NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Improving Speed of Dilithium's Signing Procedure

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17th April 2019

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2. Background
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- Lattice-based cryptography has contributed the maximum number of proposals in terms of post-quantum key exchange and post-quantum signature schemes.

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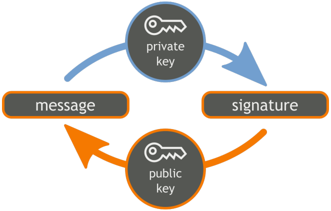
Digital Signature



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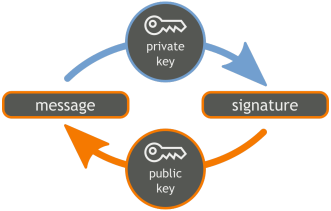

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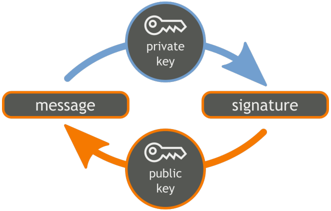

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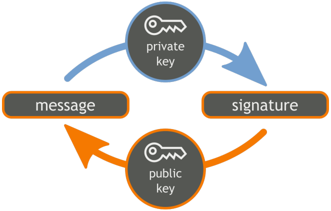

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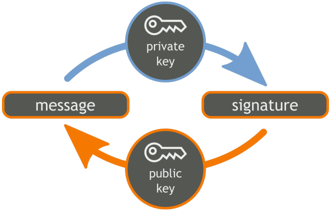

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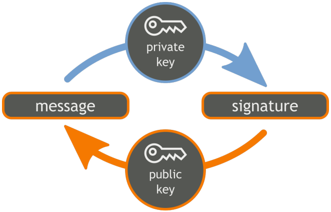

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- Module LWE: $\mathbf{R}_q^{k\times l} = (\mathbb{Z}_q[X]/(X^n + 1))^{k\times l}$ with $\mathbf{A} \in \mathbf{R}_q^{k\times \ell}$, $\mathbf{S} \in \mathbf{R}_q^{\ell}$, $\mathbf{E} \in \mathbf{R}_q^{k}$.

`Dilithium` Signature Scheme

- Security of `Dilithium` is based on the MLWE problem.
- Computations are performed over *matrices* and *vectors* of polynomials.
- Signature generation is an iterative procedure with multiple rejection conditions.
- Two algorithmic level optimizations to improve signing speed have been explored.
  - *Opt-1:* Reduction of computations in every rejected iteration.
  - *Opt-2:* Reduction of repetition rate.

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- Is it possible to detect the rejections early to reduce the overhead of the rejected iterations?
- We perform an *early-evaluation* of the rejection conditions, so we detect the rejections early and immediately abort the current iteration.

Dilithium's Signing Procedure

Procedure Sign (sk, M)
  $\mathbf{A} \in R_q^{k \times \ell} := \mathsf{ExpandA}(\rho)$
  $\mu = \mathsf{CRH}(\mathsf{tr} \| M)$
  $\kappa = 0, (\mathbf{z}, \mathbf{h}) = \perp$
  while $(\mathbf{z}, \mathbf{h}) = \perp$ **do**
    $\mathbf{y} \in S_{\gamma_1 - 1}^{\ell} := \mathsf{ExpandMask}(K \| \mu \| \kappa)$
    $\mathbf{w} = \mathbf{A} \cdot \mathbf{y}$
    $\mathbf{w}_1 = \mathsf{HB}_q(\mathbf{w}, 2\gamma_2)$
    $\mathbf{c} \in B_{60} = H(\mu \| \mathbf{w}_1)$
    $\mathbf{z} = \mathbf{y} + \mathbf{c} \cdot \mathbf{s}_1$
    $(\mathbf{r}_1, \mathbf{r}_0) := \mathsf{D}_q(\mathbf{w} - \mathbf{c} \cdot \mathbf{s}_2, 2\gamma_2)$
    if $\|\mathbf{z}\|_\infty \geq \gamma_1 - \beta$ or $\|\mathbf{r}_0\|_\infty \geq \gamma_2 - \beta$ or $\mathbf{r}_1 \neq \mathbf{w}_1$ **then**
      $(\mathbf{z}, \mathbf{h}) = \perp$
    else
      $\mathbf{h} = \mathsf{MH}_q(-\mathbf{c} \cdot \mathbf{t}_0, \mathbf{w} - \mathbf{c} \cdot \mathbf{s}_2 + \mathbf{c} \cdot \mathbf{t}_0, 2\gamma_2)$
      if $\|\mathbf{c} \cdot \mathbf{t}_0\|_\infty \geq \gamma_2$ or $\mathsf{wt}(\mathbf{h}) > \omega$ **then**
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    end
    $\kappa = \kappa + 1$
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  return $\sigma = (\mathbf{z}, \mathbf{h}, \mathbf{c})$

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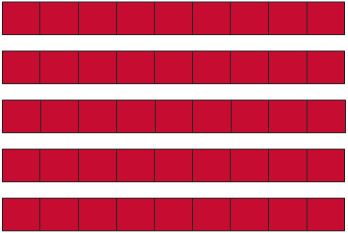
- The condition has to be satisfied for all coefficients of a given module.
- Consider the computations involving module $\mathbf{z} \in R_q^\ell$.

Evaluation of Rejection Conditions



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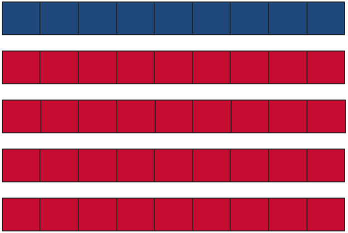
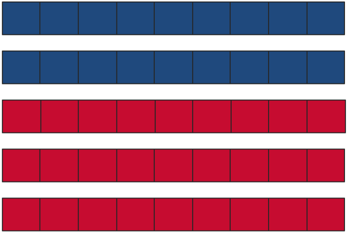


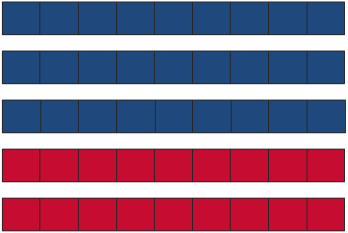
No of Computations: 1

Evaluation of Rejection Conditions



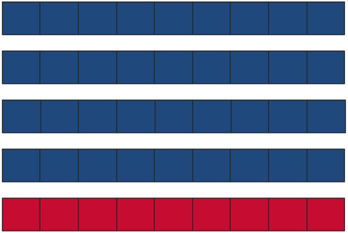
No of Computations: 2

Evaluation of Rejection Conditions



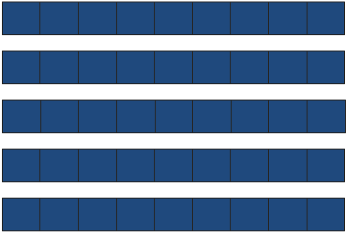
No of Computations: 3

Evaluation of Rejection Conditions



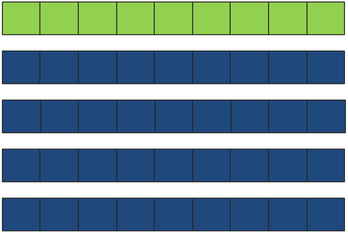
No of Computations: 4

Evaluation of Rejection Conditions



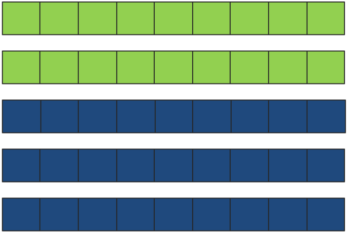
No of Computations: N

Evaluation of Rejection Conditions



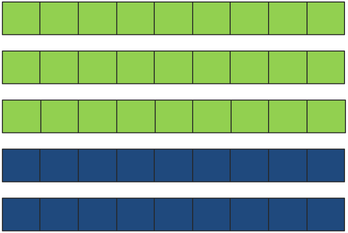
No of Computations: N+1

Evaluation of Rejection Conditions



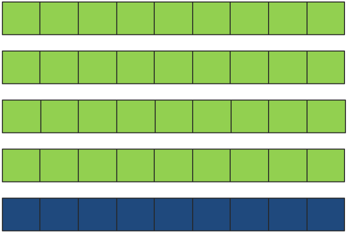
No of Computations: N+2

Evaluation of Rejection Conditions



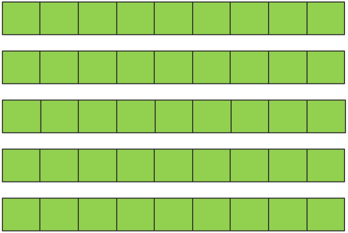
No of Computations: N+3

Evaluation of Rejection Conditions



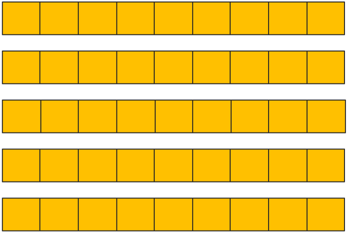
No of Computations: N+4

Evaluation of Rejection Conditions



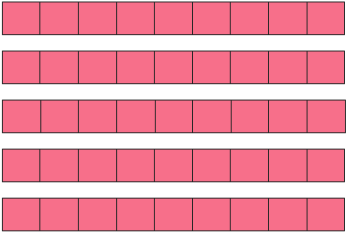
No of Computations: 2N

Evaluation of Rejection Conditions



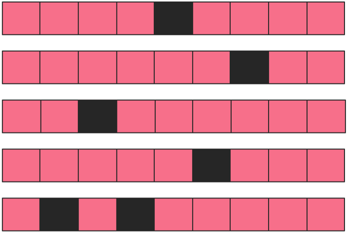
No of Computations: 3N

Evaluation of Rejection Conditions



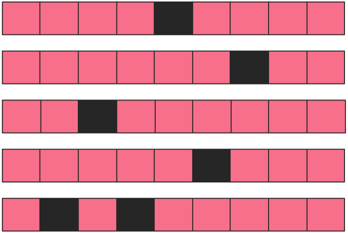
No of Computations: C*N

Evaluation of Rejection Conditions



Checking defective elements:

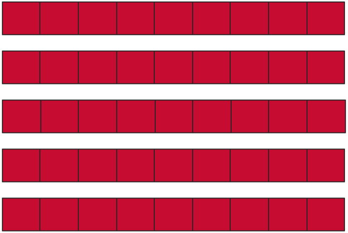
Evaluation of Rejection Conditions



If (number of black boxes > 0)
Reject

Total Computations to compute rejection: condition **: (C+1)*N**

Early Evaluation of Rejection Conditions



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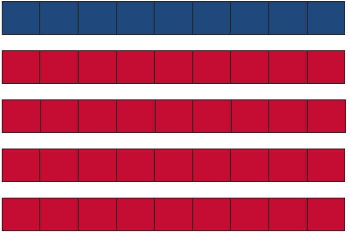

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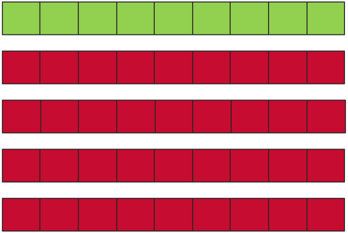

No of Computations: 2

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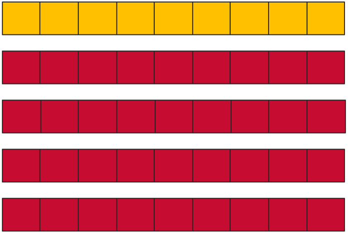

No of Computations: 3

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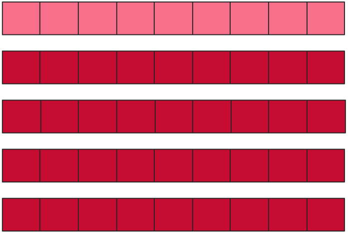

No of Computations: C

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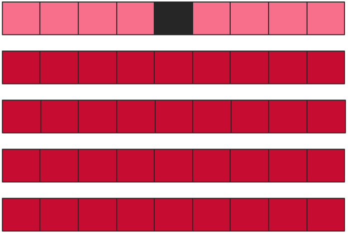

No of Computations: C+1

Rejection done with only (C+1) computations

Early Evaluation of Rejection Conditions

- We perform the complete set of computations **one polynomial at a time**.
- **Best Case** - (C+1) computations.
- **Worst Case** - ((C+1)*N) computations.
- **Average Case** - ((C+1)*$\frac{N}{2}$) computations.
- We apply the same optimization to all the *Infy_Checks* in Dilithium's signing procedure.

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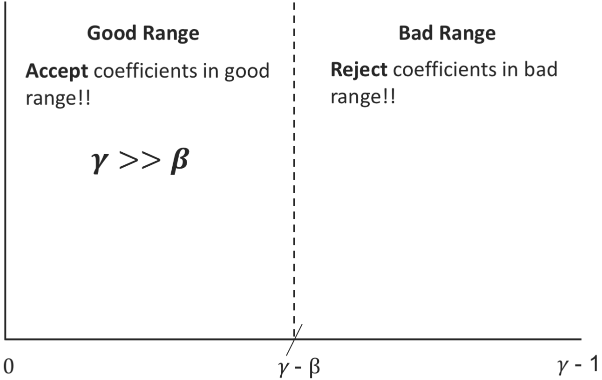
- $\|\mathbf{y}\| \gg \|\mathbf{sc}\|$.
- Coefficients of $\mathbf{y}$ are uniformly distributed in $[0, \gamma_1 - 1]$.
- Coefficients of $\mathbf{sc}$ are very small and normally distributed in $[0, \beta]$.

Generation of $\mathbf{z}$



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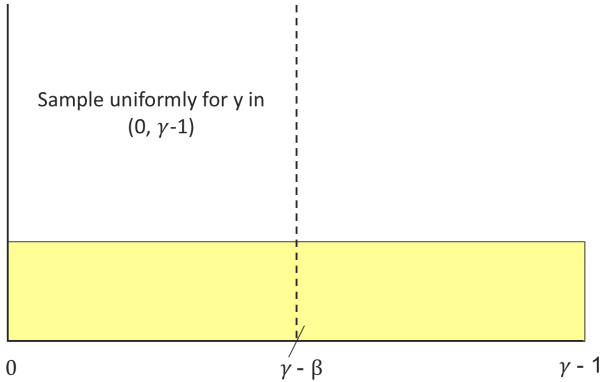

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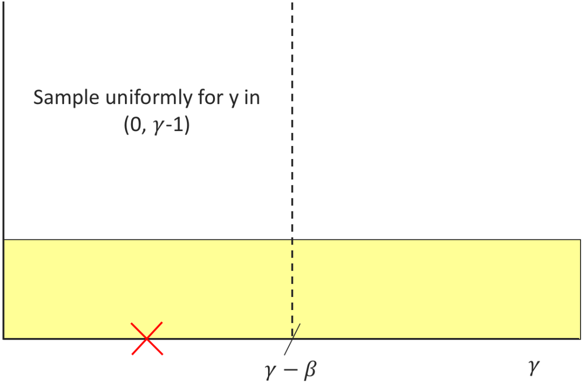

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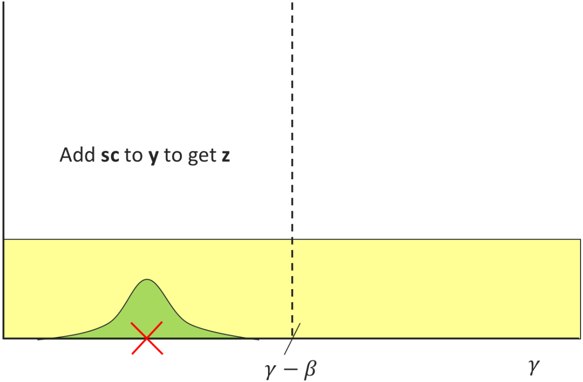

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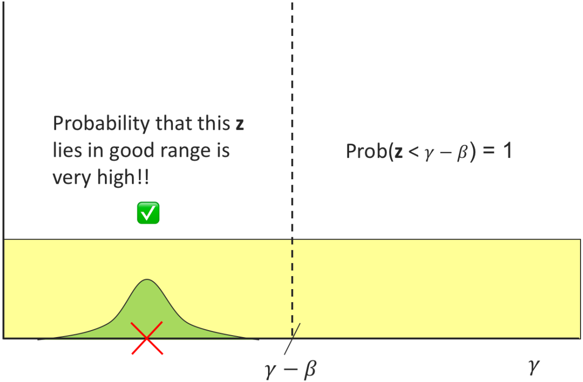

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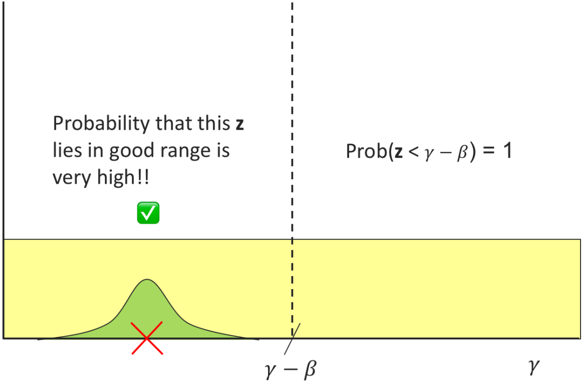

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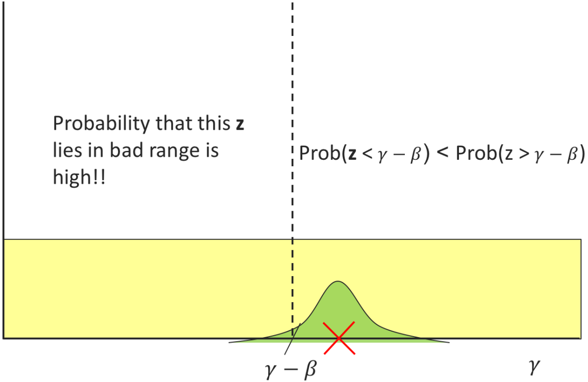

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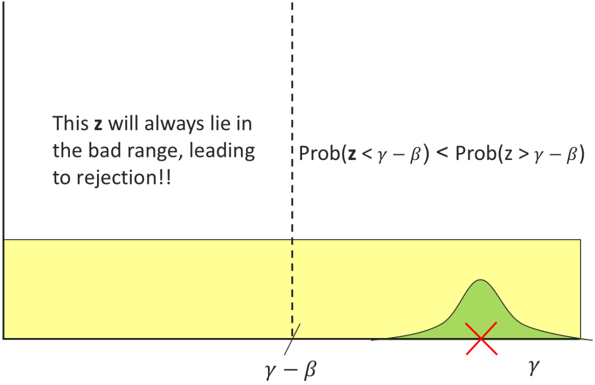

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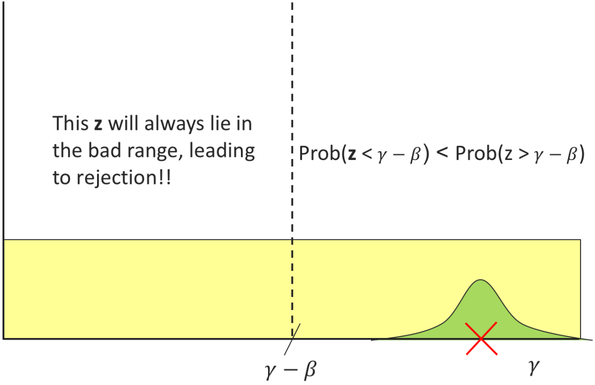

Improving the Repetition Rate

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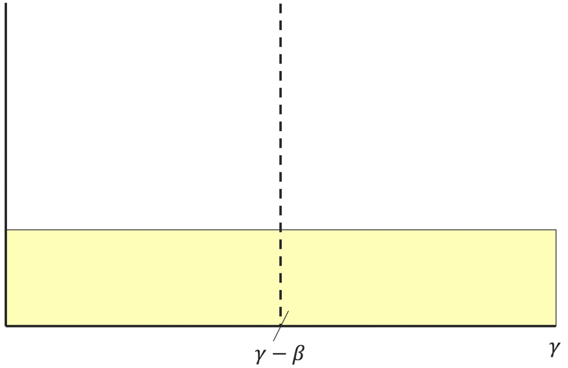
- $\mathbf{y}$ is sampled uniformly in $[0, \gamma_1]$ and hence has a certain non-negligible probability that its corresponding $\mathbf{z}$ lies in the bad range.
- Can we alter the distribution of $\mathbf{y}$ so as to reduce the occurrence of $\mathbf{z}$ in the bad range?

Uniform Distribution with Reduced Acceptance Rate



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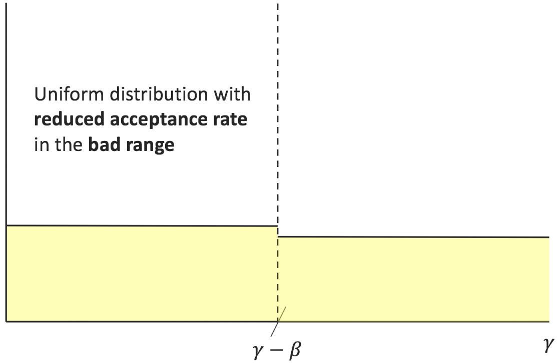

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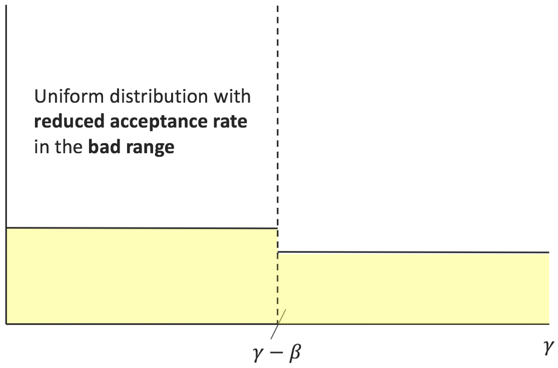

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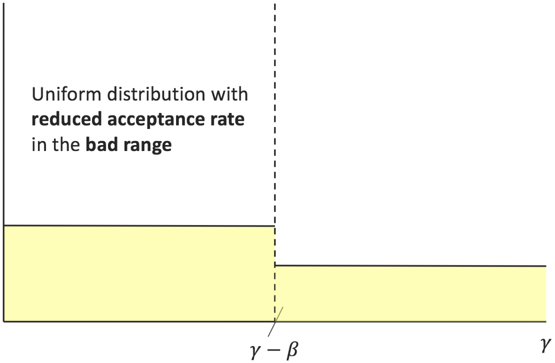

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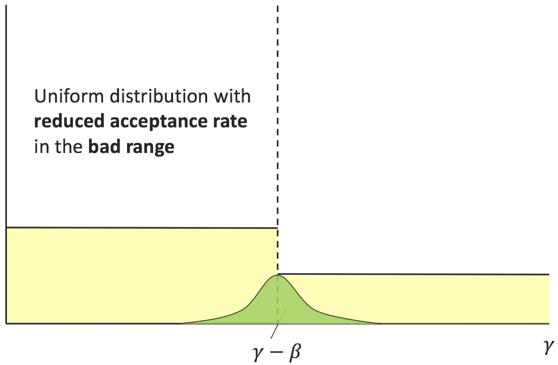
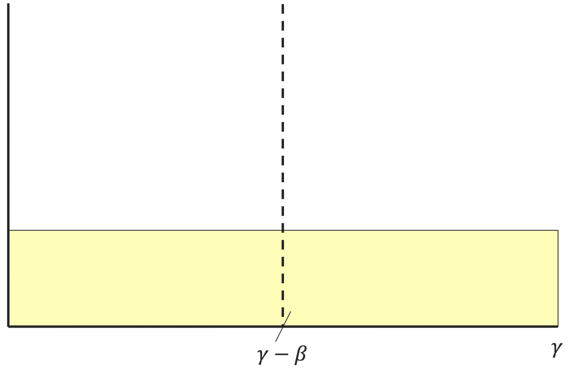


Semi-Uniform and Semi-Gaussian



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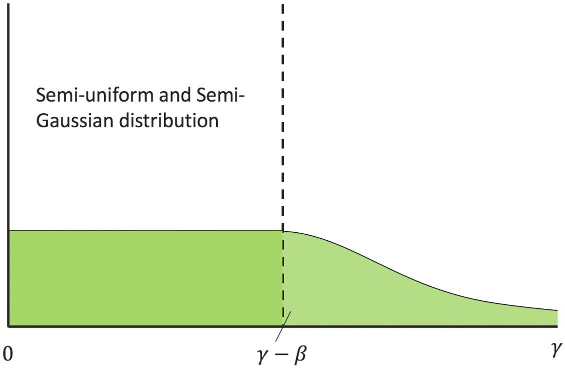

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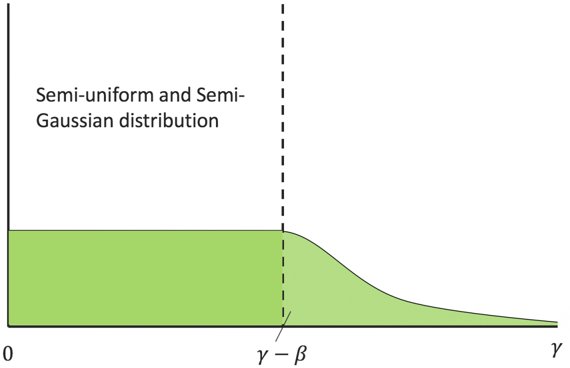

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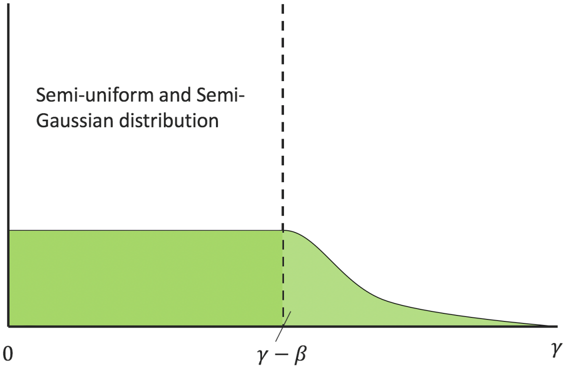

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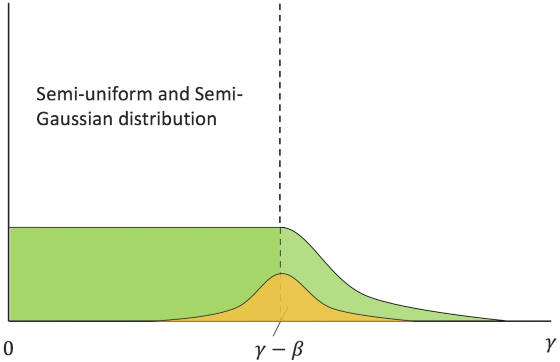

Alternate Distributions for Sampling $\mathbf{y}$

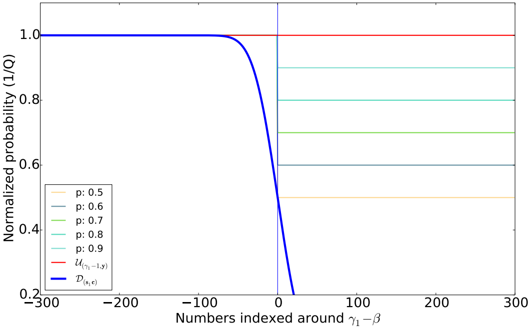

Figure: $\mathcal{U}_{(\gamma_1-\beta,\gamma_1-1,p)}$ - Uniform distribution with reduced acceptance rate p

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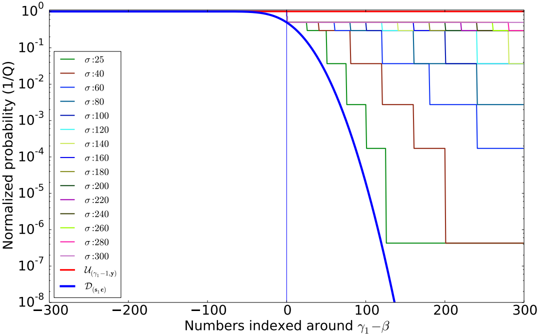

Figure: $\mathcal{D}_{(\gamma_1-\beta,\gamma_1-1,\sigma)}$ - Piece-wise Gaussian distribution with standard deviation σ

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Experimental Results

- Implementation of *Early-Eval* optimization and *Improved-Sampling* optimizations on reference implementation of `Dilithium`.
- Both the optimizations can be employed independently.
- Since both optimizations are done at the algorithmic level, they can be ported to all implementation platforms.
- Results were obtained for about 10^7 runs of the signing procedure.
- Implemented on Intel(R) Core(TM) i5-4460 CPU 3.20GHz and compiled with gcc-4.2.1.

Experimental Results

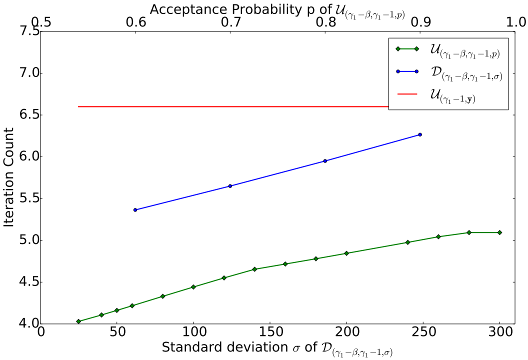

Figure: Improvements in iteration Count evaluated for various parameters of our alternate distributions

Experimental Results

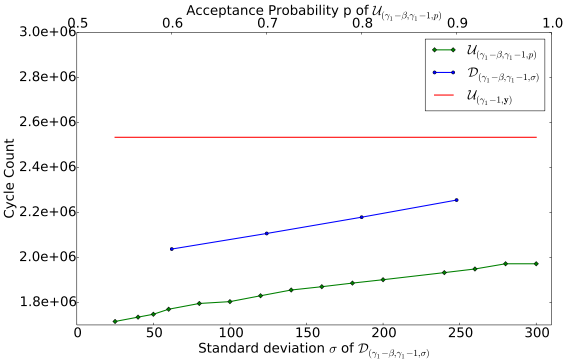

Figure: Improvements in Cycle count evaluated for various parameters of our alternate distributions

Experimental Results

- *Early-Eval* optimization yields improvement of about 8% in the signing speed.
- Combination of *Early-Eval* and *Improved-Sampling* optimizations could yield speed up upto 38%.
- *Early-Eval* optimization does not have any impact on security of the scheme.
- Does the use of improved distributions for $\mathbf{y}$ affect the security of the scheme? If so, by how much?
- How many signatures does the attacker need to observe an exploitable skew in the distribution of $\mathbf{z}$.
- This could lead to a potential quantitative trade-off between security and efficiency, which needs to be evaluated.

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Future Work

- Security Analysis of the signing procedure with improved distribution.
- Evaluation of the security-efficiency trade-off due to use of improved distributions.
- Utilization of a constant-time Gaussian sampler to sample from the improved distribution.

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Future Work

- This work proposes algorithmic optimizations for the `Dilithium` signature scheme
- We propose two optimizations:
  - *Early-Eval* optimization
  - *Improved-Sampling* optimization
- We were able to achieve a speed-up of upto 38% by employing a combination of both the optimizations.
- Incorporation of the *Improved-Sampling* optimization could lead to a potential security-efficiency trade-off.
- We intend to perform a quantitative evaluation of the security-efficiency trade-off as part of future work.

Thank you!

Any questions?