Linear Complexity of Generalized NTU Sequences

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Motivation

Geometric sequences and generalized NTU sequences

Linear complexity of generalized NTU sequences
1. Motivation

1. Motivation
2. Geometric sequences and generalized NTU sequences
3. Linear complexity of generalized NTU sequences
In cryptography, PRNGs are required to generate PRNs which have good statistical properties as well as unpredictability. M-sequences are well-distributed sequences with long period, however, we must nonlinearize these sequences for cryptographic purposes.

A geometric sequence is a sequence given by applying a nonlinear feedforward function to an m-sequence. Nogami et al. proposed a geometric sequence whose nonlinear feedforward function is given by the Legendre symbol, and showed the period, periodic autocorrelation and linear complexity of the geometric sequence.

Furthermore, Nogami et al. proposed a generalization of the geometric sequence (referred to as the generalized NTU sequence), and showed the period and periodic autocorrelation.

The purpose of our work
To investigate the linear complexity of the generalized NTU sequences
Linear Complexity

Definition of Linear Complexity
For a sequence $S = (s_n)_{n \geq 0}$ over a finite field $\mathbb{F}_\ell$, the linear complexity $L(S)$ of $S$ is the length $L$ of the shortest linear recurrence relation

$$s_{n+L} = a_{L-1}s_{n+L-1} + \cdots + a_0 s_n, \quad n \geq 0$$

for some $a_0, \ldots, a_{L-1} \in \mathbb{F}_\ell$, and the minimal polynomial $m(x)$ of $S$ is the polynomial

$$x^L - a_{L-1}x^{L-1} - \cdots - a_0 \in \mathbb{F}_\ell[x].$$
Linear Complexity

Linear Complexity of a sequence $S$

The shortest length of an LFSR that generates $S$.

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$$x^L - a_{L-1}x^{L-1} - \cdots - a_0 \in \mathbb{F}_\ell[x].$$

Properties of Linear Complexity

Assume that $S$ is a periodic sequence of period $N$ and

$$S(x) := s_0 + s_1x + \cdots + s_{N-1}x^{N-1} \in \mathbb{F}_\ell[x].$$

Then

$$L(S) = N - \deg \left( \gcd \left( x^N - 1, S(x) \right) \right).$$

In particular, $L(S) \leq N$. 
2. Geometric sequences and generalized NTU sequences

1. Motivation
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A geometric sequence is a sequence given by applying a nonlinear feedforward function to an m-sequence.
Geometric sequences

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Definition of geometric sequences (Chan–Games)

- Let $p$ be an odd prime number, $m > 1$ an integer, $\omega$ a primitive element in $\mathbb{F}_{p^m}$.
- $R = (R_n)_{n \geq 0}$ an m-sequence defined as $R_n = \text{Tr}_{\mathbb{F}_{q^m}/\mathbb{F}_q}(\omega^n)$, $n \geq 0$.
- Let $\rho : \mathbb{F}_p \to \mathbb{F}_2$ be a (nonlinear) map.
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- Let $\rho : \mathbb{F}_p \rightarrow \mathbb{F}_2$ be a (nonlinear) map.
- $S = (S_n)_{n \geq 0}$, $S_n = \rho(R_n)$, $n \geq 0$ is called a geometric sequence.
- $g = \omega^{(p^m-1)/(p-1)} \in \mathbb{F}_p$.
  $s = (s_n)_{n \geq 0}$, $s_n = \rho(g^n)$, $n \geq 0$.

Examples of geometric sequences
GMW sequences, cascaded GMW sequences, ...
Definition of generalized NTU sequences

Generalized NTU sequences

- For $A \in \mathbb{F}_p$, we define a map $\rho_A^{\text{NTU}} : \mathbb{F}_p \rightarrow \mathbb{F}_2$ as

  $$\rho_A^{\text{NTU}}(x) = \begin{cases} 
  1 & \text{if } \left(\frac{x+A}{p}\right) = -1 \\
  0 & \text{otherwise.}
\end{cases}$$
Definition of generalized NTU sequences

**Generalized NTU sequences**

- For $A \in \mathbb{F}_p$, we define a map $\rho_A^{NTU} : \mathbb{F}_p \to \mathbb{F}_2$ as

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  \rho_A^{NTU}(x) = \begin{cases} 
  1 & \text{if } \left( \frac{x+A}{p} \right) = -1 \\
  0 & \text{otherwise.}
  \end{cases}
  $$

- Let $S_A^{NTU} = (S_{A,n}^{NTU})_{n \geq 0}$, $S_{A,n}^{NTU} = \rho_A^{NTU}(R_n)$, $n \geq 0$. $S_A^{NTU}$ is called a generalized NTU sequence.

- Let $s_A^{NTU} = (s_{A,n}^{NTU})_{n \geq 0}$, $s_{A,n}^{NTU} = \rho_A^{NTU}(g^n)$, $n \geq 0$.

**NTU sequence**

If $A = 0$, then $S_0^{NTU}$ is an NTU sequence.

**Sidel’nikov sequence**

If $A = 1$, then $s_1^{NTU}$ is a Sidel’nikov sequence.
Motivation
Geometric sequences and generalized NTU sequences
Linear complexity of generalized NTU sequences

Equivalence on generalized NTU sequences

Example

\[ p = 5, \, m = 2, \, f(x) = x^2 + 2x + 3 \in \mathbb{F}_5[x] : \text{primitive polynomial.} \]

| \( R_n \) | 2 | 3 | 3 | 0 | 1 | 3 | 1 | 4 | 4 | 0 | 3 | 4 | 3 | 2 | 2 | 0 | 4 | 2 | 4 | 1 | 1 | 0 | 2 | 1 |
| \( S_{NTU}^{1,n} \) | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| \( S_{NTU}^{2,n} \) | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| \( S_{NTU}^{3,n} \) | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |
| \( S_{NTU}^{4,n} \) | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |

Lemma (Equivalence on generalized NTU sequences)

Let \( A_1, A_2 \in \mathbb{F}_p - \{0\} \).
If \( (A_1/p) = (A_2/p) \), then \( S_{A_1,n}^{NTU} \) and \( S_{A_2,n}^{NTU} \) are shift-equivalent to each other.

\[ \Rightarrow S_{A}^{NTU} \text{ can be classified into three types: } A = 0, \, A \text{ is QR and } A \text{ is QNR.} \]
NTU sequences vs Generalized NTU sequences

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- ▲ maximal
- ▲ to be maximal?
- conditions to have large LC?

### Our strategy

1. Applying a formula for general geometric sequences
2. Considering the sequence of complement numbers
3. Using the Hasse derivative and cyclotomic classes
3. Linear complexity of generalized NTU sequences

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Chan–Games formula

Strategy 1

Applying a formula for general geometric sequences
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Applying a formula for general geometric sequences

Lemma (Chan–Games formula)

Assume that \( \rho(0) = 0 \). Then

\[
L(S) = \frac{p^m - 1}{p - 1} L(s).
\]
Chan–Games formula

Strategy 1
Applying a formula for general geometric sequences

Lemma (Chan–Games formula)
Assume that $\rho(0) = 0$. Then

$$L(S) = \frac{p^m - 1}{p - 1} L(s) .$$

1. Case of $(A/p) = 1$:
   - Since $\rho_A^{NTU}(0) = 0$,
   - $L(S_A^{NTU}) = L(S_1^{NTU}) = \frac{p^m - 1}{p - 1} L(s_1^{NTU})$.

   $\uparrow$ LC of a Sidel’nikov seq.

2. Case of $(A/p) = -1$:
   - Since $\rho_A^{NTU}(0) = 1$,
     we can not apply the Chan–Games formula.
Sequence of complement numbers

**Strategy 2**

Considering the sequence of complement numbers
Sequence of complement numbers

Strategy 2
Considering the sequence of complement numbers

Sequence of complement numbers and Chan–Games formula

- We define a map $\rho_A^{\text{NTU}} : \mathbb{F}_p \rightarrow \mathbb{F}_2$ as
  $$\overline{\rho_A^{\text{NTU}}(x)} = \rho_A^{\text{NTU}}(x) + 1.$$ 

- Let $S_A^{\text{NTU}} = (S_{A,n}^{\text{NTU}})_{n \geq 0}$, $S_A^{\text{NTU}} = \overline{\rho_A^{\text{NTU}}(R_n)}$, $n \geq 0$, and $s_A^{\text{NTU}} = (s_{A,n}^{\text{NTU}})_{n \geq 0}$, $s_A^{\text{NTU}} = \overline{\rho_A^{\text{NTU}}(g^n)}$, $n \geq 0$. 

Question: What is the relationship between $L(S_A^{\text{NTU}})$ and $L(S_A^{\text{NTU}})$?
Sequence of complement numbers

Strategy 2

Considering the sequence of complement numbers

Sequence of complement numbers and Chan–Games formula

- We define a map $\rho_{\mathcal{A}}^{\text{NTU}} : \mathbb{F}_p \to \mathbb{F}_2$ as
  $$\rho_{\mathcal{A}}^{\text{NTU}}(x) = \rho_{\mathcal{A}}^{\text{NTU}}(x) + 1.$$  
- Let $S_{\mathcal{A}}^{\text{NTU}} = (S_{\mathcal{A},n}^{\text{NTU}})_{n \geq 0}$, $S_{\mathcal{A},n}^{\text{NTU}} = \rho_{\mathcal{A}}^{\text{NTU}}(R_n)$, $n \geq 0$, and $s_{\mathcal{A}}^{\text{NTU}} = (s_{\mathcal{A},n}^{\text{NTU}})_{n \geq 0}$, $s_{\mathcal{A},n}^{\text{NTU}} = \rho_{\mathcal{A}}^{\text{NTU}}(g^n)$, $n \geq 0$.
- Assume that $(\mathcal{A}/p) = -1$.
  Since $\rho_{\mathcal{A}}^{\text{NTU}}(0) = 0$, we can apply the Chan–Games formula to $S_{\mathcal{A}}^{\text{NTU}}$.

Question

What is the relationship between $L(S_{\mathcal{A}}^{\text{NTU}})$ and $L(S_{\mathcal{A}}^{\text{NTU}})$?
Case of \( (A/p) = -1, \ p \equiv 1 \mod 4 \)

**Lemma (See Lidl–Niederreiter Theorem 8.62)**

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### Theorem

Assume that \((A/p) = -1, \ p \equiv 1 \mod 4\). Then

\[
L(S_A^{\text{NTU}}) = \frac{p^m - 1}{p - 1} L(s_A^{\text{NTU}}). \quad \leftarrow \text{the same eq. as in Chan–Games formula}
\]

In fact, \(m_1(x^{p^m-1} - 1) \geq 2\) and \(m_1(x^{p-1} - 1) \geq 2\).

On the other hand, \(m_1(S_A^{\text{NTU}}(x)) = m_1(s_A^{\text{NTU}}(x)) = 0\).

Note: \((A/p) = -1, \ p \equiv 3 \mod 4 \implies m_1(S_A^{\text{NTU}}(x)) \geq 1, \ m_1(s_A^{\text{NTU}}(x)) \geq 1\).
Hasse derivative and cyclotomic classes

Strategy 3
Using the Hasse derivative and cyclotomic classes
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Using the Hasse derivative and cyclotomic classes

Hasse derivative
For $S(x) = a_0 + a_1x + \cdots + a_{N-1}x^{N-1}$,

$$S^{(k)}(x) = a_k + \binom{k+1}{k} a_{k+1}x + \cdots + \binom{N-1}{k} a_{N-1}x^{N-1-k}$$

is called the $k$th Hasse derivative of $S(x)$.

Let $\xi$ be a root of $S(x)$. Then

$$m_\xi (S(x)) = \nu \iff S(\xi) = S^{(1)}(\xi) = \cdots = S^{(\nu-1)}(\xi) = 0, \ S^{(\nu)}(\xi) \neq 0.$$
**Hasse derivative and cyclotomic classes**

**Strategy 3**

Using the Hasse derivative and cyclotomic classes

**Hasse derivative**

For \( S(x) = a_0 + a_1x + \cdots + a_{N-1}x^{N-1} \),

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\]

**Cyclotomic classes and difference parameter**

\( D_0 = \{ a \in \mathbb{F}_p \mid (a/p) = 1 \} \), **\( D_1 = \{ a \in \mathbb{F}_p \mid (a/p) = -1 \} \)** are called cyclotomic classes of order 2. For \( a \in \mathbb{F}_p \), the difference parameter is defined as

\[
d(i, j; a) = \#(D_i \cap (D_j - a)), \quad i, j \in \{0, 1\}, \ a \in \mathbb{F}_p.
\]

If \( a = 1 \), then \( d(i, j; 1) \) is nothing but the cyclotomic number \((i, j)_2\) of order 2.
Case of \((A/p) = -1, \, p \equiv 3 \mod 4\)

**Lemma**

Assume that \((A/p) = -1, \, p \equiv 3 \mod 4\) and \(m \equiv 1 \mod 2\). Then

\[
S^{NTU}_{A}^{(1)}(1) = \sum_{i=0}^{\frac{p^m-3}{2}} S^{NTU}_{A,2i+1} = \begin{cases} 
0 & \text{if } p \equiv 3 \mod 8 \\
1 & \text{if } p \equiv 7 \mod 8.
\end{cases}
\]

**Theorem**

Assume that \((A/p) = -1, \, p \equiv 3 \mod 4\) and \(m \equiv 1 \mod 2\). Then

\[
L(S^{NTU}_{A}) = \begin{cases} 
\frac{p^m-1}{p-1} \left( L(S^{NTU}_{A})+1 \right) -1 & \text{if } p \equiv 3 \mod 8 \\
\frac{p^m-1}{p-1} \left( L(S^{NTU}_{A})-1 \right) +1 & \text{if } p \equiv 7 \mod 8.
\end{cases}
\]

**Remark**

In the case of \(m \equiv 0 \mod 2\), Heguri et al. obtained a formula of LC by numerical experiments (See Remark 11 in the proceeding).
Sketch of the proof of Lemma

Interleaved structure of an m-sequence $R = (R_n)_{n \geq 0}$

\[
R_0 \quad R_1 \quad R_2 \quad \cdots \quad R_{\nu-1} \\
R_\nu \quad R_{\nu+1} \quad R_{\nu+2} \quad \cdots \quad R_{2\nu-1} \\
\vdots \quad \vdots \quad \vdots \quad \ddots \quad \vdots \\
R_{(p-2)\nu} \quad R_{(p-2)\nu+1} \quad R_{(p-2)\nu+2} \quad \cdots \quad R_{(p-1)\nu-1}
\]

\[
\nu = (p^m - 1)/(p - 1)
\]
Sketch of the proof of Lemma (cont.)

The number of terms satisfying $S_{A,iν+j}^{\text{NTU}} = 1$ and $iν + j \equiv 1 \mod 2$

$$\sum_{i=0}^{(p^m-3)/2} S_{A,2i+1}^{\text{NTU}} = \frac{p^{m-1} - 1}{p - 1} \times \frac{p - 1}{2} + \left\{ \nu - \frac{p^{m-1} - 1}{p - 1} \right\} \times \frac{p - 3}{4}$$

- # of "(0)"s
- # of "0"s in (0)
- # of "$D_0$ or $D_1$"s
- $d(0, 1; A)$ or $d(1, 1; A)$
Conditions to have a large linear complexity

Descriptions of $L(S_A^\text{NTU})$ using $L(s_A^\text{NTU})$

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<td>$\frac{p^m - 1}{p - 1} L(s_A^\text{NTU})$</td>
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Conditions to have a large linear complexity

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Conditions to have a large linear complexity

$p = 2^s r + 1$ (\(r\): odd prime number, 2 \(\in\) \(\mathbb{F}_r\): primitive root, \(r \geq \sqrt{p} + 1\)).

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<td>$s \geq 2$</td>
<td>$L(S_A^{NTU}) = p^m - 1 \leftarrow \text{max}$</td>
<td>$L(S_A^{NTU}) = \frac{p^{m+1} - 3p^m + 2}{p - 1}$</td>
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<td>$p \equiv 7 \mod 8 (s = 1)$</td>
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This table is obtained by the result of Meidl–Winterhof (Brandstatter–Meidl).
Conclusion

We investigate linear complexity of generalized NTU sequences.

We describe $L(S_{A}^{NTU})$ using $L(s_{A}^{NTU})$ with the following strategy:

1. Applying a formula for general geometric sequences
2. Considering the sequence of complement numbers
3. Using the Hasse derivative and cyclotomic classes

We can ensure that generalized NTU sequences have large linear complexity from the results on linear complexity of Sidel’nikov sequences.

Future work

- Theoretical estimation in the case of $m \equiv 0 \mod 2$.
- Estimation of linear complexity profile.
- Applications to cryptography.
Thank you for your attention.