K-Randomization

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1 Outline of the procedure

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2 Theoretical setup

In the following we work with data in the form of bit vectors. A **bit vector** is a vector $v \in \{0,1\}^L$.

First we define the randomization procedure we will be applying.

Definition. The randomization procedure R with **lie probability** $0 < q < 1/2$ flips a bit with probability q, and leaves it as-is with probability $1-q$. In other words, for a bit $b \in \{0,1\}$,

$$R(b) = R(b; X) = (1-b) \cdot X + b \cdot (1-X) \quad \text{where } X \sim Ber(q).$$

When applied to a vector, each bit is randomized independently:

$$R(v) = R\big(v; (X_1, \ldots, X_L)\big) = \big(R(v_1; X_1), \ldots, R(v_L; X_L)\big) \quad \text{where } X \overset{\text{iid}}{\sim} Ber(q).$$

Remark. The randomization R reports the original bit value with probability $1-q > q$, and lies with probability q. This is equivalent to the randomized response procedure where the value is reported as-is with probability $1-f$, and with probability f the reported value is the outcome of the toss of a fair coin. In this case, $q = f/2$.

Remark. If $q = 1/2$, then $R(0) \overset{d}{=} R(1)$, and the reported value is "completely" randomly generated, i.e., independently of the original value.

Distribution of $R(v)$.

For a bit b, the randomization lies iff $R(b) \neq b$:

$$P[R(b) = s] = q^{\mathbf{1}_{\{b \neq s\}}}(1-q)^{\mathbf{1}_{\{b=s\}}}$$

Hence, for a bit vector v,

$$P[R(v) = s] = q^{\sum \mathbf{1}_{\{b_i \neq s_i\}}}(1-q)^{\sum \mathbf{1}_{\{b_i = s_i\}}} = q^{L-m(v,s)}(1-q)^{m(v,s)},$$

where $m(v,s) = |\{i : v_i = s_i\}|$. Note that this probability is maximized when $m(v,s) = L$ (the reported vector s is identical to the original vector v), and minimized when $m(v,s) = 0$. In other words, the most likely outcome of randomizing a bit vector is obtaining an identical vector.

For a collection T,

$$P[s \in R(T)] = 1 - P[s \notin R(T)] = 1 - \prod_{v \in T} P[R(v) \neq s] = 1 - \prod_{v \in T} \left[1 - q^{L-m(v,s)}(1-q)^{m(v,s)}\right].$$

3 Differential Privacy

The typical setting for differential privacy is the following. We consider a **database** as a collection of records. The records are elements of some space D, and a database $\boldsymbol{x}$ is a vector of n records: $\boldsymbol{x} \in D^n$.

We wish to release information based on the database by applying a **query** to it. This is a function A mapping the database into another space: $A : D^n \to \boldsymbol{S}$. If the function A is random, i.e., $A(\boldsymbol{x}) = A(\boldsymbol{x}, X)$ for a random element X, then the output $A(\boldsymbol{x})$ is a random element of $\boldsymbol{S}$.

In considering the differential privacy of A, we compare the result of applying A to two very similar databases $\boldsymbol{x}$, $\boldsymbol{x'} \in D^n$. We say the databases **differ in one row** if $\sum_{i=1}^n \mathbf{1}_{\{x_i \neq x'_i\}} = 1$. The random query A is said to be ϵ-**differentially private** if, for any two databases $\boldsymbol{x}$, $\boldsymbol{x'} \in D^n$ differing in one row,

$$P[A(\boldsymbol{x}) \in S] \leq \epsilon \cdot P[A(\boldsymbol{x'}) \in S]$$

for all $S \subset \boldsymbol{S}$ (measurable). An alternative notion of differing in one row that is sometimes used is that $\boldsymbol{x} \in D^n$, $\boldsymbol{x'} \in D^{n+1}$, and $x_i = x'_i$ for $i = 1, \ldots, n$. In other words, $\boldsymbol{x'}$ includes an additional record that is not in $\boldsymbol{x}$.

If $\boldsymbol{S}$ is countable, then we can write

$$P[A(\boldsymbol{x}) \in S] = \sum_{s \in S} P[A(\boldsymbol{x}) = s].$$

Hence,

$$\frac{P[A(\boldsymbol{x}) \in S]}{P[A(\boldsymbol{x'}) \in S]} = \frac{\sum_{s \in S} P[A(\boldsymbol{x}) = s]}{\sum_{s \in S} P[A(\boldsymbol{x'}) = s]} \leq \max_{s \in S} \frac{P[A(\boldsymbol{x}) = s]}{P[A(\boldsymbol{x'}) = s]}$$

by the Lemma (need reference).

Furthermore, if A randomizes each record in the database independently, i.e., $A(\boldsymbol{x}) = A(\boldsymbol{x}, \boldsymbol{X}) := \big(A_0(x_1, X_1), \ldots, A_0(x_n, X_n)\big)$ where X_i are independent, then $\boldsymbol{S} = \boldsymbol{S}_0^n$ and $s = (s_1, \ldots, s_n)$ with $s_i \in \boldsymbol{S}_0$. In this case $P[A(\boldsymbol{x}) = s] = P[A_0(x_1) = s_1, \ldots, A_0(x_n) = s_n] = \prod P[A_0(x_i) = s_i]$. If $\boldsymbol{x}$ and $\boldsymbol{x'}$ differ in one row (wlog $x_1 \neq x'_1$ and $x_i = x'_i$ for $i = 2, \ldots, n$), then

$$\frac{P[A(\boldsymbol{x}) = s]}{P[A(\boldsymbol{x'}) = s]} = \frac{P[A_0(x_1) = s_1]}{P[A_0(x'_1) = s_1]}.$$

Therefore, in this case, the query A will satisfy differential privacy if

$$P[A_0(x) = s] \leq \epsilon \cdot P[A_0(x') = s]$$

for all $x, x' \in D$ and $s \in \boldsymbol{S}_0$. This is the formulation used in the RAPPOR paper that applies to differences between individual records rather than collections differing on a single element.

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Consider a collection T of bit vectors, and write $T_v = T \backslash \{v\}$. The randomization procedure R is ϵ-differentially private if

$$\log\left(\frac{P[R(T) \in S]}{P[R(T_v) \in S]}\right) \leq \epsilon$$

for any set of bit vectors S.

Anonymity:

$$A_p = \min_{v \in T, s \in \{0,1\}^L} \frac{P[s \in R(T_v)]}{P[s = R(v)]}$$

4 Single bit case

4.1 Estimating number of single bits

Suppose there are T set bits in the original collection of N single bit records. After randomization is performed the number of observed synthetic bits S is a random variable which we express as:

$$S = p \cdot T + q \cdot (N - T)$$

From here we can express an estimate for T, computed from observed value of S:

$$\bar{T} = \frac{S - qN}{p - q} \tag{4.1}$$

The expectation, variance and deviation of $\bar{T}$ random variable are given by:

$$E(\bar{T}) = T \tag{4.2}$$

$$VAR(\bar{T}) = \frac{qpN}{(p-q)^2} \tag{4.3}$$

$$\sigma(\bar{T}) = \sqrt{\frac{qpN}{(p-q)^2}} \tag{4.4}$$

4.2 Local Differential Privacy

We now study how differential privacy ratio changes depending on the configuration of underlying database D. Assuming that D consists of N single bit records, we are interested in deriving the expression of differential probability ratio as a function of observed number of set bits after randomization is performed.

4.2.1 Choice of D

We are seeking collection D that maximizes differential privacy ratio for any number of observed bits in the randomized collection S. Since we initially consider D to consists of single bits only, the modified record switches the original bit to an opposite value. Without loss of generality, assume that the original record was 1 and it was modified to 0. Hence the original collection D contains at least one set bit, and the modified collection D_m contains one less set bits. Both collections generate synthetic collection S. Call the number of set bits in the synthetic collection a random variable s. Then, the differential privacy ratio when s is equal a particular number i of set bits is given by:

$$R_i = \frac{P(s = i|D_m)}{P(s = i|D)}$$

Theorem 4.1. *R_i is maximized when D contains N set bits*

Proof. Suppose there are m set bits in the original collection D_m. Consider generating function for the number of set bits s in S.

$$G_m(x) = (q + px)^m (p + qx)^{N-m} = \sum_{i=0}^{N} a_i^m x^i$$

Note that coefficients a_i^m in the expansion of the generating function G_m represent probabilities of $P(s = i|D)$. We prove that for any i, the differential privacy ratio grows with m:

$$\frac{a_i^m}{a_i^{m+1}} > \frac{a_i^{m-1}}{a_i^m}$$

which holds when

$$(a_i^m)^2 > a_i^{m-1} a_i^{m+1} \tag{4.5}$$

$$(a_i^m)^2 - a_i^{m-1} a_i^{m+1} > 0 \tag{4.6}$$

Consider generating functions for $m + 1$, m and $m - 1$ respectively:

$$G_{m+1}(x) = (p+qx)^{m+1}(p+qx)^{N-m-1} \tag{4.7}$$
$$G_m(x) = (p+qx)^m(p+qx)^{N-m} \tag{4.8}$$
$$G_{m-1}(x) = (p+qx)^{m-1}(p+qx)^{N-m+1} \tag{4.9}$$

Define $Q(x)$ as:

$$Q(x) = (p+qx)^{m-1}(p+qx)^{N-m-1} = \sum_{i=0}^{N-2} b_i x^i$$

Then generating functions above are expressed as:

$$G_{m+1}(x) = Q(x)(q+px)^2 = \sum_{i=0}^{N}[b_i q^2 + 2qpb_{i-1} + b_{i-2}p^2]x^i \tag{4.10}$$
$$G_m(x) = Q(x)(q+px)(p+qx) = \sum_{i=0}^{N}[b_i qp + (q^2+p^2)b_{i-1} + b_{i-2}qp]x^i \tag{4.11}$$
$$G_{m-1}(x) = Q(x)(p+qx)^2 = \sum_{i=0}^{N}[b_i p^2 + 2qpb_{i-1} + b_{i-2}q^2]x^i \tag{4.12}$$

From here we can express coefficients of each generating function through coefficients of $Q(x)$

$$a_i^{m+1} = b_i q^2 + 2qpb_{i-1} + b_{i-2}p^2 \tag{4.13}$$
$$a_i^m = b_i qp + (q^2+p^2)b_{i-1} + b_{i-2}qp \tag{4.14}$$
$$a_i^{m-1} = b_i p^2 + 2qpb_{i-1} + b_{i-2}q^2 \tag{4.15}$$

Now, replace the coefficients a_i in the 4.6 with their expressions through b_i.

$$(a_i^m)^2 - a_i^{m-1}a_i^{m+1} = (b_i qp + (q^2+p^2)b_{i-1} + b_{i-2}qp)^2 - (b_i q^2 + 2qpb_{i-1} + b_{i-2}p^2)\cdot(b_i p^2 + 2qpb_{i-1} + b_{i-2}q^2)$$

After trivial algebraic transformations the above expression simplifies to:

$$(a_i^m)^2 - a_i^{m-1}a_i^{m+1} = (p^2-q^2)^2 \cdot (b_i^2 - b_{i+1}b_{i-1}) \geq 0$$

Note that the first term of the product is always greater than 0, and we will show that the second term is greater or equal to zero as well.

Lemma 1 If a polynomial has the from bellow

$$Q(x) = \sum_{i=0}^{n} a_i x^i = a_n \prod_{i}^{n} (r_i + x), \ where \ \ r_i \geq 0$$

Then

$$(a_i^2 - a_{i+1}a_{i-1}) \geq 0$$

Proof. Assume polynomial is monic (e.g. $a_n = 1$), and prove lemma by induction.

For n=2:

$$(r_1 + x)(r_2 + x) = r_1 * r_2 + (r_1 + r_2)x + x^2 \tag{4.16}$$

$$a_1^2 - a_0 a_2 = (r_1 + r_2)^2 - r_1 * r_2 = r_1^2 + r_2^2 + r_1 r_2 > 0 \ , since \ r_1 > 0 \ and \ r_2 > 0 \tag{4.17}$$

Assume that for n, the statement holds for all i, then for $n+1$ we can express the polynomial as:

$$Q^{n+1}(x) = \sum_{i=0}^{n+1} a_i x^i = \prod_{i}^{n+1} (r_i + x) = Q^n(x) \cdot (r_{n+1} + x) = \left(\sum_{i=0}^{n} b_i x^i \right) \cdot (r_{n+1} + x) \tag{4.18}$$

$$\sum_{i=0}^{n+1} a_i x^i = \sum_{i=0}^{n+1} [b_i r_{n+1} + b_{i-1}] x^i \tag{4.19}$$

$$a_i = b_i r_{n+1} + b_{i-1} \tag{4.20}$$

The index of r_{n+1} is irrelevant for the proof, hence we drop it. We now express $(a_i^2 - a_{i+1}a_{i-1})$ through coefficients of $Q^n(x)$ and preform algebraic simplifications:

$$a_i^2 - a_{i+1}a_{i-1} = [b_i r + b_{i-1}]^2 - [b_{i+1} r + b_i] \cdot [b_{i-1} r + b_{i-2}] \tag{4.21}$$

$$a_i^2 - a_{i+1}a_{i-1} = r^2(b_i^2 - b_{i+1}b_{i-1}) + r(b_i b_{i-1} - b_{i+1}b_{i-1}) + (b_{i-1}^2 - b_i b_{i-2}) \tag{4.22}$$

$$b_i^2 - b_{i+1}b_{i-1} \geq 0 \ by \ induction \ hypothesis \tag{4.23}$$

$$b_{i-1}^2 - b_i b_{i-2} \geq 0 \ by \ induction \ hypothesis \tag{4.24}$$

$$\tag{4.25}$$

$$b_i b_{i-1} - b_{i+1} b_{i-1} \geq 0 \ because \ all \ b_i \ are \ positive \ and \tag{4.26}$$

$$b_i^2 \geq b_{i+1}b_{i-1} \ and \ b_{i-1}^2 > b_i b_{i-2} \tag{4.27}$$

$$b_i^2 \cdot b_{i-1}^2 \geq b_{i+1} b_{i-1} b_i b_{i-2} \tag{4.28}$$

$$b_i b_{i-1} \geq b_{i+1} b_{i-1} \tag{4.29}$$

This completes the proof of **Lemma 1** for monic polynomials. Same result is true for non-monic polynomials because if $(a_i^2 - a_{i+1}a_{i-1}) \geq 0$, then multiplying each coefficient by constant factor does not change the inequality.

We now ready to finish the proof of **Theorem 4.1**. Consider the generating function $G_m(x)$ again:

$$G_m(x) = (q + px)^m (p + qx)^{N-m} = p^m q^{N-m} \left(\frac{q}{p} + x\right)^m \left(\frac{p}{q} + x\right)^{N-m}$$

Note that since p and q are probabilities, the expressions in parenthesis are of the from necessary for **Lemma 1** to hold. Which proves that:

$$\frac{a_i^m}{a_i^{m+1}} > \frac{a_i^{m-1}}{a_i^m}$$

Which in turn proves that the differential privacy ratio maximizes when $m = N$ □

□

4.3 Maximum and Local differential privacy

Since we established a notion of a differential privacy ratio R_i to be a function of the observed number of set bits in the synthetic output, it's instructive to see how this ratio changes with i. Since D consists of set bits, we have for any i

$$P(s = i|D) = \binom{N}{i} p^i q^{N-i} \tag{4.30}$$

$$P(s = i|D_m) = \binom{N-1}{i} p^{i+1} q^{N-i} + \binom{N-1}{i-1} p^{i-1} q^{N-i+1} \tag{4.31}$$

$$R_i = \frac{P(s = i|D_m)}{P(s = i|D)} = \frac{N-i}{N}\frac{p}{q} + \frac{i}{N}\frac{q}{p} \tag{4.32}$$

When all $i = 0$ - all synthetic bits are 0, the ratio reaches its maximum:

$$R_0 = \frac{p}{q}$$

When $i = N$ - the synthetic output consists of set bits entirely, the privacy ratio reaches minimum:

$$R_N = \frac{q}{p}$$

The ratio reduces as i increases, and becomes 1 when number of synthetic bits is equal to expected number of set synthetic bits after randomization:

$$R_{pN} = \frac{N - pN}{N}\frac{p}{q} + \frac{pN}{N}\frac{q}{p} = (1-p)\frac{p}{q} + p\frac{q}{p} = p + q = 1$$

This observation raises a question of reducing absolute theoretical bound of classical differential privacy by considering realistic values of i, rather then all possible outcomes of randomization. Indeed, the probability of all N bits of D generating N zeros is very low. For example, assuming $p = 0.7$, $q = 0.3$ and $N = 100$, the probability of seeing no synthetic ones is $q^{100} = 5e^{-53}$, which is improbable for any realistic scenario. Instead, we should consider values of i that are realistic. In statistical sense, we should only consider values of i that fall within certain number of σ away from the expected mean.

This brings about a notion of a **local differential privacy**, whereby the probabilistic ratio is considered only for values of i that have realistic chance of being observed. Consider the expression for R_i again.

$$R_i = \frac{P(s = i|D_m)}{P(s = i|D)} = \frac{N - i}{N}\frac{p}{q} + \frac{i}{N}\frac{q}{p}$$

The expected number of observed synthetic bits is pN, while the deviation of S random variable is $\sigma = \sqrt{pqN}$. Consider the interval $[pN - 3\sigma, pN + 3\sigma]$. Since the probabilistic ratio grows as i decreased, the maximum ratio will be attained when $i = pN - 3\sigma$. Hence, the local differential privacy reaches maximum at $i = pN - 3\sigma$, and we want to express analytically the relationship between the probabilistic privacy ratio λ, number of records N, and RRT parameters p and q:

$$i = pN - 3\sigma = pN - 3\sqrt{pqN} \tag{4.33}$$

$$R_i = \frac{P(s = i|D_m)}{P(s = i|D)} = \frac{N - i}{N}\frac{p}{q} + \frac{i}{N}\frac{q}{p} \leq \lambda \tag{4.34}$$

$$Max(R_i) = \frac{N - pN + 3\sqrt{pqN}}{N} \cdot \frac{p}{q} + \frac{pN + 3\sqrt{pqN}}{N} \cdot \frac{q}{p} \leq \lambda \tag{4.35}$$

From here:

$$\frac{N - pN + 3\sqrt{pqN}}{N} \cdot \frac{p}{q} + \frac{pN - 3\sqrt{pqN}}{N} \cdot \frac{q}{p} \leq \lambda \tag{4.36}$$

$$p + q + 3\sqrt{\frac{pq}{N}}\left(\frac{p}{q} - \frac{q}{p}\right) \leq \lambda \tag{4.37}$$

$$1 + 3\sqrt{\frac{pq}{N}}\frac{p^2 - q^2}{pq} \leq \lambda \tag{4.38}$$

$$1 + 3\sqrt{\frac{1}{N}} \cdot \frac{p - q}{\sqrt{pq}} \leq \lambda \tag{4.39}$$

$$\frac{pqN}{(p-q)^2} \geq \frac{9}{(\lambda - 1)^2} \tag{4.40}$$

This is an interesting result. Note that left side of inequality is the variance of estimate $\bar{T}$. The local differential privacy grantee simply places a lower bound on the variance of RRT estimates:

$$VAR(\bar{T}) = \frac{pqN}{(p-q)^2} \geq \frac{9}{(\lambda-1)^2} \tag{4.41}$$

For a randomization algorithm applied independently to N bits to be ϵ-differentially private in local sense, means that estimate deviation is lower-bounded by:

$$\sigma(\bar{T}) \geq \frac{3}{\lambda-1} = \frac{3}{e^{\epsilon}-1} \tag{4.42}$$

From here, we can express RRT noise parameter q through N and λ:

$$\frac{pqN}{(p-q)^2} \geq \frac{9}{(\lambda-1)^2} \tag{4.43}$$

$$\frac{(1-q)q}{(1-2q)^2} \geq \frac{9}{(\lambda-1)^2 N} \tag{4.44}$$

$$q \geq \frac{1}{2}\left(1 - \frac{1}{\sqrt{1+4\frac{9}{(\lambda-1)^2 N}}}\right) \tag{4.45}$$

Suppose $\lambda = 2$ and there are 1000 single bits records in D. The required noise is:

$$q = 0.009$$

Compare that to the level of noise that absolute differential privacy bound would require for $\epsilon = ln(2)$.

$$\frac{p}{q} \leq 2 \tag{4.46}$$

$$q \geq \frac{1}{3} = 0.333 \tag{4.47}$$

The notion of local privacy allowed us to reduce RRT noise 37 times and enabled drastic improvement in estimation accuracy. In the classical case, the estimation deviation is $\sigma = 44.7$, while for the local privacy the deviation is $\sigma = 3$, meaning that precision of RRT estimates had grown 10 fold. It's worth reflecting on what's exactly going on and why such a drastic performance increase is achievable.

Consider confidence intervals for both an original collection D and modified collection D_m. D contains 1000 set bits and D_m contains 999 set bits. Corresponding means and deviation for sum of observed synthetic bits in each case is given below:

$$E(S) = p \cdot 1000 \tag{4.48}$$
$$\sigma(S) = \sqrt{pq \cdot 1000} \tag{4.49}$$
$$E(S_m) = p \cdot 999 + q \tag{4.50}$$
$$\sigma(S_m) = \sqrt{pq \cdot 999 + pq} \tag{4.51}$$

Consider the confidence intervals for both S and S_m for RRT under classical and local differential privacy constrains. If $q = 0.333$ the confidence interval for S and S_m are:

$$S- > [621.98, 711.42] \tag{4.52}$$
$$S_m- > [621.65, 711.09] \tag{4.53}$$

Under local differential privacy, the noise level $q = 0.009$, and the confidence intervals become:

$$S- > [982.04, 999.96] \tag{4.54}$$
$$S_m- > [981.06, 998.98] \tag{4.55}$$

The intervals are nearly identical in either case. Which illustrates the point - we do not need the full power of the absolute differential privacy bound: the local privacy bound will guarantee privacy ratio for 99.98% of possible synthetic outcomes. Effectively, we exploit the noise of large collection to reduce the RRT noise required to randomize each individual record. Rephrasing this important idiom - hiding a record among other records needs less noise than obfuscating a single record.

5 K-randomization for a single bit case

We know consider an important technique for further increasing the estimation precision while providing same local privacy guarantees. Recall from previous example, that if collection D consists of $N = 1000$ records, the corresponding RRT noise at $\lambda = 2$ is $q = 0.009$. We saw that deviation in this case is $\sigma = 3$. Hence our estimation error will be roughly 9 in either direction. We can increase the estimate precision by repeating randomization k times, hence the name **k-ranomization**.

It will be shown that repeating randomization k times achieves increase in precision proportional to $\sqrt{k}$, it also causes slight increase in RRT noise necessary to maintain same differential privacy guarantee. However, the RRT noise increase is usually insignificant compared to the precision gain, which gives a nice dimension to the usual privacy vs. precision tradeoff. K-randomization enables precision increase at the same privacy level for the expense of increasing synthetic record volume k times. Instead of trading privacy for precision, k-randomization allows to trade infrastructure cost for precision while keeping privacy the same. This is especially apparent for long multivariate records, but we will lay mathematical grounds starting from a single bit case.

5.1 Estimating number of single bits under k-randomization

Suppose there are T set bits in the original collection of N single bit records. Each record is randomized k-times. The number of observed synthetic bits S is a random variable expressed as:

$$S = p \cdot kT + q \cdot (kN - kT)$$

The estimate for T, computed from observed value of S is:

$$\bar{T} = \frac{S - qkN}{k(p-q)} \tag{5.1}$$

The aggregator simply divides the estimate computed from kN records by k. The expectation, variance and deviation of $\bar{T}$ random variable are given by:

$$E(\bar{T}) = T \tag{5.2}$$

$$VAR(\bar{T}) = \frac{qpkN}{k^2 \cdot (p-q)^2} = \frac{qpN}{k \cdot (p-q)^2} \tag{5.3}$$

$$\sigma(\bar{T}) = \sqrt{\frac{qpN}{k \cdot (p-q)^2}} \tag{5.4}$$

Note that deviation of the estimate is reduced by $\sqrt{k}$ compared to a single randomization case.

5.2 Choice of D

We now prove that D consisting of only set bits maximizes local differential privacy ratio for any number of observed bits in the randomized collection S. Recall that for a time randomization, the generating function for S given that D contains m set bits is:

$$G_m(x) = (q+px)^{km}(p+qx)^{k(N-m)} = [(q+px)^m(p+qx)^{N-m}]^k = \left[\sum_{i=0}^{N} a_i^m x^i\right]^k = \sum_{j=0}^{kN} b_i^m x^i$$

The generating function for S given that D_m contains $m-1$ set bits is:

$$G_{m-1}(x) = [(q+px)^{(m-1)}(p+qx)^{(N-m+1)}]^k = \left[\sum_{i=0}^{kN} a_i^{m-1} x^i\right]^k == \sum_{j=0}^{kN} b_i^{m-1} x^i$$

Note that each coefficients b_j^m and b_j^{m-1} are products of a_i^m and a_i^{m-1} with exact same indexes of i. Hence, by Theorem 4.1:

$$\frac{b_j^m}{b_j^{m+1}} = \frac{\prod a_i^m}{\prod a_i^{m+1}} > \frac{\prod a_i^{m-1}}{\prod a_i^m} = \frac{b_j^{m-1}}{b_j^m} \tag{5.5}$$

5.3 Local differential privacy under k-randomization

Consider probabilities of seeing s set bits in the synthetic output for D and D_m respectively:

$$P(S = s|D) = \binom{kN}{s} p^s q^{kN-s} \tag{5.6}$$

$$P(S = s|D_m) = \sum_{i=0}^{k} \binom{k(N-1)}{s-i} p^{s-i} q^{k(N-1)-s+i} \cdot \binom{k}{i} p^{k-i} q^i \tag{5.7}$$

$$P(S = s|D_m) = \sum_{i=0}^{k} \binom{k(N-1)}{s-i} \binom{k}{i} p^{s+k-2i} q^{kN-s-(k-2i)} \tag{5.8}$$

Expressing the privacy ratio at given s, we have:

$$R_s = \sum_{i=0}^{k} \frac{\binom{k(N-1)}{s-i} \cdot \binom{k}{i}}{\binom{kN}{s}} \cdot \frac{p^{k-2i}}{q^{k-2i}} \tag{5.9}$$

Consider the binomial ratio in the sum:

$$\frac{\binom{k(N-1)}{s-i}}{\binom{kN}{s}} = \frac{(kN-k)!}{(kN)!} \cdot \frac{s!}{(s-i)!} \cdot \frac{(kN-s)!}{(kN-s-(k-i))!} = \frac{\prod_{j=0}^{i-1}(S-j) \cdot \prod_{j=0}^{k-i-1}(kN-S-j)}{\prod_{j=0}^{k-1}(kN-j)} \tag{5.10}$$

For positive B, A and e such that $A < B$ the following holds:

$$\frac{A-e}{B-e} < \frac{A}{B} \tag{5.11}$$

Hence the expression in 5.10 is upper bounded by:

$$\frac{\prod_{j=0}^{i-1}(s-j) \cdot \prod_{j=0}^{k-i-1}(kN-s-j)}{\prod_{j=0}^{k-1}(kN-j)} < \frac{\prod_{j=0}^{i-1} s \cdot \prod_{j=0}^{k-i-1}(kN-s)}{\prod_{j=0}^{k-1} kN} = \frac{s^i \cdot (kN-s)^{k-i}}{(kN)^k} \tag{5.12}$$

Dividing each numerator term by kN we arrive to an upper bound of the privacy ratio:

$$R_s < \sum_{i=0}^{k} \left(\frac{s}{kN}\right)^i \left(1 - \frac{s}{kN}\right)^{k-i} \cdot \binom{k}{i} \cdot \frac{p^{k-2i}}{q^{k-2i}} \tag{5.13}$$

Again, under local privacy constrains we compute privacy ratio for s located 3σ bellow the mean:

$$s = pkN - 3\sqrt{pqkN}$$

Replacing s in formula 5.13, we get:

$$\sum_{i=0}^{k} \left(\frac{pkN - 3\sqrt{pqkN}}{kN}\right)^i \left(1 - \frac{pkN - 3\sqrt{pqkN}}{kN}\right)^{k-i} \cdot \binom{k}{i} \cdot \frac{p^{k-2i}}{q^{k-2i}} = \tag{5.14}$$

$$\sum_{i=0}^{k} \left(p - 3\sqrt{\frac{pq}{kN}}\right)^i \left(1 - p + 3\sqrt{\frac{pq}{kN}}\right)^{k-i} \cdot \binom{k}{i} \cdot \frac{p^{k-2i}}{q^{k-2i}} = \tag{5.15}$$

$$\sum_{i=0}^{k} \frac{q^i}{p^i} \left(p - 3\sqrt{\frac{pq}{kN}}\right)^i \cdot \frac{p^{k-i}}{q^{k-i}} \left(q + 3\sqrt{\frac{pq}{kN}}\right)^{k-i} \cdot \binom{k}{i} = \tag{5.16}$$

$$\sum_{i=0}^{k} \binom{k}{i} \left(q - 3q\sqrt{\frac{q}{pkN}}\right)^i \cdot \left(p + 3p\sqrt{\frac{p}{qkN}}\right)^{k-i} = \tag{5.17}$$

$$\left(q - 3q\sqrt{\frac{q}{pkN}} + p + 3p\sqrt{\frac{p}{qkN}}\right)^k = \tag{5.18}$$

$$\left(q + p + 3p\sqrt{\frac{p}{qkN}} - 3q\sqrt{\frac{q}{pkN}}\right)^k = \tag{5.19}$$

$$\left(1 + \frac{3(p-q)}{\sqrt{qpkN}}\right)^k \tag{5.20}$$

Should the differential privacy ratio limit be λ we have the lower bound below:

$$R_s < \left(1 + \frac{3(p-q)}{\sqrt{qpkN}}\right)^k \leq \lambda \tag{5.21}$$

From here we have:

$$\left(1 + \frac{3(p-q)}{\sqrt{qpkN}}\right)^k \leq \lambda \tag{5.22}$$

$$\frac{qpkN}{(p-q)^2} \geq \frac{9}{(\sqrt[k]{\lambda} - 1)^2} \tag{5.23}$$

From here we express required RRT noise through λ, N and k.

$$q \geq \frac{1}{2}\left(1 - \frac{1}{\sqrt{1 + 4\frac{9}{(\sqrt[k]{\lambda}-1)^2 kN}}}\right) \tag{5.24}$$