounekhel, Franck Khayat, Salim Najib

Beam Shapes of leftmost then
ions









Test setup: 3 statior
in 6 GMMs - 3

Conclusions and further works

Saged Bounekhel, Franck Khayat, Salim Najib

- Flexibeam induces beamshapes with multiple side-lobes, targeting multiple user clusters at once rather than selecting a single one.

- As expected from the theory, flexibeam leads to higher throughput than matched beamforming.

- Collaborative beamforming is theoretically promising, but is numerically expensive and slow. Optimization algorithms better suited for penalized LASSO problems may improve speed and accuracy.

Questions?

References

[1] P. Hurley and M. Simeoni, “Beamforming towards regions of interest for multi-site mobile networks,” A. Lapidoth and S. M. Moser, Eds. Zurich: ETH Zurich, 2016, Conference Paper.
[2] ——, “Flexibeam: Analytic spatial filtering by beamforming,” in 2016 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2016, pp. 2877–2880.
[3] O. Æçal, P. Hurley, G. Cherubini, and S. Kazemi, “Collaborative randomized beamforming for phased array radio interferometers,” in 2015 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2015, pp. 5654–5658.
[4] A.-J. Veen and S. Wijnholds, Signal Processing Tools for Radio Astronomy, 05 2013, pp. 421–463.
[5] H. Krim and M. Viberg, “Two decades of array signal processing research: the parametric approach,” IEEE Signal Processing Magazine, vol. 13, no. 4, pp. 67–94, 1996.
[6] C. E. Shannon, “A mathematical theory of communication,” Bell Syst. Tech. J., vol. 27, pp. 623–656, 19
[7] “Pycsou github repository,” https://github.com/matthieumeo/pycsou.
[8] A. Jarret, J. Fageot, and M. Simeoni, “A fast and scalable polyatomic frank-wolfe algorithm for the LASSO,” IEEE Signal Processing Letters, vol. 29, pp. 637–641, 2022. [Online]. Available: https://doi.org/10.1109%2Flsp.2022.3149377