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Perfect Sequences Based on Golay Codes for Communication Systems

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Abstract: In data transmission systems, ensuring reliable communication while maximizing spectrum efficiency is a challenge. Code Division Multiple Access (CDMA) systems, widely used in wireless networks, depend on spreading codes to manage interference and support users. Achieving a balance between low cross-correlation and optimal autocorrelation properties is complex and involves trade-offs that affect system performance, especially as modern systems demand higher data rates and efficiency. In systems that use spectral spreading, achieving optimal autocorrelation characteristics often compromises cross-correlation characteristics, and vice versa. Codes with low cross-correlation values typically exhibit high out-of-phase autocorrelation values. Therefore, a balance between autocorrelation and cross-correlation properties is necessary for an efficient CDMA communication system. These desirable correlation properties are crucial in both periodic and aperiodic contexts. Recent innovations have led to a patented code generator derived from Golay codes/sequences, which exhibits low periodic cross-correlation values and a periodic autocorrelation function characterized by a prominent correlation peak and null values surrounding it. This development not only enhances signal quality but also mitigates interference in multi-user communication scenarios, making it particularly relevant for modern wireless networks. Furthermore, a novel solution is proposed to minimize the Peak-to-Average Power Ratio (PAPR) and reduce the cost of a new Orthogonal Perfect Discrete Fourier Transform Golay (OPDG) power transmission circuit. This approach leverages advanced signal processing techniques to achieve energy efficiency, addressing a critical challenge in high-performance communication systems. Experimental results demonstrate the practicality of these innovations in real-world implementations, paving the way for future advancements in CDMA technology.

Keywords: Perfect Sequences, OPDG codes, PAPR

1. Introduction

In many communication systems, such as Code Division Multiple Access (CDMA) and Orthogonal Frequency Division Multiple Access (OFDMA), the need for suitable coding sequences is paramount. These sequences must exhibit excellent periodic autocorrelation and near-perfect cross-correlation features to ensure effective synchronization and code identification in noisy environments. Popular orthogonal codes used in CDMA include Golay sequences [1], Frank and Chu codes [2], and Gold codes [3]. A perfect sequence is a complex sequence where all out-of-phase periodic auto-correlation values are zero. Unfortunately, perfect bipolar sequences longer than 4 and perfect quadri-phase sequences longer than 16 are currently unknown [4].

To achieve higher data rates and improved spectral efficiency, communication systems using OFDMA employ linear modulation techniques like quadrature phase-shift keying and quadrature amplitude modulation [5]. However, a significant challenge is the high Peak-to-Average Power Ratio (PAPR) of the transmitted Orthogonal Frequency Division Multiple (OFDM) signal. High PAPR results in performance degradation due to nonlinear distortion from High-Power Amplifiers (HPAs). This non-linearity leads to in-band distortion, which increases Bit Error Rate (BER), and out-of-band radiation, causing adjacent channel interference [6]. Thus, addressing the PAPR issue is critical for maintaining system power efficiency and minimizing nonlinear distortion in future wireless communication systems [7].

Pereira and Silva [8] introduced a patented Coder/Decoder (CODEC) with perfect sequences of length 2N ($N \in \mathbb{N}$), based on the Inverse Discrete Fourier Transform (IDFT) of Golay sequences [1]. These Golay sequences are not the well-known error correcting code invented by Golay. These new obtained codes are perfect sequences and complementary, unaffected by multipath Interferences (MPI) due to their correlation properties. Termed Orthogonal Perfect DFT Golay (OPDG) codes, or simply Perfect Golay codes, they exhibit satisfactory correlation properties. This paper presents an OPDG code generator to simplify the hardware implementation of lengthy perfect bipolar and quadri-phase sequences. Additionally, a novel solution to reduce PAPR and offer an economical OPDG power transmission circuit is proposed.

Section 2 reviews the concept of Perfect Sequences, while Section 3 introduces the OPDG Codec. Section 4 discusses a solution for the error probability and section 5 shows a PAPR solution based on a binary decomposition of OPDG codes. A conclusion is written at the end.

2. Perfect Sequences

In the study of stochastic processes, particularly those that are Wide-Sense Stationary (WSS), understanding the nature of perfect sequences is crucial. We should remember that, as noted by Theodoridis [9], for any WSS stochastic process, there is a unique autocorrelation sequence that characterizes it. However, the reverse is not true; a single autocorrelation sequence may correspond to multiple WSS processes. Recall that the autocorrelation function correspond to the mean value of the product of random variables, but many different random variables may share the same mean value. The Fourier transform $\boldsymbol{S_{\eta}(\omega)}$ of an autocorrelation sequence $\boldsymbol{r(k)}$ is nonnegative. Furthermore, if a sequence $\boldsymbol{r(k)}$ has a nonnegative Fourier transform, it is positive definite, and we can always construct a WSS process with $\boldsymbol{r(k)}$ as its autocorrelation sequence. Thus, the necessary and sufficient condition for a sequence to be an autocorrelation sequence remains the nonnegativity of its Fourier transform.

One common example of a WSS process is the white noise [9] sequence. White noise is essential in signal processing and communication systems. It is a random signal characterized by equal intensity at different frequencies, resulting in a constant power spectral density. The mean of white noise is zero, and its autocorrelation function is zero for any non-zero time shifts.

Instead of modeling the input signals using a white noise signal, we will use a discrete u_n sequence generated by a Codec described in the next section. This u_n can be a periodic sequence of length N, where the index point $n = 0,1,2 \ldots, N-1$. Its Discrete Fourier Transform (DFT) [10] is defined by the following expression (1):

$$DFT[u_n] = U_k = \sum_{n=0}^{N-1} u_n W_N^{kn}. \quad (1)$$

The Inverse Discrete Fourier Transform (IDFT) [10] can be expressed as follows (2):

$$IDFT[U_k] = u_n = \frac{1}{N}\sum_{k=0}^{N-1} U_k W_N^{-kn}. \quad (2)$$

For convenience of notation W_N is defined to be (3)

$$W_N = exp\,(-j\omega) = exp\left(-j\frac{2\pi}{N}\right), \text{ where } j = \sqrt{-1}. \quad (3)$$

Using the DFT and IDFT transformations, periodic cross-correlation can be defined [10, 11] by the following expression (4):

$$r_{uv}[n] = \sum_{k=0}^{N-1} u_k v^*_{mod\,[k+n,N]} = IDFT[UV^*], \quad (4)$$

where n is an integer, the superscript * represents the complex conjugate and $mod\,[a,b]$ is the rest of an integer division of (a:b). A complex value u_n is equal to $u_{mod\,[n,N]}$ when "u" is a periodic sequence with the period N.

When u = v, (4) is defined as the periodic autocorrelation function. A sequence u is called a "perfect sequence" if it has an ideal periodic autocorrelation function proportional to a Dirac unit impulse, $\delta[n]$ defined by (5):

$$r_{uu}[n] = N\delta[n] = \begin{cases} N, & mod\,[n,N] = 0 \\ 0, & mod\,[n,N] \neq 0 \end{cases}. \quad (5)$$

As it is known ($\delta[n] = IDFT[1]$), any sequence of constant amplitude in the frequency domain corresponds to a perfect sequence in the time domain.

The IDFT of a constant sequence (such as a sequence of ones) results in a Dirac unit impulse (also known as the Kronecker delta function) in the discrete-time domain.

Here is the detailed reasoning:

Given a sequence $|U_k|$=1 for k=0,1,…,N−1, which means $|U_k|$ is constant and equal to 1 for all k, the IDFT[$|U_k|$] of (4) is computed. The terms W_N^{-kn} are evenly distributed around the unit circle in the complex plane, and their sum is zero due to symmetry.

Thus, the sequence $u_n = IDFT[U_k]$ is as follows (6):

$$r_{u_n} = \begin{cases} 1, & if \quad mod\,[n,N] = 0 \\ 0, & if \quad mod\,[n,N] \neq 0 \end{cases}. \quad (6)$$

Considering one period, this is the discrete-time equivalent of the Dirac unit impulse, often represented as $\delta[n]$ on equation (7):

$$r_{u_n} = \delta[n]. \quad (7)$$

Therefore, the IDFT of a constant sequence $|U_k| = 1$ is indeed a Dirac unit impulse.

In other words, we can say that the sequence (8):

$$u_{perfect}[n] = \sqrt{N} \times IDFT[U_k], \quad (8)$$

when $0 \leq n, k \leq N-1$, is a normalized perfect sequence if

$$|U_k|^2 = 1. \quad (9)$$

Using (8) we can generate perfect sequences (with constant envelope or not) of any length N, when it $|u_n|$ is constant for all values $0 \leq n \leq N-1$. However, what is usually intended with communication systems is to find perfect sequences with good correlation properties. For example, perfect sequences with low cross-correlation values (in absolute value).

Ideally, sequences used in Code Division Multiple Access (CDMA-type) systems or Orthogonal Frequency-Division Multiplexing - Code Division Multiple Access (ODFM-type) systems should have a perfect periodic autocorrelation function [12-14] when multi-path interference is predominant. In other words, the perfect periodic autocorrelation function must be equal to the function of a Dirac unit impulse $\delta[n]$. However, since bipolar sequences with the perfect periodic autocorrelation function are not known except for x = {1, 1, 1, -1} or for any cyclic rotation of x [15, 16], it is desirable to find new sequences. Alternative solutions can be found with periodic complex sequences defined by some authors as sequences of multiple small or large alphabet phases [12, 17, 18], unimodular perfect sequences [19], codes of the type "Phase Shift Pulse" [20], perfect sequences of the root of the unit [21], sequences of Bent functions [22], or simply as perfect sequences [23-25]. Additionally, perfect sequences with four phases (small alphabet) exist for lengths N equal to 2, 4, 8, 16 (Milewski sequences and Frank sequences). Many other sequences with perfect periodic autocorrelation function can be found if a mathematical transformation is used [13,14].

Codes with a near-perfect periodic autocorrelation function and that have a reduced MaxCC (maximum periodic cross-correlation in absolute value) can be applied in asynchronous CDMA communication systems, for fast equalization, for estimation of a communication channel, for synchronization, or in other applications impaired by strong interference of the multiple paths type [26].

As already mentioned, a variety of perfect sequences have been proposed by several authors/researchers. The lower bound of the maximum absolute cross-correlation value MaxCC is a constant equal to $\sqrt{N}$ [2, 11, 27]. It is interesting to note that, theoretically, it should not be possible to generate perfect sequences with zero periodic cross-correlation for any temporal displacement.

3. OPDG code generator

Figure 1 depicts a simplified diagram of the application of real OPDG codes in a data communication system in the presence of noise [8]. It illustrates the integration of electronic circuits for coding and decoding OPDG sequences within the communication system.

- The OPDG encoder (block 101) represents the circuits in **Figures 2**(**a**) and **2**(**b**).
- The circuit transforming the sequences is shown as the 'floor of the encoder with DAC' (block 102), representing **Figures 3**(**a**) and **3**(**b**).
- The 'Transmission medium' (block 103) indicates the means of transmission, receiving the sequences with additive noise.
- The 'floor of the decoder with ADC' (block 104) includes an ADC converter and filters to minimize noise effects.
- The OPDG decoder (block 105) corresponds to the circuits in **Figures 4**(**a**), **4**(**b**), or the simplified circuit in **Figure 6**.

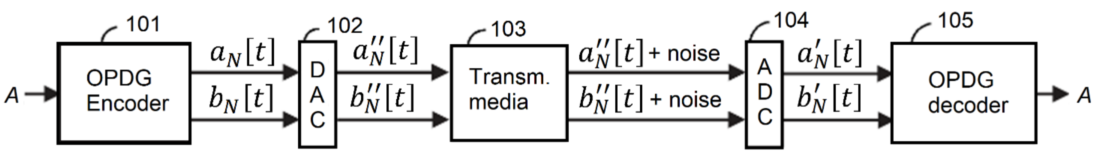
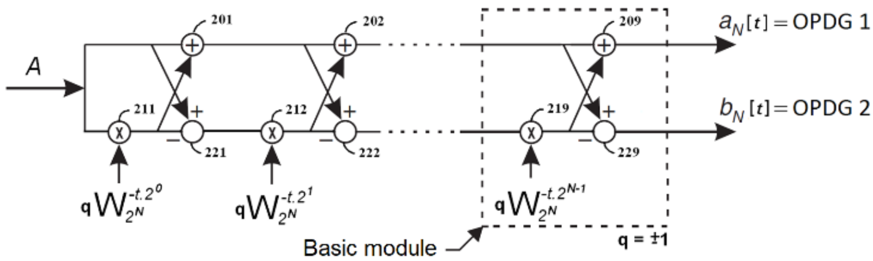
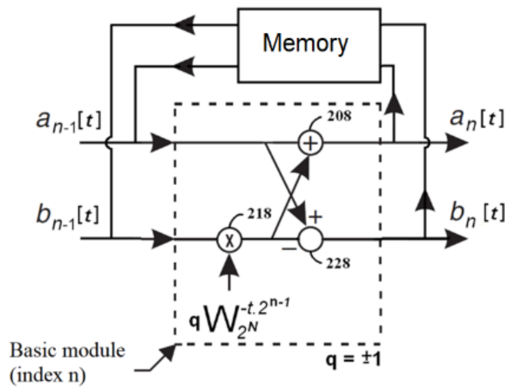


Figure 1. Block diagram of the proposed solution.

The OPDG coding block (101) serves as the electronic generator of OPDG codes, while the OPDG decoder (105) acts as the electronic detector of OPDG codes transmitted in a CDMA medium (103) with noise or electronic interference. The information transmitted by the user is proportional to the detection of the assigned OPDG code.

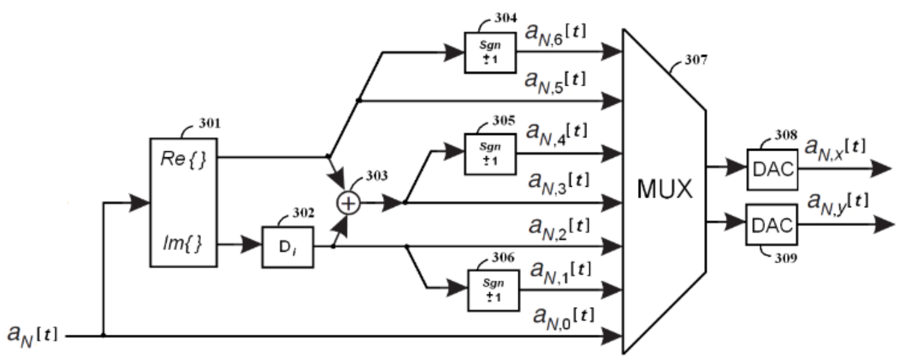


(a)

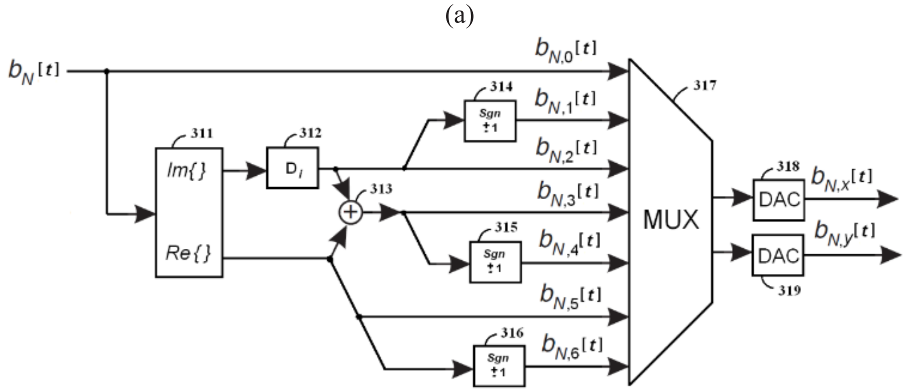


(b)

Figure 2. (**a**) Hardware implementation of the generator circuit (encoder) of a pair of perfect orthogonal sequences (**b**) Hardware implementation of the electronic encoder of OPDG codes using recursive process.



(a)



(b)

Figure 3. (**a**) Transformation of the complex sequence a_N shows how to apply a set of electronic transformations

to codes. (**b**) Transformation of the complex sequence b_N illustrates how to apply the same set of electronic transformations to codes.

Figure 2(**a**) illustrates the generator circuit (encoder) of a pair of perfect orthogonal sequences. The perfect sequences aN[t] is called the OPDG code 1 and bN[t] is called the OPDG code 2.

- The generator circuit produces a pair of discrete orthogonal and perfect sequences, OPDG 1 and OPDG 2, of length L = 2N.
- The encoder incorporates adders, differentiators, and multipliers (multiplying by a vector complex 'twiddle factor' WL = exp (-j2π/L)).
- The value of the 'twiddle factor' in each module is crucial for generating OPDG codes with perfect autocorrelation and zero cross-correlation.

Figure 2(**b**) shows the hardware implementation of the coder of OPDG codes using a recursive process.

- This method employs a single module called recursively N times, advantageous when N is high.
- The recursive process involves input vectors an-1[t] and bn-1[t] and output vectors an[t] and bn[t], with n as an integer (1 ≤ n ≤ N).
- The initial condition is $a_0[t] = A$ and $b_0[t] = A$, where A is a real constant vector or signal, performed only at the first iteration (n = 1).

Mathematical Proofs

Golay Sequences Recap

We start with the Golay sequences generated using Budisin's recursive method [28], defined as (10-13):

$$A_0[k] = \delta[k] \quad (10)$$

$$B_0[k] = \delta[k] \quad (11)$$

$$A_n[k] = A_{n-1}[k] + q.B_{n-1}[k - D_n] \quad (12)$$

$$B_n[k] = A_{n-1}[k] - q.B_{n-1}[k - D_n]. \quad (13)$$

After applying the IDFT to the bipolar Golay sequences (12) and (13), we get the sequences $a_n[t]$ and $b_n[t]$ as follows (14,15):

$$a_n[t]= a_{n-1}[t] + q.W_{2N}^{-t.2^{n-1}}.b_{n-1}[t] \quad (14)$$

$$b_n[t] = a_{n-1}[t] - q.W_{2N}^{-t.2^{n-1}}.b_{n-1}[t]. \quad (15)$$

Here, $q = \pm 1$.

The initial condition is $a_0[t] = A$ and $b_0[t] = A$, where A is a real constant vector or signal, and each electronic module uses a complex hardware implementation equal to (16):

$$q.W_{2N}^{-t.2^{n-1}}. \quad (16)$$

Length L = 2N, with WL = exp(-j2π/L).

Autocorrelation Analysis

Autocorrelation of $a_n[t]$

The autocorrelation function of $a_n[t]$ is defined as (17,18):

$$R_{a_n a_n}[m] = \sum_{t=0}^{L-1} a_n[t] \cdot a_n[t+m] \quad (17)$$

$$a_n[t] = a_{n-1}[t] + q \cdot W_{2N}^{-t \cdot 2^{n-1}} \cdot b_{n-1}[t] \quad (18)$$

The autocorrelation becomes (19):

$$R_{a_n a_n}[m] = \sum_{t=0}^{L-1} \left(a_{n-1}[t] + q \cdot W_{2N}^{-t \cdot 2^{n-1}} \cdot b_{n-1}[t]\right)\left(a_{n-1}[t+m] + q \cdot W_{2N}^{-(t+m) \cdot 2^{n-1}} \cdot b_{n-1}[t+m]\right) \quad (19)$$

Expansion of Terms

Breaking it down, we have (20):

$$R_{a_n a_n}[m] = \sum_{t=0}^{L-1} \left[a_{n-1}[t] a_{n-1}[t+m] + q \cdot W_{2N}^{-(t+m)\cdot 2^{n-1}} a_{n-1}[t] b_{n-1}[t+m] \right]$$

$$\left(+q \cdot W_{2N}^{-t\cdot 2^{n-1}} b_{n-1}[t] a_{n-1}[t+m] + |q|^2 \cdot b_{n-1}[t] b_{n-1}[t+m] \right) \quad (20)$$

Simplification Using Complementary Properties

First and Last Terms: The terms $a_{n-1}[t]a_{n-1}[t+m]$ and $b_{n-1}[t]b_{n-1}[t+m]$ contribute significantly at zero offset due to the Golay sequence's autocorrelation property, maintaining the main peak.

Mixed Terms Cancellation: The mixed terms $q \cdot W_{2N}^{-(t+m)\cdot 2^{n-1}} a_{n-1}[t] b_{n-1}[t+m]$ and $q \cdot W_{2N}^{-t\cdot 2^{n-1}} b_{n-1}[t] a_{n-1}[t+m]$ cancel for $m \neq 0$, thanks to the orthogonal properties imposed by the phase shifts W_{2N}.

Result: This ensures $R_{a_n a_n}[m] \approx \delta[m]$, resulting in a Dirac-like impulse for the autocorrelation.

Cross-Correlation Analysis

Cross-Correlation between $a_n[t]$ and $b_n[t]$

The cross-correlation function is (21):

$$R_{a_n b_n}[m] = \sum_{t=0}^{L-1} a_n[t] \cdot b_n[t+m] \quad (21)$$

Using the recursive definitions we have (22, 23):

$$a_n[t] = a_{n-1}[t] + q \cdot W_{2N}^{-t\cdot 2^{n-1}} \cdot b_{n-1}[t] \quad (22)$$

$$b_n[t] = a_{n-1}[t] - q \cdot W_{2N}^{-t\cdot 2^{n-1}} \cdot b_{n-1}[t] \quad (23)$$

Substitute to get (24, 25):

$$R_{a_n b_n}[m] = \sum_{t=0}^{L-1} \left(a_{n-1}[t] + q \cdot W_{2N}^{-t\cdot 2^{n-1}} b_{n-1}[t] \right) \left(a_{n-1}[t+m] - q \cdot W_{2N}^{-(t+m)\cdot 2^{n-1}} b_{n-1}[t+m] \right) \quad (24)$$

$$R_{a_n b_n}[m] = \sum_{t=0}^{L-1} \left[a_{n-1}[t] a_{n-1}[t+m] - q \cdot W_{2N}^{-(t+m)\cdot 2^{n-1}} a_{n-1}[t] b_{n-1}[t+m] \right]$$

$$\left(+q \cdot W_{2N}^{-t\cdot 2^{n-1}} b_{n-1}[t] a_{n-1}[t+m] - |q|^2 \cdot b_{n-1}[t] b_{n-1}[t+m] \right) \quad (25)$$

Simplification

Mixed Terms Cancellation: The terms $q \cdot W_{2N}^{-(t+m)\cdot 2^{n-1}} a_{n-1}[t] b_{n-1}[t+m]$ and $q \cdot W_{2N}^{-t\cdot 2^{n-1}} b_{n-1}[t] a_{n-1}[t+m]$ cancel each other, significantly reducing cross-correlation contributions.

Zero Cross-Correlation: The structure ensures that $R_{a_n b_n}[m] \approx 0$, ensuring near-zero cross-correlation.

Mathematical Proof of the Orthogonality of $\mathrm{Re}(a_n[t])$ and $\mathrm{Im}(a_n[t])$ for Any Cyclic Translation t

Let's prove the orthogonality of the real and imaginary parts of the sequences $\boldsymbol{a_n[t]}$ and $\boldsymbol{b_n[t]}$ generated by applying the IDFT to Golay pairs. We aim to show that for any cyclic translation $\boldsymbol{t}$ (26):

$$\sum_{t=0}^{L-1} \mathrm{Re}\,(a_n[t]) \cdot \mathrm{Im}(a_n[t+m]) = 0 \quad (26)$$

for any $\boldsymbol{m}$, where $\boldsymbol{L = 2^N}$ is the sequence length.

Step-by-Step Proof

Expand $\boldsymbol{a_n[t]}$ in terms of real and imaginary parts (27):

$$a_n[t] = \mathrm{Re}(a_n[t]) + j \cdot \mathrm{Im}(a_n[t]) \quad (27)$$

and similarly for $\boldsymbol{b_n[t]}$.

Substitute the recursive definition:

$$a_n[t] = \mathrm{Re}\left(a_{n-1}[t] + q \cdot W_{2^N}^{-t\cdot 2^{n-1}} \cdot b_{n-1}[t] \right) + j \cdot \mathrm{Im}\left(a_{n-1}[t] + q \cdot W_{2^N}^{-t\cdot 2^{n-1}} \cdot b_{n-1}[t] \right)$$

Orthogonality condition: The condition for orthogonality between $\mathrm{Re}(\boldsymbol{a_n[t]})$ and $\mathrm{Im}(\boldsymbol{a_n[t+m]})$ requires that (28):

$$\sum_{t=0}^{L-1} \mathrm{Re}\,(a_n[t]) \cdot \mathrm{Im}(a_n[t+m]) = 0 \quad (28)$$

for all m.

This means the real and imaginary parts are uncorrelated for any shift $\boldsymbol{m}$.

Recursive nature and symmetry: The recursive nature of $\boldsymbol{a_n[t]}$ and $\boldsymbol{b_n[t]}$ ensures that both the real and imaginary parts are constructed in such a way that they are balanced (i.e., their contributions cancel out over a full cycle of length $\boldsymbol{L}$). Given the symmetry and the orthogonality properties imposed by the IDFT and Golay sequences, we get (29):

$$\sum_{t=0}^{L-1} \mathrm{Re}\,(a_n[t]) \cdot \mathrm{Im}(a_n[t+m]) = \mathrm{Re}\big(DFT\big[a_n[t]\big]\big) \cdot \mathrm{Im}\big(DFT\big[b_n[t]\big]\big) + \mathrm{Re}\big(DFT\big[b_n[t]\big]\big) \cdot \mathrm{Im}\big(DFT\big[a_n[t]\big]\big) = 0 \tag{29}$$

due to the orthogonality and symmetry in the frequency domain.

General result: The same logic applies to $\boldsymbol{b_n[t]}$, proving that the real and imaginary parts of the sequences $\boldsymbol{a_n[t]}$ and $\boldsymbol{b_n[t]}$ are orthogonal under any cyclic translation.

Why this property is rare and useful in communication systems?

Rarity: Orthogonality between the real and imaginary parts of sequences after cyclic shifts is rare because it requires a careful balance in the construction of the sequences. Most random sequences do not exhibit this property due to the lack of inherent structure and symmetry.

Utility in communication systems:

Improved Signal Separation: Orthogonality between the real and imaginary parts means that these components can be separated cleanly, which is particularly useful in quadrature amplitude modulation (QAM) schemes where signals are transmitted using both real and imaginary components.

Reduced Interference: In systems where multiple sequences are used simultaneously (e.g., CDMA), orthogonal components reduce the likelihood of cross-interference, leading to cleaner signal detection and decoding.

Enhanced Multiplexing: With orthogonal real and imaginary parts, it becomes easier to multiplex different data streams in a way that minimizes interference, enhancing the overall system capacity.

In summary, the orthogonality of $\mathrm{Re}(\boldsymbol{a_n[t]})$ and $\mathrm{Im}(\boldsymbol{a_n[t]})$ (and similarly for $\mathrm{Re}(\boldsymbol{b_n[t]})$ and $\mathrm{Im}(\boldsymbol{b_n[t]})$) is a direct consequence of the structured recursive construction of the sequences and the inherent symmetry and balance provided by the IDFT of Golay pairs. This property is highly desirable in communication systems due to its ability to reduce interference and enhance signal clarity, especially in complex modulation schemes.

In **Fig. 2** (**b**) the two outputs (14) and (15) are stored in a memory component before being injected into the two inputs of the basic electronic module (with index n) in the next iteration. The hardware implementation of the encoder of OPDG codes alternative to that of **Figure 2**(**a**) incorporates an adder, a differentiator and a multiplier.

Figure 3(**a**) is a complex sequence a_N transformation, and shows how to apply a set of hardware implementations to codes $a_N[t]$; and **Figure 3**(**b**) shows transformation of the complex sequence b_N, and illustrates how to apply the same set of hardware implementations to the codes $b_N[t]$. **Figures 3**(**a**) and **3**(**b**) are complementary to **Figure 2**(**a**). The OPDG codes 1, in **Figure 2**(**a**), will be the entry codes in **Figure 3**(**a**). The OPDG 2 codes, in **Figure 2**(a), will be the entry codes in **Figure 3**(**b**). The multiplexers (307) and (317) will allow the user to use the desired exit codes which can be $a_{N,X}[t]$, $a_{N,Y}[t]$, $b_{N,X}[t]$ and $b_{N,Y}[t]$.

The hardware implementation of the encoder in **Figure 2**(**a**), of an OPDG code pair, requires an hardware implementation of the decoder capable of reversing the operation of the specific encoding.

Figure 4(**a**) represents the decoder circuit of a pair of perfect orthogonal sequences $a_N[t]$ and $b_N[t]$, consisting of N basic electronic modules. Each basic electronic module consists of an adder, a differentiator and a multiplier by a complex hardware implementation derived from a "twiddle factor" (WL = exp (j2π/L)) specific to each electronic modules. The specific connections of the three operators, of the basic module of **Figure 4**(**a**), allow the electronic decoding of OPDG codes of a certain length. This hardware implementation is a recursive process, that is, the decoding of an OPDG code of length 2N is obtained based on the electronic decoding of a code of length 2N-1. The entry codes $a_N^{'}[t]$

and $b'_N[t]$, the first basic module of **Figure 4**(**a**), can be the same as the codes $a_N[t]$ and $b_N[t]$ of **Figure 2**(**a**), respectively. However, entry codes $a'_N[t]$ and $b'_N[t]$ may also be the codes $a_{N,X}[t]$, $a_{N,Y}[t]$, $b_{N,X}[t]$ and $b_{N,Y}[t]$, of **Figures 3**(**a**) and (**b**). In addition, entry codes $a'_N[t]$ and $b_N[t]$ may also be the codes referred to above when they are contaminated by noise or another source of electronic interference. The block (432) of **Figure 4**(**a**) performs the electronic operation 'real part' of an FFT (Fast Fourier Transform) that allows generating the signal equal to a Dirac unit impulse with amplitude A[q]N22N+1. This impulse will appear to be temporarily displaced by a 2N-1 value.

Figure 4(**b**) shows the electronic OPDG code decoder (105) when the basic modules are used in a recursive process. Instead of having N electronic modules connected in a chain, only one is used which is called recursively N times. This method is advantageous when the N value is high. The recursive process is defined by two complex input vectors $a_n[t]$ and $b_n[t]$, and two complex output vectors $a_{n-1}[t]$ and $b_{n-1}[t]$, where n is an integer. The output is the same as the expression (30):

$$a_{n-1}[t] = q.W_{2^N}^{-t2^{n-1}}.\{a_n[t] + b_n[t]\}. \tag{30}$$

The output $b_{n-1}[t]$ is equal to the expression (31)

$$b_{n-1}[t] = a_n[t] - b_n[t], \tag{31}$$

with $q = \pm 1$.

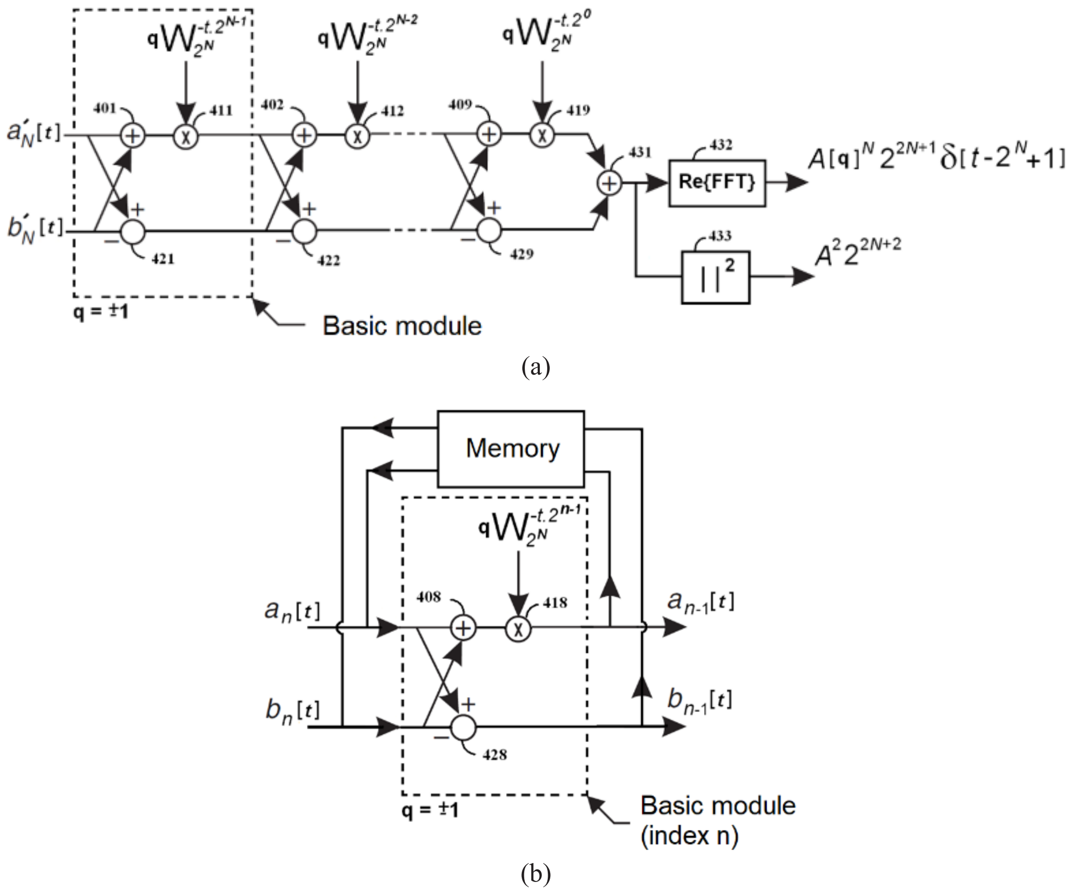


Figure 4. (**a**) Decoder circuit of a pair of perfect orthogonal sequences (**b**) OPDG hardware implementation of the decoder (105) when the basic modules are used in a recursive process.

In the last iteration, two output vectors $a_0[t]$ and $b_0[t]$ are added together to generate a unimodular complex vector. Each specific module of an iteration, represented by an index n, uses a complex vector equal to (32)

$$q.W_{2^N}^{-t.2^{n-1}} \quad (32)$$

of length L = 2N, where WL = exp(-j2π/L).

The two outputs $a_{n-1}[t]$ and $b_{n-1}[t]$ of the electronic module are stored in a memory component before being injected into the two inputs of the basic electronic module (index n) in the next iteration. The initial condition is and is only performed the first time, at the first iteration n = N. Unlike the OPDG encoder, here the iteration index is decremented by one, starting at n = N and ending at n = 1.

Figure 5 depicts a simplified diagram of the application of bipolar codes OPDG {-1, +1} in a data communication system in the presence of noise, illustrating the communication system of **Figure 1** when a single signal $a_{N,4}[t]$, of **Figure 3**(**a**), is used and transmitted by the transmission medium (603). This signal is a bipolar sequence {-1, +1} that depends on the cyclical displacement Di (302) applied. Because the value i can take L different values ($0 \leq i < L$), it will be possible to generate L different bipolar sequences of length L. These bipolar codes have excellent correlation properties. The detection of the correct sequence can be done with an electronic circuit that allows estimating the value of the autocorrelation.

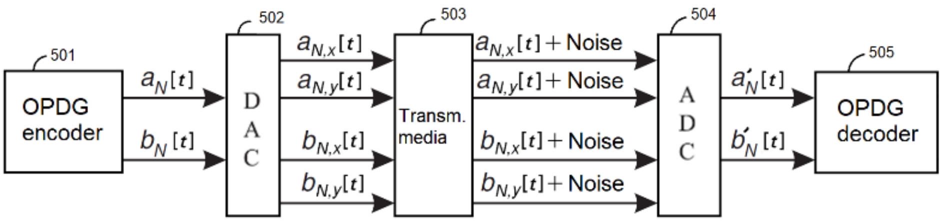


Figure 5. Simplified illustration of the application of bipolar codes OPDG in a data communication system with noise.

Figure 6 depicts a circuit that implements a classic correlation function where the input signal is multiplied by the sequence $a^{i}_{N,4}[t]$ (which has a specific cyclic shift i). The integrator will electronically implement a sum of L discrete elements. This circuit is an alternative to the decoder of **Figures 4**(**a**) and **4**(**b**), when the strings have a short length. When the length (L = 2N) is long, it is preferable to use the circuit of the **Figures 4**(**a**) or **4**(**b**).

Figure 7 shows a correlation function between the vector received $a^{i}_{N,4}[t]$ and the reference vector $a^{i}_{N,4}[t]$. The multiplication of this correlation function is performed by the block (701) and the integration (or summation) function is performed by the block (702).

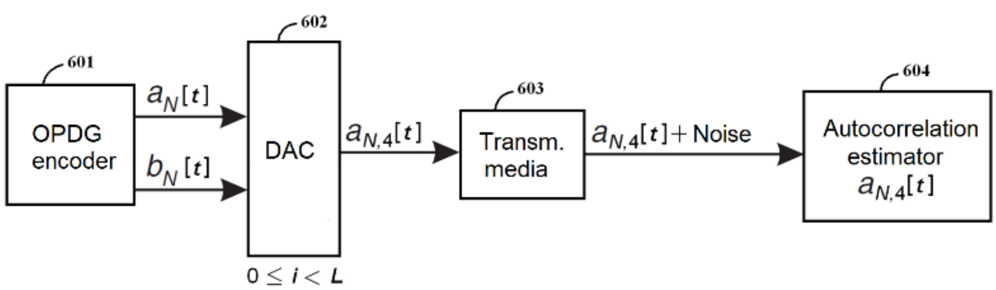


Figure 6. Simplified application of bipolar codes OPDG {-1, +1} in a data communication system in the presence of noise.

Figure 8 illustrates the implementation of the electronic circuit encoding in **Figure 2**(**a**) when N = 5. Five basic electronic modules in **Figure 2** were used. Figure 8 is equivalent to the generator of **Figure 2**(**a**) when there are 5 basic electronic modules that allow the generation of OPDG codes of length 32.

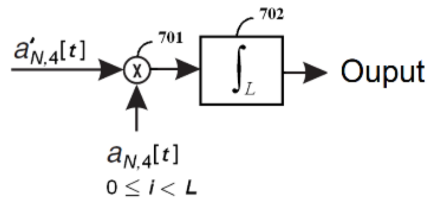


Figure 7. Circuit to perform a correlation function of the codes $a'_{N,4}[t]$.

When N = 5, the normalized periodic autocorrelation function of OPDG1 (and OPDG2) is qual to $\delta[n]$ and the periodic cross-correlation between OPDG1 and OPDG2 has a maximum value equal to 1/16. This maximum value is lower than the maximum value of the normalized periodic cross-correlation between the two Golay sequences of the same length 32.

Figure 9 illustrates the hardware implementation of the decoder circuit of **Figure 4**(**a**) when N = 5. Five basic electronic modules of **Figure 4**(**a**) were used. Depending on the type of application, blocks (932) and (933) may be omitted. **Figure 9** represents the hardware implementation of the decoder of the OPDG codes of **Figure 2**(**a**) when the hardware implementation of the encoder consists of 5 basic electronic modules.

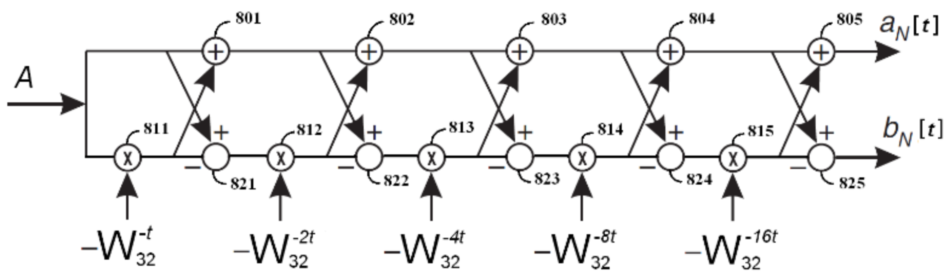


Figure 8. Generator circuit (encoder) of a pair of OPDG sequences of length 32.

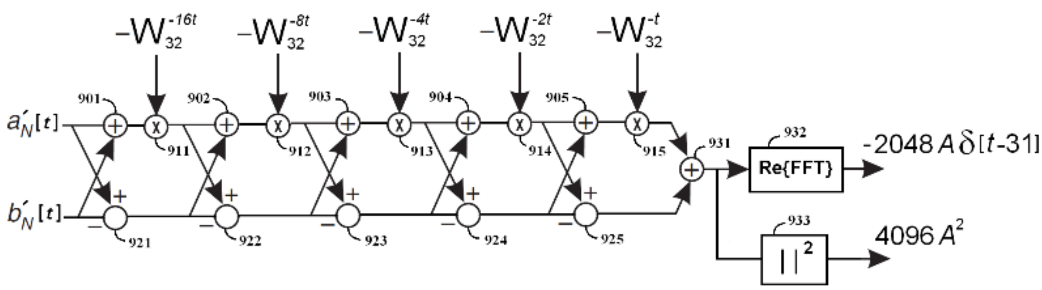


Figure 9. Decoder circuit of a pair of OPDG sequences of length 32.

Figure 10 represents some periodic autocorrelation functions for different codes generated based on the encoder in **Figure 8**. The superiority of the OPDG 1 and OPDG 2 codes are highlighted in relation to the Golay codes. The periodic autocorrelations of the OPDG 1, OPDG 2, [Re (OPDG 1) + Im (OPDG 1)] and [Re (OPDG 2) + Im (OPDG 2)] sequences are proportional to a Dirac unit impulse. This does not happen with the complementary Golay code pairs (Golay 1 and Golay 2).

Figure 11 represents the periodic cross correlation functions for different codes. The complementary sequences Re(OPDG 1) and Im(OPDG 1) are orthogonal to any cyclic shifts with $0 \leq i < L$. The same happens with the pair of sequences Re(OPDG 2) and Im(OPDG 2), but not with the complementary pairs of Golay (Golay 1 and Golay 2). In this last property lies the great difference between the Golay codes and the OPDG codes of the present codec.

Figure 12 represents aperiodic cross correlation functions for different codes. A pair of complementary sequences Re(OPDG 1) and Im(OPDG 1) has low correlation values for any cyclic shifts with $0 \leq i < L$. The same happens with the pair of sequences Re(OPDG 2) and Im(OPDG 2), but it is not so efficient with the complementary pairs of Golay (Golay 1 and Golay 2).

Figure 13 presents absolute values of the aperiodic autocorrelation functions for bipolar codes. The bipolar sequences derived from the OPDG sequences have maximum, lagged, absolute values lower than those of the Golay sequences.

Finally, **Figure 14** shows the absolute values of the periodic autocorrelation functions for four bipolar codes, with better values than Golay sequences.

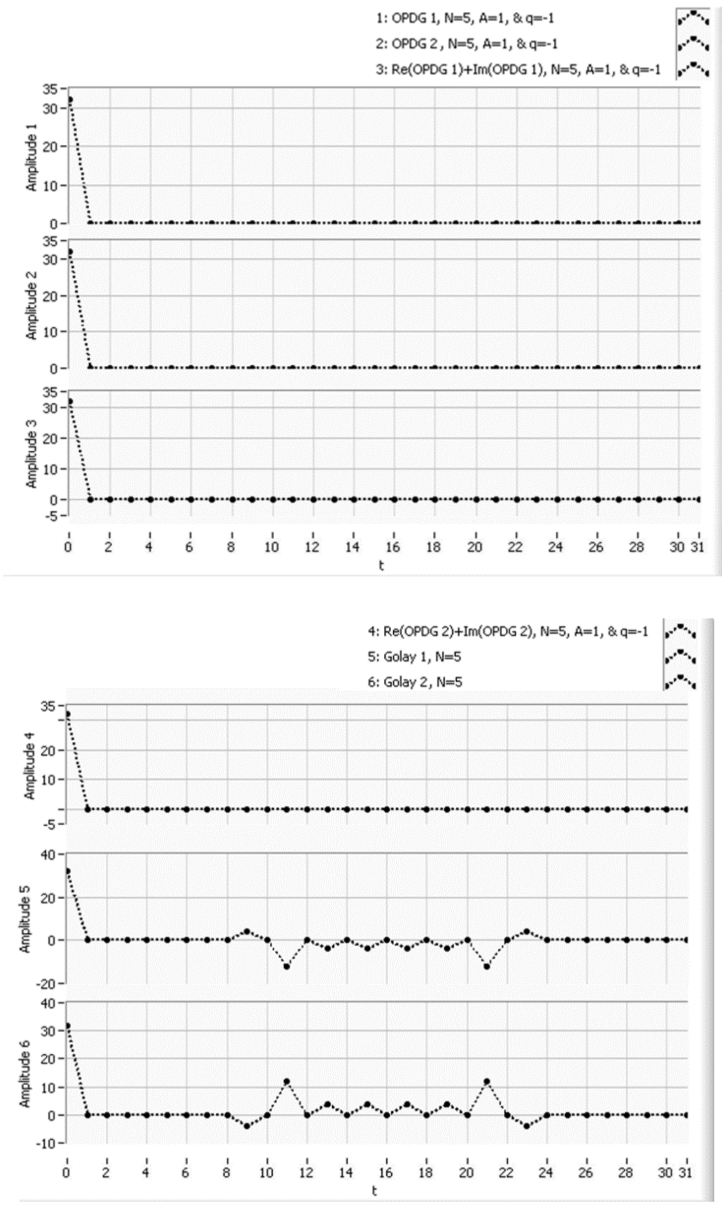


Figure 10. Periodic autocorrelation functions for various codes.

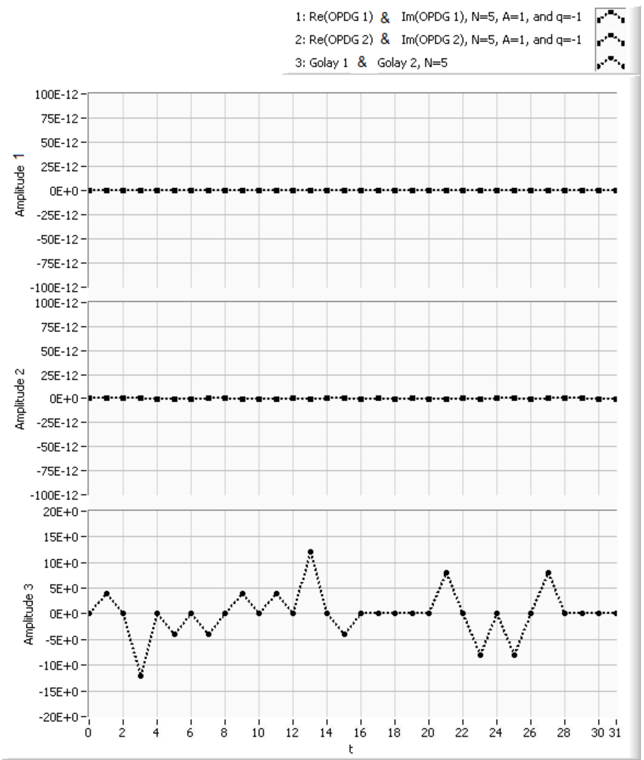


Figure 11. Periodic cross correlation functions for different codes showing complementary sequences having low correlation values for any cyclic shifts.

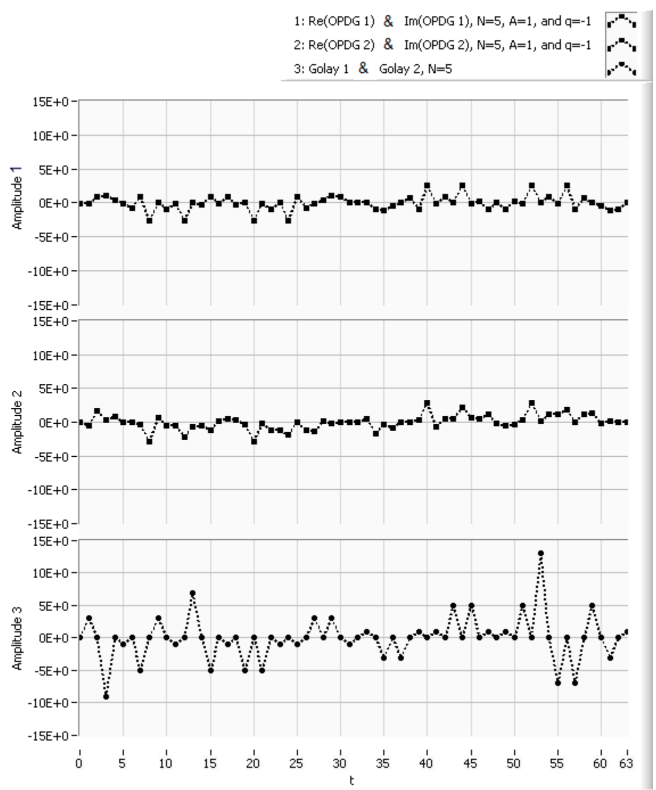


Figure 12. Absolute values of the aperiodic cross correlation functions for bipolar codes.

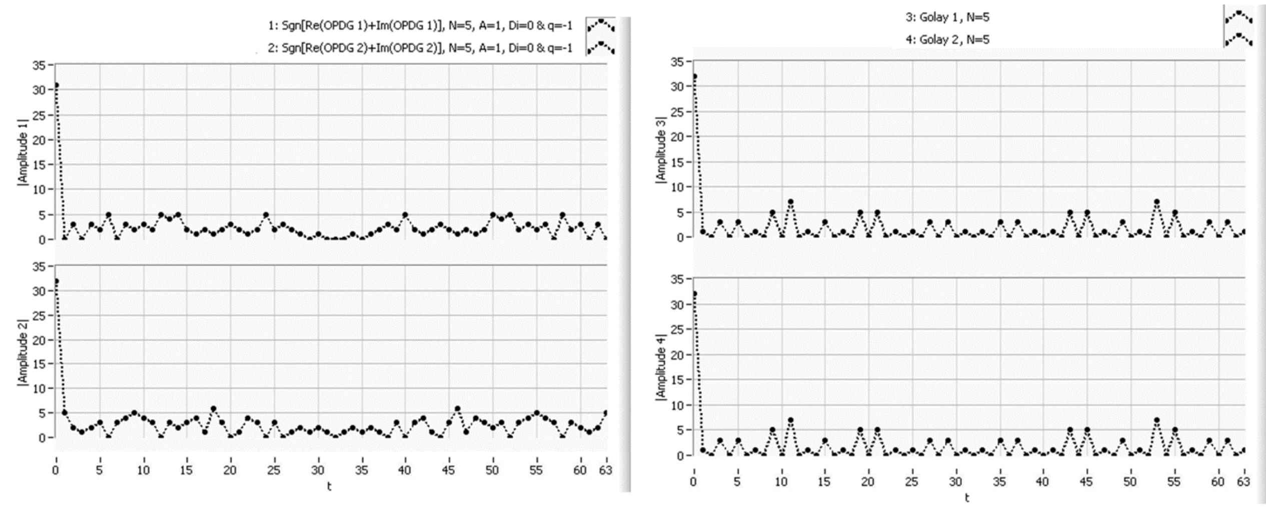


Figure 13. Absolute values of the aperiodic autocorrelation functions for four bipolar codes.

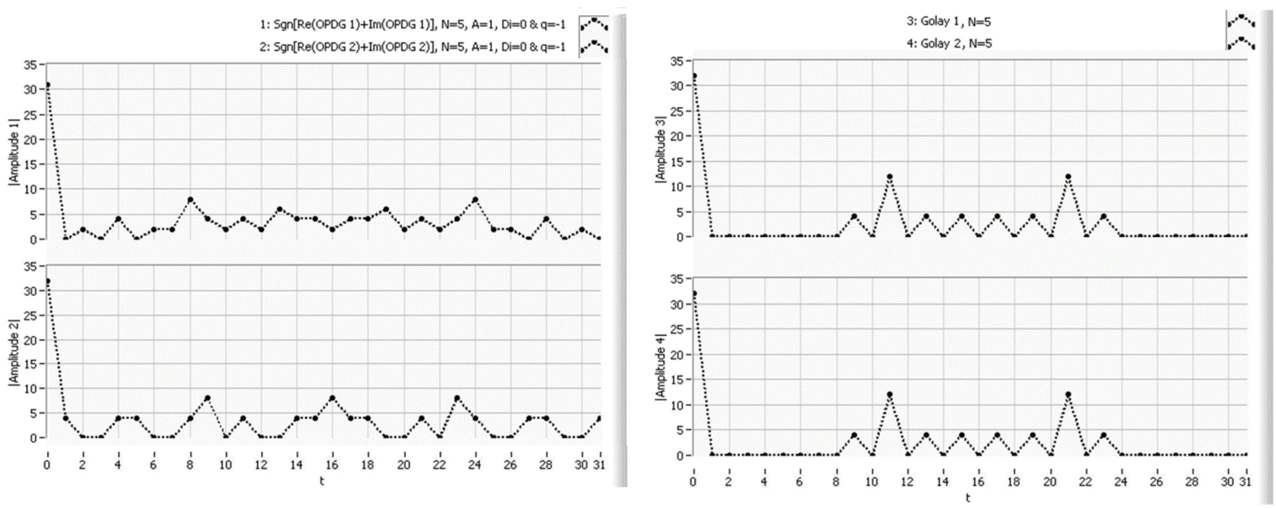


Figure 14. Absolute values of the periodic autocorrelation functions for four bipolar codes.

4. Error probability

To streamline the study and analysis of the PAPR solution through binary decomposition, we opted to focus exclusively on bipolar codes. In this context, a straightforward CDMA system is suitable for evaluating these new bipolar codes. The phase modulation utilized is a simple Binary Phase-Shift Keying (BPSK) modulation, allowing us to employ a known error probability P_e to establish an upper bound for the CDMA system. This upper bound, $max\{P_e\}$, can be expressed as a function of the cross-correlation power contrast ratio, $P/C = 20\ log\left[r_k(0)/max\{r_{k,i}\}\right]$ (in dB), where $r_{k,i}$ represents the cross-correlation and r_k denotes the autocorrelation [27].

Several upper bounds for P/C, applicable to periodic correlations, have been identified. One notable example is the Welch bound [25] for K perfect sequences of length N, given by (33):

$$P/C = 20\, log\sqrt{(KN-1)/(K-1)}. \quad (33)$$

For the case of aperiodic correlation, the upper bound is (34):

$$P/C = 20\,log\sqrt{(2KN - K - 1)/(K - 1)}. \tag{34}$$

For an effective communication system, any set of codes should exhibit a high power contrast ratio. For instance, it has been recommended that codes should have power contrast ratios exceeding 17 dB for 127-chip Gold codes [28]. In this study, we examine the upper bound of the error probability, which is a function of the power contrast ratio P/C (35):

$$max\{P_e\} = 1 - \emptyset \left[\left(\frac{N_0}{2E_b} + (K-1)(1-\frac{1}{L})10^{-\frac{P/C}{10}}\right)^{-1/2}\right]. \tag{35}$$

Figures 15 and **16** illustrate the variation in error probabilities as a function of the number of simultaneously used codes. These graphs demonstrate the superiority of bipolar codes derived from OPDG sequences over Gold codes of equivalent length and quantity. The favorable autocorrelation and cross-correlation properties of these codes make them particularly well-suited for use in CDMA communication systems.

The proposed method enables the generation of optimal code sets in quantities equal to the length L. Additionally, due to their low cross-correlation values, a receiver can effectively extract its designated code and binary information even when all other codes are transmitted simultaneously. In essence, the codes generated by the new CODEC are highly resistant to interference, both from multipath effects and from adjacent communication channels.

Figures 15 and **16** reveal that bipolar codes derived from OPDG codes presents lower error probability than the well-known orthogonal Gold codes, when 4 codes are transmitted simultaneously in a CDMA systems with BPSK modulation.

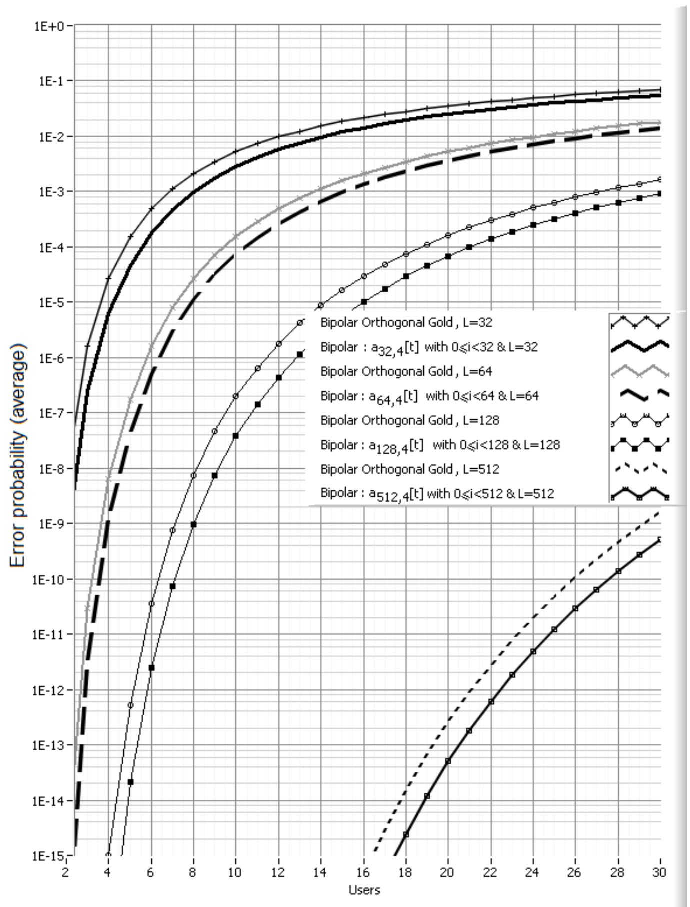


Figure 15. Probability of error according to the number of codes used simultaneously.

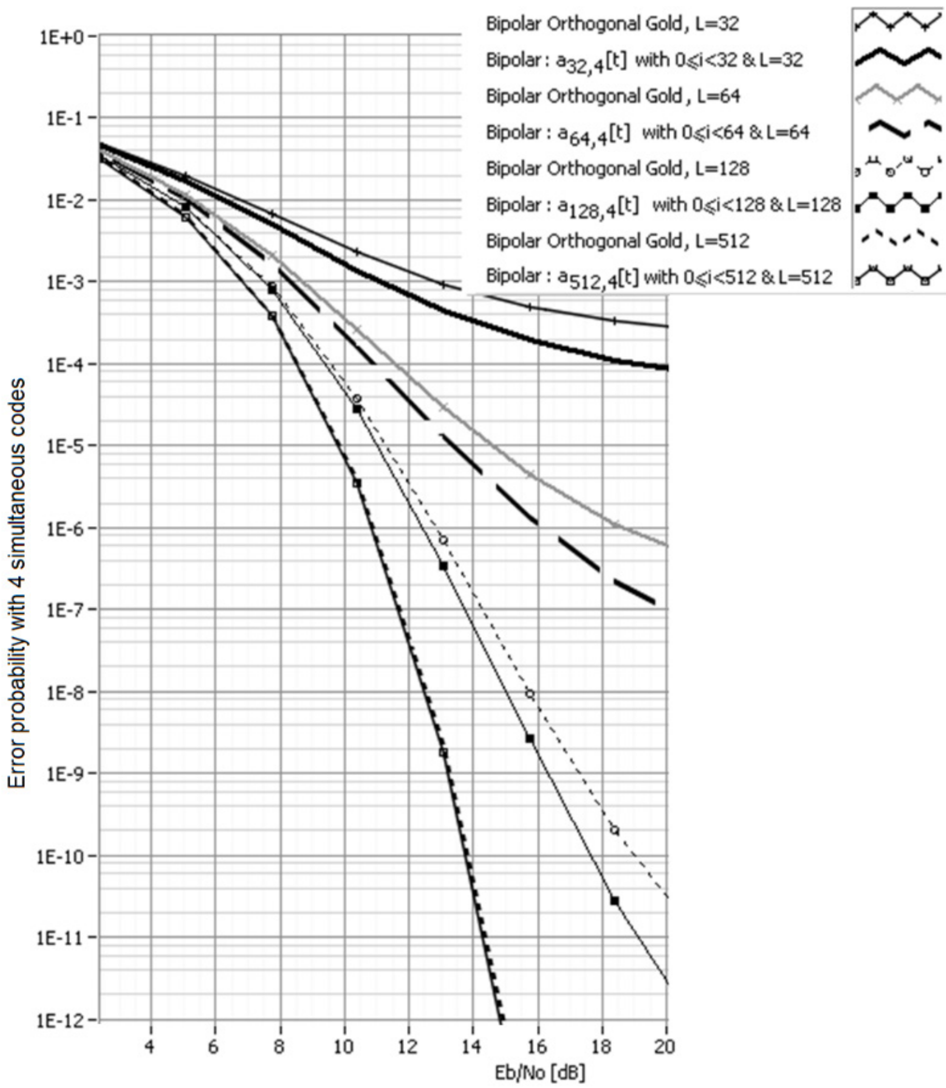


Figure 16. Probability of error as a function of Eb/No.

5. PAPR Solution with Binary Decomposition

In an OFDM system, radio frequency signals can exhibit high peak amplitude values in the time domain due to the summation of multiple subcarrier factors via an IDFT operation. Consequently, OFDM systems are known to have a high PAPR compared to single-carrier systems. Decomposed sequences generated by the OPDG generator can be bipolar {+1, -1} codes, ensuring a minimal PAPR of 1. A real sequence can be decomposed into a sum of several bipolar Seq_n sequences, each having a PAPR of 1 for n = 0, 1,..., N.

The well-known definition of PAPR [29] is given in Equation (36), where $|X_{peak}|$ is the absolute maximum value and Xrms is the root mean square value of the sequence *X*:

$$PAPR = \frac{|X_{peak}|^2}{X_{rms}{}^2} \tag{36}$$

To minimize the PAPR of any *X* sequence, we demonstrate that it is possible to transform *X* into a sum of bipolar sequences, each with a PAPR of 1. The process begins by converting the complex sequence into two parts (real and imaginary). Each part is then converted into positive sequences by adding a constant offset value if necessary. The sequences are sampled with an Analog-to-Digital Converter (ADC) resolution of N+1 bits and converted into binary numbers within the range [0; 2N+1]. Any positive base-10 number can be expressed as the sum of N+1 weighted base-2 numbers for each sequence element.

In other words, a sequence can be the sum of N+1 Seq_n sequences of any length L, as defined in (37), where n is an integer ranging from 0 to N, and i ranges from 0 to L:

$$Seq_{\,n}[i] = Bit\_n[i] \times\ 2^{n} -\ 2^{n-1} \tag{37}$$

Here, Bit_n[i] are the values at each n-level binary conversion, with level zero representing the least significant bit and level N the most significant bit. For example, the transformation of a real sequence is as follows (38):

$$Sgn(X) \cong\ \frac{Seq\_N[i]}{2^{N-1}}. \tag{38}$$

PAPR is crucial in communication systems because low-cost electronic amplifiers struggle to implement linear functions effectively. However, if the amplifier's response is nonlinear, it can transmit significantly more power at a reduced cost. Rather than using a single amplifier, multiple nonlinear amplifiers can be employed. We propose using N+1 low-cost amplifiers for all Seq_n bipolar sequences (n = 0, 1, ..., N), each with a PAPR of 1. Each Seq_n bipolar sequence can be transmitted separately using N+1 BPSK modulators and low-cost nonlinear amplifiers. Each Seq_n bipolar sequence can be transmitted synchronously in the same channel using N+1 BPSK modulators, effectively utilizing the channel's bandwidth. At the receiver, a MIMO-like (Multiple-input Multiple-output) processing approach can be employed to separate and reconstruct these sequences, leveraging the orthogonality of the sequences or their distinct transmission characteristics. This technique ensures robust signal recovery despite potential channel variations. The proposed method not only minimizes the PAPR across all sequences, allowing for the use of low-cost nonlinear amplifiers, but also improves overall system power efficiency and signal integrity. By capitalizing on MIMO techniques, the system can achieve scalable, high-quality transmission with reduced complexity and cost, making it a practical and efficient solution for modern communication systems.

Figure 17 illustrates the construction of a signal estimator with a resolution of N+1 bits. By decomposing a signal into N+1 bipolar signals and summing these components (at the MIMO-like receiver), we obtain an estimated combined signal $\widetilde{X}$. The sum of N+1 Seq_n signals is also depicted in **Figure 17**.

The signal X in Figure 17 can be either a perfect sequence or any other multilevel sequence within the range [-2N; 2N], while the estimated signal $\widetilde{X}$ is the sum of the N+1 bipolar sequences (Seq_0, Seq_1, …, Seq_N). Each of these sequences has a PAPR of 1. These N+1 bipolar sequences can be transmitted over separate channels or different BPSK modulation carriers using low-cost nonlinear amplifiers, as shown at the input of amplifier A in **Figure 17**.

Utilizing a single bipolar sequence Seq_N derived from OPDG codes, it is possible to achieve excellent correlation values in CDMA or OFDMA wireless systems employing BPSK modulation. Our comparison between the Seq_N sequences from OPDG codes and Golay codes reveals that OPDG codes significantly outperform Golay sequences in terms of correlation characteristics [8][30]. The performance of CDMA transmission improves with each additional sequence, reducing the error between X and $\widetilde{X}$. As anticipated, these bipolar sequences maintain a minimum PAPR [31] value of 1.

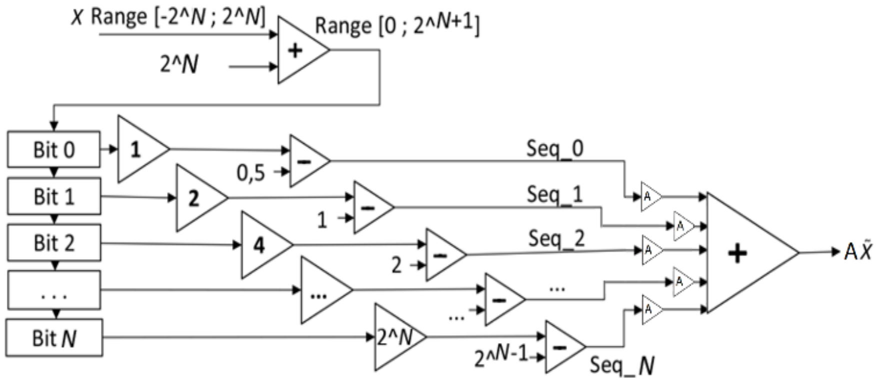


Figure 17. The signal estimation $\tilde{X}$ is the sum of the N bipolar sequences (Seq_0, Seq_1, …, Seq_N).

6. Conclusions

The superiority of bipolar codes derived from OPDG sequences over other orthogonal codes for the same lengths and quantities was demonstrated in this paper. The autocorrelation and cross-correlation of its codes makes it suitable for use in CDMA communication systems. The codes generated by the new CODEC are immune to interference caused by the code itself (multiple paths) and by the other codes.

Using low-cost nonlinear amplifiers to make the amplification of bipolar sequences, before the reconstruction of real sequences, will avoid the PAPR problem. All pre-amplified bipolar sequences will be summed at the end of the reconstruction process (a MIMO-like receiver) to generate the real perfect OPDG sequences with enough power. By this way, the PAPR problem is mitigated and costly linear amplifier are not required.

Author Contributions

Conceptualization, J.P.; methodology, J.P.; software, J.P.; validation, J.P.; formal analysis, J.P.; investigation, J.P.; resources, J.P. and H.F.; data curation, J.P. and H.F.; writing—original draft preparation, J.P. and H.F.; writing—review and editing, J.P. and H.F.; visualization, J.P. and H.F.; supervision, J.P.; project administration, J.P.; funding acquisition, J.P. All authors have read and agreed to the published version of the manuscript.

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Communication

A Study on AR Education Application That Applies Social Functions

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Abstract: As outside gatherings were banned after Corona, online education remotely conducted at home instead of at school or academy has become commonplace. This study examined the current state of the education industry post-COVID-19, prior research on augmented reality applications, and education case studies using Edutech. Through this research, the necessity of designing and developing customized explanation applications using the metaverse was established, and an AR education application was proposed using application design elements. The discussions of this study are as follows. First, an application is proposed based on the current status of the edutech market, a case analysis of the metaverse platform in education, and a design element analysis. The metaverse education-related market is revitalizing, but the related research is insufficient.Second, by proposing a metaverse AR education application, it can be used as content in the education industry. This application can overcome the limitations of practical subjects taught in school classes. Third, if educational AR application is developed, launched, and used in classrooms, positive changes in teaching can be expected. Fourth, the application should enable multilateral experiences. Multilateral experience means that several people share an experience while pursuing the same objective and achieving their goals. This is intuitive because the explanation process can be viewed in detail from various angles using AR technology, and is significant because it can communicate with users through social functions.

Keywords: Education; Application; Social Functions, Edutech; VR; AR; Metaverse

1. Introduction

As public gatherings were banned after COVID-19, online education conducted remotely at home instead of at school became commonplace. Amid this trend, Edutech, which combines ICT such as artificial intelligence, virtual reality, augmented reality, blockchain, and big data, garnered attention. The Edutech-related market is expected to grow significantly from $127.1 billion (about 169 trillion Won) in 2018 to $404 billion (about 538 trillion Won) in 2025 [1].

Using artificial intelligence and big data, Edutech can analyze individual students' learning abilities and knowledge levels to provide the most appropriate level of instruction, learning goals, and study methods for each student. Immersion in learning can also be increased through experiential learning using virtual reality (VR) and augmented reality

(AR) [2]. The original educational content should be the basis of understanding the personalized and customized learning direction of students who receive education from the perspective that the students are the core of the education. The possibility of Edutech growing indefinitely to present future educational models and advocate for educational directions continuously is high. Due to the COVID-19 pandemic, which has changed the paradigm of education, Edutech not only attracts offline class spaces online but also aims for online and offline interactive communication [3, 4]. Additionally, it is necessary to find a way to integrate and manage online and offline resources and learning information at universities using various Edutech services and to attempt to provide higher-quality education by converting learners' environments to digital environments [5]. Therefore, this study examined the concept of Edutech, domestic and foreign Edutech education trends, the use of metaverse platforms in the field of education, and the precedent cases of Edutech. Thus, the necessity of designing and developing a customized explanation application using a metaverse was confirmed, and an AR-customized explanation app was proposed using the application design elements. The AR application designed in this study helps students review and learn parts that are not understood in class several times in practical subjects such as development, design, and experimentation. Additionally, it provides an explanatory video in page format using AR, and an educational function that allows learning without dropouts through communication between users.

The research questions of this study are as follows:

<Research Question 1> How can educational AR applications be developed for practical subjects?

<Research Question 2> How are design elements incorporated into AR applications?

2. Theoretical Background and Prior Research

2.1. Concepts of Edutech

Edutech is a compound word for Education and Technology that refers to a technology used to improve existing services or provide new services by incorporating ICT technology into education or to improve educational services or provide new values [6]. Recently, artificial intelligence (AI) and AR/VR have attracted attention as technologies that innovate existing education. Concepts similar to those of Edutech include e-learning and smart learning. E-learning emerged with the rapid spread of the Internet in the late 1990s and was mainly focused on digital textbooks and online learning. As smartphones and tablets spread in earnest around 2010, smart learning to improve educational outcomes through smart devices received attention from industry and academia. In the case of e-learning and smart learning, the main conceptual focus was on the means of learning (Internet and desktop, smartphone, tablet, etc.) through which education was conducted [7]. Another aspect that focuses on Edutech beyond e-learning and smart learning is the activation of remote education because of the spread of COVID-19. Educational sites worldwide have begun to realize the importance of Edutech in the stable implementation of education. Under these circumstances, devices such as smartphones and tablet PCs and AI, VR, and AR technologies have begun to be incorporated into existing educational services, resulting in the rapid expansion of the Edutech market [8].

Table 1. Edutech education policies for major countries

States	Key Policy	Key Contents
US	National Edutech Plan (2017)	- Establishment of National Edutech Policy and Vision divided into five areas (Learning, Teaching, Leadership, Evaluation, Infrastructure)
UK	Edutech Framework (2019)	- Step 1: Establishing a vision in the areas of administration, evaluation, instruction, and continuous career development for the use of Edutech - Step 2: Establishment of digital infrastructure, capability/technology development and effective procurement, and policy trends in digital security promotion areas - Step 3: Step 1 and Step 2 Based Execution, Integration, Repeat, and Pursue Innovation

EU	Digital Education Action Plan (2017)	- Improve digital capabilities and innovation of all educational institutions and open up the education system - Search for policy measures in teaching and learning, digital capabilities and technology development, and data analysis area
China	Education Information 2.0 Action Plan (2018)	- Active Efforts to Combine ICT Technology and Education - Establishment of 10 or more 'Wisdom Education Teacher Zones,' a smart learning space - Application of learning methods using blockchain and big data in all higher curriculums
Japan	3rd Basic Plan for the Promotion of Education (2018)	- Establishment of information utilization ability, ICT utilization in subject maps, ICT utilization in school affairs, and promotion of ICT environment improvement as four detailed goals for ICT utilization
Korea	Edutech Promotion Act (2023)	- Promote the combination of technology and content by establishing data standards and expanding public data opening - Establishment of a Hazard Check System - Establishment of 'digital education norms' in the AI era

2.2. Trends in Edutech Education at Home and Abroad

Edutech education is a global trend. Many countries worldwide are investing in large-scale budgets for Edutech and setting specific roadmaps to promote it. Korea aims to revitalize its K-Edutech exports by establishing a national-level educational support system. Edutech is indispensable for students to lead the world [9]. Edutech education policies for each major country are as follows [10].

2.3. Metaverse Platforms in Education

Like the real world, the metaverse refers to a three-dimensional virtual world where social, economic, and cultural activities occur, and are characterized by the possibility of an experience similar to the real world. Since the spread of COVID-19, non-face-to-face culture, such as online education, has been spreading, and extended reality technology, which implements an environment similar to reality, has been expanding.

Against this background, various metaverse platforms are emerging rapidly, and services using these platforms are increasing, especially in the field of education. The second is the main platform used in the current educational environment. 'Mozila Hubs' is an open-source platform that allows users to create and customize virtual spaces for meetings, events, and education. It supports functions such as spatial audio, customizable avatars, and 3D content integration. Therefore, it is suitable for immersive educational experiences. 'AltspaceVR' is a social VR platform that enables users to meet, interact with, and participate in virtual spaces. It is also used for virtual conferences, workshops, and educational sessions to provide opportunities for joint learning and participation. 'Engage' is a VR education platform that provides functions such as virtual classrooms, interactive presentations, and collaborative projects. It supports a multi-user environment and customized content; therefore, it is suitable for a variety of educational purposes. 'Rec Room' is a social VR platform that provides a variety of multiplayer games, activities, and creative tools. Although it mainly focuses on games, it is also used for educational purposes such as virtual field trips, language learning, and coding workshops. 'Spatial' is a mixed-reality collaboration platform that allows users to meet and work together in virtual spaces using AR and VR devices. It is used for virtual meetings, educational sessions, and workshops, allowing participants to interact with 3D content and simulations [11]. In this study, we propose a customized explanation platform that combines AR technology for students who have difficulties in practical subjects, such as development, design, and experimentation, because they are not understood in class.

2.4. Prior Research on Edutech

Interest in Edutech has increased during the pandemic, and studies on the application, scope, and effects of the technology base are increasing as well.

Lim Cheol-in et al. (2023) derived the Edutech classification system by reviewing prior literature on teaching and learning and conducting a comprehensive analysis of the use of Edutech by the Future Education Center, a teacher training institution, suggesting the necessity of developing and sharing a specialized teaching and learning model for each university, and argued the importance of a direction for co-evolution [6]. Another study developed and applied future education programs linked to the curriculum, confirmed the effectiveness of future education programs using Edutech in inventions highly related to creativity and creation, and suggested that it is important to set UCC, work activities, and future education class modules in four stages, depending on whether Edutech devices are needed. They also argued that future educational programs that secure connectivity with the regular school curriculum could be an effective and efficient way of approaching students' future competencies [12]. In addition, in a study on the development and application of elementary convergence education programs using Edutech, creative science, career, SW, and AI education were fused using Edutech's VR, AR, and AI and consisted of experience- and practice-oriented programs, suggesting that the Edutech convergence education program can increase students' learning outcomes and class participation [13].

3. Research Design

3.1. AR Application Design Elements

This study reviewed prior research to propose a explanation application using AR technology. The identified design elements are shown in Table 2.

Table 2. Metaverse application design

Name	Contents
Lee et al. (2019)	- Integration with existing portal accounts, allowing users to log in without the need for registration. - Users should be able to conduct live broadcasts through their device's camera. - During live viewing, there should be an option for easy payments to support the performers.
Na and Hwang (2022)	- Avatars should serve as replacements for users in the gaming context and allow personalization. - Users should be able to produce and sell content in addition to being content consumers. - Integration with entertainment services to include elements of fun. - Users should be able to form communities based on their interests.

In this study, we propose an application that uses fun elements among the snow crab elements of Jiyoung Na and Yongjun Hwang, social studies, and AR, the core technology of this study [14].

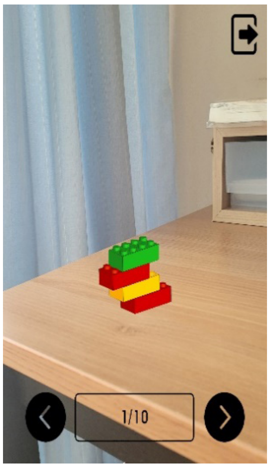
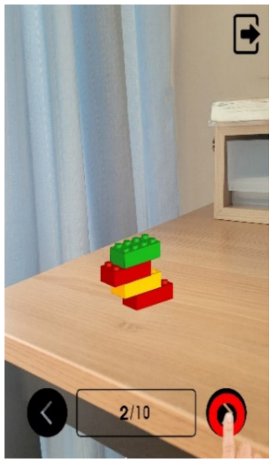
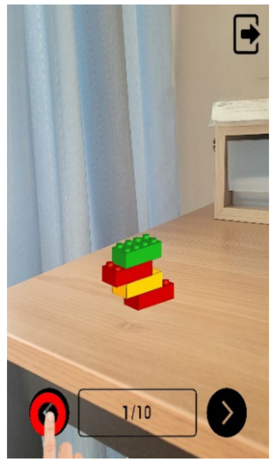
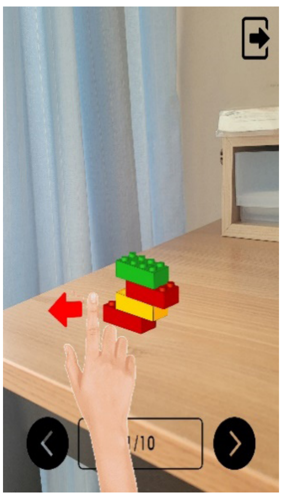
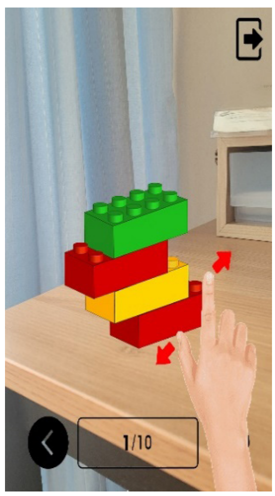
3.2. Overview

The application developed in this study operates by producing and uploading explanatory videos when a user who has difficulty with practical subjects, such as development, design, and experimentation, requests a platform. When a user who requested help utilized the answer of the user who produced the video, the user received points for using the paid content in the app. Popular videos help developers to use AR technology to understand the explanation process in more detail and vividly from various angles [15].

3.3. Main Page Configuration

Developers can implement the most popular video in real-time or video with more than 5,000 views among the videos uploaded to the application in AR. The manager reviews and determines whether the video meets the purpose of the application, and then creates an AR explanation video. AR images can only be uploaded by the manager, and the assembly process is divided into details and organized sequentially, as shown in Table 3.

Table 3. Composition of an AR videos screen

		
1. Place the exit button on the top right of the screen and the forward and backward buttons on the bottom of the page.	2. on the bottom right If you press the "Go Forward" button. The page moves forward to page 1.	3. If you press the 'Go Back' button on the bottom left, the page will be displayed Move back page 1.
		
4. When you drag the screen with one finger, the object rotates in the direction you dragged.	5. If you touch the screen with two fingers and open it in a different direction, the object is magnified.	6. If you touch the screen with two fingers, and then put both fingers in one place, the object shrinks.

A scene divided by organizing the explanation process is defined as a 'page.' In the video, the explanation process can be moved as if turning a page by adding forward or backward buttons. When switching to the previous page, it shows how it has been decomposed, in which the user can see an explanation that is difficult to understand. On the AR video screen, the user can rotate and zoom in on the object by dragging the screen with their finger, allowing the user to understand the explanation method in more detail. In addition, adding a function to display drawings on a screen can help users understand the drawings in various ways.

The produced video was uploaded directly to the video page by an administrator. When the video is uploaded, an upload notification is sent to all users. The composition of the main page is shown in **Figure 1**.

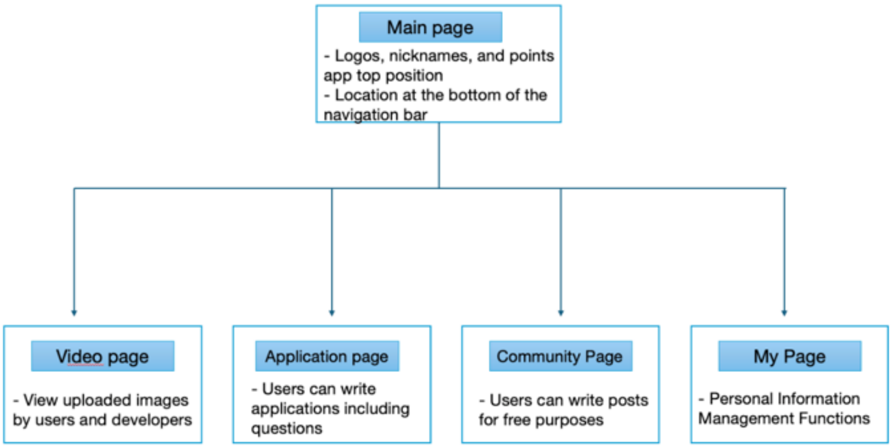


Figure 1. Composition of the Main Page of the Application

3.4. Community Page

Users can write free posts on a community page. In addition, the comment function within the post enables communication between users, which can be effectively used to increase application retention even when questions and answers are not asked.

3.5. Analysis of AR Application Design Elements

3.5.1. AR Elements

When a user requests an explanatory video of the desired content through the application page, other users can view the article and upload the video, while the manager produces a popular video in AR. If an AR image exceeds a specific number of views, it becomes a paid feature. On the AR image screen created by the manager, users can rotate and zoom in on the object by dragging it. Additionally, the page can be moved forward or backward by adding buttons to the AR image.

3.5.2. An Element of Fun

If you ask questions in a practical subject, you can receive real-time feedback through community pages and videos. Rather than in a one-way class, one can experience fun through interactions with questions and answers. Respondents earned points as a reward when their videos are adopted. You can also post questions, watch AR videos, and spend a certain amount of money in connection with real life.

3.5.3. Social

Users can write free posts on a community page. In addition, the comment function within the posts enables communication between users, which can effectively increase application retention even in the absence of direct questions and answers.

4. Discussion

The discussions of this study are as follows. First, an application is proposed based on the current status of the edutech market, a case analysis of the metaverse platform in education, and a design element analysis. The metaverse education-related market is revitalizing, but the related research is insufficient. In this study, the elements required for application design were defined as fun, social, and AR through prior research, and a customized explanation application was designed based on these elements. Currently, the education-related market is increasingly being digitized after COVID-19, and if the metaverse market is activated in the education industry in the future, the results of this study can be used as basic or reference data for metaverse education applications.

Second, by proposing a metaverse AR education application, it can be used as content in the education industry. This application can overcome the limitations of practical subjects taught in school classes. Not all students understand the instructor's explanation, and academic achievement is bound to differ because there are differences in levels between learners. In particular, in the case of practical subjects, once an explanation is missed, it is very difficult to follow the content afterwards. This study is more intuitive than textbooks because the practical process of using AR technology can be viewed in detail from various angles, and it is significant because it can communicate with users through social functions.

Third, if educational AR application is developed, launched, and used in classrooms, positive changes in teaching can be expected. There is a research case that utilized "Our Body's Shape AR Content," a collaboration between KERIS and ETRI in Korea, which demonstrated that classes incorporating AR showed significant results in all areas compared to traditional classes. Both students and teachers who learned through immersive content integrated with AR technology responded positively. In addition, it can also be used for self-directed learning after class. According to a study on teachers' perceptions of immersive content usage, teachers found that immersive content stimulates students' interest and curiosity about the lessons, enabling active participation and making it convenient.

Fourth, the application should enable multilateral experiences. Multilateral experience means that several people share an experience while pursuing the same objective and achieving their goals. Through this AR application, participants can converse freely in a relaxed atmosphere, revealing what they have "already" understood and what they "still" do not grasp, thereby making their learning more accurate and solid. In addition, they can experience learning by openly adjusting and re-evaluating their thoughts. Since interaction with peers is essential during the learning process, it is possible to enable multilateral experiences by using the AR application together while learning practical subjects.

There were also clear limitations to this study. As an AR application for use in schools, there is room for students to develop their research content through user evaluations while using this app in the future. In addition, it is necessary to expand content, such as discussions and team activities, for interaction in class, and not just through questions and answers.

5. Conclusion

Post-COVID-19, a digital transformation has occurred in the education industry due to increasing interest in edutech. Amid the growing interest in and expectations for the use of edutech in the education field, this study proposes a customized learning explanation application that incorporates AR technology for students who have difficulty in learning practical subjects. The application, which allows students to share and watch the explanation process as an AR video, helps them review and learn parts that are not understood in class.

This is intuitive because the explanation process can be viewed in detail from various angles using AR technology, and is significant because it can communicate with users through social functions. Future studies should address these limitations.

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JYN performed the research and authored the manuscript.

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Review

A Study on the Feasibility of Utilizing the Metaverse Platform in Education

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Abstract: As digital transformation accelerated after the COVID-19 pandemic, the use of metaverse has been increasing not only in the industry but also in the educational field. To adapt to the class site, it is necessary to derive a direction through foreign metaverse platforms. The following conclusions can be drawn from this study: First, it is difficult to express individuality through avatars, and non-verbal communication for conveying messages is challenging. Platforms like ZEPETO and ifland are in 3D, whereas Gather.Town is in 2D, and even then, the design is simplistic. Second, as the platforms are not specifically designed for educational purposes, there are limitations in supporting classes. Most are created for entertainment purposes. Third, most are one-time events. Particularly in the case of domestic Metaverse educational uses, the focus has been on one-time events rather than developing content that can be continuously used in classes. Fourth, most are one-time events. Particularly in the cases of domestic metaverse education cases, one-time events dominated rather than continuously available content in class. Fourth, when introducing metaverses into education, highlighting the purpose and benefits of using metaverse technology is crucial. Fifth, creating a user-friendly interface with a clear and simple menu is essential. Sixth, strong interactions between metaverse providers, suppliers, and users are essential.In this study, an analysis of the usage of metaverse in in the educational field and the direction of studying metaverse in this context in the future has been done. It is expected that the results of this study can be used as basic data in schools and development centers or development related to education content.

Keywords: Metaverse; Education; Platform; Interaction; Immersion

1. Introduction

Our lifestyles have experienced significant changes before and after COVID-19. Beyond 'untact,' which means non-face-to-face and non-contact interactions, the 'ontact' culture—i.e., online communication and contact, video conferencing for remote classes, and telecommuting—has become commonplace. Consequently, digital disparity has emerged as a social issue [1].

In the first semester of 2020, when COVID-19 occurred, all classes suddenly converted to online formats, causing considerable confusion at the beginning of the semester. Higher education institutions, elementary and secondary education schools, parents, and education-related institutions experienced an unexpected “webcam crisis” with soaring prices and shortages of devices such as cameras and microphones for online classes. In the second semester of 2020, offline classes were partially implemented for practical subjects that were difficult to conduct remotely. From the first semester of 2021, various efforts were made to establish a class environment that enables smooth hybrid learning. Meanwhile, as digital transformation accelerated after the COVID-19 pandemic, the use of metaverse technology has been increasing, in both industry and the educational field. In particular, as the ‘metaverse,’ a fusion of real and virtual spaces, is being used throughout society, higher education institutions are interested in utilizing it to create offline-like learning environments [2]. Currently, research on methods to efficiently implement metaverse-related education is required. An analysis of international case in the educational field using metaverses is initially necessary. Through this study, I explored the direction of using metaverses in education. The research questions of this paper are as follows:

<Research Question 1>: What are the cases of education using domestic and international metaverses?

<Research Question 2>: What is needed for a smooth metaverse-based class?

2. Concept and Use Case of Metaverse

2.1. Concepts and Types of Metaverse

A metaverse is a three-dimensional (3D) virtual space where reality is fused with a computer-generated environment. The term “metaverse” first appeared in Neil Stephenson’s science-fiction novel Snow Crash in 1992. In this novel, people are active in a virtual world called the metaverse using avatars. Second-life websites, which appeared in the early 2000s, can be considered early versions of the metaverse [3, 4].

With the recent development of digital technologies, such as big data, blockchain, and artificial intelligence, the demand for alternative spaces beyond the physical world is increasing as people shift from offline to online environments. In particular, platform-type metaverses have become more prevalent. The mobile game “Pokemon Go,” launched in 2017 and gaining worldwide popularity, is a representative example of this type of metaverse. Recent examples include “Roblox,” “Fortnite,” “Zepeto,” and “Jump virtual reality (VR)” in Korea [5].

The Acceleration Studies Foundation, a nonprofit technology research organization in the United States, announced the ‘metaverse roadmap’ in 2007. This roadmap, considering two axes reflecting the degree of virtual world and reality, divided the metaverse into four categories: VR, augmented reality (AR), mirror world, and life logging. VR, a compound word combining “virtual world” and “reality,” refers to a world where people can experience real life in a computer-created virtual environment. Specifically, VR indicates a ‘specific environment or situation’ rather than real life. It implies the technology itself that implements computer-based VR, and is 100% computer-generated (CG). Examples of its applications include VR games, which are virtual but can be experienced as reality, and virtual roller coasters. AR is a graphical technology that synthesizes virtual information or objects into an actual environment to make them appear as if they were in the real world. The technology adds 3D virtual objects to the real world and displays them to the user, effectively combining reality with CG. One prominent example is the Pokémon Go platform. Lifelogging refers to activities in which individuals organize, store, and share information that they see, hear, meet, and feel in their lives. SNS and wearable devices are examples of life-logging. The mirror world refers to a virtual world that reflects the landscape, appearance, information, and composition of the real world as realistically as possible. Examples include Google Maps and Zoom [4].

2.2. Metaverse Use Cases in Education

2.1.1. Case Analysis Method

In this study, the metaverse cases used in the education industry were investigated and analyzed. Uses of metaverse-based content include university lectures, entrance ceremonies, festivals, career counseling sessions, and job fairs. Specifically, the utilization of domestic and international education-related Metaverse content was detailed based on articles and reports.

2.2.2. Case Analysis

When the graduation ceremony at the UC Berkeley in the United States could not be held due to COVID-19, students voluntarily created a campus in the Minecraft game and held a virtual graduation ceremony at a playground called Blockly, which combined blocks and Berkeley. This event was broadcasted on Twitch, an Internet broadcasting platform. Although it is less lively than an offline graduation ceremony, a virtual graduation ceremony is important because it can record all situations and provide unique experiences through avatars.

The University of California (UC), San Diego, is one of the universities leading the integration of a metaverse campus. They advocate for the introduction of metaverse campuses in higher education. A real-time virtual lecture was conducted at the UC San Diego to provide a digital space for students to learn independently. Students showed a positive perception of the metaverse campus, citing a sense of immersion, which they had not experienced in face-to-face lectures, along with other advantages such as playful elements and convenience [6, 7].

As an alternative to offline classroom instructions, Pennsylvania State University in the United States provides opportunities for learners to interact with each other by conducting classes in Minecraft [4].

Examples of the use of the metaverse in comparative domestic activities are as follows:

Soonchunhyang National University developed a game called "SCNU Picks" that introduced useful information about college life to help new students in 2021. This game includes 27 AR/VR missions and useful content that students need to know to adapt to and succeed in university life [8]. In addition, Soonchunhyang University implemented a metadata map for immersion. A metaverse map and a virtual dam were created as the main stage, applied to "negative World" in jump VR. Approximately 2,500 new students participated in the entrance ceremony using this virtual setup[9].

The Foundation University is operated by a VR game company. Konkuk University utilized "Gather Town" to create a virtual version of their campus, which was promoted by student clubs [10, 11].

In terms of textbook activities, metadata technology was used for experimental subjects as alternatives. The Korea Institute of Industrial Technology conducted the first VR lab, while Seoul National University demonstrated the "Dimensional image" technology [12–15].

3. Conclusion

Higher education post COVID-19 is primarily conducted through remote education methods using real-time platforms. However, remote education has limitations in providing learners with an experience similar to the offline learning atmosphere. Metadata-based classes for remote education have recently received considerable attention to overcome this disadvantage. To adapt to this new format, deriving direction from international metaverse implementations is necessary.

The following conclusions were drawn from this study:

Study 1. What are cases of education using domestic and international metaverses?

In Students can create lecture rooms in their minds and attend classes, fostering familiarity with each other in the virtual space and providing opportunities to interact. In addition, metaverse platforms have been used for events such as entrance ceremonies, graduation ceremonies, and festivals, as well as for teaching, experiments, and experimental subjects.

Problem Identification: Analyzing domestic and international cases of educational use of the metaverse revealed the following issues. First, it is difficult to express individuality through avatars, and non-verbal communication for conveying messages is challenging. Platforms like ZEPETO and ifland are in 3D, whereas Gather.Town is in 2D, and even then, the design is simplistic. In addition, avatar movement is restricted and must be controlled with arrow keys, which can be inconvenient until users learn the tutorial, and many quit early on.

Second, as the platforms are not specifically designed for educational purposes, there are limitations in supporting classes. Most are created for entertainment purposes. For example, on the ifland platform, private communication is impossible, only allowing for general audio, and when users are apart, they cannot hear each other, which is inconvenient.

Third, most are one-time events. Particularly in the case of domestic Metaverse educational uses, the focus has been on one-time events rather than developing content that can be continuously used in classes. Without the development of sustainable content, there are inherent limitations in achieving educational outcomes through the use of the Metaverse.

Fourth, most are one-time events. Particularly in the cases of domestic metaverse education cases, one-time events dominated rather than continuously available content in class. Without sustainable content development, there are inevitably several limitations to using the metaverse to achieve educational results.

Study 2. What are the requirements for a smooth metaverse-based class?

First, when introducing metaverses into education, highlighting the purpose and benefits of using metaverse technology is crucial. For example, learning about history through a metaverse space can emphasize its importance and maximize immersion by incorporating fun elements such as games. This approach can provide a realistic experience, allowing students to directly explore historical buildings and cultures.

Second, creating a user-friendly interface with a clear and simple menu is essential. Understanding how the technology works can help overcome any inconvenience, allowing users to focus on the content it provides. If the menu is complicated, it should be organized more effectively, and each educational institution should provide a description of the service cases.

Third, strong interactions between metaverse providers, suppliers, and users are essential. As evidenced by successful international examples, maintaining good communication and cooperation is key. Using a metaverse space can help organize the virtual environment and facilitate various activities. Additionally, expanding metaverse systems is necessary to support these interactions.

This study analyzes the use of the metaverse in the educational field and explores its future direction in this context. However, a limitation of this study is its reliance on overseas cases of metaverse usage. In the future, research should include surveys or interviews with learners who have participated in metaverse classes to assess their satisfaction and the effectiveness of learning through this medium. The results of this study are expected to serve as foundational data for schools, development centers, and developers of educational content.

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