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Implementation of Max-Plus Algebra on Image Steganography with Bicover

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ABSTRAK

Penelitian ini mengusulkan metode steganografi berbasis konsep bicover dengan memanfaatkan aljabar Max-Plus melalui operasi perkalian matriks tanpa invers. Metode yang diusulkan menggunakan dua cover image untuk menyisipkan satu secret image, yaitu cover image pertama untuk menyimpan bit MSB (Most Significant Bit) dan cover image kedua untuk menyimpan bit LSB (Least Significant Bit). Proses penyisipan dilakukan dengan mengombinasikan representasi biner citra rahasia dan citra penampung menggunakan aturan aljabar Max-Plus sehingga informasi rahasia dapat disembunyikan tanpa memerlukan proses invers matriks pada tahap ekstraksi. Kinerja metode dievaluasi menggunakan parameter Mean Squared Error (MSE) dan Peak Signal-to-Noise Ratio (PSNR). Hasil pengujian menunjukkan bahwa metode ini mampu merekonstruksi citra rahasia secara utuh dengan kualitas citra stego yang baik. Nilai PSNR yang diperoleh sebesar 31,18 dB pada Stego 1 dan 31,77 dB pada Stego 2, sedangkan nilai MSE sebesar 49,5457 pada Stego 1 dan 43,2352 pada Stego 2. Hasil tersebut menunjukkan bahwa perubahan visual pada citra penampung relatif kecil sehingga keberadaan citra rahasia sulit dikenali. Dengan demikian, metode yang diusulkan dapat menjadi alternatif dalam meningkatkan keamanan pertukaran data digital melalui teknik penyembunyian informasi yang efektif dan mudah diimplementasikan.

Kata kunci: Aljabar Max-Plus, Bicover, Steganografi

ABSTRACT

This study proposes a steganographic method based on the bicover concept by utilizing Max-Plus algebra through matrix multiplication operations without matrix inversion. The proposed method employs two cover images to embed a single secret image, where the first cover image stores the Most Significant Bits (MSBs) and the second cover image stores the Least Significant Bits (LSBs). The embedding process is performed by combining the binary representations of the secret image and the cover images using Max-Plus algebra rules, allowing the secret information to be concealed without requiring matrix inversion during the extraction stage. The performance of the proposed method was evaluated using the Mean Squared Error (MSE) and Peak Signal-to-Noise Ratio (PSNR) metrics. Experimental results show that the method can reconstruct the secret image completely while maintaining good stego-image quality. The obtained PSNR values were 31.18 *dB for Stego 1 and* 31.77 *dB for Stego 2, while the corresponding MSE values were* 49.5457 *and* 43.2352*, respectively. These results indicate that the visual distortions introduced to the cover images are relatively small, making the presence of the secret image difficult to detect. Therefore, the proposed method can serve as an alternative approach for enhancing the security of digital data transmission through an effective and easily implementable information-hiding technique.*

Keywords: *Bicover, Max-Plus Algebra, Steganography*

A. Introduction

The development of information technology has simplified the process of exchanging digital data without the constraints of time and space. However, this convenience also increases the risk of information system crimes, such as theft, eavesdropping, and data manipulation. The leak of thousands of confidential documents at a major agency demonstrates the critical importance of security in the exchange and storage of information, as the risks can have fatal consequences (Rachmawati, 2025).

One way to maintain data confidentiality is through cryptography. In addition to cryptography, which secures data by converting message content into a specific code, steganography is also used to hide confidential data within digital media. This technique is widely used because it can embed messages without causing any noticeable visual changes (Aksani dkk., 2025).

Modern steganography is not limited to simple message embedding, but also encompasses various methods such as End of File (EOF) and Least Significant Bit (LSB). The LSB method is widely developed because it can embed data in low bits, making image changes difficult to visually detect(Haikal dkk., 2023).

Steganography development has also focused heavily on increasing data storage capacity and the quality of image embedding. One effort is to modify the Least Significant Bit (LSB) method to increase the amount of data that can be embedded without significantly degrading image quality (Sari dkk., 2026). The quality of the embedding results can be analyzed using the Peak Signal-to-Noise Ratio (PSNR) value, which is an indicator of the similarity between the original image and the embedded image (A. Muh. Ramadhani & Tasrif Hasanuddin, 2021).

Algebra itself is a fundamental branch of mathematics that is introduced as early as junior high school, where students are taught to understand and manipulate algebraic forms as a basis for solving more complex problems through a problem-solving approach (Elie, 2025). From this fundamental algebraic structure, various extended algebraic systems have been developed for specific applications, one of which is Max-Plus algebra.

One development in steganography is the application of Max-Plus algebra through matrix multiplication without inverse. This method is capable of embedding large secret images, even as large as the cover image (Santoso dkk., 2018) However, this method still has a weakness because it only processes the Most Significant Bit (MSB) and ignores the Least Significant Bit (LSB), so some of the secret image information cannot be fully reconstructed during extraction.

Based on these issues, this study proposes the development of a steganography method using the bicover concept, which utilizes two cover images to conceal a single secret image. One cover image is used to embed the MSB bits, and the other to embed the LSB bits. This approach has been proven to maintain the integrity of the secret image data and produce better extraction quality than previous methods.

B. Research Methods

1. Max-Plus Algebra

Max-Plus Algebra (Subiono, 2015; Susilowati, 2024) is defined as the set $R_\epsilon = R \cup \{\epsilon\}$ wheew R is the set of all real numbers and $\epsilon = -\infty$, which uses two binary operations $\oplus$ and $\otimes$. For each $a, b \in R_\epsilon$, the operations are defined as

$$a \oplus \mathrm{b} = \max(a, b),$$
$$a \otimes \mathrm{b} = \mathrm{a} + \mathrm{b}.$$

The neutral element with respect to the $\oplus$ operation is $\epsilon = -\infty$, while the unit element with respect to the $\otimes$ operation $e = 0$. In addition, for every $a \in R_\epsilon$, it holds that $a \oplus \varepsilon = \varepsilon \oplus \mathrm{a} = \mathrm{a}$ and $a \otimes \varepsilon = \varepsilon \otimes \mathrm{a} = \varepsilon$. Thus, ε is both a neutral element with respect to the $\oplus$ operation and an absorbing element with respect to the $\otimes$ operation.

The structure $(R_\epsilon, \oplus, \otimes)$ is a *semiring idempotent* (or *dioid*) because it satisfies the idempotent property (Kurniawan, 2023)

$$x \oplus \mathrm{x} = x$$

for every $x \in R_\epsilon$, since every element of $x \neq \epsilon$ has an inverse to the $\otimes$ operation, namely $-x$, this structure is also called an idempotent semifield.

In max-plus aljebraic operation, the operation $\otimes$ has higher priority than $\oplus$. For example,

$$10 \otimes (-7) \oplus 6 \otimes 2$$

can be written in the form

$$\big(10 \otimes (-7)\big) \oplus (6 \otimes 2) = 3 \oplus 8$$
$$= 8$$

The $\otimes$ and $\oplus$ operations are also defined for matrics and vectors. Let $R_\epsilon^{n \times m}$ e the set of matrices of size $n \times m$ on aljabar max-plus. For matrices $A, B \in R_\epsilon^{n \times m}$(Muanalifah, 2023), the matrix addition $A \oplus \mathrm{B}$ is defined as

$$[A \oplus B]_{ij} = a_{ij} \oplus b_{ij} = \max\big(a_{ij}, b_{ij}\big)$$

for $i = 1, \ldots, n$ and $j = 1, \ldots, m$. The multiplication of matrices $A \otimes B$ for matrices $A \in R_\epsilon^{n \times m}$ is defined by

$$[A \otimes B]_{ij} = \bigoplus_{k=1}^{p} \big(a_{ik} \otimes b_{kj}\big)$$
$$= \max_{k \in \{1, \ldots, p\}} \{a_{ik} + b_{kj}\}$$

for $i = 1, \ldots, n$ and $j = 1, \ldots, m$. Matrix multiplication in max-plus algebra is not always commutative, that is,

$$A \otimes B \neq A \otimes B$$

2. Steganography

Steganography is a technique for hiding secret messages within digital media so that the existence of the message remains unknown to others (Napitupulu dkk., 2023). Unlike cryptography, which focuses on securing the content of a message by converting it into a specific code, steganography places greater emphasis on concealing the existence of the message to avoid arousing suspicion (Aqsa & Hidayatullah, 2026; Teknik Informatika Universitas Khairun dkk., 2018). The media used to carry the message can be images, audio, video, or text (Nur'aini, 2019).

In a steganography system, there are several main components: the cover-object as the host medium, the message as the secret message, the secret key as the security key, and the stego-object as the medium into which the message is embedded (Santoso dkk., 2018). In digital image steganography, the most commonly used method is the Least Significant Bit (LSB), which is a technique for embedding a message in the last bit of an image pixel(Yanti & Budayawan, 2023). This method is widely applied to 24-bit BMP images because this format can preserve image data without reducing the original information, so that the embedded message is not easily lost (Alasi, 2023). In addition to the LSB method, there are also the Most Significant Bit (MSB), Discrete Cosine Transform (DCT), and End Of File (EOF) methods, which are used to enhance security and data embedding capacity (Basim, 2020; Putra & Supriana, 2024).

The quality of a steganographic image can be analyzed using the Mean Square Error (MSE) and Peak Signal-to-Noise Ratio (PSNR) metrics. The MSE value is used to measure the degree of difference between the original image and the steganographic image (Hidayat & Andono, 2025). The smaller the MSE value, the smaller the difference between the two images. The MSE calculation can be expressed by the following formula:

$$MSE = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left(I(i,j) - K(i,j)\right)^2$$

Where:

M = number of image rows,
N = number of image columns,
$I(i,j)$ = pixel value of the original image,
$K(i,j)$ = pixel value of the stego image.

Next, the PSNR value is used to determine the quality of the steganographically processed image based on a comparison between the original image and the stego image. The higher the PSNR value, the smaller the changes in the stego image, resulting in better image quality after insertion and making it more difficult to distinguish from the original (Mulyono dkk., 2023). The PSNR calculation can be expressed by the following formula:

$$PSNR = 10\log_{10}\left(\frac{C_{max}^2}{MSE}\right)$$

With the following note:

C_{max}= the maximum pixel value of an image (typically 255 for 8-bit images),
MSE = Mean Square error,
$PSNR$= a measure of image quality in decibels (dB).

C. Method

The method used is an extension of Max-Plus algebra-based steganography that utilizes two cover images (Cover 1 and Cover 2) of the same size as the secret image. In this method, Cover 1 is used to embed the MSB portion of the secret image into the LSB portion of the cover image, while Cover 2 is used to embed the LSB portion of the secret image into the LSB portion of the cover image. The encryption and decryption processes are performed using the same steps as the previous method, but are applied separately to both cover images.

Suppose we are given test data in the form of initial pixel values for the Red component as follows:

Secret Image = 93

Cover Image 1 = 52
Cover Image 2 = 52

The following are the steps of the insertion algorithm, integrated directly with calculation examples:

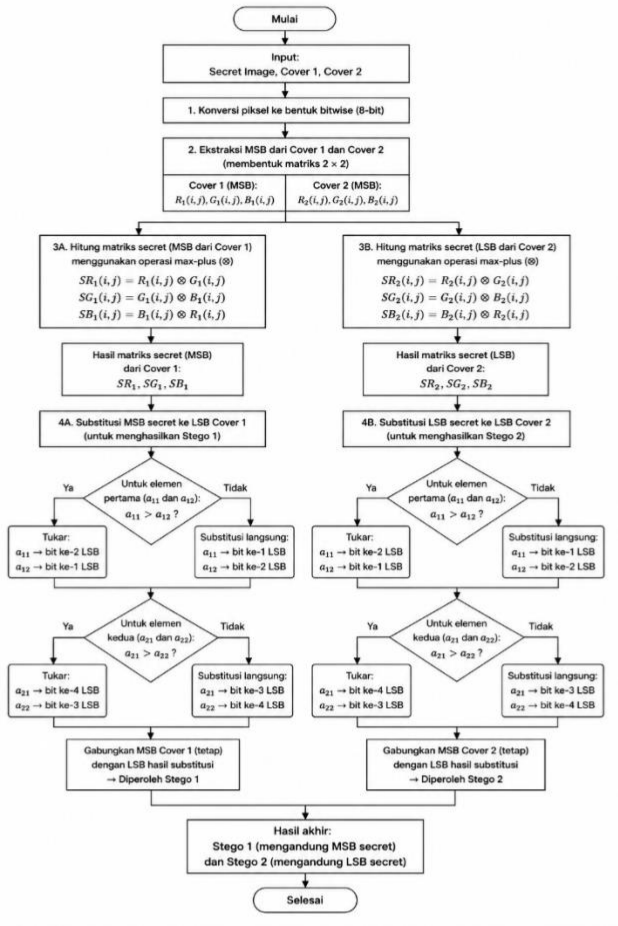

Figure 1. Bicover flowchart

1. Conversion of Pixels to Bitwise Form (8-bit)
   Each decimal pixel value is converted to 8-bit binary form. Then, the binary value is divided into two parts: the first 4 bits as the MSB and the last 4 bits as the LSB.
   Then:
   Secret image: 93 = 01011101 (MSB = 0101, LSB = 1101)
   Cover 1: 52 = 00110100 (MSB = 0011, LSB = 0100)
   Cover 2: 52 = 00110100 (MSB = 0011, LSB = 0100)

2. Extraction and Formation of a 2 × 2 matrix
   The separated bit components are then arranged into a 2 × 2 matrix. This matrix is used for max-plus algebraic operations as well as to determine the bit-swapping rules
   example:
   The MSB of the Secret Image (0101) is formed into matrix A:
   $$A = \begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix}$$
   (Element values obtained: $a_{11} = 0$, $a_{12} = 1, a_{21} = 0, a_{22} = 1$)
   The MSB of Cover 1 (0011) is formed into matrix R_1:
   $$R_1 = \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix}$$

3. Calculation Using the Max-Plus Operation
   The process continues by multiplying the Cover MSB matrix (R_1) by the Secret MSB matrix (A).
   Excemple: ($S_R = R_1 \otimes$ A):
   $$S_{11} = (0 \otimes 0) \oplus (0 \otimes 0) = 0$$
   $$S_{12} = (0 \otimes 1) \oplus (0 \otimes 1) = 1$$
   $$S_{21} = (1 \otimes 0) \oplus (1 \otimes 0) = 1$$
   $$S_{22} = (1 \otimes 1) \oplus (1 \otimes 1) = 2$$
   Thus, the matrix S_R is abtained:
   $$S_R = \begin{pmatrix} 0 & 1 \\ 1 & 2 \end{pmatrix}$$

4. Substitution and Bit Swapping Rules for the Stego Image
   Bits from the Secret Image are inserted into the LSB area of the Cover Image. Before the substitution process is performed, the bit positions are first checked based on the conditions of the Secret Matrix elements (a_{ij}):
   - If $a_{11} > a_{12}$, then swap the first MSB bit of the secret image with the second LSB bit of the stego image, and the second MSB bit of the secret image with the first LSB bit of the stego image.
   - If $a_{11} \leq a_{12}$, then perform a direct substitution: the first bit of the secret's MSB to the first bit of the stego's LSB, and the second bit of the secret's MSB to the second bit of the stego's LSB.
   - If $a_{21} > a_{22}$, then swap the third bit of the secret MSB with the fourth bit of the stego LSB and the fourth bit of the secret

MSB with the third bit of the stego LSB.

- If $a_{21} \leq a_{22}$, then perform a direct substitution: the third bit of the secret MSB to the third bit of the stego LSB, and the fourth bit of the secret MSB to the fourth bit of the stego LSB.

exemple:
Forming Stego 1 (Storing the MSB Secret: 0101 into Cover 1): Since $a_{11}(0) \leq a_{12}(1)$ dan $a_{21}(0) \leq a_{22}(1)$, the bit pairs are not swapped so that the new LSB remains 0101, then combined with the original MSB of Cover 1, which is 0011, resulting in the binary 00110101 with a final pixel value for Stego 1 of 53.
Forming Stego 2 (Storing the Secret LSB: 1101 into Cover 2): Using the same matrix indicators and comparison rules, the new LSB 1101 is obtained, which is then combined with the original MSB of Cover 2, 0011, resulting in the binary 00111101 with a final Stego 2 pixel value of 61.

Here is the algorithm for extracting the secret image from two stego images:

1. Convert the pixels of the stego images to 8-bit binary
   The decimal values of Stego 1 and Stego 2 are converted back to 8-bit binary to separate their constituent bits into MSB and LSB.
   example:
   Stego 1: 53 = 00110101 (MSB = 0011, LSB = 0101)
   Stego 2: 61 = 00111101 (MSB = 0011, LSB = 1101)

2. Matrix Extraction from LSB Stego
   The LSB portion of each stego image is extracted (since it contains the secret bits), then arranged into a 2×2 matrix.
   example:
   The LSB of Stego 1 is 0101, arranged into Matrix A:
   $$A = \begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix}$$
   (The resulting element values are $a_{11} = 0, a_{12} = 1, a_{21} = 0, a_{22} = 1$)
   The LSB of Stego 2 is 1101, arranged into Matrix B:
   $$B = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$$

3. Bit Position Check and Restoration
   The values of the elements in Matrix A (the result of Stego 1's LSB) are checked again to determine whether a bit swap occurred during the insertion process. If the condition is met, the bit positions must be restored to their original state:
   - If $a_{11} > a_{12}$, swap the 1st bit with the 2nd bit in LSB Stego 1 and Stego 2.
   - If $a_{21} > a_{22}$, swap the 3rd bit with the 4th bit in LSB Stego 1 and Stego 2.

   example:
   In row 1, the condition $a_{11}(0) > a_{12}(1)$ is not satified $(0 \leq 1)$, so the first and second bits of the LSB of Stego 1 remain (01) and those of the LSB of Stego 2 remain (11).
   In row 2, the condition $a_{21}(0) > a_{22}(1)$ is not satified $(0 \leq 1)$, so the 3rd and 4th bits in the LSB of Stego 1 remain (01) and in the LSB of Stego 2 remain (01)
   Thus, the original secret bit sequence is obtained:
   Secret MSB (from LSB Stego 1) = 0101, and Secret LSB (from LSB Stego 2) = 1101.

4. Recovering the Secret Image Pixels
   The final step is to combine the 4 MSB Secret bits and the 4 LSB Secret bits obtained into a complete 8-bit binary number, then convert it back to decimal form.
   example:
   Combine MSB (0101) + LSB (1101) = Binery: 01011101, convert binery 01011101 to decimal, Final Pixel Value of the Successfully Recovered Secret Image = 93

Based on the calculation example above, the embedding process is performed by separating the MSB and LSB components of the secret image and then embedding each into two different

carrier images. The result of the transformation using the max-plus algebraic operation produces a new matrix that is used as a reference in the bit substitution process
This method enhances steganographic security by separating the MSB and LSB of the secret image into two separate stego images, thereby requiring both stego images for complete recovery.

D. Reselt and Discussion

A steganography method based on the bicover concept, utilizing Max-Plus algebra through matrix multiplication without inverses, has been successfully developed to hide a single secret image in its entirety using two cover images. In this method, the first cover image is used to embed the Most Significant Bit (MSB), while the second cover image is used to embed the Least Significant Bit (LSB). This approach addresses the limitations of previous methods, which only processed the MSB portion, preventing the complete reconstruction of the secret image.

The test results show that the quality of the stego images remains good after the embedding process. This is indicated by a Peak Signal-to-Noise Ratio (PSNR) value of 31.18 dB for Stego Cover 1 and 31.77 dB for Stego Cover 2. Additionally, the Mean Square Error (MSE) values obtained were 49.5457 for Stego Cover 1 and 43.2352 for Stego Cover 2. The relatively low MSE values and sufficiently high PSNR values indicate that the visual changes in both host images are insignificant, making the presence of the hidden image difficult to detect with the naked eye.

By processing all bits of the hidden image that is, the MSB and LSB separately across two cover images, the hidden image can be reconstructed with greater integrity compared to previous methods. Overall, the Max-Plus algebra-based bicover steganography method has proven effective in improving the quality of hidden image extraction while maintaining the visual similarity of the host image. Therefore, this method can serve as a better alternative to support the security of digital data exchange.

Figure 2. Cover Image

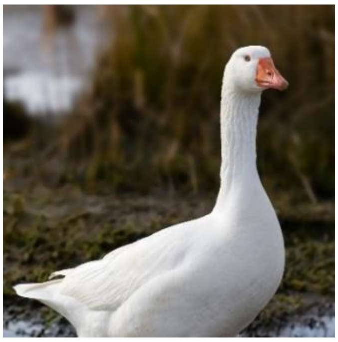

Figure 3. Secret Image

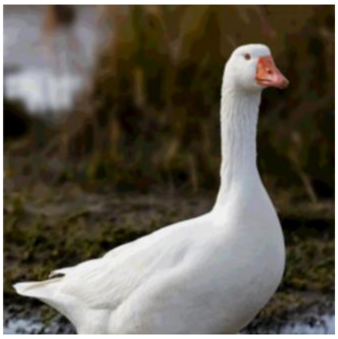

Figure 4. Bit Pemisahan MSB

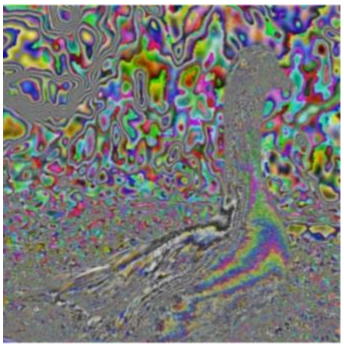

Figure 5. Bit Permisahan LSB

Figure 6. Stego 1 (MSB part)

Figure 7. Stego 2 (LSB Part)

E. Conclusion

This study successfully developed a steganography method based on the bicover concept utilizing Max-Plus algebra through matrix multiplication without inverses. This method employs two cover images to conceal a single secret image in its entirety, where the first cover image stores the MSB bits and the second cover image stores the LSB bits of the secret image.

The proposed method addresses the limitation of previous methods that only processed the MSB portion, which prevented the complete reconstruction of the secret image. By processing all bits of the secret image separately across two cover images, the integrity of the secret image during extraction is better preserved.

The test results demonstrate good stego image quality, evidenced by PSNR values of 31.18 dB for Stego 1 and 31.77 dB for Stego 2, along with MSE values of 49.5457 for Stego 1 and 43.2352 for Stego 2. These values indicate that the visual changes in both host images are insignificant and difficult to detect with the naked eye.

Therefore, the Max-Plus algebra-based bicover steganography method has proven effective in improving the quality of secret image extraction while maintaining the visual similarity of the host image, making it a viable alternative to support the security of digital data exchange.

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