Tailoring Differentially Private Bayesian Inference to Distance Between Distributions

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Objectives

1. Design a differentially private Bayesian inference mechanism.
2. Improve accuracy by calibrating noise to the sensitivity of a metric over distributions (e.g. Hellinger distance ($\mathcal{H}$), f-divergences, etc…).

Bayesian inference (BI), the Beta-Binomial model example:

- Prior on θ : $\mathbb{P}_\theta = \mathbf{beta}(\alpha, \beta), \alpha, \beta \in \mathbb{R}^+$, observed data $\mathbf{x} = (x_1, \dots, x_n) \in \{0,1\}^n, n \in \mathbb{N}$.
- Likelihood function: $\mathbb{L}_{\theta|\mathbf{x}} = \theta^{\Delta\alpha}(1-\theta)^{n-\Delta\alpha}$, where $\Delta\alpha = \sum_{i=1}^{n} x_i$.
- Posterior on θ: $\mathbf{BI}(\mathbf{x}) \equiv \mathbb{P}_{\theta|\mathbf{x}} = \mathbf{beta}(\alpha + \Delta\alpha, \beta + n - \Delta\alpha) \propto \mathbb{L}_{\theta|\mathbf{x}} \cdot \mathbb{P}_\theta$.

Differentially private Bayesian inference and motivations

1. Baseline approach:
   - Release $\mathbf{beta}(\alpha + \lfloor\widetilde{\Delta\alpha}\rfloor_0^n, \beta + n - \lfloor\widetilde{\Delta\alpha}\rfloor_0^n)$,
   - $\widetilde{\Delta\alpha} \sim \mathcal{L}(\Delta\alpha, \frac{S}{\epsilon})$
   - $[[\ S \propto ||\cdot||_1\ ]]$.
   - Measure accuracy with a metric over distributions, e.g. $\mathcal{H}$.

   But S grows linearly with the dimension: too noisy when we generalize to Dirichlet-Multinomial ($\mathbf{DL}(\cdot)$) model.
2. Another approach:
   - Calibrate noise w.r.t *global* sensitivity of $\mathcal{H}$: but global sensitivity is still too big.
   - Fig. 1 shows that there is a gap between global and local sensitivity of $\mathcal{H}$.
3. A better approach:
   - Calibrate noise w.r.t. the *smooth* sensitivity of $\mathcal{H}$.

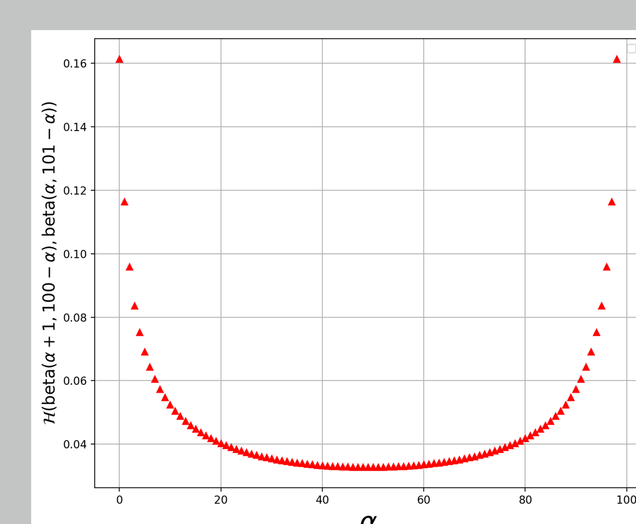


Figure 1: Sensitivity of $\mathcal{H}$. There is a gap between Global and Local sensitivity.

Our approach: smoothed Hellinger distance based exponential mechanism

We define the mechanism $\mathcal{M}_{\mathcal{H}}^{B}$ which produces an element r in $\mathcal{R}_{\text{post}}$ with probability:

$$\mathbb{P}_{r \sim \mathcal{M}_{\mathcal{H}}^{B}} = \frac{\exp\left(\frac{-\epsilon \cdot \mathcal{H}(\mathbf{BI}(\mathbf{x}), r)}{2 \cdot S(\mathbf{x})}\right)}{\sum_{r \in \mathcal{R}_{\text{post}}} \exp\left(\frac{-\epsilon \cdot \mathcal{H}(\mathbf{BI}(\mathbf{x}), r)}{2 \cdot S(\mathbf{x})}\right)}$$

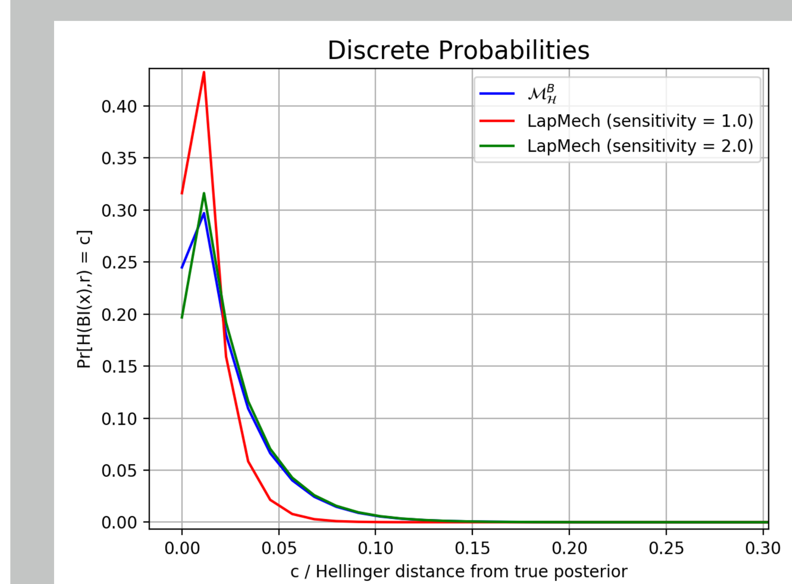
where:

- $\mathcal{R}_{\text{post}} \equiv \{\mathbf{beta}(\alpha', \beta') \mid \alpha' = \alpha + \Delta\alpha, \beta' = \beta + n - \Delta\alpha\}$. With prior distribution $\beta_{\text{prior}} = \mathbf{beta}(\alpha, \beta)$.
- $-\mathcal{H}(\mathbf{BI}(\mathbf{x}), r)$ denotes the scoring function.
- $S(\mathbf{x}) \equiv \max_{\mathbf{x}' \in \{0,1\}^n} \left\{LS(\mathbf{x}') \cdot e^{-\gamma \cdot d(\mathbf{x}, \mathbf{x}')}\right\}$: smooth sensitivity[1], d is the Hamming distance.
- $LS(\mathbf{x}') \equiv \max_{y \in \mathcal{X}^n : \text{adj}(y, \mathbf{x}'), r \in \mathcal{R}} |\mathcal{H}(\mathbf{BI}(y), r) - \mathcal{H}(\mathbf{BI}(\mathbf{x}'), r)|$ is the local sensitivity of $\mathbf{x}'$, $\gamma = \ln(1 - \frac{\epsilon}{2\ln(\frac{\delta}{2(n+1)})})$.

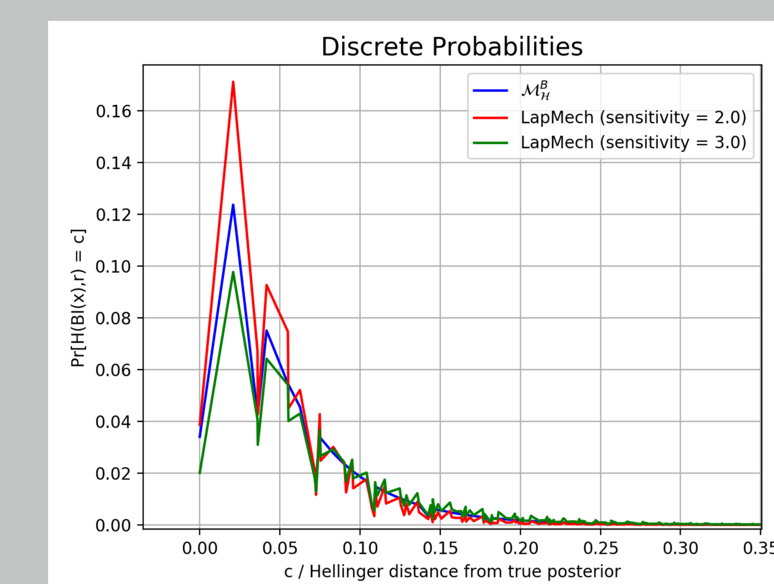
Preliminary Experimental Results

Experiments are on three mechanisms and plotted as follows:

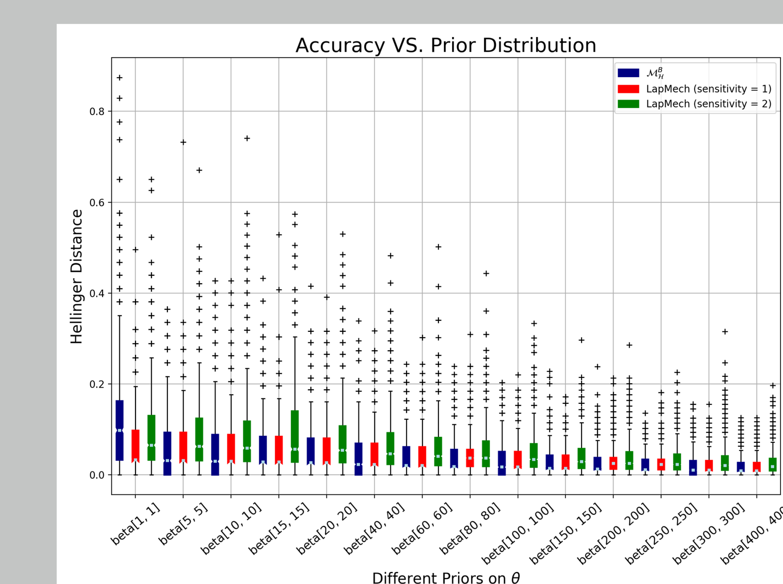
- **Green**: Baseline approach.
- **Red**: Improved baseline approach with sensitivity **1** in 2 dimensions and **2** in higher dimensions, since it's equivalent to histogram problem (posteriors of adjacent data sets differ only in two dimensions).
- **Blue**: $\mathcal{M}_{\mathcal{H}}^{B}$.



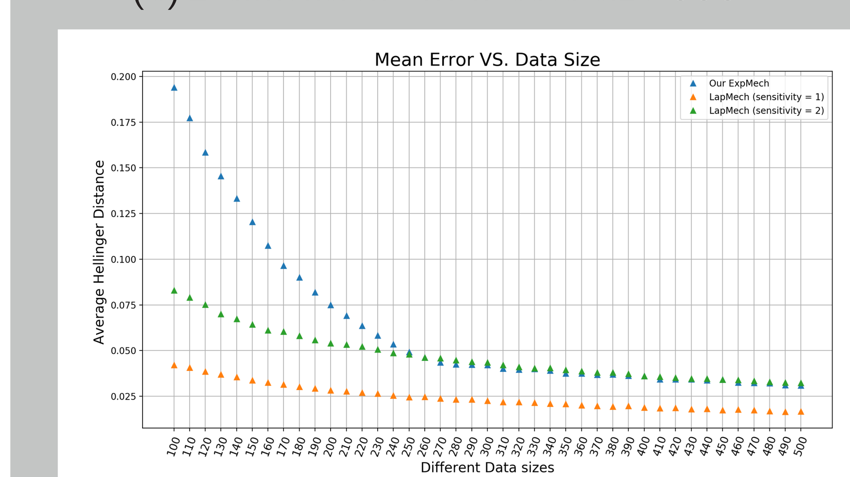
(a) 2 dimensions with data size **600**



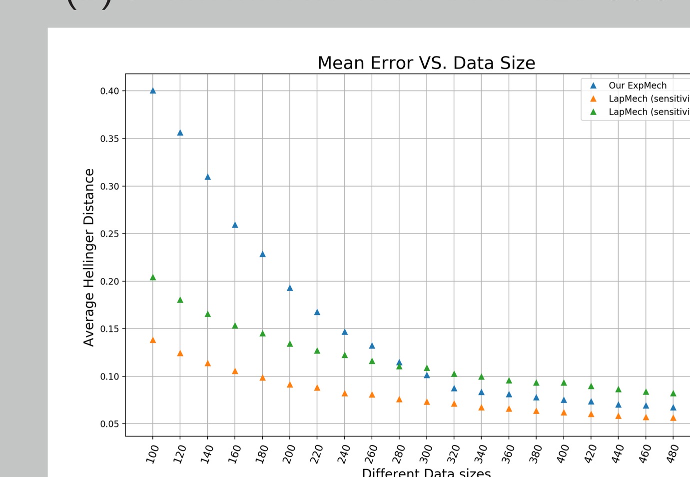
(b) 3 dimensions with data size **600**



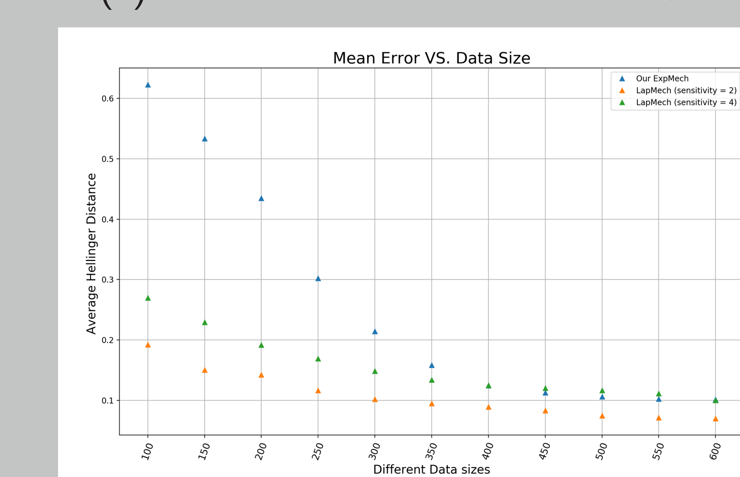
(c) 2 dimensions with data size **100**



(d) 2 dimensions, data size $\in$ **[100, 500]**



(e) 3 dimensions, data size $\in$ **[100, 500]**



(f) 4 dimensions, data size $\in$ **[100, 600]**

Figure 2: Priors are $\mathbf{beta}(1,1), \mathbf{DL}(1,1,1)$ and $\mathbf{DL}(1,1,1,1)$ (except for Figure 2(c)) , balanced datasets, $\epsilon = 1.0$ and $\delta = 10^{-8}$.

Conclusion

- The smoothed Hellinger distance based exponential mechanism outperforms asymptotically the baseline approach when the latter uses a sensitivity proportional to dimensionality.
- Under the same data set size, $\mathcal{M}_{\mathcal{H}}^{B}$ can outperform LapMech by increasing the prior.

References

[1] Kobbi Nissim, Sofya Raskhodnikova, and Adam Smith. Smooth sensitivity and sampling in private data analysis. In *Proceedings of the thirty-ninth annual ACM symposium on Theory of computing*, pages 75–84. ACM, 2007.

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