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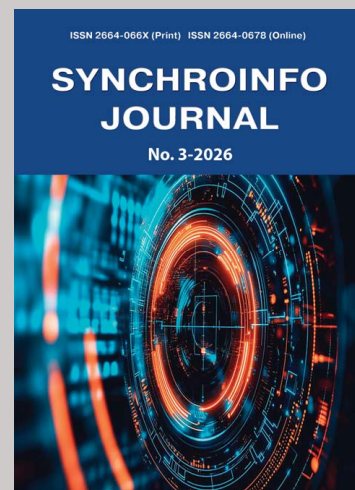
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SYNCHRONIZATION OF M-SEQUENCES AND GOLD PSEUDORANDOM SEQUENCES BASED ON THE FAST HADAMARD TRANSFORM

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ABSTRACT

Methods have been developed for constructing circulant matrices for any maximal-length sequence (MLS) based on the automorphic multiplicative groups of an extended Galois field – a field constructed using the same irreducible primitive polynomial that defines the original MLS. This approach reveals new ways to transform the circulant matrices of an MLS into a matrix of Walsh functions, ordered according to the powers of the field's primitive element. It is demonstrated, for the first time, that – depending on the initial transformation conditions – any set of cyclic shifts of an MLS (where each shift is offset by a single symbol relative to the others) can be mapped to a sequence of consecutive rows within an ordered Walsh function matrix. This finding facilitates the simplification of MLS synchronization algorithms, particularly when the range of possible cyclic shifts is known – a significant advantage for sequences with long repetition periods. Furthermore, it reduces the computational complexity of processing algorithms when operating within a truncated Walsh-Hadamard basis. Based on an analysis of the structures of isomorphic multiplicative groups within extended Galois fields, it has been established that any cyclic shift of a Gold pseudorandom sequence can be transformed into a function belonging to the complete set of analogues of Rademacher functions for a given dimension. This insight has enabled the development of a new fast synchronization algorithm for Gold sequences, which relies on computing their discrete convolution via a fast spectral transform within a truncated Walsh-Hadamard basis.

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KEYWORDS: *noise-like signals, vector-matrix multiplication, Rademacher functions, periodic autocorrelation function, Galois field.*

Introduction

The previous article [1] points out the interrelation between the tasks of joint detection and parameter estimation for a low-power noise-like complex signal (NCS) and the decoding of block codes constructed based on cyclic shifts of their codewords. This article examines the problem of synchronizing a Gold pseudorandom sequence (PRS), highlighting the connection between this task and the synchronization of a periodic NCS during its processing at a receiver. In this context, PRS synchronization is defined as the determination of its cyclic shift – relative to the start of the observation interval for the NCS from which the PRS was generated.

When addressing the synchronization of PRS (pseudorandom sequences) with long repetition periods, it becomes crucial to identify the correspondence between the row indices of a Walsh-Hadamard matrix and the initial blocks of cyclic shifts of the PRS – or, in matrix terms, the rows of a circulant matrix derived from the PRS. As shown below, such a circulant matrix can be constructed in various ways. Consequently, this section explores methods for constructing PRS-based circulant matrices using multiplicative groups of an extended Galois field (defined modulo an irreducible primitive polynomial). It also examines techniques for transforming these matrices into full or truncated Hadamard matrices (or their analogues) to facilitate the development of accelerated PRS synchronization algorithms for processing noise-like signals. The findings presented in this section have been published by the author of this dissertation in [2-5].

Construction of circulant matrices based on multiplicative groups of a Galois field

Let us consider an arbitrary finite field (GF) with elements $\{0, 1\}$, constructed based on an irreducible primitive polynomial $f_m(x)$, as a row vector ${}_i^N \mathfrak{S}_i = [x_{i,k}, k = 0, \dots, N-1]$, where $i = 0, \dots, m-1$ – the number of the cyclic shift of the MS on $l_i \in \{0, 1, \dots, N-1\}$ symbols relative to the MS ${}_0^N \mathfrak{S}_0$ with a nominally zero cyclic shift, $N = 2^m - 1$ – length (period) of the MS, m – order $f_m(x)$, n – the number of the chosen method for ordering MSs based on their cyclic shifts [4, 6-8].

One can choose a way of ordering any m MS (as described above) such that the columns $\alpha^k = [x_{i,k}, i = 0, \dots, m-1]^T, k = 0, \dots, N-1$, form the multiplicative group of an extended Galois field $GF(2^m)$ built on a modular basis $f_m(x)$, where k – is the number of the group element, $[\cdot]^T$ – notation for a transposed matrix [7-9]. Such a group has a cyclic structure and consists of the maximum possible number N of distinct non-zero elements, which are powers of a primitive element α^0 fields, moreover $\alpha^k = H_n \alpha^{k-1}$, where H_n – companion matrix $f_m(x)$ [8]. Typically, four types of such matrices are considered [7]:

$$\begin{aligned} H_1 &= \begin{bmatrix} 0 & 0 & \cdots & 0 & a_0 \\ 1 & 0 & \cdots & 0 & a_1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & a_{m-2} \\ 0 & 0 & \cdots & 1 & a_{m-1} \end{bmatrix} & H_2 &= \begin{bmatrix} 0 & 1 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 1 \\ a_0 & a_1 & \cdots & a_{m-2} & a_{m-1} \end{bmatrix} \\ H_3 &= \begin{bmatrix} a_{m-1} & 1 & \cdots & 0 & 0 \\ a_{m-2} & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ a_1 & 0 & \cdots & 0 & 1 \\ a_0 & 0 & \cdots & 0 & 0 \end{bmatrix} & H_4 &= \begin{bmatrix} a_{m-1} & a_{m-2} & \cdots & a_1 & a_0 \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix}, \end{aligned} \quad (1)$$

where $a_0, a_1, \dots, a_{m-2}, a_{m-1}$ – polynomial coefficients $f_m(x)$, belonging to the set $\{0,1\}$; thus, the dimension of these matrices will be $m \times m$. An important property is the cyclicity of a group – that is, $\alpha^0 = \alpha^N, \alpha^1 = \alpha^{N+1}, \dots$. As α^0 you can select any of its elements. Thus,

$$\mathfrak{Z}_{m,1} = \begin{bmatrix} {}^n\mathfrak{Z}_0 \\ {}^n\mathfrak{Z}_1 \\ \dots \\ {}^n\mathfrak{Z}_{m-1} \end{bmatrix} = [\alpha^0 \quad \alpha^1 \quad \dots \quad \alpha^{N-1}], \quad \alpha^k = H_n \alpha^{k-1}, \quad (2)$$

where the columns α^k can be obtained by any of the possible methods – that is, when choosing a matrix H_n , which determines the values of the cyclic shifts of the MS l_i ($i = 0, \dots, m-1$) regarding the MS ${}^n\mathfrak{Z}_0$ with the selected α^0 . Table 1 shows the values of the elements of four maximal multiplicative groups of the Galois field obtained based on the polynomial $f_5(x) = x^5 + x^3 + 1$ and represented in the decimal numeral system. We shall henceforth denote this representation as $[\alpha^k]_{10}$. A primitive element was chosen $\alpha^0 = [1 \ 0 \ 0 \ 0 \ 0]^T$, so in all cases $[\alpha^0]_{10} = 16$.

Table 1

Maximal multiplicative groups of a Galois field modulo a polynomial $f_5(x) = x^5 + x^3 + 1$

k	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
H_1	16	8	4	2	1	18	9	22	11	23	25	30	15	21	24	12	6	3	19	27	31	29	28	14	7	17	26	13	20	10	5
H_2	16	1	2	5	10	21	11	23	14	29	27	22	24	17	3	7	6	15	31	30	28	25	19	6	13	26	20	9	18	4	8
H_3	16	1	18	13	26	29	19	15	30	21	3	6	12	24	25	27	31	23	7	14	28	17	11	22	5	10	20	1	2	4	8
H_4	16	8	20	10	21	26	29	14	23	27	13	6	3	17	24	28	30	31	15	7	19	25	12	22	11	5	18	9	4	2	1

For a matrix H_1 , The elements of the multiplicative group of a Galois field can be calculated using the formula:

$$\alpha^{k+1} = \begin{bmatrix} x_{0,k+1} \\ x_{1,k+1} \\ \dots \\ x_{m-1,k+1} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \dots & 0 & a_0 \\ 1 & 0 & \dots & 0 & a_1 \\ 0 & 0 & \dots & 0 & a_{m-2} \\ 0 & 0 & \dots & 1 & a_{m-1} \end{bmatrix} \begin{bmatrix} x_{0,k} \\ x_{1,k} \\ \dots \\ x_{m-1,k} \end{bmatrix}, \quad k = 0, \dots, N-1, \quad (2.3)$$

where m are cyclic shifts of the generated MS (that is, on $l_0, l_1, \dots, l_{m-1}$ characters relative to ${}^1\mathfrak{Z}_0$) are located in the rows of the matrix [7]:

$$\mathfrak{Z}_{m,1} = \begin{bmatrix} x_{0,0} & x_{0,1} & \dots & x_{0,N-1} \\ x_{1,0} & x_{1,1} & \dots & x_{1,N-1} \\ \dots & \dots & \dots & \dots \\ x_{m-1,0} & x_{m-1,1} & \dots & x_{m-1,N-1} \end{bmatrix}, \quad (2.4)$$

where $\mathfrak{Z}_{m,1}$ – corresponding matrix H_1 . Its columns represent the elements of the multiplicative group of the Galois field modul $f_m(x)$ with coefficients $a_0, a_1, \dots, a_{m-2}, a_{m-1}$. As an example, the elements of the matrix are presented in Table 2. $\mathfrak{Z}_{5,1}$ for a polynomial $f_5(x) = x^5 + x^4 + x^2 + x + 1$, and in Table 3 – for the dual polynomial $f_5(x) = x^5 + x^4 + x^3 + x + 1$.

Table 2

Elements of the multiplicative group of a Galois field based on the companion matrix H_1 polynomial $f_5(x) = x^5 + x^4 + x^2 + x + 1$

k	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
$[\alpha^k]_{10}$	16	8	4	2	1	29	19	20	10	5	31	18	9	25	17	21	23	22	11	24	12	6	3	28	14	7	30	15	26	13	27
$x_{0,k}$	1	0	0	0	1	1	1	1	0	0	1	1	0	1	1	1	1	1	0	1	0	0	0	1	0	0	1	0	1	0	1
$x_{1,k}$	0	1	0	0	0	1	0	0	1	0	1	0	1	1	0	0	0	0	1	1	1	0	0	1	1	0	1	1	1	1	1
$x_{2,k}$	0	0	1	0	0	1	0	1	0	1	1	0	0	0	0	1	1	1	0	0	1	1	0	1	1	1	1	1	0	1	0
$x_{3,k}$	0	0	0	1	0	0	1	0	1	0	1	1	0	0	0	0	1	1	1	0	0	1	1	0	1	1	1	1	1	0	1
$x_{4,k}$	0	0	0	0	1	1	1	0	0	1	1	0	1	1	1	1	1	0	1	0	0	0	1	0	0	1	0	1	0	1	1

Table 3

Elements of the multiplicative group of a Galois field based on the companion matrix H_1 polynomial $f_5(x) = x^5 + x^4 + x^3 + x + 1$

k	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
$[\alpha^k]_{10}$	16	8	4	2	1	27	22	11	30	15	28	14	7	24	12	6	3	26	13	29	21	17	19	18	9	31	20	10	5	25	23
$x_{0,k}$	1	0	0	0	1		1	0		0	1		0	1		0	0	1	0		1	1		1	0		1	0		1	1
$x_{1,k}$	0	1	0	0	0		0	1		1	1		0	1		0	0	1	1		0	0		0	1		0	1		1	0
$x_{2,k}$	0	0	1	0	0		1	0		1	1		1	0		1	0	0	1		1	0		0	0		1	0		0	1
$x_{3,k}$	0	0	0	1	0		1	1		1	0		1	0		1	1	1	0		0	0		1	0		0	1		0	1
$x_{4,k}$	0	0	0	0	1		0	1		1	0		1	0		0	1	0	1		1	1		0	1		0	0		1	1

Circulant matrix MS $\mathfrak{Z}_{m,n,\mathfrak{u}}$ with elements (0,1), containing its cyclic shifts by $l_0, l_1, \dots, l_{m-1}$ symbols, and also all other shifts that do not coincide with them, we shall form in accordance with the rule:

$$\mathfrak{Z}_{m,n,c} = \begin{bmatrix} \mathfrak{Z}_{m,n} \\ H_n^m \mathfrak{Z}_{m,n} \\ H_n^{2m} \mathfrak{Z}_{m,n} \\ \dots \\ H_n^{C(N)m} \mathfrak{Z}_{m,n} \end{bmatrix}, \quad (5)$$

where $C(N) = \left(\frac{A(N)}{m}\right) - 1$, $A(N)$ – a number as close as possible to N that is perfectly

divisible by m and satisfies the inequality $A(N) > N$. Thus, $\frac{A(N)}{m}$ – this is the total number

of blocks in the matrix $\mathfrak{Z}_{m,n,c}$, containing a matrix $\mathfrak{Z}_{m,n}$ or a transformation of it of the form $H_n^x \mathfrak{Z}_{m,n}$. The size of each block will be $m \times (N - 1)$. Matrix dimension $\mathfrak{Z}_{m,n,c}$ will be $A(N) \times (N - 1)$, as a result of which the last block $\mathfrak{Z}_{m,n,c}$ in one's own $A(N) - N$ the rows will contain MPs whose cyclic shifts coincide with the shifts of the MPs in the first block. As an example, the elements $\mathfrak{Z}_{5,1,\mathfrak{u}}$, formed on the basis of $f_5(x) = x^5 + x^3 + 1$ and H_1 , are presented in Table 4.

Table 4

Matrix $\mathfrak{Z}_{5,1,c}$, formed on the basis of $f_5(x) = x^5 + x^3 + 1$

k	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30			
$[\alpha^k]_{10}$	16	8	4	2	1	18	9	22	11	23	25	30	15	21	24	12	6	3	19	27	31	29	28	14	7	17	26	13	20	10	5	i	l_i	
$x_{0,k}$	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	0	0	
$x_{1,k}$	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	1	30	
$x_{2,k}$	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	2	29	
$x_{3,k}$	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	3	2	
$x_{4,k}$	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	4	1	
$x_{5,k}$	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	5	5	
$x_{6,k}$	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	6	4	
$x_{7,k}$	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	7	3	
$x_{8,k}$	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	8	7	
$x_{9,k}$	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	9	6	
$x_{10,k}$	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	1	0	1	0	1	10	10
$x_{11,k}$	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	1	0	1	0	11	9
$x_{12,k}$	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	12	8	
$x_{13,k}$	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	13	12	
$x_{14,k}$	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	14	11	
$x_{15,k}$	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	15	15	
$x_{16,k}$	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	16	14	
$x_{17,k}$	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	17	13	
$x_{18,k}$	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	18	17	
$x_{19,k}$	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	19	16	
$x_{20,k}$	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	20	20	
$x_{21,k}$	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	21	19	
$x_{22,k}$	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	22	18	
$x_{23,k}$	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	23	22	
$x_{24,k}$	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	24	21	
$x_{25,k}$	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	25	25	
$x_{26,k}$	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	26	24	
$x_{27,k}$	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	27	23	
$x_{28,k}$	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	28	27	
$x_{29,k}$	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	29	26	
$x_{30,k}$	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	30	30	
$x_{31,k}$	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	31	29	
$x_{32,k}$	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	32	28	
$x_{33,k}$	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	33	1	
$x_{34,k}$	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	34	0	

From her analysis it follows that the sequence $l_0, l_1, \dots, l_{34}$, located in the last column of Table 4, looks random, although the second block $\mathfrak{Z}_{5,1,c}$ from $m = 5$ its rows are shifted by 5 character positions relative to the first block consisting of the same number of

rows, the third block is shifted by 10 character positions relative to that one, and so on. Furthermore, the columns $\mathfrak{Z}_{5,1,c}$ не являются МП.

It has a completely different structure $\mathfrak{Z}_{5,2,c}$, formed based on the same polynomial $f_5(x) = x^5 + x^3 + 1$ and H_2 and the one presented in Table 5, since its rows contain cyclic shifts of the MP, each shifted one symbol to the right relative to the others. Furthermore, its columns contain cyclic shifts of the same MP, with the MS in each successive column being cyclically shifted by one symbol compared to the preceding column. It is evident that this property is characteristic of all $\mathfrak{Z}_{m,2,c}$, built on the basis of H_2 , and it is not characteristic $\mathfrak{Z}_{m,1,c}$, $\mathfrak{Z}_{m,3,c}$, $\mathfrak{Z}_{m,4,c}$ formed on the basis of H_1 , H_3 и H_4 . We shall refer to all circulant matrices formed on the basis of H_2 as being ordered by cyclic shifts, or simply as ordered.

Table 5

Matrix $\mathfrak{Z}_{5,2,c}$, formed on the basis of $f_5(x) = x^5 + x^3 + 1$

k	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30		
$[\alpha^k]_{10}$	16	1	2	5	10	21	11	23	14	29	27	22	12	24	17	3	7	15	31	30	28	25	19	6	13	26	20	9	18	4	8	i	l_i
$x_{0,k}$	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	0	0
$x_{1,k}$	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	1	1
$x_{2,k}$	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	1	0	0	1	1	0	1	0	0	1	2	2
$x_{3,k}$	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	3	3
$x_{4,k}$	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	4	4
$x_{5,k}$	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	5	5
$x_{6,k}$	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	6	6
$x_{7,k}$	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	7	7
$x_{8,k}$	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	1	0	8	8
$x_{9,k}$	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	1	0	1	9	9
$x_{10,k}$	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	1	0	1	0	10	10
$x_{11,k}$	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	1	0	1	0	1	11	11
$x_{12,k}$	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	1	0	1	0	1	1	12	12
$x_{13,k}$	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	1	0	1	0	1	1	1	13	13
$x_{14,k}$	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	14	14
$x_{15,k}$	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	15	15
$x_{16,k}$	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	16	16
$x_{17,k}$	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	0	1	1	0	1	1	0	17	17
$x_{18,k}$	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	0	1	1	0	1	1	0	0	18	18
$x_{19,k}$	1	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	19	19
$x_{20,k}$	1	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	20	20
$x_{21,k}$	1	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	21	21
$x_{22,k}$	1	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	22	22
$x_{23,k}$	0	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	23	23
$x_{24,k}$	0	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	24	24
$x_{25,k}$	1	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	25	25
$x_{26,k}$	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	26	26
$x_{27,k}$	0	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	27	27
$x_{28,k}$	1	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	28	28
$x_{29,k}$	0	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	29	29
$x_{30,k}$	0	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	30	30
$x_{31,k}$	1	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	31	0
$x_{32,k}$	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	0	1	32	1
$x_{33,k}$	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	1	0	0	1	1	0	1	0	0	1	33	2
$x_{34,k}$	0	0	1	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	1	0	0	1	1	0	1	0	0	1	0	34	3

A crucial property of ordered circulant matrices is the clear and simple relationship between their row index i and the absolute cyclic shift of the matrix pattern (MP) located in that row—a shift determined by the set of m symbols that make up the pattern:

$$H_2^i \alpha^0 = b_i, \quad (6)$$

where $b_i = [x_{i,k}, k = 0, \dots, m-1]$ – the initial block of the MS located in the i -th row of the circulant matrix.

Another important property of an ordered circulant matrix is the cyclic shift of the sequence of elements of multiplicative groups. $H_2^x \mathfrak{S}_{m,n}$ ($x = 0, m, 2m, \dots$) by one element to the right each time the next element of the group is chosen as the generator, resulting in N possible versions of this matrix. In any of these, the rows from the i -th to the $(i + m - 1)$ -th will contain the elements of the multiplicative group of a Galois field, cyclically shifted by i symbols relative to $\mathfrak{S}_{m,2}$, where i can take any value from 1 to $(N - 1)$.

Transformation of a circulant matrix into a matrix consisting of Walsh functions

Let's rearrange the columns of the matrix $\mathfrak{S}_{m,2,c}$ for any value α^0 in increasing order of the values of the elements of the multiplicative group of a Galois field $[\alpha^k]_{10}$, formed on the basis of H_2 at the same value α^0 [10, 11]. As a result $\mathfrak{S}_{m,2}$ will be converted into a matrix R_{ma} , the columns of which form a so-called simple binary code, while the rows are analogues of Rademacher functions [12, 13], excluding the zero symbol when indexing the symbols starting from zero: $r_{0a}, r_{1a}, \dots, r_{(m-1)a}$. Matrix $R_{ma} = [r_{0a} \ r_{1a} \ \dots \ r_{(m-1)a}]^T$ at $m = 5$ shown in Table 6.

Table 6

Analogues of Rademacher functions for $m = 5$

k	0	1						7	8			10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
r_{0a}	0	0						0	0																1	1						
r_{1a}	0	0						1	1																1	1						
r_{2a}	0	0						0	0																0	0						
r_{3a}	0	1						0	0																0	0						
r_{4a}	1	0						0	1																0	1						

Then $\mathfrak{S}_{m,2,c}$ is transformed into a matrix

$$W_{m,p(1,0)} = \begin{bmatrix} R_{ma} \\ H_2^m R_{ma} \\ H_2^{2m} R_{ma} \\ \dots \\ H_2^{C(N)m} R_{ma} \end{bmatrix} = \begin{bmatrix} I_m R_{ma} \\ H_2^m R_{ma} \\ H_2^{2m} R_{ma} \\ \dots \\ H_2^{C(N)m} R_{ma} \end{bmatrix} = \begin{bmatrix} I_m \\ H_2^m \\ H_2^{2m} \\ \dots \\ H_2^{C(N)m} \end{bmatrix} R_{ma}, \quad (7)$$

where $W_{m,p(1,0)}$ – an extended Walsh function matrix without a zero symbol, with elements (0, 1), containing a certain number of repeating rows; I_m – identity matrix of size $m \times m$.

Matrix rows $H_2^x R_{ma}$ ($x = m, 2m, \dots$) are combinations of sums of the matrix rows R_{ma} upon addition of the symbols modul 2. As is well known, such sums form Walsh functions (excluding the zero-valued functions, when the symbols are indexed starting from zero).

In order to determine how they are ordered in (7), let us consider the matrix

$$H = \begin{bmatrix} H_2^m \\ H_2^{2m} \\ \dots \\ H_2^{C(N)m} \end{bmatrix}, \quad (8)$$

We will show that its rows form the multiplicative group of a Galois field constructed based on H_1 . Indeed,

$$\begin{aligned} H &= (H^T)^T = [((H_2^T)^T)^m \quad ((H_2^T)^T)^{2m} \quad \dots \quad ((H_2^T)^T)^{C(N)m}]^T = \\ &= [(H_1^T)^m \quad (H_1^T)^{2m} \quad \dots \quad (H_1^T)^{C(N)m}]^T = \begin{bmatrix} (H_1^m)^T \\ (H_1^{2m})^T \\ \dots \\ (H_1^{C(N)m})^T \end{bmatrix}, \end{aligned} \quad (9)$$

since $H_2^T = H_1$. In addition, we take into account that

$$(H_1)^m = (H_1)^{m-1} H_1 = (H_1)^{m-1} \begin{bmatrix} 0 & 0 & \dots & 0 & a_0 \\ 1 & 0 & \dots & 0 & a_1 \\ 0 & 0 & \dots & 0 & a_{m-2} \\ 0 & 0 & \dots & 1 & a_{m-1} \end{bmatrix}. \quad (10)$$

Assuming that the primitive element of the group coincides with the first column H_1 , that is $\alpha^0 = [0 \ 1 \ 0 \ \dots \ 0 \ 0]^T$, let us note that $H_1 \alpha^0 = \alpha^1 = [0 \ 0 \ 1 \ \dots \ 0 \ 0]^T$ and coincides with the second column H_1 etc.

The last element $\alpha^{m-1} = H_1 \alpha^{m-2} = H_1 [0 \ 0 \ \dots \ 0 \ 1]^T = [a_0 \ a_1 \ \dots \ a_{m-1}]^T$ coincides with the last column H_1 . Thus, $H_1 = [\alpha^0 \ \alpha^1 \ \dots \ \alpha^{m-1}]$. Then

$$(H_1)^m = [(H_1)^{m-1} \alpha^0 \quad (H_1)^{m-1} \alpha^1 \quad \dots \quad (H_1)^{m-1} \alpha^{m-1}] = [\alpha^{m-1} \ \alpha^m \quad \dots \quad \alpha^{2m-2}]. \quad (11)$$

Similarly, we obtain: $(H_1)^{2m} = (H_1)^{2m-1} H_1 = [\alpha^{2m-1} \ \alpha^{2m} \quad \dots \quad \alpha^{3m-2}]$ etc.

As a result

$$H = [\alpha^{(m-1)^T} \ \alpha^{m^T} \ \dots \ \alpha^{(2m-2)^T} \ \alpha^{(C(N)m-1)^T} \ \alpha^{C(N)m^T} \ \dots \ \alpha^{((C(N)+1)m-2)^T}]^T, \quad (12)$$

where $\alpha^0 = [0 \ 1 \ 0 \ \dots \ 0 \ 0]^T$, moreover H contains, in its rows, elements of a multiplicative group constructed based on the companion matrix H_1 – or $(m-1)$ -ro to $((C(N)+1)m-2)$ (at $m=5$ – from 4 to 33, in total 30), that is, the group represented in this matrix will be a truncated group. A primitive element of the truncated group will be $\alpha^{(m-1)} = H_1^{m-1} \alpha^0 = [a_0 \ a_1 \ \dots \ a_{m-1}]^T$.

From the formulas (7), (8), (12) it follows:

$$\mathbf{W}_{m,p(1,0)} = \begin{bmatrix} \mathbf{I}_m \\ \mathbf{H} \end{bmatrix} \mathbf{R}_{ma} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ & \mathbf{H}_p & & \end{bmatrix} \mathbf{R}_{ma}, \quad (13)$$

where $\mathbf{H}_p$ – augmented matrix $\mathbf{H}$, containing in its rows elements of a multiplicative group constructed based on $\mathbf{H}_1$ – from the element $\alpha^0 = [0 \ 1 \ 0 \ \dots \ 0 \ 0]^T$ to $((C(N) + 1)m - 2)$ element, total $(C(N) + 1)m - 1 > N$ elements. $\mathbf{H}_1[1 \ 0 \ \dots \ 0 \ 0]^T = [0 \ 1 \ 0 \ \dots \ 0 \ 0]^T$. In other words, by preserving within the matrix $\mathbf{W}_{m,p(1,0)}$ only N From the first few rows, one can construct a matrix consisting of Walsh functions – indexed starting from zero and excluding the zero-index function – in the following form:

$$\mathbf{W}_{m(1,0)} = \mathfrak{Z}_{m,1}^T \mathbf{R}_{ma} = \begin{bmatrix} x_{0,0} & x_{1,0} & \cdots & x_{m-1,0} \\ x_{0,1} & x_{1,1} & \cdots & x_{m-1,1} \\ \vdots & \vdots & \ddots & \vdots \\ x_{0,N-1} & x_{1,N-1} & \cdots & x_{m-1,N-1} \end{bmatrix} \mathbf{R}_{ma}, \quad (14)$$

moreover, all rows of the matrix $\mathfrak{Z}_{m,1}^T$ – these are elements of the multiplicative group of a Galois field constructed based on a matrix $\mathbf{H}_1$ with a primitive element $\alpha^0_{H_1} = [x_{0,0} \ x_{1,0} \ \cdots \ x_{m-1,0}]^T = [1 \ 0 \ \dots \ 0 \ 0]^T$.

Accordingly, to transform any cyclic shift of an M-sequence into a Walsh function (excluding the zero symbol, assuming a zero-based indexing), one must reorder its elementary symbols according to the ascending values of the elements of the multiplicative group of the Galois field, which is constructed based on the companion matrix of a polynomial of the form $\mathbf{H}_2$. In this context, the choice of a primitive element of the group is of great importance $\alpha^0_{H_2}$, depending on which, this cyclic shift can be transformed into any row of the matrix $\mathbf{W}_{m(1,0)}$. But given a specified $\alpha^0_{H_2}$ correspondence between the cyclic shifts of the MS being transformed and the rows of the matrix $\mathbf{W}_{m(1,0)}$ will be one-to-one; that is, an M-sequence with an absolute cyclic shift b will be transformed into a Walsh sequence (excluding the zero symbol, when indexed from zero) that is located in the i -th row of the matrix $\mathbf{W}_{m(1,0)}$, where i can be found by solving the equation: $\mathbf{H}_2^i \alpha^0_{H_2} = b$. At the same time, in the rows of the matrix

$$\mathbf{W}_{m(1,0)} = \begin{bmatrix} x_{0,0} \mathbf{r}_{0a} \oplus x_{1,0} \mathbf{r}_{1a} \oplus \cdots \oplus x_{m-1,0} \mathbf{r}_{(m-1)a} \\ x_{0,1} \mathbf{r}_{0a} \oplus x_{1,1} \mathbf{r}_{1a} \oplus \cdots \oplus x_{m-1,1} \mathbf{r}_{(m-1)a} \\ \vdots \\ x_{0,N-1} \mathbf{r}_{0a} \oplus x_{1,N-1} \mathbf{r}_{1a} \oplus \cdots \oplus x_{m-1,N-1} \mathbf{r}_{(m-1)a} \end{bmatrix}, \quad (15)$$

Analogous of Rademacher functions are summed modulo 2 with weighting coefficients that are symbols of elements of the multiplicative group of a field constructed using the companion matrix of a polynomial $\mathbf{H}_1$ with a primitive element $\alpha^0_{H_1} = [1 \ 0 \ \dots \ 0 \ 0]^T$. In (15) $\oplus$ – notation for the operation of addition modul 2.

Accordingly, in the i -th row of the matrix $\mathbf{W}_{m(1,0)}$ the result is a Walsh function – excluding the zero-indexed one (when using zero-based numbering) – obtained by summing analogues of Rademacher functions, with weighting coefficients equal to the symbol values of the vector $\mathbf{x} = \mathbf{H}_1^i \boldsymbol{\alpha}_{H_1}^0$. Thus, any i -th row of the matrix (15)

$$\mathbf{w}_{i(1,0)} = x_{0,i} \mathbf{r}_{0a} \oplus x_{1,i} \mathbf{r}_{1a} \oplus \dots \oplus x_{m-1,i} \mathbf{r}_{(m-1)a}, \quad (16)$$

is a Walsh function without a zero symbol when numbering them from zero, where

$$\begin{bmatrix} x_{0,i} \\ x_{1,i} \\ \dots \\ x_{m-1,i} \end{bmatrix} = \mathbf{H}_1^i \begin{bmatrix} 1 \\ 0 \\ \dots \\ 0 \end{bmatrix}. \quad (17)$$

By replacing the MS symbols in $\mathfrak{S}_{m,n,\mathbb{U}}$ according to the rule $0 \rightarrow 1, 1 \rightarrow -1$, we get:

$$\mathbf{W}_{m(1,-1)} = \begin{bmatrix} \mathbf{r}_0^{x_{0,0}} \cdot \mathbf{r}_1^{x_{1,0}} \cdot \dots \cdot \mathbf{r}_{(m-1)}^{x_{m-1,0}} \\ \mathbf{r}_0^{x_{0,1}} \cdot \mathbf{r}_1^{x_{1,1}} \cdot \dots \cdot \mathbf{r}_{(m-1)}^{x_{m-1,1}} \\ \dots \\ \mathbf{r}_0^{x_{0,N-1}} \cdot \mathbf{r}_1^{x_{1,N-1}} \cdot \dots \cdot \mathbf{r}_{(m-1)}^{x_{m-1,N-1}} \end{bmatrix}, \quad (18)$$

where $\mathbf{r}_0, \dots, \mathbf{r}_{(m-1)}$ – Rademacher functions with elements $\{1, -1\}$ (excluding zero), indexed starting from zero. In this context, the i -th row of the matrix $\mathbf{W}_{m(1,-1)}$ is defined as

$$\mathbf{w}_{i(1,-1)} = \mathbf{r}_0^{x_{0,i}} \cdot \mathbf{r}_1^{x_{1,i}} \cdot \dots \cdot \mathbf{r}_{(m-1)}^{x_{m-1,i}}, i = 0, \dots, N-1, \quad (19)$$

where Powers of Rademacher functions are still calculated using formula (17).

By augmenting the Walsh function matrix (18) with a zero row (when indexing starts from zero) and an leftmost column – both consisting of ones – we obtain a complete set of orthogonal Walsh basis functions. The ordering of these functions within the matrix (excluding the zero row, which consists entirely of ones) is determined by the sequence of elements of the multiplicative group of a Galois field, defined modulo an irreducible primitive polynomial. $f_m(x)$ with coefficients $a_0, a_1, \dots, a_{m-2}, a_{m-1}$ and its companion matrix of the form $\mathbf{H}_1$ given a primitive element $\boldsymbol{\alpha}_{H_1}^0 = [1 \ 0 \dots 0 \ 0]^T$.

Let us consider a matrix $\mathbf{W}_{m(1,-1)}^T$. It consists of rows in which the cyclic shifts of the sequences are ordered by row number; that is, each sequence begins with a block of m symbols corresponding to the binary representation of the row number in which it is located within the matrix $\mathbf{W}_{m(1,-1)}^T$. The columns of this matrix contain Walsh functions, ordered according to the elements of the multiplicative group of the Galois field corresponding to the matrix $\mathbf{H}_1$. Therefore, the columns of this matrix are rearranged in increasing order of the values of the elements of the multiplicative group of the Galois field, which is constructed based on the companion matrix of its polynomial of the form $\mathbf{H}_1$ given a primitive element $\boldsymbol{\alpha}_{H_1}^0 = [1 \ 0 \dots 0 \ 0]^T$, transforms this matrix into a Hadamard matrix that contains no zero-valued columns or rows (when using zero-based indexing). Each i th row of this matrix consists of a Walsh function that contains no zero-valued symbols (again, using zero-based indexing).

$$\mathbf{w}_{i(1,-1)Ad} = \mathbf{r}_0^{h_{0,i}} \cdot \mathbf{r}_1^{h_{1,i}} \cdot \dots \cdot \mathbf{r}_{(m-1)}^{h_{m-1,i}}, i = 0, \dots, N-1, \quad (20)$$

where $h_{0,i}, h_{1,i}, \dots, h_{m-1,i}$ – values of the bits in the binary representation of the row number j ($h_{m-1,i}$ – least significant digit).

M-sequences (MS) synchronization

The first method for synchronizing the MS involves the following sequence of actions:

1) values of a discrete signal X_N . The signals obtained from the output of the in-phase or quadrature channel of the receiver are rearranged in increasing order of the values of the elements of the multiplicative group $\alpha^0_{H_2}, \alpha^1_{H_2} \dots, \alpha^{N-1}_{H_2}$ for any chosen $\alpha^0_{H_2}$; that is, the values X_N are written into a storage device, with the zero-indexed value – assuming a zero-based numbering scheme – being placed into the memory cell at the address $\alpha^0_{H_2}$, the first – into the cell with the address $\alpha^1_{H_2}$ and so on, with memory cells numbered from 0 to N ; in this arrangement, the zeroth memory cell remains unoccupied, since the multiplicative group of a Galois field lacks an element $00\dots 0$;

2) a unit is written to memory cell number 0, and the FAT of the resulting vector is performed;

3) the number of cell i is read, which contains the highest value of the FPA result (cell zero is ignored); thus, the row of the Hadamard matrix to which the cyclic shift of the original MS is converted is identified;

4) the reverse binary representation of i , that is $h_{m-1,i}h_{m-2,i} \dots h_{0,i}$ is considered as an element of the multiplicative group of a Galois field constructed based on the companion matrix H_1 of the polynomial being used, with respect to a primitive element $\alpha^0_{H_1} = [1\ 0 \dots 0\ 0]^T$;

5) the row number in which the obtained Walsh function is located is determined $W_{m(1,-1)}$, ordered according to the values of the elements of the multiplicative group of a Galois field, constructed on the basis of H_1 , (hereinafter referred to as groups 1), when solving the equation $H_1^i \alpha^0_{H_1} = [h_{m-1,j}h_{m-2,j} \dots h_{0,j}]^T$ relatively i ;

6) the required initial block of the MS is calculated using the formula: $b = H_2^i \alpha^0_{H_2}$.

In practice, solving the matrix equation and performing the calculations can be implemented using generators of the multiplicative groups of a Galois field, constructed based on the companion matrices of the original polynomial H_1 and H_2 (hereinafter referred to as Group 1 and Group 2). For the first of these $\alpha^0_{H_1} = [1\ 0 \dots 0\ 0]^T$, and for the second, the primitive element coincides with $\alpha^0_{H_2}$, from which the rearrangement of values began X_N . When the numbers at the outputs of these generators coincide, the output of the group 2 generator will yield the desired initial block for the MS (microprogram).

Another variant of this algorithm involves permuting the contents of the memory device cells after the execution of the BPA (basic microprogram algorithm), in accordance with the sequence of elements from group 1. That is, after completing step 2), one must launch the generator for this group using a primitive element $\alpha^0_{H_1} = [1\ 0 \dots 0\ 0]^T$ and move the contents of the 1st cell to the address $\alpha^0_{H_1}$, 2nd – to the address $\alpha^1_{H_1}$ etc. Next, it is necessary to determine the index of the cell with the maximum content.

This index will correspond to the target starting block of the memory area (MA) containing the values of the discrete signal X_N . The identified initial block must be loaded into the generator for group 2, the output of which will form the reference M-sequence.

The key components of an M-sequence synchronization device based on a Galois field primitive element (GFPE) approach are the generators for the multiplicative groups of the Galois field. It can be readily shown that the generators for group 1 and group 2 are, in fact, variations of an M-sequence generation device [10]. Indeed, by considering the structures of matrices H_1 and H_2 , one can derive recurrence relations for the elements of the corresponding multiplicative groups:

$$\text{– for the elements of group 1:} \begin{cases} x_{0,i} = a_0 x_{m-1,i-1}, (a_0 = 1), \\ x_{1,i} = x_{0,i-1} \oplus a_1 x_{m-1,i-1}, \\ \dots \\ x_{m-1,i} = x_{m-2,i-1} \oplus a_{m-1} x_{m-1,i-1}; \end{cases} \quad (21)$$

– for the elements of group 2:

$$\begin{cases} x_{0,i} = x_{1,i-1}, \\ x_{1,i} = x_{2,i-1}, \\ \dots \\ x_{m-1,i} = a_0 x_{0,i-1} \oplus a_1 x_{1,i-1} \oplus \dots \oplus a_{m-1} x_{m-1,i-1}. \end{cases} \quad (22)$$

Following the tradition of analyzing transformations within Galois fields – and considering the generators of maximal-length sequences (MLS) as shift registers based on D-flip-flops – we present the functional diagrams for the generators of multiplicative groups 1 and 2, as shown in Figure 1a, b.

As can be seen, the elements of the groups are read out in parallel from the outputs of all the flip-flops (memory cells) in the shift registers, while an MLS – with shifts corresponding to the structure of matrix H_1 or H_2 – is produced serially from each individual flip-flop. At the moment when the memory cells of the group 2 generator contain the required initial block of the input MLS, the sequence $x_{0,i}, x_{0,i+1}, x_{0,i+2} \dots$ from the output of its flip-flop D_0 will be generated synchronously with it, provided that this generator – much like the generator in group 1 – operates at the clock frequency of the input microprocessor.

Furthermore, it would be necessary for the duration of all the aforementioned transformations and operations to be zero, which is impossible. In reality, a digital synchronization device designed using modern microprocessor technology operates at the highest speed it can achieve, governed by its own clock frequency. It should be emphasized once again that, in this work, the generators of multiplicative groups are represented as shift registers using D flip-flops is merely a nod to tradition.

Thus, it is necessary, first, to record the total duration of all performed operations, expressed in units of the elementary pulse duration of the input multiplicative sequence (MS); second, to shift the generated reference MS – output from the D_0 flip-flop of the group 2 generator – by a corresponding number of elementary symbols; and third, to reduce the clock frequency of the generated reference MS to match the frequency of the input MS.

Consequently, the group 2 generator is well-suited for use as a source for a reference MS that is synchronous with the input MS, since the values of any m elementary symbols of the generated MS – as they emerge from the D_0 flip-flop – will correspond to the symbols of the multiplicative group 2 that were stored in the memory cells of its shift register at the moment the first of these m symbols appeared.

The second, simpler MS synchronization algorithm corresponds to the matrix $W_{m(1,-1)}^T$: values X_N . It is necessary to reorder the elements of the multiplicative group of a Galois field – constructed based on the companion matrix of a polynomial of a certain form – in ascending order H_1 , but only in the case of a primitive element $\alpha_{H_1}^0 = [1\ 0\ \dots\ 0\ 0]^T$. Upon completion of the BPA, the memory cell number – expressed in the binary numeral system – that contains the maximum value will serve as the starting block for the MS (microprogram) that was contained therein X_N .

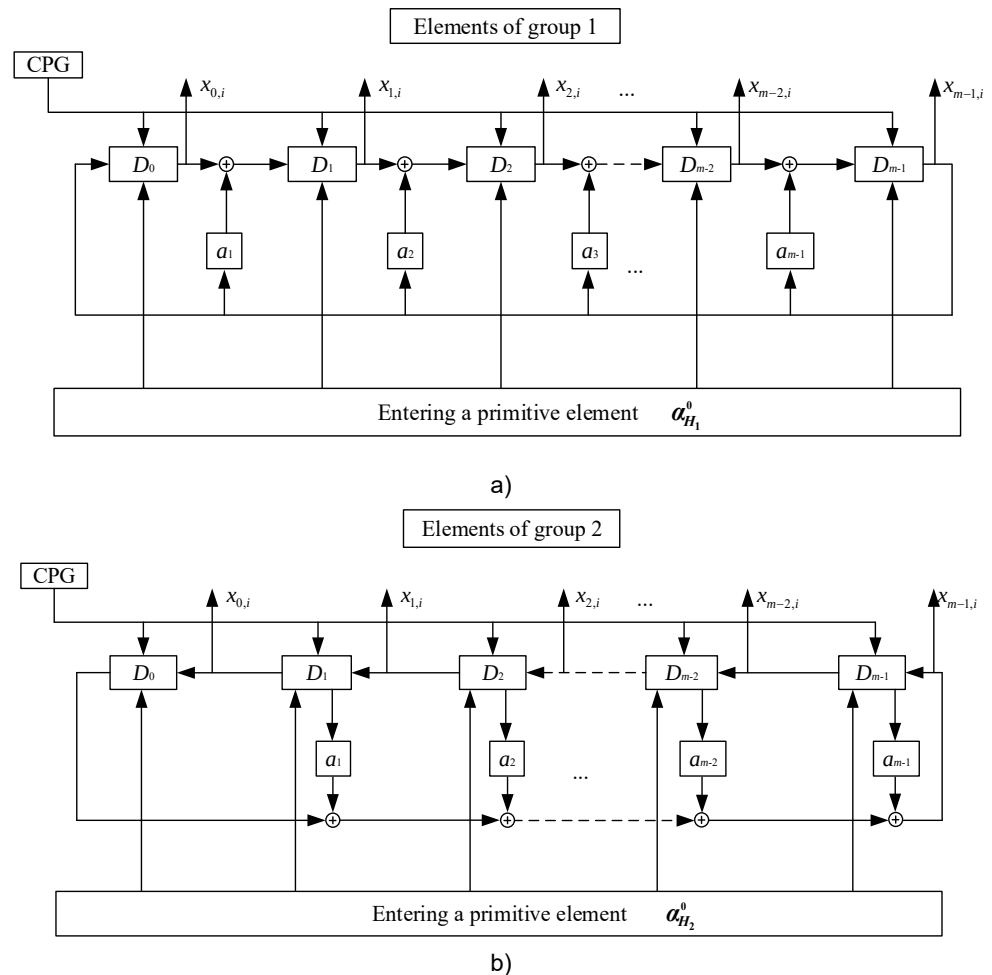


Fig. 1. Generators of multiplicative groups of a Galois field modulo an irreducible primitive polynomial with coefficients $a_0, a_1, \dots, a_{m-2}, a_{m-1}$; CPG – clock pulse generator

This initial block should be written into the memory cells of the generator of group 2, as a result of which the reference MS will be formed precisely from this initial block. Thus, in this case it is necessary to use both a group 1 generator and a group 2 generator.

We emphasize that the method of synchronizing the MP, based on the permutation of the symbols of the input MS in accordance with the multiplicative group formed on the basis of the matrix $\mathbf{H}_1$ (a simpler algorithm), assumes the only option for a permutation of this kind, and the multiplicative group on the basis of which it is made must always begin with $\alpha^0_{H_1} = [1\ 0\ \dots\ 0\ 0]^T$.

Permuting the sequence according to the same multiplicative group, but using a different primitive element, will not transform an M-sequence (maximal-length sequence) into a Walsh function. Furthermore, this approach assumes that the correspondence between a cyclic shift of an M-sequence and a Walsh function within a Hadamard matrix is the only one possible.

In contrast, permuting the symbols of an M-sequence according to a multiplicative group derived from the matrix $\mathbf{H}_2$ (a more complex algorithm) can be performed starting from any primitive element $\alpha^0_{H_2}$, as a result, any cyclic shift of the input MS can be reduced to any Walsh function, but for the chosen $\alpha^0_{H_2}$ – to only one such function. Furthermore, if the range of cyclic shifts – within which the shift of an input maximal-length sequence (MLS) might fall, or within which several of its cyclic shifts might occur due to multipath signal propagation – is known in advance, then permuting the symbols of the MLS according to multiplicative group 2 transforms them into Walsh sequences (excluding the zero-indexed symbol). In a matrix of such functions ordered according to multiplicative group 1, these resulting sequences appear consecutively. Consequently, given that only these specific functions are retained within a Hadamard matrix, the Fast Walsh-Hadamard Transform (FWHT) algorithm can be optimized, thereby reducing its computational complexity. Other cyclic shifts of the input MLS can be mapped to these same Walsh sequences (excluding the zero-indexed symbol) through an appropriate selection $\alpha^0_{H_2}$ group 2, according to which the symbols are rearranged.

Thus, if the range of possible cyclic shifts of the received sequence is known, an appropriate value can be selected $\alpha^0_{H_2}$ and transform it into one of several Walsh functions that appear in succession within a Hadamard matrix. Any other cyclic shift of an M-sequence with the same time-uncertainty region width can be mapped to a specific Walsh function from that same set, given an appropriate choice $\alpha^0_{H_2}$. Thus, to detect any cyclic shift of a binary pattern (BP), one can use a Walsh-Hadamard transform (WHT) within the same truncated basis of Walsh-Hadamard functions. If this truncated basis contains a relatively small number of Walsh functions, then computations may not be required.

Algorithm and block diagram of an M-sequence synchronization device

Time synchronization of an M-sequence reduces to implementing an algorithm for detecting and distinguishing its cyclic shifts. A simple rearrangement of the samples of the

received M-sequence, in accordance with the algorithm described in the previous section, yields a Walsh sequence, the symbols of which can be represented as a row vector of a matrix $\mathbf{W}_{m(1,-1)}$. As shown, this Walsh PRS corresponds uniquely to a specific cyclic shift of the original m-sequence, which is determined by its initial block of length m. The index i of the row in a Hadamard matrix of dimension 2^m – where this Walsh PRS is located – is $\mathbf{W}_{m(1,-1)}$, unambiguously linked to the code of the initial block of the original MS.

The square Hadamard matrix can be represented as the m-th Kronecker power of the second-order Hadamard matrix for $m=1$. As is known, when forming the Kronecker product of two matrices, each element of the second matrix is multiplied by all elements of the first matrix; as the number of matrices being multiplied increases, Kronecker products are found by a similar rule. Thus, if

$$\mathbf{W}_{1(1,-1)} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \mathbf{A} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \mathbf{A} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \quad (23)$$

for $\mathbf{W}_{m(1,-1)} = \mathbf{W}_{1(1,-1)}^m$. To use the fast Hadamard transform for multiplying the corresponding matrix by any given vector, one must utilize the factorization property of the Hadamard matrix—that is, the fact that it can be expressed as a product of simple, sparse matrices [14-16].

After the transformation of the MS, written as a string, we denote it as $\mathbf{X}_p \mathbf{X}_{np} \mathbf{X}_{np}$. Next, we convert the row into a column $\mathbf{X}_p^T$. After multiplying the matrix $\mathbf{W}_{m(1,-1)} \mathbf{X}_{np}^T \mathbf{X}_{np}^T$. Using this column, we obtain a column vector, which we denote as $\mathbf{Y}$. The maximum value of this vector corresponds to the main peak of the autocorrelation function (ACF) of the MS. The index of this value, within the sequential numbering of the elements of the column vector $\mathbf{Y}$, corresponds to a cyclic shift of the original M-sequence. Note that, due to a fundamental property of the periodic autocorrelation function (ACF) of an M-sequence, the remaining elements of the vector $\mathbf{Y}$ are all equal to "minus 1."

Thus, the determination of the cyclic shift index for a received M-sequence is described by the expression:

$$C = \max_i (\mathbf{Y} = \mathbf{W}_{m(1,-1)} \mathbf{X}_p^T), \quad (24)$$

where $i = 1, \dots, 2^m$ – номер элемента столбца $\mathbf{Y}$.

According to (23) and (24), the algorithm for accelerated MS detection consists of multiplying a column of input signal samples by a factorized Hadamard matrix.

$$\mathbf{W}_{m(1,-1)} = \mathbf{B}_2^m, \quad (25)$$

where $\mathbf{B}_2^m$ – simple m-th power of a matrix $\mathbf{B}_2$ on the order of $2^m N_{SPM} = 2^m$. Matrix element values $\mathbf{B}_2^m$ are determined in accordance with Good's theorem on the factorization of matrices that are Kronecker powers [17]. One version of such a matrix is:

$$B_{2^m} = \begin{bmatrix} 1 & 1 & & & & \dots & 0 & 0 \\ 0 & 0 & & & & \dots & 0 & 0 \\ 0 & 0 & & & & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & & & & \dots & 1 & 1 \\ 1 & -1 & 0 & 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & \dots & 0 & 0 \\ 0 & 0 & & & & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & & & & \dots & 1 & -1 \end{bmatrix}, \quad (26)$$

Given the structure of the matrix B_{2^m} and (24), we obtain an algorithm for accelerated detection of MPs

$$C = \max(Y = W_{m(1,-1)} X_p^T = B_{2^m}^{m-1} Y_{m-1} = B_{2^m} [B_{2^m} \dots (B_{2^m} X_p^T)]), \quad (27)$$

From (27) it follows that at the first stage of implementing this approach it is necessary to calculate the column $Y_1 = B_{2^m} X_p^T$. The second stage involves calculating a column $Y_2 = B_{2^m} Y_1$, etc. The m -th stage involves calculating a column $Y = Y_m = B_{2^m}^{m-1} Y_{m-1}$. The final column contains the values of the periodic autocorrelation function (PACF) of the received maximal-length sequence (MLS), adjusted to account for the discrepancy between the length of the MLS and the length of the Walsh function. The resulting values can be interpreted as a complete set of cross-correlation function (CCF) values for Walsh-based pseudorandom sequences (PRS), each calculated at a single point – that is, with zero time shift. One of these values corresponds to the autocorrelation function (ACF). It is well known that Walsh-based PRSs are orthogonal at this point; consequently, all the calculated values are zero, with the exception of one.

Column calculation procedures $Y_1, Y_2, \dots, Y_m$ are identical and can be described by an elementary graph, based on the factorization algorithm for a Hadamard matrix. An analysis of this graph shows that, to determine the elements of column Y , the received sequence must first be converted into a Walsh pseudorandom sequence (PRS), with its symbols stored in random-access memory (RAM). Next, during the calculation of Y_1 , the values of the Walsh PRS symbols stored in adjacent RAM memory locations – specifically, locations 1 and 2, 3 and 4, 5 and 6, and so on – must be added and subtracted using an arithmetic unit (AU) connected to the RAM. The results of these additions and subtractions are then written back into the RAM. Moreover, the sums of the symbols are written into memory cells numbered from 0 to 2^{m-1} -th, and the differences of the same symbols are written into RAM memory cells with numbers from $(2^{m-1} + 1)$ to 2^m .

When calculating $Y_2, \dots, Y_m$ the operations used during the calculation are applied each time Y_1 . As a result, we determine the elements of the vector $Y_m = Y$, in which one of the elements is equal to the value of the main peak of the ACF of the Walsh PRS corresponding to the received pseudorandom sequence (PRS), while the remaining elements of Y correspond to the peak values of the CCF between this Walsh PRS and the rows of the Hadamard matrix, assuming no relative time shifts between them.

Figure 2 shows a block diagram of a device for detecting a noise-like signal, which implements the aforementioned operating algorithm. After conversion to video frequency, the samples of the pseudo-random sequence (PRS) and noise from the analog-to-digital

converter (ADC) output are written into the random-access memory (RAM). Each sample is stored in a memory cell whose address corresponds to an element of a Galois field – generated by a Galois field generator (GFG) associated with either "group 1" or "group 2" – which is connected to the RAM's input/output address buses via a switching element (K1). The GFG unit incorporates generators for both group 1 and group 2; these are used by the decision-making unit (DMU) to determine the time shift of the received PRS.

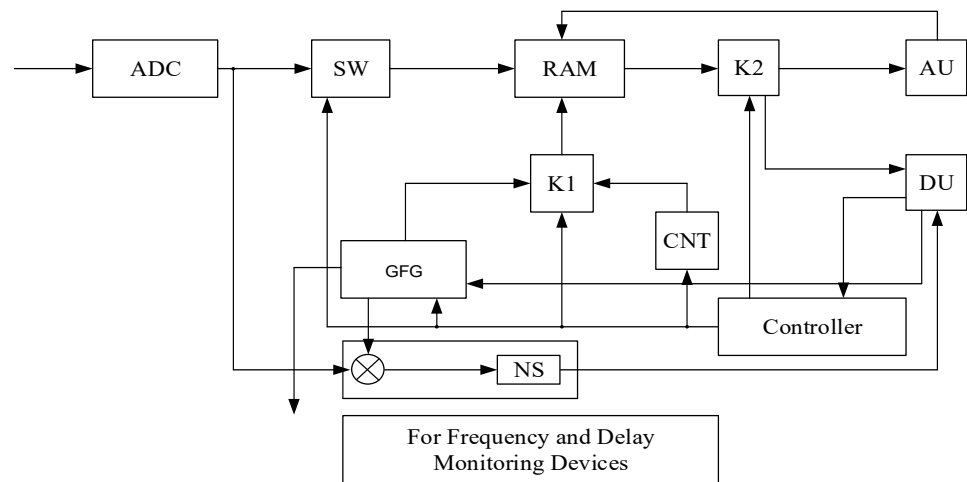


Fig. 2. Microprocessor accelerated synchronization unit

Thus, in accordance with the algorithm described above, a Walsh pseudorandom sequence (PRS) is written into the RAM. Neither its index within an ordered set of such sequences – for instance, as represented in a Hadamard matrix – nor its specific structure is known. To identify the index of the Walsh PRS within the Hadamard matrix, it is necessary to perform a high-speed multiplication of this matrix by the received additive mixture of noise and the unknown Walsh PRS. To achieve this, switch K1 is used to disconnect the pseudorandom sequence generator (PRSG) from the RAM and connect a counter (CNT). Simultaneously, switch K2 connects an arithmetic unit (AU) to the RAM data bus; the AU performs pairwise addition and subtraction of the values stored in the RAM, with the results then written back into available memory locations.

Following the algorithm defined by equations (26) and (27), after the m -th iteration of this procedure, the RAM will contain an auto-correlation function (ACF) of the maximal-length sequence (MLS) – cyclically shifted in a specific manner – summed with the samples resulting from the non-coherent accumulation of noise interference. At this stage, the position of the ACF's primary peak is unknown. The index of the memory location containing this primary peak determines the cyclic shift of the original MLS relative to the moment its samples began to be recorded in the RAM. Subsequently, switch K2 connects a decision unit (DU), which compares the values stored in the RAM and identifies the

memory location index where the maximum value was recorded. The relationship between this memory location index and the initial block of the MLS – from which the recording of its samples into the RAM commenced – is described in the preceding section.

Furthermore, it is necessary to account for the time required to calculate the autocorrelation function (ACF), as well as the fact that, during this interval, the incoming pseudorandom sequence (PRS) will have shifted in time; consequently, the initial segment of the PRS present at the receiver input will have changed. This new segment can be determined only with a certain margin of error, which depends on both the processing speed of the signal processor used in the device and the symbol rate (chip rate) of the PRS. This error manifests as an uncertainty equivalent to an unknown number of PRS chips. Therefore, an additional component – a serial or parallel correlator – is required. A pseudorandom sequence generator (PRSG) can serve as the reference PRS source, with the signal being tapped from one of the cells in its cyclic memory. This correlator, which can also function as a verification circuit, consists of a PRSG and a digital accumulator. In this way, a serial correlation search can be performed within the uncertainty region of the incoming PRS. Synchronization between the incoming PRS and the reference PRS is then verified using a decision unit.

Construction of a Gold PRS circulant matrix

The circulant matrices of Gold sequences are obtained by summing modulo two matrices $\mathfrak{J}_{m,2,c}$ [3] two so-called preferred MPs [18, 19]. Let, on the basis of the accompanying matrix H_2 of the first preferred polynomial and the primitive element $\alpha^0_{1H_2}$ a circulant matrix MS has been constructed $\alpha^0_{1H_2} \mathfrak{J}_{m,2,c}$, and based on a matrix H_2 , but of the second preferred polynomial and the primitive element $\alpha^{0+z}_{2H_2}$ – matrix $\alpha^{0+z}_{2H_2} \mathfrak{J}_{m,2,c}$. Then, the circulant matrices for the entire set of Gold sequences corresponding to these two preferred maximal-length sequences (excluding the sequences themselves) can be described as:

$$\mathfrak{J}_{m,2,c,g}(z) = \alpha^0_{1H_2} \mathfrak{J}_{m,2,c} \oplus \alpha^{0+z}_{2H_2} \mathfrak{J}_{m,2,c}, z = 0, \dots, N-1, \quad (28)$$

where $\oplus$ – notation for the operation of addition modul 2.

As an example, a circulant matrix of a Gold code constructed based on polynomials $f_5(x) = x^5 + x^4 + x^2 + x + 1$ and $f_5(x) = x^5 + x^3 + 1$ at $\alpha^0_{1H_2} = \alpha^0_{2H_2} = [1\ 0\ 0\ 0\ 0]^T$ and $z = 0$ is presented in Table 7. It is ordered, meaning that each subsequent row is cyclically shifted by one character relative to the preceding one [3].

Figure 3 shows the periodic cross-correlation function (PCCF) [20] $\chi_{PCCF}(i)$ Gold's PRS and MS, formed on the basis of the second of the two above polynomials. The PVCF values for negative i were obtained by mirroring the graph relative to the ordinate axis.

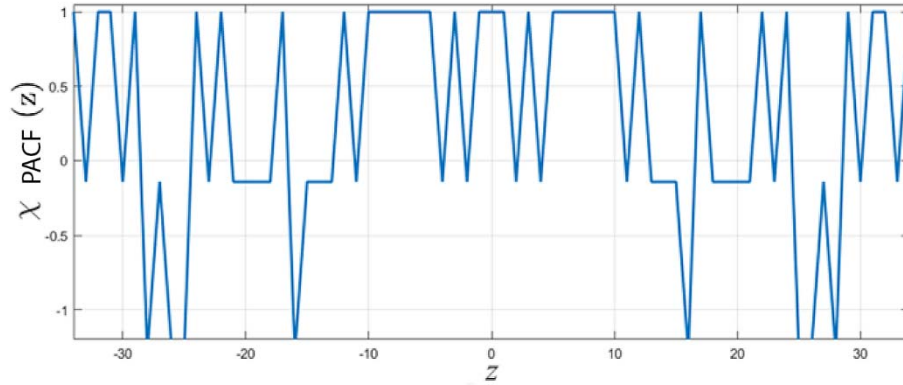


Fig. 3. Periodic autocorrelation function (PACF) of a Gold code

Thus, the matrix presented in Table 7 corresponds to a Gold sequence, as a three-valued periodic cross-correlation function (PCCF) is obtained.

Ordered circulant matrix of a Gold code for the selected values $\alpha^0_{1H_2}$, $\alpha^0_{2H_2}$ and z has the following form:

$$\mathfrak{Z}_{m,2,c,g}(z) = \begin{bmatrix} \mathfrak{Z}_{m,2}^1 \oplus \mathfrak{Z}_{m,2}^2 \\ H_{21}^m \mathfrak{Z}_{m,2}^1 \oplus H_{22}^m \mathfrak{Z}_{m,2}^2 \\ H_{21}^{2m} \mathfrak{Z}_{m,2}^1 \oplus H_{22}^{2m} \mathfrak{Z}_{m,2}^2 \\ \dots \\ H_{21}^{C(N)m} \mathfrak{Z}_{m,2}^1 \oplus H_{22}^{C(N)m} \mathfrak{Z}_{m,2}^2 \end{bmatrix}, \quad (29)$$

where $\mathfrak{Z}_{m,2}^1$ – matrix of m cyclic shifts of the first preferred MP, constructed based on the companion matrix H_{21} of its irreducible primitive polynomial, $\mathfrak{Z}_{m,2}^2$ – the corresponding matrix for the second preferred polynomial, constructed based on the companion matrix H_{22} of its irreducible primitive polynomial. In the notation for the companion matrices H_{21} and H_{22} , the first digit, 2, indicates that the matrices are of the type H_2 , while the second digit – 1 or 2 – denotes whether the matrix corresponds to the first or the second preferred polynomial.

It is evident that the columns of the first m rows of matrix (29) represent the sums of the powers of the primitive elements of two multiplicative groups; that is,

$$\mathfrak{Z}_{m,2}^1 \oplus \mathfrak{Z}_{m,2}^2 = \alpha^k_{1H_2} + \alpha^k_{2H_2}, k = 0, \dots, N - 1, \quad (30)$$

and meanings $[\alpha^k_{1H_2} + \alpha^k_{2H_2}]_{10}$ may coincide for different k . Furthermore, in (29), elements consisting solely of zeros may appear; that is, the sum of isomorphic maximal multiplicative groups of two distinct Galois fields does not form a multiplicative group.

Table 7

Circulant matrix of a Gold code corresponding to preferred polynomials

 $f_5(x) = x^5 + x^4 + x^2 + x + 1$ and $f_5(x) = x^5 + x^3 + 1$ at $\alpha^0_{1H_2} = \alpha^0_{2H_2} = [1\ 0\ 0\ 0\ 0]^T$ and $z = 0$

k	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
$[\alpha^k_{1H_2} + \alpha^k_{2H_2}]_{10}$	0	0	1	2	4	8	16	1	2	5	11	23	15	30	29	27	23	15	30	28	24	16	0	1	2	4	9	18	4	8	16	i
$x_{1,0,k} \oplus x_{2,0,k}$	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0
$x_{1,1,k} \oplus x_{2,1,k}$	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	1
$x_{1,2,k} \oplus x_{2,2,k}$	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	2
$x_{1,3,k} \oplus x_{2,3,k}$	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	3
$x_{1,4,k} \oplus x_{2,4,k}$	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	4
$x_{1,5,k} \oplus x_{2,5,k}$	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	5
$x_{1,6,k} \oplus x_{2,6,k}$	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	6
$x_{1,7,k} \oplus x_{2,7,k}$	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	7
$x_{1,8,k} \oplus x_{2,8,k}$	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	8
$x_{1,9,k} \oplus x_{2,9,k}$	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	9
$x_{1,10,k} \oplus x_{2,10,k}$	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	10
$x_{1,11,k} \oplus x_{2,11,k}$	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	11
$x_{1,12,k} \oplus x_{2,12,k}$	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	12
$x_{1,13,k} \oplus x_{2,13,k}$	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	13
$x_{1,14,k} \oplus x_{2,14,k}$	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	14
$x_{1,15,k} \oplus x_{2,15,k}$	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	15
$x_{1,16,k} \oplus x_{2,16,k}$	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	16
$x_{1,17,k} \oplus x_{2,17,k}$	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	17
$x_{1,18,k} \oplus x_{2,18,k}$	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1	18
$x_{1,19,k} \oplus x_{2,19,k}$	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1	0	19
$x_{1,20,k} \oplus x_{2,20,k}$	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1	0	1	20
$x_{1,21,k} \oplus x_{2,21,k}$	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1	0	1	1	21
$x_{1,22,k} \oplus x_{2,22,k}$	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	22
$x_{1,23,k} \oplus x_{2,23,k}$	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	23
$x_{1,24,k} \oplus x_{2,24,k}$	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	0	24
$x_{1,25,k} \oplus x_{2,25,k}$	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	0	0	25
$x_{1,26,k} \oplus x_{2,26,k}$	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	1	0	0	0	26
$x_{1,27,k} \oplus x_{2,27,k}$	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	1	0	0	0	0	27
$x_{1,28,k} \oplus x_{2,28,k}$	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	1	0	0	0	0	1	28
$x_{1,29,k} \oplus x_{2,29,k}$	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	1	0	0	0	0	0	1	29
$x_{1,30,k} \oplus x_{2,30,k}$	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	1	0	0	0	0	0	1	0	30
$x_{1,31,k} \oplus x_{2,31,k}$	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0
$x_{1,32,k} \oplus x_{2,32,k}$	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	1
$x_{1,33,k} \oplus x_{2,33,k}$	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	2
$x_{1,34,k} \oplus x_{2,34,k}$	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	3

Transformation of a Gold PRS circulant matrix into analogues of Rademacher functions

Having transformed the symbols $\alpha^k_{1H_2} + \alpha^k_{2H_2}$ according to the rule $0 \rightarrow 1, 1 \rightarrow -1$ and rearranging the columns (8) in ascending order $[\alpha^k_{1H_2} + \alpha^k_{2H_2}]_{10}$, By simultaneously summing identical values and replacing missing elements with zeros, we obtain functions that contain symbols other than 1 or -1, as well as symbols with zero values.

Thus, by rearranging the columns of the matrix shown in Table 7 according to this rule, we obtain the matrix presented in the rows of Table 8.

Table 8

The result of transforming a circulant matrix of a Gold code, ordered by the increasing values of the sum of multiplicative groups

k	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	i
r_{0a}	3	3	3	0	3	1	0	0	2	1	0	1	0	0	0	2	-3	0	-1	0	0	0	0	-2	-1	0	0	-1	-1	-1	-2	0
r_{1a}	3	3	3	0	3	1	0	0	-2	-1	0	-1	0	0	0	-2	3	0	1	0	0	0	0	2	-1	0	0	-1	-1	-1	-2	1
r_{2a}	3	3	3	0	-3	-1	0	0	2	1	0	1	0	0	0	-2	3	0	1	0	0	0	0	-2	1	0	0	1	-1	-1	-2	2
r_{3a}	3	3	-3	0	3	1	0	0	2	1	0	-1	0	0	0	-2	3	0	-1	0	0	0	0	-2	1	0	0	-1	1	1	-2	3
r_{4a}	3	-3	3	0	3	-1	0	0	2	-1	0	-1	0	0	0	-2	3	0	1	0	0	0	0	-2	1	0	0	-1	1	-1	2	4
r'_{5}	-1	3	1	0	1	-1	0	0	2	1	0	-1	0	0	0	2	1	0	1	0	0	0	0	-2	1	0	0	-1	1	-1	0	5
r'_{6}	1	1	-1	0	3	-1	0	0	0	1	0	-1	0	0	0	0	1	0	1	0	0	0	0	2	1	0	0	-1	1	-1	0	6
r'_{7}	3	-1	1	0	1	-1	0	0	2	1	0	1	0	0	0	0	-1	0	1	0	0	0	0	0	-1	0	0	1	1	-1	0	7
r'_{8}	1	1	-1	0	3	1	0	0	-2	1	0	-1	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0	1	-1	1	0	8
r'_{9}	3	-1	3	0	-1	-1	0	0	0	1	0	-1	0	0	0	0	-1	0	1	0	0	0	0	0	1	0	0	1	1	1	0	9
r'_{10}	1	3	-1	0	1	-1	0	0	0	1	0	-1	0	0	0	0	1	0	-1	0	0	0	0	0	-1	0	0	1	1	1	2	10
r'_{11}	1	-1	-1	0	1	-1	0	0	0	-1	0	-1	0	0	0	2	3	0	1	0	0	0	0	0	1	0	0	1	-1	1	2	11
r'_{12}	1	-1	-1	0	-1	-1	0	0	2	1	0	1	0	0	0	2	-1	0	1	0	0	0	0	2	1	0	0	-1	1	1	0	12
r'_{13}	-1	-1	-3	0	3	1	0	0	-2	1	0	1	0	0	0	0	1	0	1	0	0	0	0	2	1	0	0	1	1	-1	2	13
r'_{14}	-1	-3	3	0	-1	1	0	0	0	1	0	1	0	0	0	2	-1	0	1	0	0	0	0	0	1	0	0	1	1	1	0	14
r'_{15}	-3	3	1	0	1	1	0	0	-2	1	0	1	0	0	0	0	-1	0	-1	0	0	0	0	2	1	0	0	-1	1	1	2	15
r'_{16}	1	1	1	0	-1	1	0	0	-2	-1	0	1	0	0	0	2	-1	0	1	0	0	0	0	0	1	0	0	1	1	-1	2	16
r'_{17}	1	1	1	0	-3	1	0	0	0	1	0	-1	0	0	0	2	1	0	-1	0	0	0	0	2	-1	0	0	1	1	1	0	17
r'_{18}	-1	1	-1	0	1	-1	0	0	0	-1	0	1	0	0	0	0	3	0	-1	0	0	0	0	2	1	0	0	1	-1	1	2	18
r'_{19}	-1	-1	1	0	-1	1	0	0	2	-1	0	1	0	0	0	2	1	0	-1	0	0	0	0	0	1	0	0	1	1	1	0	19
r'_{20}	-3	1	1	0	1	1	0	0	0	-1	0	-1	0	0	0	0	1	0	-1	0	0	0	0	2	1	0	0	1	1	1	2	20
r'_{21}	1	1	1	0	-1	-1	0	0	0	-1	0	1	0	0	0	2	-3	0	1	0	0	0	0	0	1	0	0	1	1	1	2	21
r'_{22}	1	1	-1	0	-1	1	0	0	-2	1	0	1	0	0	0	2	1	0	-1	0	0	0	0	2	-1	0	0	-1	1	1	2	22
r'_{23}	1	-1	1	0	-1	1	0	0	0	-1	0	1	0	0	0	2	1	0	-1	0	0	0	0	2	1	0	0	1	-1	-1	2	23
r'_{24}	1	1	1	0	-1	1	0	0	2	-1	0	1	0	0	0	2	-1	0	-1	0	0	0	0	2	-1	0	0	1	1	1	-2	24
r'_{25}	1	1	1	0	1	1	0	0	0	-1	0	1	0	0	0	-2	1	0	-1	0	0	0	0	2	-1	0	0	1	-1	1	2	25
r'_{26}	1	1	1	0	-1	1	0	0	2	-1	0	1	0	0	0	2	1	0	1	0	0	0	0	-2	-1	0	0	1	-1	1	0	26
r'_{27}	-1	1	-1	0	1	1	0	0	2	1	0	-1	0	0	0	0	3	0	1	0	0	0	0	2	-1	0	0	-1	-1	1	0	27
r'_{28}	1	-1	1	0	3	-1	0	0	2	1	0	1	0	0	0	0	-1	0	1	0	0	0	0	0	1	0	0	1	-1	-1	0	28
r'_{29}	-1	1	1	0	3	1	0	0	0	1	0	1	0	0	0	0	1	0	1	0	0	0	0	0	-1	0	0	-1	1	1	-2	29
r'_{30}	-1	1	3	0	1	1	0	0	2	1	0	1	0	0	0	-2	1	0	1	0	0	0	0	0	-1	0	0	-1	-1	-1	2	30
r_{0a}	3	3	3	0	3	1	0	0	2	1	0	1	0	0	0	2	-3	0	-1	0	0	0	0	-2	-1	0	0	-1	-1	-1	-2	0
r_{1a}	3	3	3	0	3	1	0	0	-2	-1	0	-1	0	0	0	-2	3	0	1	0	0	0	0	2	-1	0	0	-1	-1	-1	-2	1
r_{2a}	3	3	3	0	-3	-1	0	0	2	1	0	1	0	0	0	-2	3	0	1	0	0	0	0	-2	1	0	0	1	-1	-1	-2	2
r_{3a}	3	3	-3	0	3	1	0	0	2	1	0	-1	0	0	0	-2	3	0	-1	0	0	0	0	-2	1	0	0	-1	1	1	-2	3

As can be seen, half of the symbols in the transformed matrix – those in its second row – are either positive or zero, while the other half are either negative or zero. In the third row, the first 8 symbols are positive or zero, followed by 8 negative or zero symbols, then another 8 positive symbols, then 8 negative ones, and so on. That is, the first m rows of the circulant matrix of the Gold sequence, transformed according to the rule described

above, are analogs of the Rademacher functions (we denote them as r_{ia} , where $i = 0, \dots, (m-1)$ – function number), but the remaining rows of the original circulant matrix do not reduce to analogues of Walsh functions (excluding the zero symbol, when indexed from zero). Let us denote them as r'_i , where $i = m, \dots, (C(N) + 1)m - 1$, $C(N) = \left(\frac{A(N)}{m}\right) - 1$, $A(N)$ – a number as close as possible to N that is perfectly divisible by m and satisfies the inequality $A(N) > N$ [3].

But the functions r'_i can be reduced to analogs of Rademacher functions by choosing the corresponding primitive elements of the multiplicative groups. That is, by choosing $\alpha^0_{1H_2}$ and $\alpha^0_{2H_2}$ and by rearranging the columns of the Gold code's circulant matrix in ascending order $[\alpha^k_{1H_2} + \alpha^k_{2H_2}]_{10}$, we transform its first m rows into a matrix of analogues of Rademacher functions. However, if the columns of this matrix are permuted, starting from the element $\alpha^m_{1H_2} + \alpha^m_{2H_2}$, then the second m rows of the circulant matrix of the Gold code are transformed into analogs of the Rademacher functions. When rearranging starting from $\alpha^{2m}_{1H_2} + \alpha^{2m}_{2H_2}$ we transform the following m rows, etc.

This approach to mapping cyclic shifts of a Gold code to analogues of Rademacher functions is meaningful only if there exists a fast algorithm for multiplying a matrix of Rademacher functions by a vector – an algorithm whose computational complexity, in terms of the number of elementary mathematical operations, is significantly less than mN , given that mN is the complexity associated with multiplying a matrix of size $m \times N$ per column.

Gold's fast PRS synchronization algorithm

This algorithm effectively boils down to the accelerated multiplication of a matrix of Rademacher functions and a transformed Gold PRS.

At $m = 5$ the gain in the number of elementary arithmetic operations is approximately 1.84, compared to simple multiplication of the metric by the vector, but for typical PRS lengths used in constructing, for example, navigation codes, it is more significant – for $N = 511$ ($m = 9$) the winnings are 3 times, and when $N = 1023$ ($m = 10$) – 3.4 times [21].

The proposed algorithm for synchronizing Gold sequences based on FPA for a given cyclic shift of preferred MSs z is as follows: in order to ensure the possibility of synchronizing the entire set of Gold sequences, for the formation of which this pair of preferred MPs is used, select $\alpha^0_{1H_2}$ and $\alpha^0_{2H_2}$ multiplicative groups of their Galois fields and find the sums $\alpha^k_{1H_2} + \alpha^{k(z)}_{2H_2}$, where $k(z) = k + z$ at $k + z \leq N$ and $k(z) = k + z - N$ at $k + z > N$, $k = 0, \dots, N - 1$;

1) rearrange the values of the input discrete signal X_N , containing a Gold sequence with an unknown cyclic shift, in order of increasing values $[\alpha^k_{1H_2} + \alpha^{k(z)}_{2H_2}]_{10}$, writing these symbols into memory cells with the corresponding numbers; if the write addresses for different symbols coincide, they are written into the same cell and summed; elements $[\alpha^k_{1H_2} + \alpha^{k(z)}_{2H_2}]_{10}$, consisting solely of zeros, these determine the writing of an input code symbol into the zero-indexed cell and its summation with any symbols previously stored therein; the contents of any remaining empty cells are set to zero;

2) the resulting vector – whose symbol values are stored in the memory unit – is multiplied by a matrix of Rademacher functions; the resulting m values from this multiplication correspond to m values of the periodic autocorrelation function (PACF) of the Gold sequence;

3) to identify the primary peak of the PACF, it is advisable in this case to employ a threshold-based algorithm; if this peak is found among the calculated PACF values, the synchronization procedure is complete; otherwise, the next step is performed;

4) values X_N they are rearranged once again according to the rule described above, but this time in order of increasing values $[\alpha^{k+m}{}_{1H_2} + \alpha^{k(z)+m}{}_{2H_2}]_{10}$; After multiplying the resulting vector by the matrix of Rademacher functions, we obtain the following m values of the periodic autocorrelation function (PACF) for the Gold sequence, etc.

5) to synchronize another Gold sequence, it is necessary to change the value $z = 0, \dots, N - 1$.

Following the algorithm described above, the periodic autocorrelation function (PACF) of a Gold-sequence-based pseudorandom sequence (PRS) was calculated; its circulant matrix is presented in Table 7. The corresponding plot is shown in Figure 4, while Figure 5 displays the PACF of this Gold-sequence-based PRS, obtained by simply multiplying its circulant matrix by its first row (transposed into a column vector).

The slight discrepancy between the PACFs of the same sequence, when calculated using different methods, is attributable to the differing lengths of the Gold-sequence-based PRS and the Rademacher-Walsh function. The traditional method for calculating the periodic autocorrelation function (PACF), the reference pseudo-random sequence (PRS) must be shifted by one symbol at a time relative to the values of the received discrete signal, with each shift followed by the calculation of a single PACF value – a process that requires N multiply-accumulate operations. Consequently, computing the entire PACF necessitates N shifts of the reference PRS relative to the received signal and a total of N^2 multiply-accumulate operations.

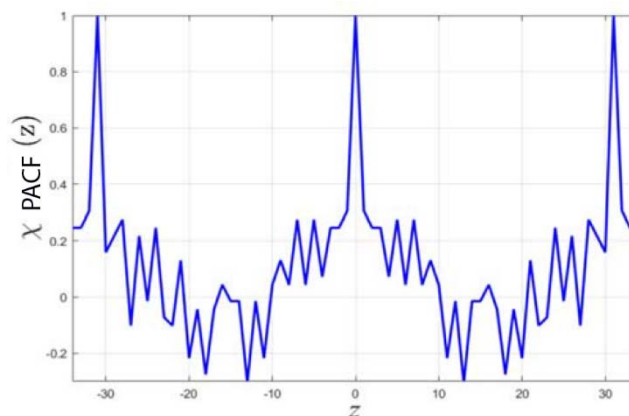


Fig. 4. Result of the accelerated computation of the periodic autocorrelation function (PACF) of a Gold code ($m = 5$)

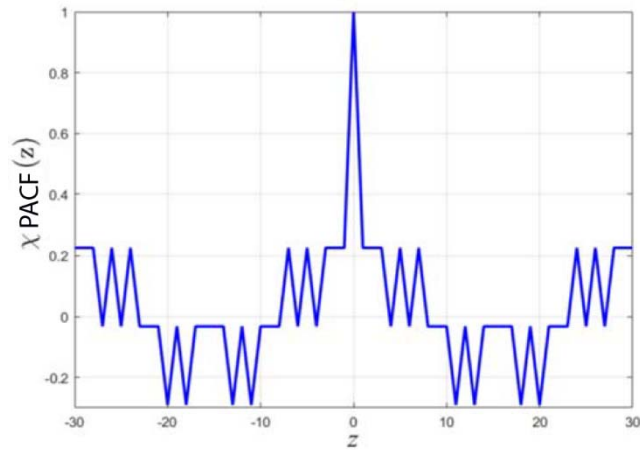


Fig. 5. Aperiodic Autocorrelation Function (AACF) of a Gold code ($m = 5$)

In the proposed algorithm, the number of permutations of the sequence's symbols is equal to $\frac{A(N)}{m}$, following each of these, m values of the periodic autocorrelation function (PACF) are computed simultaneously, requiring significantly fewer elementary summation operations than the traditional method for calculating m PACF values. The reduction in the number of arithmetic operations achieved by the proposed algorithm, compared to the traditional one, as a function of m . The rule for permuting the symbols of the input discrete signal is determined by the same Gold sequence generator used to produce the reference signal in the traditional PACF calculation algorithm.

Gold PRS accelerated synchronization device

The difference between this device and the one shown in Figure 2 is that a generator is used to write input signal samples into the RAM $\alpha^k_{1H_2} + \alpha^k_{2H_2}$. Furthermore, before each write operation to a RAM cell, its current content is added to the new value being written from the receiver input. The corresponding block diagram of the device is shown in Figure 6.

Let us examine the sequence generator. $\alpha^k_{1H_2} + \alpha^k_{2H_2}$. It corresponds to a version of a Gold code generator. Having derived the recurrence relations for the elements of a Gold code, let us present the generator $\alpha^k_{1H_2} + \alpha^k_{2H_2}$ as shown in Figure 7. This sequence originates from the outputs of the adders of the MS elements $x^1_{0,i+z} \oplus x^2_{0,i+z}$.

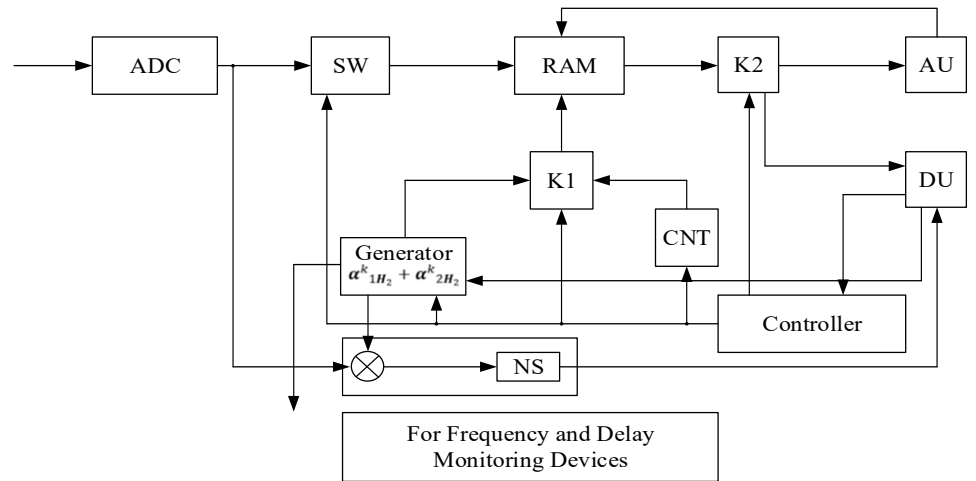


Fig. 6. Gold PRS synchronization device

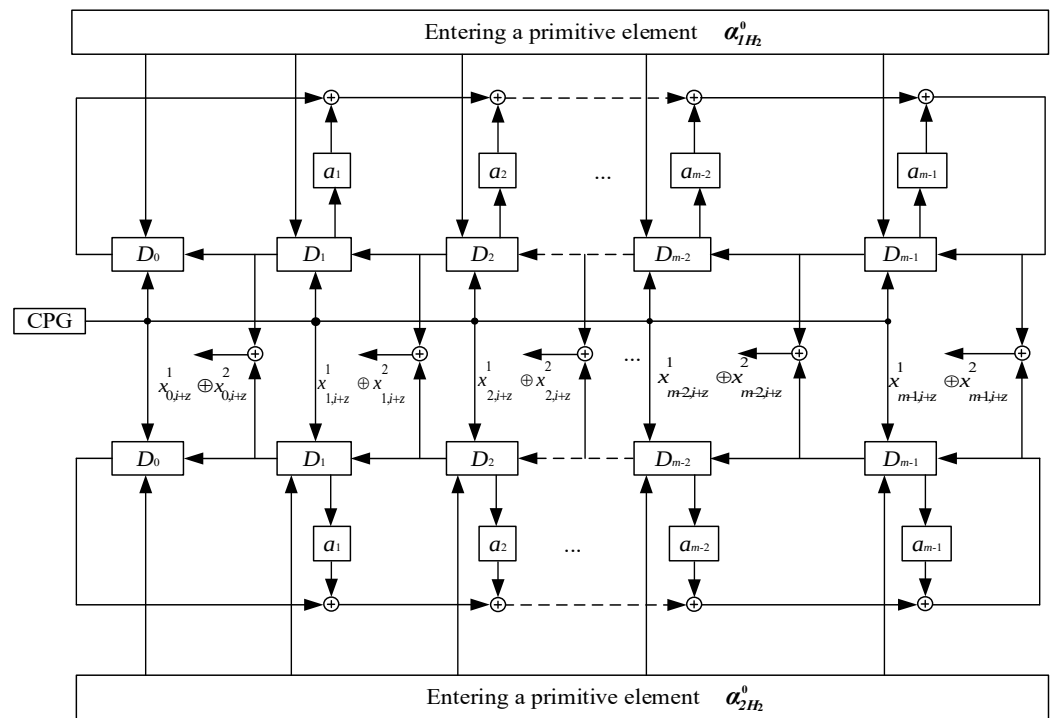


Fig. 7. Sequence generator $\alpha^k_{1H_2} + \alpha^k_{2H_2}$.

Each set of m consecutive characters represents an element of the sequence $\alpha^k_{1H_2} + \alpha^k_{2H_2}$. In this setup, a Gold sequence can be obtained from any of these adders. To change the value of z , it is necessary to introduce a different primitive element from any of the Galois fields used to generate the sequence $\alpha^k_{1H_2} + \alpha^k_{2H_2}$.

Conclusion

1. The algorithm for permuting the values of a discrete signal when transforming it into a row of a Walsh function matrix, as well as the method for identifying the cyclic shift of the corresponding PRS (pseudorandom sequence) after performing a Fast Walsh-Hadamard Transform (FWHT), depend on the choice of the circulant matrix structure for that PRS.

2. A circulant matrix MP , whose rows begin with blocks of binary symbols corresponding to the decimal indices of these rows (under binary-coded decimal representation), can be transformed into a Hadamard matrix – excluding the zero-indexed row and column – by permuting the matrix columns according to the elements of the unique multiplicative group of an extended Galois field. The method for constructing this group is illustrated in Figure 1a and corresponds to the form H_1 of the companion matrix associated with the original irreducible primitive polynomial; this transformation holds specifically when the primitive element of this group is assigned a particular value $\alpha^0_{H_1} = [1\ 0\ \dots\ 0\ 0]^T$.

3. Any of the N ordered circulant matrices of an M-sequence (where N is the length of the M-sequence) can be transformed into a matrix consisting of Walsh functions, ordered according to the powers of the multiplicative group of an extended Galois field. In this process, the columns of the circulant matrix must be permuted in increasing order of the elements of the Galois field's multiplicative group, corresponding to the form of the matrix H_2 . Furthermore, any cyclic shift of an M-sequence can be mapped to any Walsh function (excluding the one consisting of zeros, when indexed starting from zero), depending on the choice of the primitive element $\alpha^0_{H_2}$ of this group, which determines the structure of the circulant matrix. But for a given value $\alpha^0_{H_2}$ there is a one-to-one correspondence between a cyclically shifted M-sequence and a Walsh function (excluding the zero symbol), assuming both are indexed starting from zero. Consequently, all possible circulant matrices derived from an M-sequence – where each subsequent row is a cyclic shift of the preceding row by one symbol – can be reduced to the same matrix of Walsh functions (excluding zero symbols). In this representation, the functions are indexed from zero and ordered according to the powers of the elements of the multiplicative group of a Galois field, defined by a primitive element $\alpha^0_{H_1} = [1\ 0\ \dots\ 0\ 0]^T$, to the corresponding companion matrix of a polynomial of the form H_1 . Let us also note an important property of this matrix transformation: if, for the chosen $\alpha^0_{H_2}$, which defines the structure of a circulant matrix whose rows are ordered according to the cyclic shifts of an M-sequence, a certain i -th row of this matrix corresponds to the u -th row of a Walsh function matrix (excluding the zero-index row, when indexed starting from zero); thus, if one chooses as a primitive element $\alpha^{0+l}_{H_2}$ the same row of the circulant matrix is reduced to $(u + l)$ -th a row of a matrix of Walsh functions.

4. A Hadamard matrix can be obtained from a matrix of Walsh functions – ordered according to the powers of the maximal multiplicative group of a Galois field – by permuting its rows in increasing order of the values of the elements of this group, and by adding a zero row and a zero column (using zero-based indexing).

5. Any of the methods for transforming an M-sequence (according to the rules described in points 2 and 3) allows it to be converted into a Walsh function – excluding the zero symbol when using zero-based indexing. By subsequently appending this zero symbol and applying a Fast Walsh-Hadamard Transform (FWHT) to the resulting vector, one can efficiently compute the periodic autocorrelation function (PACF) of the M-sequence, with an adjustment made for the difference in length between the M-sequence and the Walsh sequences. This approach offers a computational complexity advantage of a factor of N/m compared to the traditional algorithm for calculating the discrete convolution of an M-sequence.

6. The first m rows of any ordered circulant matrix derived from a Gold sequence can be transformed into analogues of Rademacher functions by permuting the matrix columns according to the ascending order of the sums of the elements of the maximal multiplicative groups associated with the two preferred irreducible primitive polynomials used to construct the code. The structure of these groups is determined by the companion matrices of the preferred polynomials, specifically those of the form H_2 . Shifting the primitive elements of the constituent multiplicative groups by m positions results in the next m rows of the original matrix becoming Rademacher functions; a shift by $2m$ positions yields the same result for the subsequent m rows, and so on.

7. Transforming a Gold sequence allows for the rapid computation of its periodic autocorrelation function (PACF) using a fast transform algorithm (FTA) based on a truncated Walsh-Hadamard function basis; the gain in terms of the number of elementary operations depends on the length of the pseudorandom sequence (PRS) $N = 2^m - 1$.

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DEVELOPMENT AND INVESTIGATION OF AN SDN MODEL FOR MULTISERVICE TRAFFIC TRANSMISSION IN LEO SATELLITE COMMUNICATION NETWORKS

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ABSTRACT

This article focuses on the development and simulation-based study of a model for multiservice traffic transmission in low Earth orbit (LEO) satellite communication networks. The relevance of this work stems from the rapid expansion of LEO satellite constellations and the need to ensure guaranteed Quality of Service (QoS) for latency-sensitive applications. The objective is to construct a model that accounts for the dynamic topology of LEO networks – specifically, frequent handovers – and provides differentiated service for four traffic classes: real-time traffic with strict (RT1) and relaxed (RT2) requirements, interactive (INT) traffic, and best-effort (BE) traffic. The model is based on Software-Defined Networking (SDN) principles, employing priority-based scheduling disciplines and queue management mechanisms. The effectiveness of the proposed solutions was evaluated through discrete-event simulation using the ns-3 simulator, with subsequent data analysis performed in MATLAB. The results demonstrate that, compared to a standard FIFO (First-In, First-Out) scheme, the proposed approach significantly reduces both latency and packet loss for real-time traffic across various LEO network load levels.

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KEYWORDS: *low-Earth orbit (LEO) satellite network, multiservice traffic, QoS, SDN, handover, NS-3, FlowMonitor.*

Introduction

Modern multiservice network traffic – including voice, real-time video, streaming services, cloud applications, and IoT – requires communication networks to provide a guaranteed quality of service (QoS), even under uneven load distribution. Low Earth orbit (LEO) satellite systems [1] are considered a promising platform for global broadband coverage that can be integrated into 5G/6G infrastructure, primarily due to their significantly lower signal propagation latency compared to geostationary (GEO) satellites. For instance, the one-way signal propagation latency in LEO systems is on the order of a few milliseconds – an order of magnitude lower than the ~120 ms latency associated with GEO systems – making LEO networks well-suited for interactive services and cloud applications. However, this reduction in orbital altitude comes at the cost of a highly dynamic topology: each LEO satellite remains within a ground user's field of view for only a few minutes, after which the connection must be handed over to the next satellite. In LEO networks, handovers occur regularly (every few minutes) and affect numerous active sessions, placing stringent demands on the robustness of protocols, routing algorithms, and QoS mechanisms. While existing solutions for ensuring QoS in satellite networks and their integration with terrestrial infrastructure – such as the use of multi-channel queuing, traffic prioritization, and traffic duplication – have been extensively studied, the dynamic nature of LEO constellations necessitates new approaches [2].

One promising avenue for the development of satellite networks is the transition toward centralized software-defined networking (SDN) architectures. Software-defined networking enables the separation of the control plane from the data plane, allowing a central controller to maintain a global view of the network state, including its topology, link loads, and queue status. This enables the dynamic adaptation of routing and the allocation of resources in response to current conditions – a capability particularly crucial given the frequent handovers and variable environment characteristic of LEO (Low Earth Orbit) satellite networks. When combined with Differentiated Services (DiffServ) mechanisms, centralized SDN (Software-Defined Networking) control provides a flexible means of maintaining required Quality of Service (QoS) parameters for various traffic classes, even within a rapidly changing network topology. This paper proposes an SDN-based model for LEO networks that implements traffic classification and prioritization, QoS-aware dynamic routing, and handover management. The modeling methods, the architecture, and the core components of the model are described below, followed by the results of simulation experiments conducted to evaluate the effectiveness of these approaches [4].

Methods

Model architecture. The LEO network model under development comprises two planes: a data plane, which includes user nodes and forwarding nodes, and a control plane, represented by a centralized SDN controller. The model's topology consists of key nodes: a user equipment (UE) terminal, two low-Earth orbit (LEO) satellites (Sat1, Sat2), a ground gateway (GW), and an application server (Server). Each node in the data plane

functions as a switch that supports IP routing and multi-queue traffic processing. The SDN controller is connected to these nodes via a dedicated logical control channel and maintains global knowledge of the network state – such as satellite positions, link utilization, and queue status – enabling it to calculate optimal routes and allocate resources to maintain Quality of Service (QoS). Specifically, the controller updates routing rules during hand-over events by proactively rerouting traffic flows and adjusting priorities, thereby minimizing the impact of satellite switching on critical services. The logical topology of the network segment and the interactions between its components are illustrated in Figure 1.

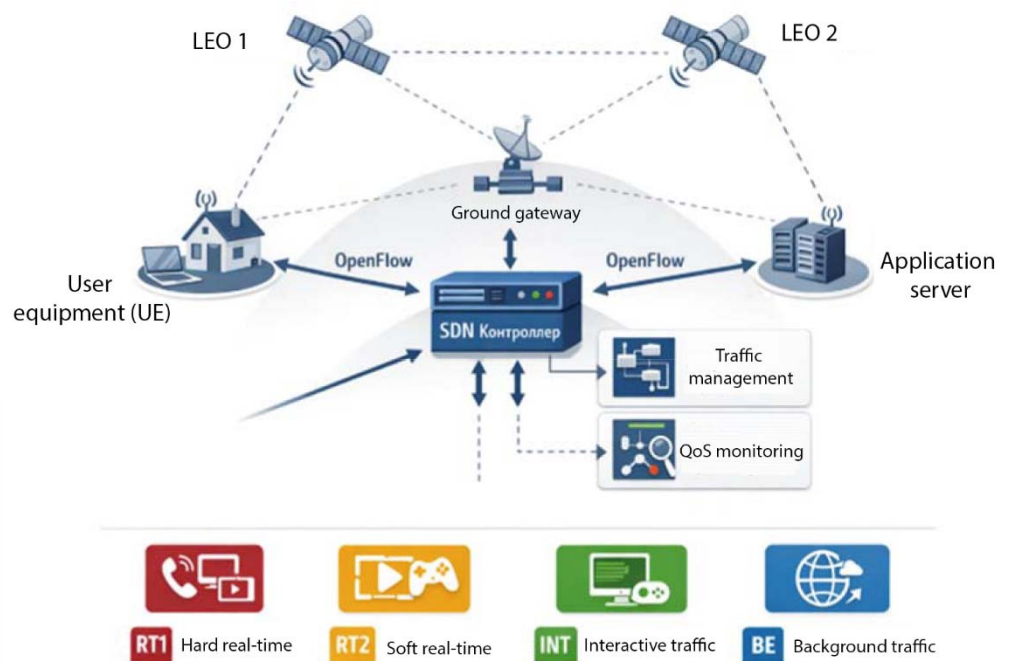


Fig. 1. Logical topology of a LEO network fragment with an SDN controller and four traffic classes (RT1, RT2, INT, BE)

QoS mechanisms. To ensure differentiated service, traffic is divided into four classes: RT1 – real-time services with strict latency requirements (e.g., voice); RT2 – real-time services with moderate requirements (e.g., video); INT – interactive services (web, transactions); and BE – background traffic with no guarantees ("best effort"). At satellite nodes and the gateway, a separate queue is allocated for each class (a multi-queue system). The RT1 class queue is serviced using strict priority with minimal latency (Low Latency Queue); the RT2 and INT queues are allocated a guaranteed share of bandwidth (using a method such as Weighted Round Robin); and the BE queue is serviced on a residual basis and equipped with an active buffer management mechanism (RED/WRED).

All queues are connected to a central scheduler that selects packets based on their assigned priorities and weights. This combination of disciplines aligns with the DiffServ model and aims to reduce latency and packet loss for sensitive traffic classes by limiting background traffic [3]. Such an approach has previously proven effective in both terrestrial and satellite networks for improving the quality of TCP traffic through the use of Differentiated Services. In our model, an SDN controller centrally configures the queue and scheduler parameters – such as priorities, weights, and buffer limits – at each node in accordance with the established QoS policy. This enables the dynamic reallocation of resources among traffic classes as load conditions change, while also preventing congestion in high-priority queues [5].

Simulation modeling. To evaluate the effectiveness of the proposed solutions, a software suite based on the ns-3 network simulator was developed. This discrete-event simulator supports a realistic model of IP protocols, routing, queuing, and traffic scheduling, as well as the FlowMonitor module for collecting QoS statistics. The model implements the aforementioned LEO network topology (UE – Sat1/Sat2 – GW – Server) with channel parameters approximating real-world conditions: the UE–Sat radio link accounts for propagation delay (tens of milliseconds) and limited bandwidth; the Sat–GW links reflect typical Earth-to-space satellite channel characteristics; and the GW–Server segment represents a high-speed, low-latency terrestrial connection. An SDN controller is incorporated as a distinct logical entity that manages traffic routing between nodes via control interfaces.

Traffic generation is handled by built-in ns-3 applications: for each traffic class (RT1, RT2, INT, BE), flows are created with specified intensities and packet distributions (using Poisson and self-similar ON/OFF processes to model different types of traffic). During the simulation, QoS metrics – such as average end-to-end delay, packet loss ratio, and average throughput – are recorded for each traffic flow using FlowMonitor. Data processing is performed using Python scripts (which parse the XML logs generated by FlowMonitor and aggregate statistics by class into CSV files) and the MATLAB software package; during the post-processing stage, average performance indicators for each scenario are calculated, and plots illustrating the distributions of delay, packet loss, and throughput are generated [6].

The sequence for configuring, building, and running the simulation model is shown in Figure 2. The procedure for generating FlowMonitor reports and preparing data for subsequent post-processing is illustrated in Figure 3.



```
wallys@wallys-VMware-Virtual-Platform:~/ns-3-dev$ ./ns3 run "scratch/leo_qos_sim --scenario=S1"
=== LEO QoS simulation START ===
Scenario: S1
Attribute 'RemoteAddress' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemotePort' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemoteAddress' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemotePort' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemoteAddress' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemotePort' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemoteAddress' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemotePort' is deprecated: Replaced by Remote in ns-3.44.
CSV saved: results_S1.csv
FlowMonitor saved: leo_qos_flowmon_S1.xml
=== LEO QoS simulation END ===
```

Fig. 2. Compiling and running a simulation model in ns-3

```
wallys@wallys-Virtual-Platform:~/ns-3-dev$ ls -lh leo_qos_flowmon_*.xml
-rw-rw-r-- 1 wallys wallys 6.7K Jan 25 17:51 leo_qos_flowmon_S1.xml
-rw-rw-r-- 1 wallys wallys 107K Jan 24 22:40 leo_qos_flowmon_S2.xml
-rw-rw-r-- 1 wallys wallys 821K Jan 24 22:41 leo_qos_flowmon_S3.xml
wallys@wallys-Virtual-Platform:~/ns-3-dev$ ls -lh results_*.csv
-rw-rw-r-- 1 wallys wallys 455 Jan 25 17:51 results_S1.csv
-rw-rw-r-- 1 wallys wallys 711 Jan 24 22:40 results_S2.csv
-rw-rw-r-- 1 wallys wallys 1.2K Jan 24 22:41 results_S3.csv
```

Fig. 3. Generating FlowMonitor reports and preparing data for post-processing

Scenarios and experiments. A series of experiments was conducted across three distinct load scenarios. Scenario S1 represents a moderate network load, where the aggregate bitrate of all traffic flows does not exceed ~50% of the bottleneck link capacity, and handover events are infrequent. This mode simulates a relatively favorable environment for evaluating the baseline resource allocation among different traffic classes. Scenario S2 involves an increased load: the intensity of interactive and background traffic rises, with total channel utilization reaching 60-80% of its capacity. This scenario tests the model's ability to maintain an acceptable Quality of Service (QoS) for real-time (RT) traffic as the background load intensifies. Scenario S3 represents a stress condition: the network operates near saturation, the UE–Sat (user equipment-to-satellite) link is nearly 100% utilized, and handovers occur frequently.

This scenario reveals the stability limits of the proposed mechanism under congestion. Each experiment was run for a specified duration (tens of seconds of simulated time); for S3, multiple handover events were scheduled at intervals of several seconds, whereas for S1, no more than one handover occurred throughout the entire duration. Upon completion of each run, the average QoS metric values for each traffic class and scenario were recorded. Furthermore, to demonstrate the advantages of the proposed model, a comparison with a First-In-First-Out (FIFO) scheduling discipline was performed. Specifically, for the stress scenario S3, the network was simulated using a simple FIFO approach (a single, non-prioritized queue) to benchmark real-time latency performance against the proposed QoS scheme [7, 8].

Results

Simulation results confirm the effectiveness of the proposed differentiated service model for LEO networks. Under moderate load (S1), all traffic classes achieve low latency and negligible packet loss. Critical classes RT1 and RT2 exhibit minimal average latency (<20-30 ms), while interactive traffic (INT) shows slightly higher, yet still acceptable, latency; background traffic (BE) utilizes the remaining bandwidth without significantly impacting high-priority flows. Under increased load (S2), latency and packet loss rise for the INT and BE classes; however, real-time classes maintain an acceptable level of quality, with the average latency for RT1 remaining well below 100 ms and packet loss being virtually non-existent. In a stress scenario (S3) – where total traffic approaches the channel

capacity – the developed model demonstrates robust performance. Any degradation in Quality of Service (QoS) primarily affects the lowest-priority traffic: latency and packet loss rates for the BE class increase sharply, and the INT class also experiences some degradation, whereas the performance metrics for RT1/RT2 traffic remain within acceptable limits. Thus, during periods of congestion, the network automatically sacrifices the performance of background services to ensure that critical real-time flows continue to be handled at an acceptable level, consistent with the established prioritization policy. A comparison of average latency across traffic classes for scenarios S1-S3 is provided in Figure 4, while the estimated packet loss probability for each traffic class under the same scenarios is presented in Figure 5.

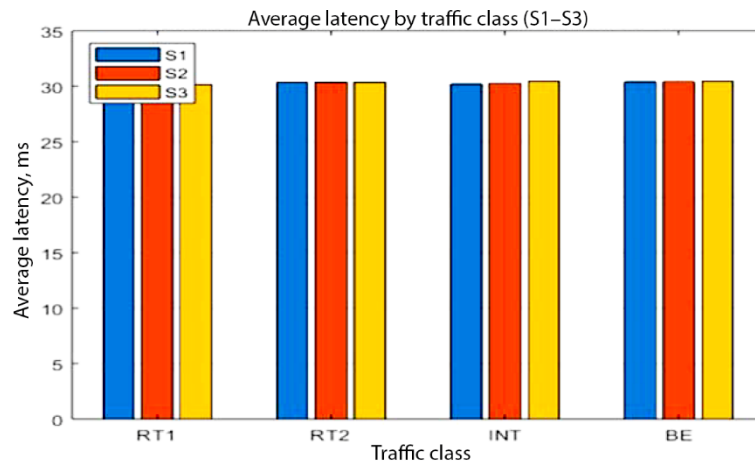


Fig. 4. Average latency by traffic class in scenarios S1-S3

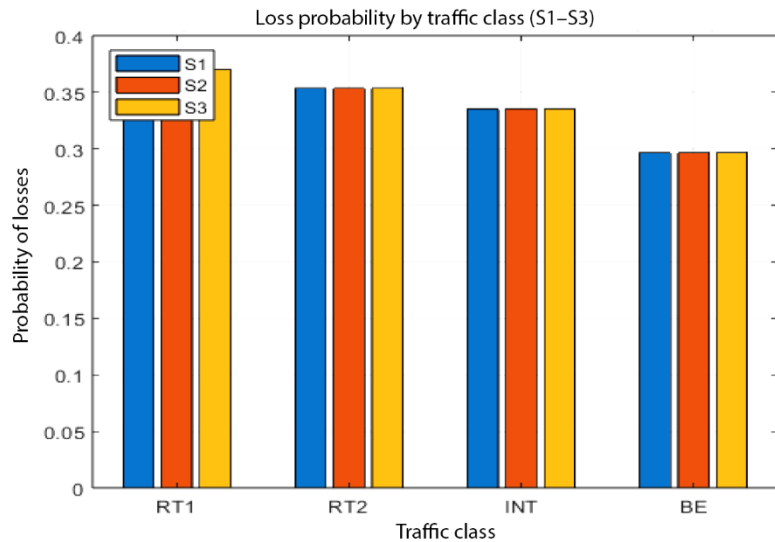


Fig. 5. Loss probability by traffic class in scenarios S1-S3

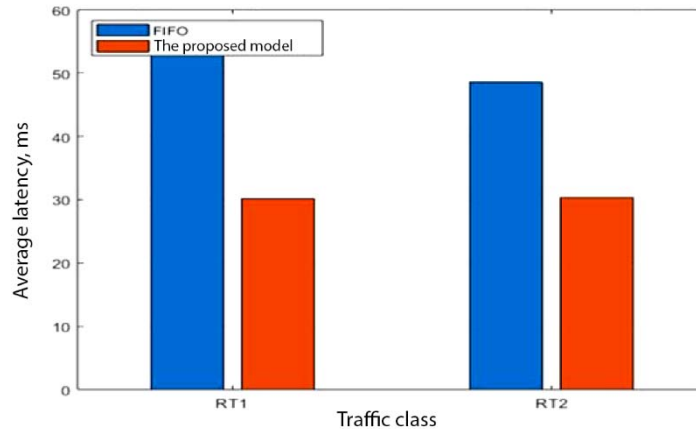


Fig. 6. Comparison of average latency (RT1/RT2) for FIFO and the proposed model (scenario S3)

A key result is the notable improvement in RT (real-time) traffic performance compared to a scenario without differentiation (FIFO). In comparative experiments for scenario S3, the average packet latency for the RT1 class in our model was significantly lower than under FIFO scheduling – with an improvement of tens of milliseconds – while the RT2 class also showed a reduction in latency, albeit less pronounced. This is clearly illustrated in Figure 6: transitioning from FIFO to the proposed model leads to a substantial decrease in latency for high-priority traffic, achieved through the implementation of a priority queue and a guaranteed share of resources. The packet loss probability for RT1/RT2 traffic is also lower with the QoS model than in the FIFO scheme, as the priority-based queuing mechanism prevents critical packets from being displaced from the buffer during periods of congestion. Furthermore, overall channel capacity is utilized more efficiently; high-priority traffic does not lead to resource underutilization, as any unused bandwidth is made available to lower-priority classes. Taken together, these data demonstrate that SDN-based management with differentiated queues enables the achievement of required QoS levels for critical services without the need for excessive bandwidth provisioning.

Additional experiments examined the impact of handovers on traffic parameters. During the switching of the serving satellite, brief spikes in latency were observed for the affected flows – primarily in the RT2 class, due to route reconfiguration – along with a reduction in throughput for some BE (best-effort) packets. However, thanks to proactive management at the controller level, these effects subsided quickly and did not result in any prolonged degradation of service quality. Time-series charts showed that, following a handover event, latency returns to a stable level within a few tens of milliseconds, confirming the validity of the implemented flow-reassignment mechanism. Thus, even with frequent handovers (scenario S3), the proposed architecture maintains the benefits of differentiated service.

Conclusion

This paper presents an SDN-oriented model for multiservice traffic transmission in low Earth orbit (LEO) satellite networks, featuring centralized routing and Quality of Service (QoS) management with traffic classified into four distinct categories. A simulation framework, developed using ns-3 and MATLAB, implements the proposed architecture and enables a series of experiments under reproducible load scenarios. The simulation study confirms that combining differentiated queuing mechanisms (LLQ, WRR/CBWFQ, and RED) with global SDN-based control effectively addresses QoS challenges in LEO networks characterized by dynamic topologies. Compared to a traditional FIFO scheme, this model offers a clear advantage for real-time traffic: as network load increases and frequent handovers occur, latency and packet loss for the RT1/RT2 traffic classes remain significantly lower than those for the INT/BE classes, while the total channel bandwidth is utilized more efficiently.

Congestion primarily affects background services, whereas critical traffic flows maintain an acceptable level of service quality—a result that aligns with prioritization objectives and validates the effectiveness of the chosen algorithms. Consequently, the proposed model provides an accurate representation of multiservice traffic transmission in LEO networks, ensuring the required QoS through a combination of differentiated packet processing and awareness of the satellite infrastructure's dynamics. These findings can inform the design of next-generation satellite systems integrated with terrestrial networks and serve as a foundation for further model development. Specifically, future work will focus on an in-depth investigation of multi-criteria QoS routing algorithms and adaptive resource management in LEO networks, building upon the proposed approach.

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ASSESSMENT OF THE MICROFRONTEND ARCHITECTURE IMPACT ON THE WEB APPLICATIONS PERFORMANCE AND SCALABILITY

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ABSTRACT

This article examines the impact of microfrontend architecture on the performance and scalability of web applications. The relevance of the study is due to the increasing complexity of client applications and the need to ensure independent development and deployment of functional modules. The paper provides a comparative analysis of three architectural approaches: monolithic implementation, integration of modules using iframes, and microfrontends based on a modular federation mechanism. The experimental part includes the development of a test application and the measurement of key performance metrics – first render time, number of HTTP requests, volume of transferred resources, and total load time. The results show that modular federation provides a more balanced combination of performance and modularity compared to alternative solutions, especially as the system grows in scale. Conclusions are drawn about the feasibility of using microfrontend architecture in large and dynamically developing web projects.

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KEYWORDS: *microfrontends; scalability; architecture; code management; web development; web application performance.*

Introduction

Modern web applications are characterized by increasingly complex functionality and growing demands on the speed of software system development. The evolution of development approaches has led to a transition from sequential implementation of functional capabilities to parallel work by several teams on different aspects of the application [1-3]. With a clear division between the client level, the server part, and the data storage layer, it becomes possible to develop system components simultaneously while minimizing inter-team dependencies.

This decomposition helps make development more efficient and cuts down on the time it takes to bring new features to market. Abstracting the interaction between application layers lets you modify individual components without significantly affecting the rest of the system. On the server side, this trend is implemented by transitioning from a monolithic architecture to a microservice model, which involves dividing a large application into autonomous specialized services coordinated through a single interaction mechanism. This approach reduces deployment time and improves the manageability of complex systems.

Similar processes are also observed at the client application level. The growth in the volume of front-end code and the increase in the number of development teams have necessitated architectural solutions that provide modularity, isolation, and independence in the deployment of the user interface. One such solution is the microfrontend architecture, which involves the structural decomposition of the interface into autonomous functional modules.

Despite the active implementation of the microfrontend approach, its impact on the performance characteristics of web applications, including loading performance and system scalability, requires quantitative assessment. In engineering practice, it is important to determine how the architectural decomposition of the client side affects loading time, the volume of transmitted resources, and network activity [4-6].

The purpose of this study is to analyze and experimentally evaluate the impact of microfrontend architecture on the performance and scalability of web applications compared to alternative client-side models. The paper reviews existing approaches to microfrontend implementation and identifies their advantages and limitations in terms of performance characteristics.

Architectural models of front-end applications

The current stage of development in the software industry is characterized by a widespread shift away from monolithic architecture in favor of a microservices approach. To understand the reasons for this transition, it is necessary to consider the fundamentals of both paradigms.

Monolithic architecture

In software engineering, the term "monolith" describes an application assembled into a single logical unit, where all components and services are deployed and operate within a common infrastructure platform. In such a system, modules and services operate in a

common infrastructure environment and are typically developed within a single code base. A typical monolithic solution structure includes the following parts:

- A user authentication and authorization mechanism that provides access control.
- A business logic core that implements the main data processing scenarios.
- A presentation layer that forms the user interface and interacts with the server side via HTTP requests.
- Integration modules responsible for data exchange with third-party services via network protocols and REST interfaces.
- Monitoring and notification components designed to log events and handle failures.

Despite the active spread of microservice architecture, monolithic solutions are still widely used in industrial development [7]. Their advantage is relative simplicity in the early stages of the system lifecycle. A single code base and centralized configuration simplify dependency control and version management.

However, as functionality grows and the number of development participants increases, the limitations of this approach become apparent. Supporting a large-scale monolithic system becomes difficult, and making changes requires coordination between multiple teams. Key disadvantages of monolithic architecture include:

- Increased consumption of computing resources and longer build times as the code base expands.
- Reduced system visibility and increased maintenance complexity.
- Increased risk of complete unavailability in the event of a single component failure.
- Limited flexibility when implementing new technological solutions, as changes affect the entire system [8].

Microservices architecture

Microservice architecture is seen as a natural stage in the development of the service-oriented approach (SOA), focused on increasing the flexibility and manageability of complex software systems. Although the ideas behind SOA were formed much earlier, the independent conceptualization of microservices took place in the early 2010s [9]. The approach is based on the principle of decomposing a software system into a set of autonomous, loosely coupled components, each of which implements a limited business function and interacts with others through clearly defined interfaces. This division by subject area simplifies system maintenance, modernization, and scaling [10].

A key feature of microservice architecture is the independence of the service lifecycle. Each component can be developed, tested, and deployed in isolation, which reduces the risks associated with making changes. The failure of a single service does not usually lead to complete system unavailability, but is limited to the degradation of a specific functionality, which increases the overall stability of the solution.

Advantages of the microservice approach:

- Continuous delivery and deployment are greatly simplified because the application is divided into small services, each of which performs a limited set of functions [11].
- Ensuring parallel work of teams, as areas of responsibility are clearly delineated and the number of conflicts during code integration is reduced.
- Increased fault tolerance through isolation of failures and the ability to localize problems within a single service.
- The limited scope of service responsibility facilitates the development of modular and integration tests.
- The choice of programming language, frameworks, and architectural solutions can be made individually for each service, provided that uniform interaction protocols are followed [12].
- Development can be scalable and organized between multiple teams.

Monoliths vs. microservices

Considering the advantages and limitations discussed above, it can be noted that in a number of practical situations, the microservice approach is preferable. When the load on a specific functional area of the system increases, only those services that are responsible for that area are scaled, which allows for the efficient distribution of resources and ensures the required level of performance [13].

Horizontal scaling in a microservice architecture can be done quickly because individual services are small and start up fast. Scalability is also possible in monolithic applications, but in this case, the resources for the entire system increase, leading to higher consumption of computing power.

Figure 1 compares the principles of layer separation in monolithic and microservice architectures.

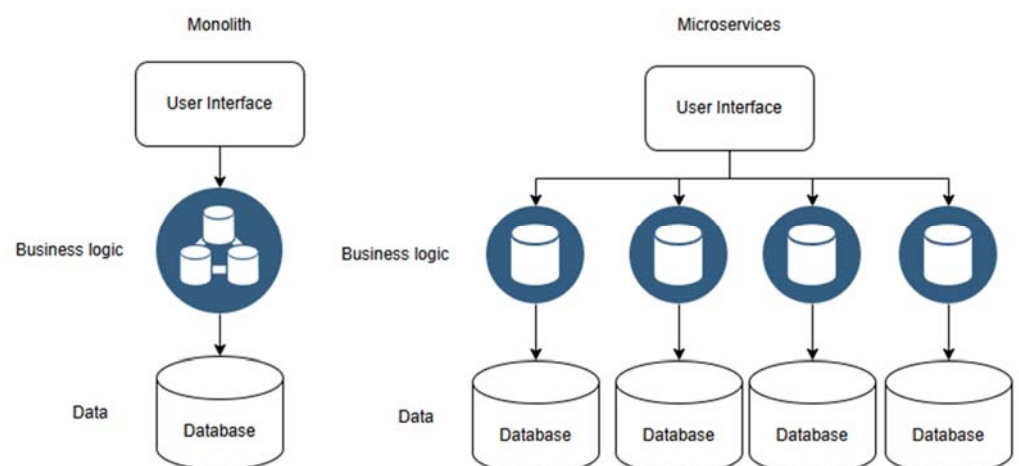


Fig. 1. Monolith and microservices architecture

Microfrontends

With the current development of cloud web applications and the transition of business logic to microservice architecture, front-end applications are becoming increasingly complex and loaded. A significant part of the logic is gradually being transferred to the client side, which increases the complexity of supporting and developing such applications [14]. Just as dividing a backend monolith into microservices brings significant benefits, a similar approach is appropriate for the user interface. This allows the interface to be broken down into independent modules that function autonomously while remaining part of a single application shell [15]. Microfrontends are a solution to this problem.

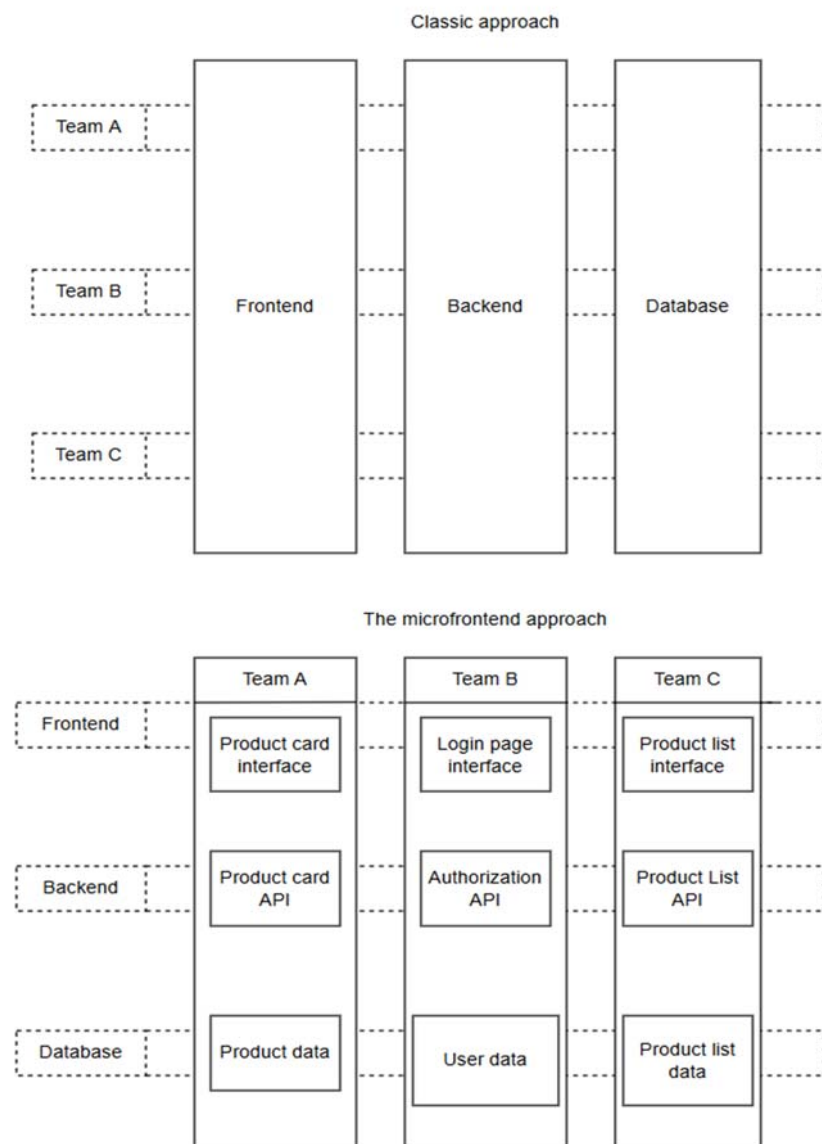


Fig. 2. Cross-functional teams with microfrontends

The frontend ecosystem is constantly evolving, with new frameworks and tools emerging to make developers' work easier. At the same time, there is growing interest in modern, optimized tools that accelerate development and improve application performance. There are many approaches to organizing front-end applications, including single-page applications (SPA) and server-side rendering (SSR). However, most existing solutions are monoliths that load in parts but are not technologically independent and cannot be deployed autonomously [16].

As shown in Figure 2, an application with microfrontends is a composition of functions or microapplications that together form a larger application. Independent modules are controlled by cross-functional teams. Thus, there is a loose coupling between applications, and they coexist using well-defined contracts. Such micro-applications or functions can belong to one or more application packages, which reinforces the idea of reuse. A perfect example of a micro-frontend module is a shopping cart used in several e-commerce solutions developed by the same company.

Experimental evaluation of architectural strategies for implementing microfrontends

To obtain an objective quantitative assessment of the impact of different microfrontend architecture implementation strategies, an experimental study was conducted to compare the performance characteristics of client applications built using different architectural approaches.

As part of the experiment, a test web application was developed (Figure 3), representing a typical interface with several functional blocks (navigation, content display area, user interaction widget). The architectural complexity of the application was deliberately limited in order to minimize the influence of extraneous factors and focus on differences caused specifically by the architectural model.

The application was implemented in three variants:

- A monolithic single-page application (single code base and build process).
- Architecture using iframe to isolate functional modules.
- Microfrontend architecture based on the Module Federation mechanism.

Thus, both the traditional centralized model and two variants of client-side decomposition were compared: isolated integration via iframe and integration at the build level through the sharing of dependencies.

Measurement methodology and metrics system

To ensure the comparability of results, a single set of metrics was defined, reflecting both technical and user aspects of performance, which corresponds to modern approaches to evaluating the quality of web applications [17]:

- time to first paint (First Paint)
- number of HTTP requests
- total volume of resources loaded

- total application load time

Practical significance of the selected metrics:

- Time to first paint – the speed at which the interface starts working as perceived by the user
- HTTP requests – show the load on the network and server
- Resource volume – directly affects network bandwidth and data transfer time
- Load time – reflects the overall readiness of the application for operation

The measurements were taken using the built-in developer tools of the Google Chrome browser, which ensured a consistent testing environment. The analysis was performed under identical network connection and hardware configuration conditions, which allowed to eliminate the influence of external factors.

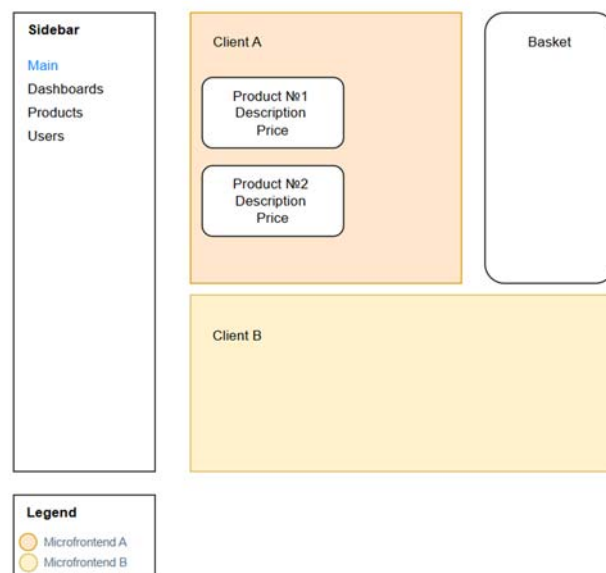


Fig. 3. Simple application layout

Analysis of the results

The experimental data obtained (Table 1) indicate significant differences between the architectural approaches under consideration, both in terms of absolute indicators and their relative deviations.

As shown by the results of testing a simple web application (Table 1), a solution based on modular federation has significant advantages over implementation of microfrontends via iframe.

- The monolithic implementation demonstrated the minimum number of HTTP requests (13) and the smallest amount of transferred resources (5.4 MB), as shown in Table 1. This result is explained by centralized assembly and the absence of duplicate dependencies. However, as theoretical scaling assumptions show, as the functionality of

the system increases, the monolithic model inevitably leads to an increase in the size of the final bundle and complicates maintenance, which reduces its effectiveness in the long term.

- The approach using iframe showed the worst values for most metrics (Table 1). The number of HTTP requests increased to 34, and the volume of downloaded resources reached 16.6 MB, which is more than three times higher than the monolith. The increase in network activity is due to the fact that each isolated part of the application loads its own dependencies independently of other modules. The lack of a common library pool leads to code duplication and increased overhead. In addition, isolation via iframe creates additional costs for initialization and cross-context interaction.

- The microfrontend architecture based on modular federation demonstrated a compromise but most balanced result. According to Table 1, the resource volume was 6.6 MB, which is 60% less than the iframe approach, and the total load time was reduced to 0.774 seconds, which is 42% faster than the monolithic implementation. Despite an increase in the number of requests compared to the monolith (26 vs. 13), modular federation provides more efficient load distribution thanks to the mechanism of asynchronous on-demand module loading.

Table 1

Comparative analysis of the performance of different architectural approaches

Factor	Monolith	IFrame	Microfrontends	Deviation of MF from monolith
First Paint, ms	418	1222	540	+29 %
Number of HTTP requests	13	34	26	+100 %
Volume of resources, MB	5,4	16,6	6,6	+22 %
Total loading time, s	1,35	1,12	0,774	–42 %

Interpretation of results in terms of scalability

The experiment was conducted on a relatively simple application prototype, but even under these conditions, the quantitative indicators (Table 1) demonstrate differences that allow the results to be extrapolated to larger systems. In an industrial environment, as the number of functional modules increases and business logic becomes more complex, monolithic architecture is characterized by increased build times, larger final bundles, and slower delivery of changes, due to the high degree of component interdependence and centralized deployment process.

In contrast, the microfrontend approach provides both organizational scalability, through the decomposition of areas of responsibility between independent teams, and technical scalability, through the autonomous deployment and updating of individual modules.

Therefore, although a monolithic solution remains the simplest and most economical for small systems, as the application grows in scale, the advantages of microfrontends become more pronounced, manifesting themselves in reduced loading times, support for partial initialization of functionality, and ensuring an independent component lifecycle.

Conclusion

This paper provides a theoretical and experimental assessment of the impact of microfrontend architecture on the performance and scalability of web applications. A comparison of the monolithic model, implementation via iframe, and a modular federation-based approach revealed differences in key performance characteristics.

Experimental results showed that modular federation provides the most balanced combination of performance and modularity: with a slight increase in the number of requests compared to the monolith, there is a reduction in total loading time and a significant decrease in resource consumption compared to the iframe approach. Monolith remains an effective solution for small systems, but as complexity increases, its limitations become more pronounced.

Thus, microfrontends represent a promising architectural model for large and dynamically developing web applications, where team independence, deployment flexibility, and long-term system scalability are important.

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VISIBLE LIGHT COMMUNICATION (VLC): COMMUNICATION USING VISIBLE LIGHT

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ABSTRACT

The growing number of wireless devices and increasing traffic density place a significant strain on the radio-frequency spectrum. Traditional communication channels – such as Wi-Fi and Bluetooth – face bandwidth limitations and are susceptible to interference. Against this backdrop, Visible Light Communication (VLC) technology emerges as a compelling alternative: it leverages LED lighting infrastructure for data transmission, without competing for radio-frequency resources. VLC technology provides additional, high-capacity communication channels and creates new opportunities for establishing secure, high-speed networks within indoor environments and for various specialized applications. VLC is a non-fiber-optic data transmission technology based on the use of visible light. A key motivation for this technology is that light can simultaneously serve the purposes of illumination, communication, and/or positioning. Consequently, this multifunctionality eliminates the need for an additional power source for data transmission or location tracking. The transition from legacy light sources to light-emitting diodes (LEDs) can be integrated with VLC technology. This article examines the operating principles of VLC, technical approaches, advantages, limitations, current challenges, and potential solutions. It also presents results from computer simulations and mathematical models of VLC systems.

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KEYWORDS: VLC, modulation, optical wireless communication, On-Off Keying (OOK), Pulse Position Modulation (PPM).

Introduction

The growing number of wireless devices and increasing traffic density place a significant strain on the radio-frequency (RF) spectrum. Visible Light Communication (VLC) technology [1, 2, 11] opens up additional, high-capacity communication channels and creates new opportunities for developing secure, high-speed networks for indoor environments and various specialized applications [2, 3].

The system operates within the visible portion of the spectrum, spanning from 400 THz ($\lambda \approx 750$ nm) to 790 THz ($\lambda \approx 380$ nm), as illustrated in Fig. 1. As shown, visible light represents only a small fraction of the entire optical spectrum (which also encompasses infrared and ultraviolet). In this context, modulation and demodulation are performed directly – bypassing the need for radio frequencies – which makes optical transmission systems significantly simpler than their RF-based counterparts. Furthermore, visible light remains the most accessible segment of the optical spectrum, largely due to the development of affordable technology.

Light-emitting diodes (LEDs) were invented in the 1960s. Over the course of just a few decades, they have evolved from single-color to multi-color, from low-brightness to high-brightness, and from short-lived to long-lasting components. Brightness has increased twentyfold every decade, while costs have dropped to just 1% of their original price. However, the concept of VLC was proposed only about two decades ago by Japanese scientists, who suggested that information could be encoded into a light source by having it flicker rapidly in accordance with the data being transmitted [1-3].

Fortunately, this flickering is imperceptible to the human eye, provided the frequency is at least 200 Hz. This allows for the seamless integration of VLC-capable LEDs with standard lighting LEDs [7, 9]. The first VLC standard, known as LiFi (Light Fidelity), was introduced as recently as 2011 [8, 14].

Since its inception, the VLC concept has evolved significantly; by 2019, data transmission speeds had exceeded 15 Gbps. Specifically, a data rate of 15.73 Gbps was reported over a 1.6-meter link using OFDMA as an access scheme, with standard off-the-shelf LEDs [10, 13]. Furthermore, it has been reported that connections with speeds exceeding 6.5 Gbps and 1.5 Gbps can be maintained at distances of 10 meters and 20 meters, respectively.

Despite the numerous advantages of VLC – as outlined in the introduction to this chapter – the technology also faces several challenges. It should be noted that the more frequently an LED flickers, the brighter it becomes. This presents two issues: first, it leads to increased power consumption; second, if the same LED is being used for illumination, the emitted light may become too intense for the space in question [1, 2].

In such cases, various LED dimming techniques must be employed. Another challenge involves interference from other light sources – whether artificial (such as incandescent lamps) or natural (such as sunlight).

The presence of other light sources is perceived by the system as noise, which leads to a reduction in data transmission speed and an increase in the bit error rate (BER). Fortunately, it has been demonstrated that blue bandpass filters can limit the degradation

caused by solar radiation. Finally, light intensity drops sharply with distance, which may constrain the potential deployment scenarios.

VLC structural system

The basic structural diagram of a VLC system includes a transmitter and a receiver. A diagram illustrating this process is presented below.

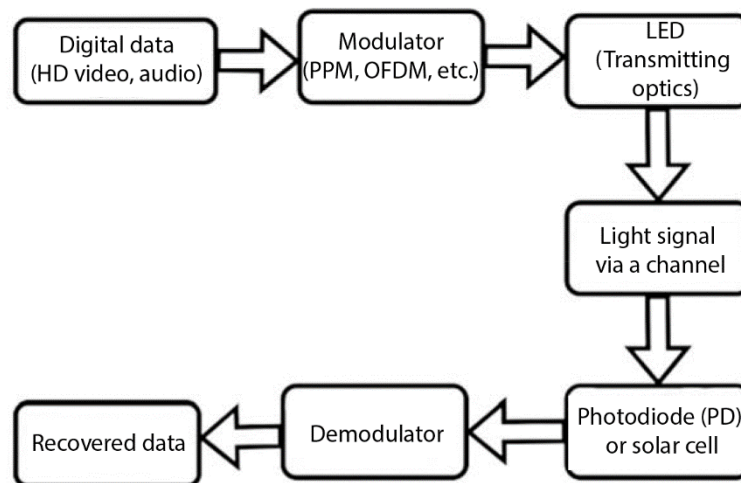


Fig. 1. Block diagram of a VLC system

Transmitter

A transmitter is designed to convert input electrical data into an optical signal, which is emitted by an LED (or an LED array) or a laser diode. Modulation, in essence, involves converting a data signal, $m(t)$, into a drive current for the LED (or laser diode), thereby creating a light signal, $x(t)$, whose intensity varies over time. This process is also known as optical intensity modulation. The resulting signal is transmitted over an optical channel to be received by a photodetector. The drive current must remain within the LED's dynamic range to avoid distorting the optical signal [1, 2].

Furthermore, the control signal must be real-valued and non-negative. Figure 2 also illustrates a dimming control unit, which is used to precisely adjust the LED's brightness to a desired level.

Dimming is employed for at least two reasons. First, it can be used to reduce the LED's brightness – for instance, when high data rates are required – while ensuring the resulting illumination meets the lighting requirements for a given environment. Second, it can help improve the LED's response time [4-6].

In indoor settings, LEDs are often preferred over laser diodes, partly due to their lower cost and wider field of view, and partly because they can also serve the purpose of general illumination. LEDs can be monochromatic (emitting a single color, typically blue, green, or red) or white (theoretically containing all colors simultaneously).

VLC systems are typically implemented using white light, which can be generated in several ways:

1) In the first method, red, green, and blue (RGB) light sources are emitted at specific intensities.

2) The second method is slightly more complex and involves using a blue LED coated with a phosphor material that emits yellow light. Thus, short wavelengths are absorbed, and yellow light is emitted. In the subsequent stage of light processing, the wavelength shifts toward the red end of the spectrum, where it combines with a portion of the blue light that was not absorbed. Ultimately, this results in white light with a specific spectrum. This method is more popular than the RGB approach, though it produces light with a limited bandwidth due to the relatively slow absorption and emission processes within the phosphor layer.

3) A third method generates broadband radiation that closely resembles the solar spectrum.

The optical configuration of an LED is also significant. Several implementation options are typically considered [2]:

- Direct approach, where light from the LED is emitted without passing through any optical device;
- Diffusive approach, where light is scattered to reduce surface brightness and expand the illumination range;
- Reflective approach, where light from the LED is directed via external reflectors;
- Transmissive approach, where a lens is placed in front of the LED to modify the light distribution pattern; and
- Combination of reflective and transmissive approaches.

It should be noted that there are several challenges associated with LED-based transmitters [2]. These include compensating for LED non-linearity, the need for precise control over LED chromaticity, and the aforementioned requirements for brightness control and flicker-free data transmission. Consequently, the power electronics used to drive LEDs play a critical role in the controlled transmission of VLC signals.

Receiver

The optical receiver is based on a photodetector. The photodetector receives the transmitted signal $x(t)$ – which has passed through a channel with an impulse response $h(t)$ – and generates a photocurrent $y(t)$.

Other key components of the receiver include an optical concentrator, which reflects and focuses the incoming light onto the photodetector, and an optical filter, which removes unwanted wavelengths. The optical filter can also be integrated into the optical

concentrator. An electronic amplifier is typically required within the receiver to process the detected current for subsequent stages of the receiver system.

There are at least three types of photodetectors: photodiodes, image sensors (including cameras), and solar panels. Among these, photodiodes are the most common. Commercial VLC systems typically employ two types of photodiodes: PIN photodiodes and avalanche photodiodes (APDs). While APDs offer higher gain than PIN photodiodes, they also suffer from higher shot noise. PIN photodiodes, by contrast, are inexpensive and exhibit greater temperature stability. Other types of photodetectors also offer distinct advantages; for instance, solar panels can simultaneously be used for energy harvesting, while camera sensors—already present in many devices, such as mobile phones—can be utilized for VLC with minimal additional cost [1, 2].

VLC channel and signal propagation model

Optical propagation links can be divided into two categories: line-of-sight (LOS) links and non-line-of-sight (nLOS) links. Due to the low reflection coefficient of light, LOS links are significantly more energy-efficient, and the amount of power reflected more than once is negligible. However, in indoor environments, there is typically at least one reflected path, which means that signals can still be detected even when obstacles are present. Propagation links can also be classified based on the directivity of the transmitter and the receiver. Both the transmitter and the receiver can be either directional or omnidirectional. Scenarios where one is directional and the other is not are referred to as "hybrid" links. When the presence of a LOS path is also taken into account, eight types of links can be identified:

- LOS / directional link
- LOS / omnidirectional link;
- LOS / hybrid link (directional transmitter, omnidirectional receiver);
- LOS / hybrid link (omnidirectional transmitter, directional receiver);
- nLOS / directional link
- nLOS / omnidirectional link
- nLOS / hybrid link (directional transmitter, omnidirectional receiver);
- nLOS / hybrid link (omnidirectional transmitter, directional receiver).

One of the fundamental differences between RF systems and optical systems is that RF systems are susceptible to multipath fading, whereas optical systems are not. This is because the physical detection area of a photodiode is significantly larger than the square of the wavelength of the incident light. Optical systems – especially outdoor, directional systems – are, by contrast, far more susceptible to pointing errors and pointing losses.

The attenuation in a VLC system can be modeled based on the signal loss that occurs as light propagates from the transmitter to the receiver. As previously mentioned, only two

paths are possible: the direct channel and the single-reflection channel. VLC channel attenuation can be characterized using the following model. A generalized Lambertian law can be applied to the transmitter side, indicating that the intensity of the emitted light depends on the cosine of the angle ϕ between the emitted light and the normal to the LED surface. Therefore, to calculate the path loss, one must first determine the Lambertian order as follows:

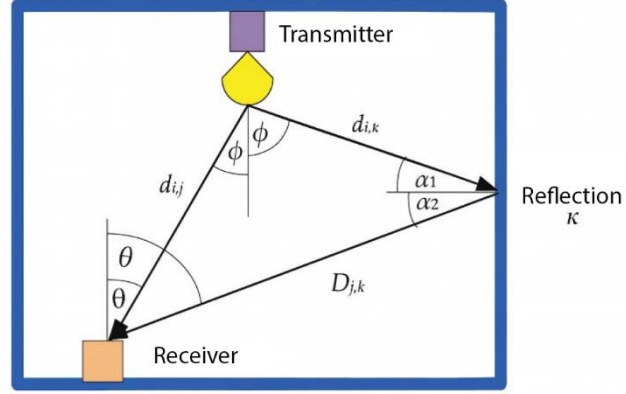


Fig. 2. Principle of optical wave propagation, accounting for both the direct ray and the reflected ray [1]

$$m = \frac{-1}{\log_2(\cos \theta_{1/2})} \quad (1)$$

where $\theta_{1/2}$ is the LED's emission angle at half-intensity. On the receiver side, the gain of the optical concentrator is equal to

$$f(\theta) = \begin{cases} \theta \frac{n^2}{\sin^2 \Theta}, & 0 \leq \theta \leq \Theta, \\ 0, & \theta > \Theta \end{cases} \quad (2)$$

where n is the refractive index and Θ is the field-of-view angle of the receiver photodiode. In this case, for a direct link, the DC gain (which is less than 1 – essentially an attenuation) can be expressed as

$$h_{i,j} = \frac{A_p(m+1)}{2\pi d_{i,j}^2} \cos^m \phi g_{of}(\theta) f(\theta), \quad (3)$$

where: A_p – the physical area of the photodiode, $d_{i,j}$ – the distance between the transmitter and the receiver, and g_{of} – the gain of the optical filter. In the case of $\theta > \Theta$ a direct line of sight, there is no [reflected component], and the DC gain is equal to zero.

For a reflected link, the DC gain can be determined using the formula

$$dh_i = \frac{A_p(m+1)}{2\pi d_{i,k}^2 d_{j,k}^2} \rho dA_s \cos^m \phi_r \cos \alpha_1 \cos \alpha_2 g_{of}(\theta_r) f(\theta_r) \cos \theta_r, \quad (4)$$

where $d_{i,k}$ is the distance from the transmitter to the reflecting surface, d_{jk} is the distance from the reflecting surface to the receiver, ϕ_r and θ_r are the angles associated with the reflection path, α_1 and α_2 are the angles of incidence and reflection at the point of reflection, and, finally, ρ is the reflection coefficient and dA_s is the effective reflecting area.

VLC channel capacity and throughput

The fundamental differences between RF and VLC systems mean that the capacity of a VLC channel does not correspond to the standard Shannon channel capacity. There are, in fact, two primary constraints on channel capacity: the requirement for non-negative real-valued signals and the limitation on average light intensity for the sake of eye safety. Furthermore, one must account for the illumination requirements of the environment in which the VLC system is deployed, as well as the dynamic range of the LEDs. Unfortunately, there is no analytical expression for channel capacity that incorporates both average and peak power constraints; one can only determine bounds (lower and upper) for the capacity.

These bounds vary depending on the specific constraints applied, and various alternative capacity limits have been proposed [1, 2].

An alternative metric to consider in the context of VLC is the achievable data rate (throughput). It has been established that the OFDM principle, which is widely used in RF systems, is also applicable to VLC. For a single user employing OFDM, the achievable data rate can be calculated using the following formula:

$$X_j = \frac{W}{\beta L} \sum_{i=1}^{\beta L-1} \eta_i \quad (4)$$

where W is the signal bandwidth, L is the number of subcarriers, β is a constant depending on the type of OFDM signal used (typically $\beta = 0.5$), and η is a subcarrier efficiency constant that accounts for the influence of the modulation scheme, the coding scheme, and the signal-to-noise ratio.

Modulation methods for VLC

Like RF transmitters, VLC transmitters require signal modulation for transmission over a wireless channel [13, 15]. However, there is a fundamental difference between modulation in the optical domain and in the RF domain. While RF modulation involves varying the frequency, phase, or amplitude of a signal, in the optical domain, one can only vary the intensity of the light emitted by an LED. Several categories of modulation schemes are considered for VLC, some of which bear similarities to those used in RF communications.

The modulation scheme for a specific VLC system is typically selected based on several criteria:

- Energy efficiency;
- Spectral efficiency (bandwidth utilization);
- Transmission reliability;
- Complexity;
- Robustness against external light sources.

Furthermore, all modulation schemes must eliminate long sequences of consecutive 0s or 1s, which could otherwise cause flickering, regardless of the data transmission rate. Additionally, it is necessary to ensure data recovery and clock synchronization.

Modulation schemes for VLC include:

- On-Off Keying (OOK);
- Pulse Amplitude Modulation (PAM);
- Pulse Position Modulation (PPM);
- Pulse-Interval Modulation (PIM);
- Pulse-Width Modulation (PWM).

Modulation OOK (On-Off Keying)

OOK is the simplest (and slowest) modulation scheme. In OOK, the LED is on if the transmitted signal is a binary 1, and off if the transmitted signal is a binary 0. Sometimes, instead of the complete absence of a signal in the 0 state, the LED simply emits light at a different intensity. If data is encoded using multiple levels of light intensity or amplitude, PAM modulation is achieved. The concept of PAM in the context of VLC is very similar to PAM in the RF domain.

Mathematically, a VLC signal can be expressed as:

$$s(t) = \begin{cases} A_c \cos(2\pi f_c t), & \text{if } b(t) = 1 \\ 0, & \text{if } b(t) = 0 \end{cases} \quad (5)$$

where: A_c – carrier amplitude, f_c – carrier frequency, $b(t) \in \{0,1\}$ – binary information signal.

Modeling and analysis of VLC system characteristics

As a result of the simulation, graphs showing the dependence of the Bit Error Rate (BER) on the Signal-to-Noise Ratio (SNR) were obtained. The simulation was performed using OOK modulation.

A total of 3,000 experiments were conducted, covering an SNR range from 1 to 15 dB with a step of 1 dB. The program utilized a LOS communication channel, with the OOK modulation corresponding to a VLC scenario under LOS conditions. Figure 3 presents the simulation results alongside the theoretical BER curves.

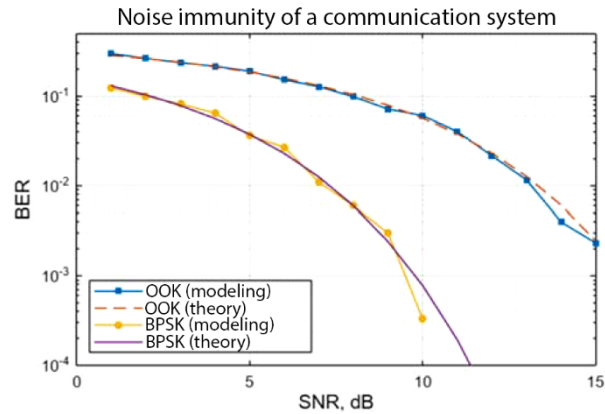


Fig. 3. Noise immunity of a communication system

The noise immunity of a VLC system improves more slowly as the SNR increases. At a BER 10^{-1} , BPSK modulation offers a 6 dB advantage over OOK; in other words, a VLC system requires a higher energy budget compared to a traditional radio communication system, and its communication range is limited – typically to just a few meters.

Analysis of simulation results for the VLC scenario.

First, there is a significant gap in noise immunity, with OOK underperforming relative to BPSK. This is expected and theoretically sound, as BPSK – a form of phase modulation—offers greater energy efficiency and better noise resilience than OOK, which is an amplitude-based modulation scheme. For instance, to achieve a bit error rate (BER) of approximately 10^{-3} , an OOK-based system requires an SNR that is about 5–6 dB higher than that of a BPSK-based system. This energy penalty is the trade-off for the simplicity of implementing OOK – a factor of particular relevance to VLC systems, which often utilize low-cost LEDs and photodetectors.

Second, it is worth noting the close alignment between the theoretical curves and the experimental (simulated) results for both modulation schemes. This indicates that the simulation was conducted with high precision and that the mathematical models used for the communication channel are accurate. The slight discrepancy between the "OOK (simulation)" and "OOK (theory)" curves in the moderate SNR range can be attributed to the fact that the simulation model accounts for real-world destabilizing factors inherent to optical channels – such as multipath propagation, photodetector noise, and transmitter nonlinearity – which are not considered in the basic theoretical model.

Thus, it can be concluded that, although OOK modulation is less energy-efficient than BPSK, its use in VLC systems is justified in terms of implementation simplicity and cost. The obtained results robustly validate the theoretical premises and support the use of this model for the further design and optimization of specific optical wireless communication systems [12].

Advantages of VLC

- Significant spectral resource: the visible spectrum is essentially unlicensed and has high potential for data transmission, theoretically enabling gigabit speeds with good equipment.
- Security and privacy: light does not penetrate opaque barriers, limiting coverage and reducing the risk of signal interception.
- No radio interference: VLC operation is possible in environments where RF radiation is undesirable or prohibited (medical facilities, aviation, industrial facilities).
- Dual-use: LED luminaires simultaneously provide illumination and data transmission, improving energy efficiency and cost-effectiveness.
- High positioning accuracy: localization using light beacons provides centimeter-level accuracy, useful for indoor navigation and contextual services.

Limitations and ways to overcome them

Key limitations of VLC and potential solutions:

Line-of-Sight (LoS) requirement: Data rates decrease when a direct path is obstructed. Solutions: use of multi-path receivers, distributed access points, and optical MIMO technologies.

Impact of ambient light: Introduces noise at the receiver. Solutions: use of optical filters, narrow-band receivers, and adaptive digital signal processing algorithms.

Uplink challenge: Difficulty in transmitting data from mobile devices. Solutions: hybrid architectures (VLC for downlink, RF or IR for uplink) and optical backscatter technologies.

Ensuring mobility: The need for seamless switching between light sources. Solutions: intelligent control systems with handover mechanisms.

Compatibility with lighting: Modulation must not cause perceptible flickering. Solutions: specialized modulation schemes and dimming algorithms that comply with lighting quality standards.

Areas of application, limitations, practical use

VLC systems are used in many areas of human activity, for example [1-4]:

– Li-Fi in offices and educational institutions: high-speed local network access, where each light fixture serves as an access point; useful for secure corporate networks and educational laboratories.

– Medicine: data transmission in intensive care units with minimal RF interference affecting medical equipment; secure data exchange between monitoring devices and a central system.

– Automotive (V2V and V2I): the use of headlights and brake lights to exchange short messages between vehicles – such as braking warnings or information for autonomous control systems.

Conclusion

VLC is a promising technology that complements traditional wireless systems in environments where the radio-frequency spectrum is congested. Its key advantages – high data security, the absence of electromagnetic interference, the capability for precise positioning, and its dual-purpose nature (providing both illumination and data transmission) – make VLC particularly valuable in sectors such as healthcare, industry, logistics, and secure corporate networks.

The future of VLC lies in its integration into next-generation (6G) hybrid networks, the miniaturization of components, and the advancement of standardization. In the coming years, the technology will be deployed in niche areas, while in the long term, it is set to become an integral part of smart city infrastructure, expanding connectivity options and laying the foundation for new services.

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OPPORTUNITIES FOR CITIES IN THE AGE OF ARTIFICIAL INTELLIGENCE

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**Overview of report materials based on the Global Initiative on AI and Virtual Worlds
– Discovering the Citiverse [1]**

ABSTRACT

Cities generate vast amounts of information. Neural network models make it possible to process this data quickly. For example, predictive algorithms can forecast the load on power grids or identify problematic sections of roads. This publication was developed based on the Global Initiative on AI and Virtual Worlds – Discovering the Citiverse [1], which is a global multistakeholder platform launched by the International Telecommunication Union (ITU), the United Nations International Computing Center (UNICC) and Digital Dubai, and supported by more than 70 international partners. Review based on AI-Enabled Citiverse (Foundational Capabilities, A Strategic Blueprint and Use Cases for Cities in the Age of AI). The Initiative advances the development of the AI-enabled citiverse, where artificial intelligence, spatial intelligence, digital twins, and immersive systems converge to deliver real-world impact. It aims to ensure that this transformation is inclusive, trusted and interoperable, and that it serves people, cities and communities. AI-enabled citiverse constitutes a transformative, people-centric paradigm, enabling policymakers to harness these developments to build urban governance models. Examines the foundational elements that underpin urban intelligence, simulation, participation, interoperability, trust and inclusion, and assessing them through the lens of their relevance to urban governance and civic outcomes rather than on the basis of technical novelty alone.

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KEYWORDS: *Artificial intelligence, Strategic Blueprint, Digital twins, AI-enabled citiverse.*

Introduction

The changes currently underway are creating a need for more integrated, adaptive, and human-centric models of urban digital development. Artificial intelligence (AI) is being actively deployed within intelligent transport systems (ITS), while "smart" cameras are capable of recognizing various objects and situations. Digital twins – virtual replicas of cities that aggregate data from sensors, cameras, and information systems – enable the simulation of diverse scenarios, ranging from shifts in traffic flow to the consequences of emergency situations. For instance, a digital twin can help optimize public transport routes or forecast loads on energy grids. Meanwhile, chatbots and voice assistants, powered by natural language processing (NLP) models, automate the handling of inquiries from citizens.

An "AI-enabled citiverse" [1] is more than just another technological trend or a functional upgrade to the traditional "smart city" concept. It represents a profound evolution toward intelligent, interactive, and immersive urban ecosystems that prioritize the human experience and societal well-being. Such an environment seamlessly integrates immersive virtual spaces, artificial intelligence, and smart urban infrastructure, all designed to enhance quality of life, optimize municipal services, and ensure the sustainable functioning of the city. In practice, this creates an adaptive urban ecosystem that allows citizens and municipal authorities to interact through data-driven processes and participatory mechanisms, ultimately leading to meaningful outcomes in urban governance.

The development of such an urban environment relies on foundational technologies and supporting structures that facilitate interaction, intelligent analysis, simulation, immersion, and the cultivation of trust across the entire city.

These foundations support key urban functions, enabling cities to:

- connect systems and data within the urban environment;
- facilitate intelligent management, modeling, and simulation of urban processes;
- create opportunities for immersive and interactive engagement;
- strengthen coordination among various institutions;
- establish trusted digital environments, while enhancing the efficiency and accessibility of urban services for citizens;
- foster conditions for expanded economic opportunities and broader civic participation in urban life.

Without these foundations, an "AI-enabled citiverse" cannot function as an effective urban ecosystem. The development of such an environment should not be viewed merely as a collection of technological components or digital layers. The creation of public value depends on how these foundational elements are transformed into holistic, outcome-oriented capabilities that improve governance, service delivery, and public well-being. This requires a fundamental shift in approach:

- from an emphasis on technology stacks to a focus on the functional capabilities of cities;
- from fragmented, autonomous tools to integrated and interoperable urban functions;
- from the simple implementation of digital solutions to the systematic creation of public value.

Thus, the core issue is not so much the availability of technology, but rather its effective transformation into capabilities that strengthen essential urban functions: governance, planning, coordination, service delivery, public engagement, and decision-making. Technology should be viewed as the bedrock that enables the development of urban capabilities.

This text explores how the technological foundations of an "AI-enabled citiverse" can be reconceptualized as operational capabilities – essential for cities to implement in practice – and how these capabilities contribute to the creation of more resilient and efficient urban systems.

From technology to civic capabilities

The significance of an "AI-enabled citiverse" is defined not merely by a collection of advanced digital tools, but by how these resources are transformed into "civic capabilities" that enhance governance mechanisms. In an urban context, "capabilities" refer to practical and replicable ways of applying technology to support core city functions. It is essential to clearly distinguish between technologies, capabilities, and civic outcomes:

- Technologies encompass the tools, systems, and infrastructures that enable and support new forms of urban activity. In the context of an "AI-enabled citiverse," this includes artificial intelligence, digital twins, immersive and spatial interfaces, geospatial systems, sensor networks, communication infrastructure, and secure platforms for digital interaction.

- Capabilities are sustainable institutional capacities that emerge from the effective integration of technologies with governance mechanisms, data ecosystems, human potential, operational processes, and clearly defined public goals. They represent an organized and institutionalized ability to apply technology in support of essential urban functions.

- Civic outcomes are the socially significant effects achieved through the effective use of these capabilities – such as more responsive service delivery, increased urban resilience, better-informed (data-driven) decision-making, strengthened public trust, and broader, more inclusive citizen participation. These civic outcomes serve as the primary criterion for determining whether a digital transformation is creating genuine public value.

Table 1

Distinguishing Technologies, Capabilities, and Civic Outcomes

Layer	Meaning	Illustrative examples
Technologies	Tools, systems, and infrastructure that enable urban action	AI, digital twins, immersive interfaces, sensors, secure digital interaction
Capabilities	Repeatable institutional abilities enabled by technology and shaped by governance	Anticipatory governance, participatory planning, adaptive infrastructure management
Civic outcomes	Public results produced when capabilities are applied effectively	Responsive services, enhanced resilience, improved trust, more inclusive participation

This distinction clarifies the significance of technological convergence for cities. The result is not merely a more digitized urban environment, but one that creates public value more effectively.

In this context, five areas of transformation are particularly important:

- A profound understanding of urban systems.

By combining geospatial data, digital twins, simulation environments, and immersive interfaces, cities can make complex urban processes more visible, understandable, and navigable. This fosters a shared vision among urban planners, government bodies, and decision-makers.

- Proactive management.

The integration of data, artificial intelligence, and modeling tools helps to identify risks in advance, systematically explore potential scenarios, and prepare more deliberately for emerging challenges.

- Participatory planning.

Interactive and immersive urban environments make development plans and proposed solutions more accessible and comprehensible to residents. This creates the conditions for meaningful citizen engagement, allowing residents to explore alternatives, assess potential consequences, and provide well-founded, constructive feedback.

- Autonomous and adaptive infrastructure.

Interconnected infrastructure, real-time monitoring systems, and intelligent management mechanisms make urban services more flexible. This facilitates seamless service delivery, the implementation of predictive maintenance, and a more dynamic adaptation of infrastructure to changing conditions.

- Evidence-based policy development.

By leveraging comprehensive data, modeling, and analytical tools, cities can more rigorously evaluate various options – and the associated trade-offs – during both the preparation and implementation phases of decision-making. The practical significance of technological convergence lies not in the complexity of the technologies themselves, but in the opportunities and socially meaningful outcomes they enable. It represents an evolution in urban governance: a shift from fragmented perspectives to a shared understanding; from reactive administration to proactive action; from formal consultations to genuine citizen participation; from static systems to adaptive processes; and from ad hoc decision-making to continuous learning.

At the same time, such opportunities do not emerge automatically simply through the presence of digital tools. Realizing them requires the creation of an enabling environment – one that encompasses robust data management, system interoperability, secure and trusted digital interaction, advanced computational infrastructure, effective inter-institutional coordination, and inclusive access. Governance conditions must be in place to ensure that technologies are implemented transparently, accountably, and in alignment with the public interest. Without these conditions, technological convergence is likely to remain fragmented, and its impact uneven. Conversely, when the necessary conditions are established, cities gain a greater capacity to transform innovations into practical, effective tools.

Core civic capabilities and enabled outcomes in the ai-driven citiverse

The development of a "city of the future" (citiverse) – grounded in artificial intelligence technologies – relies on a set of key civic capabilities that transform a technological foundation into tangible, meaningful outcomes for the urban environment. These capabilities define how cities coordinate the operation of various systems, generate and

apply analytical insights, forecast and model future scenarios, ensure inclusive and participatory processes, and foster a secure, open, and accessible digital environment.

Cities have the capacity to aggregate, integrate, and coordinate data originating from administrative, geospatial, infrastructural, and operational systems.

This capability is critical, as the functioning of artificial intelligence, modeling systems, and "digital twins" depends on urban data – data that must be integrated, interpreted, and made available for use within robust, well-governed frameworks.

The elements listed below support this capability, enabling cities to consolidate and align their data.

1) Integrated urban data platforms.

- The consolidation of disparate systems, enabling data access and reuse across various municipal departments.

- Technologies (examples): data platforms, APIs, data pipelines, access control systems.

2) Geospatial data infrastructure.

- Linking various datasets to specific locations, objects, and networks, allowing cities to understand and manage their urban environment.

- Technologies (examples): GIS services, base maps, land parcel and address layers, building footprints, common spatial identifiers.

3) Real-time data streams (operational data).

- Facilitating continuous monitoring of changes within the urban environment, enabling a shift from static reporting to real-time situational awareness.

- Technologies (examples): IoT sensors, data streaming systems (real-time or low-latency), dashboards, alert systems.

4) Semantic interoperability.

- Ensuring that data from different systems can be accurately interpreted and used consistently by various departments, organizations, and digital services.

- Technologies (examples): common data models, standardized metadata, unified identifiers, controlled vocabularies, compatible APIs.

5) Federated urban data spaces.

- Enabling various stakeholders to securely share and utilize data while retaining control over it, without the need for full centralization.

- Technologies (examples): data-sharing platforms, access rights management systems, secure data-processing environments.

Enabling anticipatory governance and intelligent decision-making

When this capability is applied effectively, it contributes to:

- more responsive and reliable public services;
- improved resilience to disruptions and shocks;
- better-informed and more timely decision-making;
- more efficient allocation of public resources; and
- increased confidence in public decision-making processes.

This capability builds on integrated urban data and supports simulation, planning and operational decision-making across city systems.

Cities can anticipate risks, prioritise actions and support decision-making across urban systems.

The following elements support this capability by enabling cities to generate insight, anticipate change and inform action.

1) Predictive modeling.

- Identifying future conditions, risks, and demand patterns to support planning and proactive measures.

- Technologies (examples): machine learning models, statistical forecasting tools, simulation models.

2) Access to knowledge, communication, and service navigation.

- Ensuring that information of public interest and administrative knowledge are accessible, understandable, and actionable.

- Technologies (examples): large language models, generative AI platforms, conversational interfaces.

3) Urban analytics.

- Identifying patterns and risks, and deriving targeted analytical insights from vast and heterogeneous urban datasets.

- Technologies (examples): data analysis platforms, computer vision, geospatial analytics tools.

4) Support for operational and administrative decision-making.

- Translating analytical findings into concrete recommendations.

- Technologies (examples): dashboards, decision-support platforms, workflow management systems, notification tools.

Governance Issues

- Maintain human oversight and accountability when using high-impact systems, ensuring that levels of autonomy are appropriate to the context, risk, and the organization's level of maturity.

- Define tiered levels of autonomy and requirements for human intervention, including: (1) Fully human-controlled: AI provides recommendations, while a human makes the final decision; (2) Human-in-the-loop: AI operates under human supervision, with the possibility for human adjustment; (3) Autonomous with audit: AI operates independently, subject to subsequent review.

- Define the purpose, limitations, ownership, and avenues for redress for each AI system.

- Conduct regular testing for bias, drift, reliability, data quality, and user experience.

- Redesign business processes where necessary and sequence implementation accordingly.

- Utilize secure data sources and ensure appropriate transparency, civic engagement, and user testing.

Providing capabilities for modeling, testing, and planning at a systemic level

Effective use of this tool contributes to:

- reducing risks in government decision-making;

- more efficient and rational use of public resources;

- improved long-term planning outcomes;

- increased resilience to environmental, economic, and operational shocks; and

-
- greater transparency in the processes used to evaluate and justify decisions.

This capability relies on integrated data and analytical insights, and supports more transparent and participatory engagement through immersive interfaces.

Cities can simulate, test and explore the impacts of policies, infrastructure changes and operational decisions before implementation.

In practice, it allows cities to:

- represent and model current urban systems and conditions in a dynamic and integrated way;
- test future scenarios, interventions, and external shocks;
- assess the impacts of policy and planning decisions before implementation;
- evaluate infrastructure performance under different conditions; and
- improve coordination across interconnected urban systems.

The following elements support this capability by enabling cities to represent, simulate, and test urban systems.

1) Dynamic digital representations of cities

- Creating integrated and continuously updated depictions of the urban environment.
- Technologies (indicative): 3D city models, geospatial data platforms, digital twin environments.

2) Scenario modeling

- Testing how urban systems respond to future conditions, interventions, or shocks.
- Technologies (indicative): simulation engines, scenario modeling tools, predictive models.

3) Infrastructure modeling

- Understanding the condition, performance, and interdependencies of infrastructure systems.
- Technologies (indicative): asset management systems, infrastructure models, sensor-integrated platforms.

4) Policy-testing environments

- Evaluating the potential consequences of planned decisions before they are implemented.
- Technologies (indicative): decision-support platforms, simulation environments, scenario analysis tools.

Cities can represent urban systems, plans, and models – and interact with them—in ways that allow people to visualize, navigate, and perceive them within a spatial dimension. This enables cities to shift from static, abstract methods of presenting urban information toward more interactive, accessible, and intuitive formats.

In practice, this allows cities to:

- present proposals for territorial development in a more accessible and understandable way;
- facilitate more meaningful public participation in planning processes;
- foster collaboration between municipal departments and various stakeholders;
- provide users with the ability to interactively explore the urban environment and different development scenarios;
- compare scenarios, test proposed solutions, and make well-informed, data-driven management decisions.

The elements listed below support the realization of these capabilities, enabling cities to represent, explore, and engage with the urban environment.

- 1) Collaborative immersive participation and design.
 - Enabling users to interact with the urban environment and perceive it as a navigable digital space, rather than as a static image.
 - Technologies (examples): XR (extended reality) platforms, immersive visualization systems, augmented reality (AR) and virtual reality (VR) devices.
- 2) Location-based interaction and on-site decision support.
 - Linking digital information to real-world locations, urban assets, and the environment to facilitate interaction within a spatial context.
 - Technologies (examples): geospatial positioning systems, spatial mapping technologies, integration with digital twins.
- 3) Immersive visualization of the urban environment.
 - Presenting complex urban data in intuitive, visual formats.
 - Technologies (examples): 3D modeling tools, visualization platforms, rendering engines, XR interfaces, spatial tracking systems.
- 4) Environments for collaborative planning.
 - Allowing multiple users to explore design proposals, compare various scenarios, and work with urban data within a unified digital space.
 - Technologies (examples): collaborative platforms, shared virtual environments, interaction tools.

Enabling scalable, resilient and real-time urban operations

This capability ensures the reliable functioning of systems related to data, analytics, modeling, and interaction, while also supporting service integration, identity management, and overall administration at a city-wide scale. Cities can manage their urban environment in real time and provide digital services, ensuring that computing power, storage resources, and communication channels can scale according to demand, maintain minimal latency, and remain reliable and resilient in the event of failures.

The elements listed below facilitate the realization of this capability, enabling cities to reliably process, store, and transmit data across various systems and environments.

- 1) Reliable delivery of digital services across all municipal functions.
 - Ensuring the reliable and scalable delivery of digital services across various departments through shared environments that support multiple functions and users.
 - Technologies (indicative): cloud platforms, shared application environments, data platforms, API gateways, microservices, containerized environments.
- 2) Low-latency and resilient operational response.
 - Supporting timely and reliable operational responses in situations where urban conditions change rapidly and delays would diminish service effectiveness.
 - Technologies (indicative): edge computing nodes, gateways, local processors, IoT devices, streaming platforms, event-driven architectures, low-latency network infrastructure.
- 3) Continuity, coordination, and stable performance.
 - Maintaining reliable, coordinated, and continuous digital operations as the volume of services, users, and data grows throughout the city.

-
- Technologies (indicative): monitoring and observation tools, logging systems, backup and recovery systems, orchestration tools, cyber-resilience measures, failover infrastructure.

Enabling trusted, secure and inclusive digital interaction

This capability enables trusted interaction within digital services and platforms, and supports the provision, coordination, and management of interconnected urban systems. This is critical, as the functioning of digital services, platforms for civic engagement, and interconnected systems depends on the ability of users to authenticate themselves, exchange data, and conduct transactions with the assurance that their privacy and security are protected.

In practice, this allows cities to:

- securely verify the identity of users and organizations as they interact with digital services;
- protect personal data and ensure privacy during digital interactions;
- provide secure access to services, platforms, and systems;
- facilitate trusted digital transactions and approval processes.

The elements listed below contribute to the realization of this capability, ensuring secure, trusted, and private digital interaction.

1) Digital identification systems.

• Verifying the authenticity of individuals, organizations, and systems within digital services through secure authentication, identity assurance, and accountability mechanisms.

- Technologies (examples): digital identification systems, decentralized identifiers (DIDs), authentication services, identity management platforms.

2) Privacy protection.

- Ensuring the responsible handling of personal data.
- Technologies (examples): consent management systems, data protection tools, privacy-enhancing technologies.

3) Cybersecurity.

• Protecting digital systems, identity data, transactions, and urban infrastructure against unauthorized access, disruptions, and cyber threats—including those amplified by the use of artificial intelligence.

- Technologies (examples): encryption tools, security monitoring systems, access control mechanisms.

4) Trusted digital transactions.

• Enabling agreements, signatures, and exchanges in an online environment with guarantees of reliability and legal validity.

- Technologies (examples): digital signature platforms, verification systems, tools for conducting secure transactions.

Enabling interoperable and open urban systems

This capability enables systems, data, and services to function as an interconnected ecosystem, while also fostering scalability, integration, and the long-term development of an urban digital environment. Cities can facilitate the seamless collaboration of data, systems, and services across various departments, platforms, and providers. This is a critical aspect, as an "urban metaverse" (citiverse) – leveraging artificial intelligence – relies on shared data flows, reusable digital components, and the ability to integrate new services, all without system fragmentation or vendor lock-in.

The elements listed below support this capability by ensuring the interoperability of systems, data, and services throughout the entire urban environment.

1) Minimal Interoperability Mechanisms (MIMs).

- Providing a common, practical framework for interaction between various systems and platforms.

- Technologies (examples): APIs, common data models, metadata structures, interoperability standards.

2) Open standards and data models.

- Enabling data and systems to be understood, shared, and reused across different platforms and domains.

- Technologies (examples): open data standards, common schemas, conceptual frameworks for interoperability.

3) API and service integration.

- Ensuring reliable and efficient interaction between systems and services, as well as the exchange of data between them.

- Technologies (examples): API gateways, integration platforms, service interfaces.

4) Open and modular architectures.

- Supporting flexibility, scalability, and the future evolution of systems.

- Technologies (examples): modular platforms, microservices architectures, interoperable systems.

Enabling accessible and inclusive digital environments

This capability ensures that the benefits of data, intelligence, simulation and digital services are accessible to all users, thereby making inclusion a core principle of the AI-enabled citiverse. Cities can design digital services, platforms and interfaces so they are accessible and usable by people with different abilities, languages, literacy levels, devices and levels of digital access. This capability is essential because the AI-enabled citiverse can only be human-centric if participation and service access are inclusive and designed for diverse users from the outset. In this context, accessibility and inclusion are not optional features but core requirements for the design and delivery of digital services.

This capability enables cities to move from fragmented and exclusionary digital services and environments to accessible, inclusive and widely usable digital environments.

In practice, it allows cities to:

- design services and interfaces that are accessible to diverse users;
- support multiple languages, interaction modes and assistive technologies;
- provide alternative access channels across devices and connectivity levels;
- support participation in digital processes in an inclusive and equitable way and reduce barriers to accessing services and engaging with urban systems.

The following elements support this capability by ensuring services and interfaces are accessible and inclusive.

- 1) Principles of inclusive design.
 - Designing digital environments that are accessible from the outset to a wide range of user groups.
 - Technologies (examples): accessibility standards, inclusive design concepts, testing tools.
- 2) Accessibility in immersive environments.
 - Ensuring that immersive and spatial interfaces are usable by people with various sensory, cognitive, or motor impairments.
 - Technologies (examples): accessibility features in extended reality (XR) technologies, multimodal interaction tools, assistive interface technologies.
- 3) Multilingual and assistive interfaces.
 - Providing users with access to services in multiple languages and through the use of assistive aids.
 - Technologies (examples): translation tools, accessibility software, assistive technologies.
- 4) Equal access to digital services.
 - Ensuring that services are accessible regardless of the device used, connection quality, or level of digital literacy.
 - Technologies (examples): solutions for low-bandwidth network conditions, multichannel service delivery platforms, accessibility tools.

City-level outcomes depend on how foundational capabilities are combined and applied within the broader urban ecosystem. Their value lies in how these various capabilities interact with one another, facilitating effective urban governance and service delivery.

A strategic blueprint for cities in the age of AI



To manage a city effectively, its leaders must understand the many global factors that are reshaping urban reality [3]. Taken together, these technological, economic, and social forces confront cities with the challenge of large-scale transformation. Such systems must account for the following aspects:

- Climate and environmental instability.

- Unprecedented progress in artificial intelligence.
- Economic restructuring and the development of digital industries.
- Evolving citizen expectations and levels of trust.
- The complexity of governance processes.

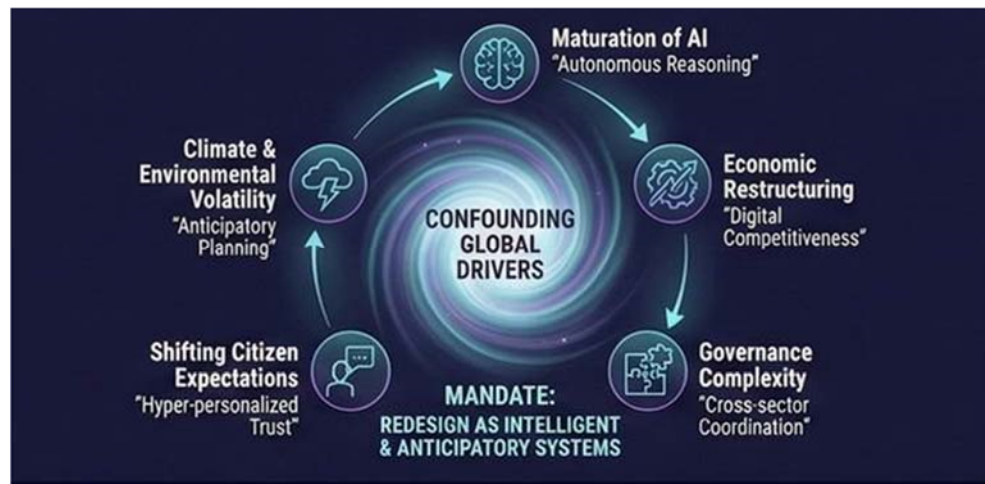


Fig. 1. The Great Convergence and the Confounding Trends

Historically, urban technologies have been narrowly focused on optimizing physical infrastructure – such as improving the efficiency of energy grids or refining the operation of traffic lights. The concept of a "citiverse" (urban metaverse), rooted in the use of artificial intelligence, shifts the focus toward unlocking human potential, strengthening civic engagement, enabling data-driven decision-making, and creating public value.

This provides city leadership with enhanced capabilities for strategic foresight. By transitioning toward "cognitive" and autonomous city models, officials can ensure that decisions are based on empirical evidence, increase governance transparency, and make public administration more agile.

Technologies alone do not transform cities; rather, it is the new functional capabilities they enable that drive change. To capitalize on these emerging opportunities, the underlying technologies must be demystified – presented to city administrators not as abstract technical concepts, but as practical tools for urban development:

- Virtual worlds that create immersive environments: Technologies such as the "spatial internet" and advanced 3D visualization methods transform complex urban data into intuitive, immersive settings. This allows urban planners, residents, and government officials to literally "step inside" future developments, facilitating collaborative design, agile planning, engineering assessment, cross-departmental decision-making, and effective coordination among various municipal services.

- Artificial intelligence that provides analytical capacity and autonomy: Advanced AI systems endow cities with the ability to perform complex logical analysis, predictive modeling, and rapid, autonomous responses. Through this, static urban systems are transformed into "cognitive networks" capable of anticipating crises – ranging from optimizing energy distribution during peak loads to rerouting emergency services around traffic congestion – and adapting to changes in real time.

- Digital twins that provide systemic intelligence: the ability to dynamically model the consequences of specific decisions, resource allocation, and infrastructure loads across interconnected urban systems, using up-to-date data. This makes it possible to foresee

how a single change in policy or infrastructure will ripple through the entire urban ecosystem.

- A robust foundational database that ensures "AI sovereignty": at the core of all these capabilities lie secure digital infrastructure, federated data spaces, and scalable system architectures. These foundations guarantee that a city retains sovereignty over its data, protecting citizens' privacy while simultaneously ensuring the interoperability required for a fully realized, AI-driven urban environment.

The true benchmark for such an urban environment is not its technological complexity, but its capacity to expand human potential. This approach rejects technology for technology's sake; it is rooted, instead, in the principle of human-centricity.



Fig. 2. Human-Centric by Design

- Natural language as a universal interface: using complex digital services will no longer require technical literacy or the ability to navigate cumbersome municipal portals. Citizens will be able to interact directly with city institutions – eliminating bureaucratic hurdles and accessibility barriers, and making governance truly inclusive.

- Human-level intelligence for urban problem-solving: by integrating data on the urban environment (via AI) with feedback from residents and advanced analytical capabilities, cities can harness an intellectual capacity comparable to that of thousands of experts to address the specific challenges of individual neighborhoods.

A future-oriented city does not merely react to change; it anticipates it. Transitioning to an AI-enabled urban ecosystem fundamentally transforms the experience and outcomes for all key stakeholders in city life:

- Strengthening local sectors: creating an environment that attracts global talent, venture capital, and cutting-edge industries.

- Scalable skills development: preparing the local labor market, civil servants, and municipal staff for the profound economic transformations driven by AI.

- Hyper-personalized urban services: shifting from a "one-size-fits-all" approach to services meticulously tailored to the specific needs, life context, language, and accessibility requirements of each resident.

- Immersive civic engagement: enabling communities to visualize projects and participate meaningfully in the planning and development of their own neighborhoods.
- Expanding civic inclusion: ensuring that individuals with specific accessibility needs or lower levels of digital literacy can fully access urban services through human-centric digital solutions that provide the necessary support.



Fig. 3. Envisioning the AI-Enabled Citiverse Ecosystem for Cities

Priorities for actual city needs

The selection of priority areas for technology deployment should be guided by a city's economic reality and geographical characteristics:

- Coastal Metropolis: A city facing the challenge of rising sea levels requires advanced predictive tools for flood modeling, resilient infrastructure planning, and real-time environmental monitoring.
- Industrial Hub: A city undergoing large-scale transformation might focus on leveraging artificial intelligence to optimize transport flows, upskill the workforce, model supply chains, and monitor the active reduction of harmful emissions.
- Rapidly Growing Urban Center: A city experiencing swift population growth can utilize AI technologies to model scalable housing projects, optimize new utility networks, and deploy autonomous public transport systems.

Artificial intelligence and the concept of a "digital city" (citiverse) provide the necessary architecture and functionality, while the city itself defines its own strategic mission. AI technologies and spatial computing are evolving exponentially, and the rules of the new digital economy are being shaped today. Delay inevitably leads to technological dependency, as well as fragmented and inefficient public services. By acting proactively, municipal authorities can exert a direct influence on governance principles, data sovereignty, and ethical standards within their local digital ecosystem.

Early adopters will set global standards. By investing in the development of AI technologies and the corresponding capacity, city authorities can build essential institutional capabilities, attract talent, and reach a level of operational maturity that enables them to manage urban processes with confidence. To help cities seize this unique opportunity and translate international dialogue into concrete, local-level transformation, the International Telecommunication Union (ITU), the UN International Computing Centre (UNICC), and Digital Dubai – in collaboration with experts from around the world – have launched the "Global Initiative on AI and Virtual Worlds: Discovering the Citiverse" [2]. The

goal of this initiative is to bridge the gap between ambitious visions and their practical implementation on the ground.

The cities of the future will be defined by more than just their physical infrastructure. Their character will depend on their capacity to respond to change, the level of immersive connectivity they offer, and an unwavering commitment to fostering human potential.

The transition from traditional "smart cities" to cognitive, proactive urban ecosystems stands as a key governance challenge for the current decade.

Conclusion

The concept of a "citiverse" – an urban ecosystem powered by artificial intelligence – should not be viewed as a single technological platform, but rather as a long-term development trajectory for cities. It serves as a framework for enhancing urban management, planning, operations, and civic engagement. The true value of this approach lies not in the mere accumulation of digital tools, but in the opportunities they create to deliver outcomes that are meaningful to residents. Consequently, the central question for cities is how these technologies can be transformed into practical instruments that foster greater sustainability, inclusivity, public trust, and social value.

This transition is anchored in several fundamental areas of development:

- Ensuring the interconnected and coordinated functioning of urban services.
- Implementing proactive management methods and intelligent decision-making processes.
- Establishing capabilities for system-level modeling, testing, and planning – enabling the analysis of various scenarios, the comparison of potential courses of action, and the assessment of risks before they are implemented in the physical urban environment.
- Developing scalable, resilient, real-time urban systems that leverage cloud computing, edge computing, and advanced communication channels.
- Creating a secure, safe, and inclusive digital environment, alongside open urban systems capable of interacting effectively with one another.

Cities should approach the development of an AI-powered "citiverse" with both ambition and pragmatism. It is not necessary to immediately build a comprehensive "digital twin" or launch a large-scale, all-encompassing AI implementation program. Instead, the focus should be on clearly defining priorities, identifying the most impactful use cases, and gradually building capacity – all while remaining mindful of local realities. An "AI-enabled urban universe" is not a ready-made model that can simply be copied; rather, it is a path that each city must forge for itself, based on its own unique needs and development trajectory.

Cities should not wait for ideal conditions to begin taking action. By engaging with a broad community of practitioners and participating in various initiatives [2], cities gain access to collective knowledge, opportunities for collaboration, and expert guidance for experimentation. In this way, an "AI-enabled urban universe" can become a practical tool for building a more efficient, inclusive, and sustainable urban future. Delaying the adoption of innovations leads to technological dependency, "brain drain," a loss of economic competitiveness, and an inability to attract the industries and talent of the future.

The central governance question of this decade is not whether to create future-ready cities, but rather who will lead the process [4-7].

Abbreviations and acronyms

AI	Artificial Intelligence
API / APIs	Application Programming Interface(s)
AR	Augmented Reality
BID	Biometrically Inferred Data
CIN	Carteira de Identidade Nacional (National Identity Card, Portugal)
CIO / CIOs	Chief Information Officer(s)
DIDs	Decentralized Identifiers
EDIC	European Digital Infrastructure Consortium
GDP	Gross Domestic Product
GIS	Geographic Information System
GPS	Global Positioning System
GOV.UK	Government of the United Kingdom
IGO	Intergovernmental Organization
IoT	Internet of Things
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
MIMs	Minimal Interoperability Mechanisms
RDG	Responsible Data Governance
SSI	Self-sovereign Identity
XR	Extended Reality

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