Cryptography using the Laplace transform for the Serbian language

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Abstract:

Introduction/purpose: In this paper, the authors develop a new mathematical method for cryptography. The procedure was performed for messages written in the Serbian language, which consists of 30 phonemes.

Methods: The standard expansion of the inverse trigonometric function in a Taylor series was used. The Laplace transform was applied to encrypt the plaintext, while the corresponding inverse Laplace transform was used for decryption.

Results: A new cryptographic algorithm has been written to encrypt and decrypt a text message written in Serbian letters.

Conclusions: In the paper, the authors presented a new algorithm in which the Laplace transform was used for the encryption and decryption of a text message. The message is written in Serbian in Cyrillic letters.

Key words: cryptography, Laplace transform, inverse trigonometric function, Taylor series.

Introduction

Cryptography is a field of mathematics that deals with hiding secret text messages. It dates back to the time of Caesar, but most of the scientific work is devoted to modern digital cryptography. Numerous authors have dealt with this field, for example: Bhuvaneswari (2020), Gencoglu (2016), Gencoglu et al. (2019), Martin (2012), Delfs and Knebl (2007). Recently, several papers have been published in which the Laplace transform is implemented in cryptographic algorithms, for example: Al-Azzani et al. (2021), Briones (2018), Gencoglu (2017, 2019a), Gupta and Mishra (2014), Hiwarekar (2012), Nagalakshmi et al. (2019, 2020). One of these works (Gencoglu, 2019a) motivated this paper. Namely, in the paper (Gencoglu, 2019a) the authors gave an algorithm for text messages in Turkish. In this paper, we have provided a new algorithm for encryption and decryption of text written in Serbian.

Considering that the mathematical model uses the Laplace transform, we first present the fundamental theory of this topic.

Definition 1. *Suppose that f is a real or complex-valued function of the time variable $t > 0$ and s is a real or complex parameter. We define the Laplace transform of f as follows:*

$$F(s) = \mathscr{L}\{f(t)\}(s) = \int_0^\infty e^{-st} f(t)\, dt,$$

whenever this integral converges for some values of s.

One of the most basic and useful properties of the Laplace operator $\mathscr{L}$ is that of linearity, namely, if $f_1 \in L$ for $Re(s) > \alpha$, $f_2 \in L$ for $Re(s) > \beta$, then $f_1 + f_2 \in L$ for $Re(s) > \max\{\alpha, \beta\}$, and

$$\mathscr{L}\{C_1 f_1(t) + C_2 f_2(t)\} = C_1 F_1(s) + C_2 F_2(s),$$

for arbitrary constants C_1 and C_2.

Definition 2. *If $\mathscr{L}\{f(t)\}(s) = F(s)$, then the inverse Laplace transform is denoted by*

$$\mathscr{L}^{-1}\{F(s)\} = f(t), \quad t \geq 0,$$

and it maps the Laplace transform of a function back to the original function.

Additionally, $\mathscr{L}^{-1}$ is linear, that is

$$\mathscr{L}^{-1}\{C_1 F_1(s) + C_2 F_2(s)\} = C_1 f_1(t) + C_2 f_2(t),$$

if $\mathscr{L}\{f_1(t)\}(s) = F_1(s)$ and $\mathscr{L}\{f_2(t)\}(s) = F_2(s)$, for arbitrary constants C_1 and C_2.

In our result we will use the values of Laplace and inverse Laplace transform for the function t^n, and these are $\mathscr{L}\{t^n\} = \frac{n!}{s^{n+1}}$; $\mathscr{L}^{-1}\left\{\frac{n!}{s^{n+1}}\right\} = t^n$.

Proposed mathematical model for encryption and decryption text message

In this section we present new algorithms for text encryption and decryption. The algorithm uses the Taylor series expansion of the arctg function, and then applies the Laplace transform to this series. We provide a detailed explanation of the text encryption.

Encryption:

Consider Tayler's expansion of these functions:

$$\operatorname{arctg} t = \int_0^t \frac{1}{1+t^2} dt = \int_0^t \left(\sum_{n=0}^{+\infty} (-1)^n t^{2n} \right) dt$$
$$= \sum_{n=0}^{+\infty} (-1)^n \int_0^t t^{2n} dt = \sum_{n=0}^{+\infty} (-1)^n \frac{t^{2n+1}}{2n+1}.$$

Each letter of the message is converted to an integer. M_l, $l = 0, ..., 29$, whereby $M_l = 0$ for $l > 29$. Thus, we must indicate that the letters take on the integer values, i.e. A = 0, B = 1, V = 2, Š = 29.

Let us consider

$$t \cdot \operatorname{arctg} rt = \sum_{n=0}^{+\infty} (-1)^n \frac{r^{2n+1} t^{2n+2}}{2n+1},$$

where r is a positive constant.

Using the previous Taylor series for $r = 2$, we observe the function:

$$f(t) = M_0 \tfrac{2t^2}{1} - M_1 \tfrac{2^3 t^4}{3} + M_2 \tfrac{2^5 t^6}{5} - M_3 \tfrac{2^7 t^8}{7} + ... + (-1)^{l-1} M_{l-1} \tfrac{2^{2l-1} t^{2l}}{2l-1}$$
$$= \sum_{n=0}^{l-1} M_n (-1)^n \tfrac{2^{2n+1} t^{2n+2}}{2n+1}.$$

Taking Laplace transformation to both sides of Taylor series we get the following.

$$\mathscr{L}\{f(t)\}(s)$$
$$= M_0 \tfrac{2 \cdot 2!}{1 s^3} - M_1 \tfrac{2^3 \cdot 4!}{3 s^5} + M_2 \tfrac{2^5 \cdot 6!}{5 s^7} - M_3 \tfrac{2^7 \cdot 8!}{7 s^9} + ... + (-1)^{l-1} M_{l-1} \tfrac{2^{2l-1}(2l)!}{(2l-1) s^{2l+1}}.$$

Let $\Phi_i = M_i \frac{2^{2i+1}(2i+2)!}{(2i+1)}, \quad i = 0, 1, ..., l-1.$

The last relation takes a simpler form

$$\mathscr{L}\left\{f\left(t\right)\right\}\left(s\right)=\frac{\Phi_0}{s^3}-\frac{\Phi_1}{s^5}+\frac{\Phi_2}{s^7}-\frac{\Phi_3}{s^9}+...+\left(-1\right)^{l-1}\frac{\Phi_{l-1}}{s^{2l+1}}.$$

We transform the previous sum by multiplying each summand by $b_i=\frac{1}{(2i+2)!}$, $i=0,1,...,l-1$:

$$F_b(s)=\frac{b_0\Phi_0}{s^3}-\frac{b_1\Phi_1}{s^5}+\frac{b_2\Phi_2}{s^7}-\frac{b_3\Phi_3}{s^9}+...+\left(-1\right)^{l-1}\frac{b_{l-1}\Phi_{l-1}}{s^{2l+1}}.$$

Let us introduce the tags $R_i=\lfloor b_i\cdot\Phi_i\rfloor$, $i=0,1,2...,l-1$, thus getting

$$G_b(s)=\frac{R_0}{s^3}-\frac{R_1}{s^5}+\frac{R_2}{s^7}-\frac{R_3}{s^9}+...+\left(-1\right)^{l-1}\frac{R_{l-1}}{s^{2l+1}}. \quad (1)$$

The letters of the cipher text are obtained from the relation $M_i'=R_i-30k_i$, $i=0,1,2...,l-1$, and the key is given with $k_i=\frac{R_i-M_i'}{30}$, $i=0,1,2...,l-1$.

Decryption:

The reader receives the message as cipher text in terms of $M_i^{;}$ $i=0,1,...,l-1$, that is

$$R_i=30k_i+M_i'.$$

From (1), we have

$$G_b(s)=\frac{R_0}{s^3}-\frac{R_1}{s^5}+\frac{R_2}{s^7}-\frac{R_3}{s^9}+...+\left(-1\right)^{l-1}\frac{R_{l-1}}{s^{2l+1}}.$$

Multiplying each summand by b_i^{-1}, $i=0,1,...,l-1$, gives

$$\frac{b_0^{-1}R_0}{s^3}-\frac{b_1^{-1}R_1}{s^5}+\frac{b_2^{-1}R_2}{s^7}-\frac{b_3^{-1}R_3}{s^9}+...+\left(-1\right)^{l-1}\frac{b_{l-1}^{-1}R_{l-1}}{s^{2l+1}},$$

i.e.

$$\mathscr{L}\left\{f\left(t\right)\right\}\left(s\right)=\frac{\Phi_0}{s^3}-\frac{\Phi_1}{s^5}+\frac{\Phi_2}{s^7}-\frac{\Phi_3}{s^9}+...+\left(-1\right)^{l-1}\frac{\Phi_{l-1}}{s^{2l+1}}.$$

By taking the inverse Laplace transform to both sides we obtain

$$\mathscr{L}^{-1}\mathscr{L}\left\{f\left(t\right)\right\}\left(s\right)=\mathscr{L}^{-1}\left\{\frac{\Phi_0}{s^3}-\frac{\Phi_1}{s^5}+\frac{\Phi_2}{s^7}-\frac{\Phi_3}{s^9}+...+\left(-1\right)^{l-1}\frac{\Phi_{l-1}}{s^{2l+1}}\right\},$$

we obtain

$$f\left(t\right)=\Phi_0\frac{t^2}{2!}-\Phi_1\frac{t^4}{4!}+\Phi_2\frac{t^6}{6!}-\Phi_3\frac{t^8}{8!}+...+\left(-1\right)^{l-1}\Phi_{l-1}\frac{t^{2l}}{(2l)!}.$$

The values of the plain text are obtained by using the formula:

$$M_i=\frac{\left(2i+1\right)\Phi_i}{2^{2i+1}\left(2i+2\right)!},\ \ i=0,1,...,l-1.$$

The algorithms of encryption and decryption

The algorithm of encryption:

1. Convert the plain text to an integer number;
2. Embed the integer numbers as the coefficients of the Taylor series of the function $t\,\mathrm{arctg}\,rt$, $r\in N$;
3. Take the Laplace transform to both sides of the Taylor series;
4. The embedding coefficient of the Laplace transform is $\Phi_i=M_i\frac{2^{2i+1}(2i+2)!}{(2i+1)},\ \ i=0,1,...,l-1;$
5. Multiply Φ_i by coefficients $b_i=\frac{1}{(2i+2)!}$, $i=0,1,...,l-1$, and take the floor of these numbers to obtain R_i, $i=0,1,...,l-1;$
6. Use the relation $M_i'=R_i-30k_i,\ i=0,1,2...,l-1$, to obtain the cipher text. The key is $k_i=\frac{R_i-M_i'}{30},\ \ i=0,1,...,l-1.$

Algorithm of decryption:

1. Use the relation $R_i=30k_i+M_i'$, $i=0,1,2...,l-1$, to obtain R_i, from the cipher text;
2. Multiply coefficients R_i by b_i^{-1}, $i=0,1,...,l-1$, to obtain Φ_i, $i=0,1,...,l-1;$
3. Take the inverse of the Laplace transform to both sides of the Taylor series;
4. Use the relation $M_i=\frac{(2i+1)\Phi_i}{2^{2i+1}(2i+2)!}$, $i=0,1,2...,l-1$, to obtain the plain text.

Application

We apply the above algorithm to a specific example for the Cyrillic alphabet. The Serbian word ЋИРИЛИЦА is first translated into a corrected message, after which the inverse procedure is performed

We assign values from 0 to 29 to each letter of this word, respectively, according to the alphabet, because the Serbian language consists of 30 letters.

Encryption:

$M_0 = 22$; $M_1 = 9$; $M_2 = 19$; $M_3 = 9$; $M_4 = 12$; $M_5 = 9$; $M_6 = 26$; $M_7 = 0$.

We apply the starting function from the algorithm:

$$f(t) = \operatorname{arctg} t = \sum_{n=0}^{+\infty} (-1)^n \frac{t^{2n+1}}{2n+1},$$

i.e.

$$t \operatorname{arctg} 2t = \sum_{n=0}^{+\infty} (-1)^n \frac{2^{2n+1} t^{2n+2}}{2n+1}.$$

We insert the given coefficients into the upper function:

$$f(t) = Mt \operatorname{arctg} 2t = \sum_{n=0}^{+\infty} (-1)^n \tfrac{2^{2n+1} t^{2n+2}}{2n+1} = \\ = 22\tfrac{2^1 t^2}{1} - 9\tfrac{2^3 t^4}{3} + 19\tfrac{2^5 t^6}{5} - 9\tfrac{2^7 t^8}{7} + 12\tfrac{2^9 t^{10}}{9} - 9\tfrac{2^{11} t^{12}}{11} + 26\tfrac{2^{13} t^{14}}{13} - 0\tfrac{2^{15} t^{16}}{15}$$

We implement the step from the algorithm in which the Laplace transform is applied:

$$\mathscr{L}\{f(t)\}(s) \\ = 22\tfrac{2^1 2!}{1\cdot s^3} - 9\tfrac{2^3 4!}{3\cdot s^5} + 19\tfrac{2^5 6!}{5\cdot s^7} - 9\tfrac{2^7 8!}{7\cdot s^9} + 12\tfrac{2^9 10!}{9\cdot s^{11}} - 9\tfrac{2^{11} 12!}{11\cdot s^{13}} + 26\tfrac{2^{13} 14!}{13\cdot s^{15}} - 0\tfrac{2^{15} 16!}{15\cdot s^{17}}.$$

From there, we obtained the coefficients $\Phi_0 = \frac{22\cdot 2^1\cdot 2!}{1}$; $\Phi_1 = \frac{9\cdot 2^3\cdot 4!}{3}$; $\Phi_2 = \frac{19\cdot 2^5\cdot 6!}{5}$; $\Phi_3 = \frac{9\cdot 2^7\cdot 8!}{7}$; $\Phi_4 = \frac{12\cdot 2^9\cdot 10!}{9}$; $\Phi_5 = \frac{9\cdot 2^{11}\cdot 12!}{11}$; $\Phi_6 = \frac{26\cdot 2^{13}\cdot 14!}{13}$; $\Phi_7 = \frac{0\cdot 2^{15}\cdot 16!}{15}$.

We take the coefficients $b_i = \frac{1}{(2i+2)!}$, $i = 0, 1, ..., l-1$, and multiply them by the coefficients Φ_i, so we obtain:

$$\mathscr{L}\{bf(t)\}(s) \\ = 22\tfrac{2^1}{1\cdot s^3} - 9\tfrac{2^3}{3\cdot s^5} + 19\tfrac{2^5}{5\cdot s^7} - 9\tfrac{2^7}{7\cdot s^9} + 12\tfrac{2^9}{9\cdot s^{11}} - 9\tfrac{2^{11}}{11\cdot s^{13}} + 26\tfrac{2^{13}}{13\cdot s^{15}} - 0\tfrac{2^{15}}{15\cdot s^{17}}.$$

We introduce the coefficients $R_i = \lfloor b_i \cdot \Phi_i \rfloor$, $i = 0, 1, ..., l-1$, from which we obtain:

$R_0 = 44$; $R_1 = 24$; $R_2 = \left\lfloor \frac{608}{5} \right\rfloor = 121$; $R_3 = \left\lfloor \frac{1152}{7} \right\rfloor = 164$; $R_4 = \left\lfloor \frac{6144}{9} \right\rfloor = 682$; $R_5 = \left\lfloor \frac{18432}{11} \right\rfloor = 1675$; $R_6 = \left\lfloor \frac{212992}{13} \right\rfloor = 16384$; $R_7 = 0$. We represent the numbers R_i, $i = 0, 1, ..., l-1$, in the form $R_i = 30k_i + M_i'$:

$$44 = 1 \cdot 30 + 14;$$
$$24 = 0 \cdot 30 + 24;$$
$$121 = 4 \cdot 30 + 1;$$
$$164 = 5 \cdot 30 + 14;$$
$$682 = 22 \cdot 30 + 22;$$
$$1675 = 55 \cdot 30 + 25;$$
$$16384 = 546 \cdot 30 + 4;$$
$$0 = 0 \cdot 30 + 0.$$

The coefficients $M_i^;$ $i = 0, 1, ..., l-1$, determine the letters in the cipher message, and the values k_i, $i = 0, 1, ..., l-1$, determine the key. In this way, the word ĆIRILICA is translated into the word МФБМЂХДА, and the key is given by: $k_0 = 1$; $k_1 = 0$; $k_2 = 4$; $k_3 = 5$; $k_4 = 22$; $k_5 = 55$; $k_6 = 546$; $k_7 = 0$.

Decryption:

The reader receives the message МФБМЂХДА, and also the key $k_0 = 1$; $k_1 = 0$; $k_2 = 4$; $k_3 = 5$; $k_4 = 22$; $k_5 = 55$; $k_6 = 546$; $k_7 = 0$.

Firstly, we assign values from 0 to 29 to each letter of the cipher message:
$M_0' = 14$; $M_1' = 24$; $M_2' = 1$; $M_3' = 14$; $M_4' = 22$; $M_5' = 25$; $M_6' = 4$; $M_7' = 0$.

In the second step of the algorithm, we determine the coefficients:

$$R_i = 30k_i + M_i' :$$

$R_0 = 44$; $R_1 = 24$; $R_2 = 121$; $R_3 = 164$; $R_4 = 682$; $R_5 = 1675$; $R_6 = 16384$; $R_7 = 0$.

We multiply these coefficients by the coefficients $b_i^{-1} = (2i+2)!$, $i = 0, 1, ..., l-1$, to determine the coefficients Φ_i, $i = 0, 1, ..., l-1$ ($b_0^{-1} = 2!$; $b_1^{-1} = 4!$; $b_2^{-1} = 6!$; $b_3^{-1} = 8!$; $b_4^{-1} = 10!$; $b_5^{-1} = 12!$; $b_6^{-1} = 14!$; $b_7^{-1} = 16!$):

$$\Phi_0 = b_0^{-1} \cdot R_0 = 2! \cdot 44;$$
$$\Phi_1 = b_1^{-1} \cdot R_1 = 4! \cdot 24;$$

$$\Phi_2 = b_2^{-1} \cdot R_2 = 6! \cdot 121;$$
$$\Phi_3 = b_3^{-1} \cdot R_3 = 8! \cdot 164;$$
$$\Phi_4 = b_4^{-1} \cdot R_4 = 10! \cdot 682;$$
$$\Phi_5 = b_5^{-1} \cdot R_5 = 12! \cdot 1675;$$
$$\Phi_6 = b_6^{-1} \cdot R_6 = 14! \cdot 16384;$$
$$\Phi_7 = b_7^{-1} \cdot R_7 = 16! \cdot 0.$$

In the last step, from the relation $M_i = \left\lceil \frac{(2i+1)\Phi_i}{2^{2i+1}(2i+2)!} \right\rceil$, $i = 0, 1, 2..., l-1$, we determine the coefficients M_i, $i = 0, 1, 2..., l-1$,, thus we obtain the coefficients $M_0 = 22$; $M_1 = 9$; $M_2 = 19$; $M_3 = 9$; $M_4 = 12$; $M_5 = 9$; $M_6 = 26$; $M_7 = 0$. The original message is ЋИРИЛИЦА.

Conclusion

This paper presents a new mathematical model for encryption and decryption of text messages. The model uses the inverse trigonometric function $\operatorname{arctg} t$ and its expansion in the Taylor series. Integers are included in this expansion and represent Cyrillic letters. The Laplace transform is applied to the resulting expression. Then, using the established congruence method, the encrypted message and the key are obtained. In this way, an algorithm for encrypting a text message is formulated. Using the inverse procedure, an algorithm for decrypting the text is derived. The theoretical part is illustrated in the final section through a concrete example.

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Kriptografija Laplasovom transformacijom za srpski jezik

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OBLAST: matematika
KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: U ovom radu autori su dali novu matematičku metodu kriptografije. Procedura je sprovedena za poruke napisane na srpskom jeziku, koji se sastoji od 30 fonema.

Memode: Metode: Koristili smo standardni razvoj inverzne trigonometrijske funkcije $\operatorname{arctg} t$ *u Tejlorov red. Takođe smo koristili Laplasovu transformaciju za šifrovanje početnog teksta i odgovarajuću inverznu Laplasovu transformaciju za dešifrovanje kodiranog teksta.*

Rezultati: Napisan je novi kriptografski algoritam za šifrovanje i dešifrovanje tekstualne poruke napisane na srpskom jeziku.

Zaključak: Autori su u radu predstavili novi algoritam u kome je korišćena Laplasova transformacija za šifrovanje i dešifrovanje tekstualne poruke. Poruka je na srpskom jeziku u ćiriličnom pismu.

Ključne reči: kriptografija, Laplasova transformacija, inverzna trigonometrijska funkcija, Tejlorov red.

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