On the maximum order complexity of the Thue-Morse and Rudin-Shapiro sequence

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Abstract

Expansion complexity and maximum order complexity are both finer measures of pseudorandomness than the linear complexity which is the most prominent quality measure for cryptographic sequences. The expected value of the Nth maximum order complexity is of order of magnitude $\log N$ whereas it is easy to find families of sequences with Nth expansion complexity exponential in $\log N$. This might lead to the conjecture that the maximum order complexity is a finer measure than the expansion complexity. However, in this paper we provide two examples, the Thue-Morse sequence and the Rudin-Shapiro sequence with very small expansion complexity but very large maximum order complexity. More precisely, we prove explicit formulas for their Nth maximum order complexity which are both of largest possible order of magnitude N. We present the result on the Rudin-Shapiro sequence in a more general form as a formula for the maximum order complexity of certain pattern sequences.

1 Introduction

1.1 Motivation

For a sequence $\mathcal{S} = (s_i)_{i=0}^{\infty}$ over the finite field $\mathbb{F}_2$ of two elements and a positive integer N, the *Nth linear complexity* $L(\mathcal{S}, N)$ is the length L of a shortest linear recurrence

$$s_{i+L} = \sum_{\ell=0}^{L-1} c_\ell s_{i+\ell}, \quad 0 \le i \le N-L-1,$$

with coefficients $c_\ell \in \mathbb{F}_2$, which is satisfied by the first N terms of the sequence.

The (Nth) linear complexity is a measure for the unpredictability of a sequence and thus its suitability in cryptography. A sequence $\mathcal{S}$ with small $L(\mathcal{S}, N)$ for a sufficiently large N is disastrous for cryptographic applications. However, the converse is not true. There are highly predictable sequences $\mathcal{S}$ with large $L(\mathcal{S}, N)$, including the example

$$s_0 = \ldots = s_{N-2} = 0 \neq s_{N-1}. \tag{1}$$

Hence, for testing the suitability of a sequence in cryptography we also have to study finer figures of merit. A recent survey on linear complexity and related measures is given in [14].

The *Nth maximum order complexity* $M(\mathcal{S}, N)$ (or *Nth nonlinear complexity*) of a binary sequence $\mathcal{S} = (s_i)_{i=0}^{\infty}$ with $(s_0, \ldots, s_{N-2}) \neq (a, \ldots, a)$ and $a \in \{0, 1\}$ is the smallest positive integer M such that there is a polynomial $f(x_1, \ldots, x_M) \in \mathbb{F}_2[x_1, \ldots, x_M]$ with

$$s_{i+M} = f(s_i, s_{i+1}, \ldots, s_{i+M-1}), \quad 0 \leq i \leq N - M - 1,$$

see [7, 8, 18]. If $s_i = a$ for $i = 0, \ldots, N-2$, we define $M(\mathcal{S}, N) = 0$ if $s_{N-1} = a$ and $M(\mathcal{S}, N) = N - 1$ if $s_{N-1} \neq a$.

Obviously we have

$$M(\mathcal{S}, N) \leq L(\mathcal{S}, N).$$

We have $M(\mathcal{S}, N) = L(\mathcal{S}, N) - 1$ for the example (1). However, the expected value of $M(\mathcal{S}, N)$ is of order of magnitude $\log N$, see [7] and also [4, 9, 18], and the expected value of $L(N)$ is $N/2 + O(1)$ by [5]. Hence, the maximum order complexity is a finer measure of pseudorandomness than the linear complexity.

Diem [3] introduced the expansion complexity of the sequence $\mathcal{S}$ as follows. We define the *generating function* $G(x)$ of $\mathcal{S}$ by

$$G(x) = \sum_{i=0}^{\infty} s_i x^i,$$

viewed as a formal power series over $\mathbb{F}_2$. (Note the change by the factor x compared to the definition in [3].) For a positive integer N, the *Nth expansion complexity* $E_N = E_N(\mathcal{S})$ is $E_N = 0$ if $s_0 = \ldots = s_{N-1} = 0$ and otherwise the least total degree of a nonzero polynomial $h(x, y) \in \mathbb{F}_2[x, y]$ with

$$h(x, G(x)) \equiv 0 \bmod x^N.$$

By [15, Theorem 3] we have

$$E(\mathcal{S}, N) \leq L(\mathcal{S}, N) + 1$$

and also in [15] examples of sequences $\mathcal{S}$ are given with $E(\mathcal{S}, N)$ substantially smaller than $L(\mathcal{S}, N)$. Hence, the expansion complexity is also a finer measure of pseudorandomness than the linear complexity. In particular, for (ultimately) non-periodic automatic sequences we have seen in [17] that they have bounded expansion complexity but linear complexity of order of magnitude N.

Now it is a natural question to compare the two finer measures of pseudorandomness, expansion complexity and maximum order complexity. On the one hand, by [15, Theorem 1] for any T-periodic sequence $\mathcal{S}$ and $N > T(T-1)$ we have $E(\mathcal{S}, N) = L(\mathcal{S}, N) + 1$ which has an expected value of order of magnitude T, see for example [14]. On the other hand, the expected value of $M(\mathcal{S}, N)$ is of order of magnitude $\log N$. This might lead to the conjecture that $M(\mathcal{S}, N)$ is a finer measure of pseudorandomness than $E(\mathcal{S}, N)$. However, in this paper we will disprove this conjecture by showing that certain pattern sequences which include the Thue-Morse and the Rudin-Shapiro sequence have bounded expansion complexity but maximum order complexity of largest possible order of magnitude N. We explain this more precisely in the next subsection.

1.2 Results of this paper

The *Thue-Morse sequence* $\mathcal{T} = (t_i)_{i=0}^{\infty}$ over $\mathbb{F}_2$ is defined by

$$t_i = \begin{cases} t_{i/2} & \text{if } i \text{ is even,} \\ t_{(i-1)/2} + 1 & \text{if } i \text{ is odd,} \end{cases} \qquad i = 1, 2, \ldots \tag{2}$$

with initial value $t_0 = 0$. Taking

$$h(x, y) = (x+1)^3 y^2 + (x+1)^2 y + x$$

its generating function $G(x)$ satisfies $h(x, G(x)) = 0$ and thus

$$E(\mathcal{T}, N) \le 5, \quad N = 1, 2, \ldots$$

Theorem 1 below gives an explicit formula for $M(\mathcal{T}, N)$ of order of magnitude N.

More generally, for a positive integer k we study the *pattern sequence* $\mathcal{P}_k = (p_i)_{i=0}^{\infty}$ over $\mathbb{F}_2$ defined by

$$p_i = \begin{cases} p_{\lfloor i/2 \rfloor} + 1 & \text{if } i \equiv -1 \mod 2^k, \\ p_{\lfloor i/2 \rfloor} & \text{otherwise,} \end{cases} \qquad i = 1, 2, \ldots \tag{3}$$

with initial value $p_0 = 0$. For $k = 1$ we get the Thue-Morse sequence and for $k = 2$ the *Rudin-Shapiro sequence*.

Taking

$$h(x, y) = (x+1)^{2^k+1} y^2 + (x+1)^{2^k} y + x^{2^k - 1}$$

its generating function $G(x)$ satisfies $h(x, G(x)) = 0$ and thus

$$E(\mathcal{P}_k, N) \le 2^k + 3, \quad N = 1, 2, \ldots$$

Theorem 2 below provides an explicit formula for $M(\mathcal{P}_k, N)$ for $k \ge 2$ of order of magnitude N. Note that the case $k = 1$ is slightly different than the case $k \ge 2$.

In Section 2 we study the maximum order complexity of the Thue-Morse sequence, that is, $\mathcal{P}_1$ and in Section 3 of $\mathcal{P}_k$ for $k \ge 2$.

2 Thue-Morse sequence

Theorem 1. *For $N \ge 4$, the Nth maximum order complexity of the Thue-Morse sequence $\mathcal{T}$ satisfies*

$$M(\mathcal{T}, N) = 2^\ell + 1,$$

where

$$\ell = \left\lceil \frac{\log(N/5)}{\log 2} \right\rceil.$$

Proof. For $N = 4, 5, 6$ the result is easy to verify.

By the monotony of the maximum order complexity it is enough to show

$$M(\mathcal{T}, 5 \cdot 2^{\ell-1} + 1) \ge 2^\ell + 1 \ge M(\mathcal{T}, 5 \cdot 2^\ell) \quad \text{for } \ell = 1, 2, \ldots$$

The first inequality follows from

$$t_i = t_{i+3\cdot 2^{\ell-1}} \quad \text{for } i = 0, 1, \ldots, 2^\ell - 1 \quad \text{and} \quad t_{2^\ell} \ne t_{5\cdot 2^{\ell-1}}, \quad \ell = 1, 2, \ldots$$

which we show by induction over ℓ. For $\ell = 1$ the assertion is obviously true and we may assume $\ell \ge 2$.
For even i we get by (2) and induction

$$t_i = t_{i/2} = t_{i/2+3\cdot 2^{\ell-2}} = t_{i+3\cdot 2^{\ell-1}}, \quad i = 0, 2, \ldots, 2^\ell - 2.$$

For odd i we get

$$t_i = t_{(i-1)/2} + 1 = t_{(i-1)/2+3\cdot 2^{\ell-2}} + 1 = t_{i+3\cdot 2^{\ell-1}}, \quad i = 1, 3, \ldots, 2^\ell - 1.$$

Moreover,

$$t_{2^\ell} = t_{2^{\ell-1}} \ne t_{5\cdot 2^{\ell-2}} = t_{5\cdot 2^{\ell-1}}.$$

Now we prove $M(\mathcal{T}, 5 \cdot 2^\ell) \le 2^\ell + 1$ for $\ell = 1, 2, \ldots$ In other words, we have to show that for any $\ell = 1, 2, \ldots$, if for some $0 \le j < k \le 2^{\ell+2} - 2$ we have

$$t_{i+j} = t_{i+k} \quad \text{for } i = 0, 1, \ldots, 2^\ell, \tag{4}$$

then we also have $t_{2^\ell+1+j} = t_{2^\ell+1+k}$. This can be easily verified for $\ell = 1$ and we may assume $\ell \geq 2$.

First we note that $(t_j, t_{j+1}, t_{j+2}, t_{j+3})$ is of the form $(x, x+1, y, y+1)$ if j is even since $t_{2m+1} = t_m + 1 = t_{2m} + 1$ and either of the form $(x, x, x+1, y)$ for $j \equiv 1 \mod 4$ or $(x, y, y+1, y+1)$ for $j \equiv 3 \mod 4$ since $t_{4m+1} = t_m + 1 = t_{4m+2}$ and $t_{4m+3} = t_m = t_{4m}$. Hence, $(t_j, t_{j+1}, t_{j+2}, t_{j+3}) = (t_k, t_{k+1}, t_{k+2}, t_{k+3})$ implies $j \equiv k \mod 2$.

If j and k are both even, then from (2) and (4) with $i = 2^\ell$ we get

$$t_{2^\ell+1+j} = t_{2^{\ell-1}+j/2} + 1 = t_{2^\ell+j} + 1 = t_{2^\ell+k} + 1 = t_{2^\ell+k+1}.$$

If j and k are both odd, then (4) implies for any even i

$$t_{i/2+(j-1)/2} = t_{i+j} + 1 = t_{i+k} + 1 = t_{i/2+(k-1)/2} \quad \text{for } i = 0, 2, \ldots, 2^\ell$$

and by induction

$$t_{2^\ell+1+j} = t_{2^{\ell-1}+(j+1)/2} = t_{2^{\ell-1}+(k+1)/2} = t_{2^\ell+1+k},$$

which completes the proof. □

Remark 1. It is easy to see that $\frac{N}{5} + 1 \leq M(\mathcal{T}, N) \leq 2\frac{N-1}{5} + 1$ for $N \geq 4$ and $M(\mathcal{T}, 1) = 0$, $M(\mathcal{T}, 2) = M(\mathcal{T}, 3) = 1$.

3 Pattern sequences

Theorem 2. *For $k \geq 2$ and $N \geq 2^{k+3} - 7$, the Nth maximum order complexity of the pattern sequence $\mathcal{P}_k$ satisfies*

$$M(\mathcal{P}_k, N) = (2^{k-1} - 1)2^\ell + 1$$

where

$$\ell = \left\lceil \frac{\log(N/(2^k - 1))}{\log 2} \right\rceil - 1.$$

Proof. By the monotony of the maximum order complexity it is enough to show

$$M(\mathcal{P}_k, (2^k - 1)2^\ell + 1) \geq (2^{k-1} - 1)2^\ell + 1 \geq M(\mathcal{P}_k, (2^k - 1)2^{\ell+1}) \quad \text{for } \ell \geq 3.$$

The first inequality follows from

$$\begin{aligned} p_i \quad &= \quad p_{i+2^{\ell+k-1}} \quad \text{for} \quad i = 0, 1, \ldots, (2^{k-1} - 1)2^\ell - 1 \\ &\text{and} \quad p_{(2^{k-1}-1)2^\ell} \neq p_{(2^k-1)2^\ell} \end{aligned} \tag{5}$$

for $\ell \geq 0$, which we show by induction over ℓ. For $\ell = 0$ the assertion is obviously true since $p_i = 0$ for $i = 0, 1, \ldots, 2^k - 2$ and $p_{2^k-1} = 1$ by (3). We

may assume $\ell \geq 1$.
For even i we get from (3) and induction

$$p_i = p_{i/2} = p_{i/2+2^{\ell+k-2}} = p_{i+2^{\ell+k-1}}, \quad i = 0, 2, \ldots, (2^{k-1}-1)2^{\ell} - 2. \tag{6}$$

For odd i we get from (3)

$$p_i = \begin{cases} p_{i-1} & \text{if } i \not\equiv -1 \bmod 2^k \\ p_{i-1}+1 & \text{if } i \equiv -1 \bmod 2^k, \end{cases}, \qquad i = 1, 3, \ldots \tag{7}$$

Now fix any odd $i = 1, 3, \ldots, (2^{k-1}-1)2^{\ell} - 1$. If $i \not\equiv -1 \bmod 2^k$, then we get from (6) and (7)

$$p_i = p_{i-1} = p_{i-1+2^{\ell+k-1}} = p_{i+2^{\ell+k-1}}.$$

If $i \equiv -1 \bmod 2^k$, then

$$p_i = p_{i-1} + 1 = p_{i-1+2^{\ell+k-1}} + 1 = p_{i+2^{\ell+k-1}}.$$

Moreover,

$$p_{(2^{k-1}-1)2^{\ell}} = p_{(2^{k-1}-1)2^{\ell-1}} \neq p_{(2^k-1)2^{\ell-1}} = p_{(2^k-1)2^{\ell}}$$

by induction.

Now we prove $M(\mathcal{P}_k, (2^k-1)2^{\ell+1}) \leq (2^{k-1}-1)2^{\ell} + 1$ for $\ell \geq 3$.

That is, we have to show for any $\ell \geq 3$ that, if for some $0 \leq j < n \leq (3 \cdot 2^{k-1} - 1)2^{\ell} - 2$ we have

$$p_{i+j} = p_{i+n} \quad \text{for } i = 0, 1, \ldots, (2^{k-1}-1)2^{\ell}, \tag{8}$$

then we also have

$$p_{(2^{k-1}-1)2^{\ell}+1+j} = p_{(2^{k-1}-1)2^{\ell}+1+n}. \tag{9}$$

First we observe that (8) implies $j \equiv n \bmod 2^k$:

We choose any m_1, m_2 with $n + m_1 \equiv 2^k - 1 \bmod 2^{k+1}$ and $n + m_2 \equiv -1 \bmod 2^{k+1}$ and see that

$$n + m_1 \equiv n + m_2 \equiv -1 \bmod 2^k, \quad (n + m_1 - 1)/2 \equiv 2^{k-1} - 1 \bmod 2^k$$

and

$$(n + m_2 - 1)/2 \equiv -1 \bmod 2^k.$$

If $j \equiv n \bmod 2$, then $j + m_1 \equiv 1 \bmod 2$. Moreover, we assume $1 \leq m_1 \leq 2^{k+1}$ in this case. Now (8) with $i \in \{m_1, m_1 - 1\}$ and (7) imply $p_{j+m_1} = p_{n+m_1} = p_{n+m_1-1} + 1 = p_{j+m_1-1} + 1$ and from (7) again we get $j + m_1 \equiv -1 \bmod 2^k$ and thus $j \equiv n \bmod 2^k$ in this case.

If $j \not\equiv n \bmod 2$, we assume $2 \le m_1, m_2 \le 2^{k+1}+1$. Then from (8) with $i \in \{m_1-1, m_1-2\}$, (3) and (7) we get $p_{j+m_1-1} = p_{n+m_1-1} = p_{(n+m_1-1)/2} = p_{(n+m_1-3)/2} = p_{n+m_1-3} = p_{n+m_1-2} = p_{j+m_1-2}$ implies $j + m_1 - 1 \not\equiv -1 \bmod 2^k$. However, $p_{j+m_2-1} = p_{n+m_2-1} = p_{n+m_2-2} + 1 = p_{j+m_2-2} + 1$ and (7) imply $j + m_2 - 1 \equiv -1 \bmod 2^k$ in contradiction to $m_1 \equiv m_2 \bmod 2^k$.

It remains to show that (8) implies (9) for any $j \equiv n \bmod 2^k$.

For $j \equiv n \equiv 0 \bmod 2$, (7) and (8) with $i = (2^{k-1}-1)2^\ell$ immediately imply (9). For $j \equiv n \equiv 1 \bmod 2$ we prove the assertion by induction.

Note that from (5) we get the last $(2^{k-1}-1)2^{\ell+1}$ elements from the first ones:

$$p_{i+2^{\ell+k}} = p_i \quad \text{for } i = 0, 1, \ldots, (2^{k-1}-1)2^{\ell+1} - 1.$$

Then for verifying our assertion for $\ell = 3$ we need only the first $3 \cdot 2^{k+2} - 7$ elements of P_k. We use the abbreviation $a^t = \underbrace{aa\ldots a}_{t}$ for the word of t consecutive a and get using (3):

$$\mathcal{P}_2 = \left(0^3 1 0^2 1 0^4 1^3 0 1 0^3 1 0^2 1 0 1^3 0^3 1 0^4 1 0^2 1 0 0 \ldots\right)$$

$$\mathcal{P}_3 = \left(0^7 1 0^6 1 0^8 1 0^4 1^2 0 1 0^7 1 0^6 1 0^8 1^5 0^2 1 0^8 1 0^6 1 0^8 1 0 \ldots\right)$$

and for $k \ge 4$

$$\begin{aligned} \mathcal{P}_k \;=\; \big(&0^{2^k-1} 1 0^{2^k-2} 1 0^{2^k} 1 0^{2^k-4} 1^2 0 1 0^{2^k-1} 1 0^{2^k-2} 1 0^{2^k} 1 0^{2^k-8} 1^4 0^2 1 \\ &0^{2^k} 1 0^{2^k-2} 1 0^{2^k} 1 0^{2^k-7} \ldots\big). \end{aligned}$$

Note that we have to compare only the patterns of length $(2^{k-1}-1)2^\ell + 2$ starting with p_j and p_n with $j \equiv n \bmod 2^k$, $j \equiv n \equiv 1 \bmod 2$ and $0 \le j < n \le 2^{k+3} - 1$.

Now we consider $\ell \ge 4$. For even i with $0 \le i \le (2^{k-1}-1)2^\ell$ we get from (3) and (8)

$$p_{i/2+(j-1)/2} = p_{i/2+(n-1)/2}.$$

From the observations above we know that this is only possible if $(j-1)/2 \equiv (n-1)/2 \bmod 2^k$. Either by induction if $(j-1)/2 \equiv (n-1)/2 \equiv 1 \bmod 2$ or using the already above verified result if $(j-1)/2 \equiv (n-1)/2 \equiv 0 \bmod 2$, we get

$$\begin{aligned} p_{(2^{k-1}-1)2^\ell+1+j} &= p_{(2^{k-1}-1)2^{\ell-1}+(j+1)/2} = p_{(2^{k-1}-1)2^{\ell-1}+(n+1)/2} \\ &= p_{(2^{k-1}-1)2^\ell+1+n}, \end{aligned}$$

which completes the proof. □

Remark 2. The restriction on N in Theorem 2 is needed. For example, for the Rudin-Shapiro sequence we have

$$M(\mathcal{P}_2, N) = \begin{cases} 0, & 1 \le N \le 3, \\ 3, & 4 \le N \le 9, \\ 6, & 10 \le N \le 24. \end{cases}$$

Remark 3. For $k \ge 2$ and $N \ge 2^{k+3} - 7$ Theorem 2 implies

$$\frac{N}{6} + 1 \le \frac{2^{k-1} - 1}{2^k - 1}\frac{N}{2} + 1 \le M(\mathcal{P}_k, N) \le \frac{2^{k-1} - 1}{2^k - 1}(N-1) + 1 < \frac{N+1}{2}.$$

4 Final remarks

The correlation measure of order k introduced by Mauduit and Sárközy [12] is another figure of merit which is finer than the linear complexity, see [1]. A cryptographic sequence must have small correlation measure of all orders k up to a sufficiently large k. In [6] the maximum order complexity of a binary sequence was estimated in terms of its correlation measures. Roughly speaking, it was shown that any sequence with small correlation measure up to a sufficiently large order k cannot have very small maximum order complexity. Moreover, the correlation measure of order 2 of both Thue-Morse and Rudin-Shapiro sequence of length N is of order of magnitude N, see [13]. The same is true for any pattern sequence, see [16]. Hence, together with the results of this paper we see that the correlation measure of order k is a finer quality measure for cryptographic sequences than the maximum order complexity.

Combining a bound of [2] on the state complexity in terms of the expansion complexity and a bound of [16] on the state complexity in terms of the correlation measure of order 2, we can also estimate the expansion complexity in terms of the correlation measure of order 2.

Furthermore, the maximum order complexity and its connections with Lempel-Ziv complexity was studied in [10].

In [19] the (periodic) sequences of largest possible maximum order complexity were classified. However, these sequences are highly predictable and not suitable in cryptography. In [18] and [11] several sequence constructions are given which have very large maximum order complexity but no obvious flaw.

Finally, we mention that although the linear complexity is a weaker quality measure for cryptographic sequences than maximum order complexity as well as correlation measure and expansion complexity, it is still of high practical importance since it is much easier to calculate than all of the finer measures.

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