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Fuzzy Graph–Based Encryption using Special Characters

[1]S. Dharani, [2]K. Jency Priya, [2]B. Amala Jasmine, [3]V. Vanitha and [4]T. Sathinathan
[1]M.Sc., Jayaraj Annapackiam College for Women (Autonomous), Periyakulam
[2]Assistant Professor in Mathematics, Jayaraj Annapackiam College for Women (Autonomous), Periyakulam
[3]Assistant Professor in Mathematics, Fatima College (Autonomous), Madurai.
[4] Assistant Professor in Mathematics, Sacred Heart College(Autonomous), Tiruppattur

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Abstract

This work presents a novel data encryption method using fuzzy graph theory. The plaintext is represented as a fuzzy graph, where characters act as vertices with membership values and their relationships form fuzzy edges. The encryption process uses two secret keys to introduce uncertainty within the interval [0,1].Different models are developed for handling alphabets, numbers and special characters. A systematic decryption process ensures accurate recovery of the original message. This approach enhances data security by making the encrypted information difficult for unauthorized users to interpret, while maintaining flexibility and efficiency.

Introduction

In the modern digital era, the need for secure communication has become increasingly important due to the rapid growth of data exchange over networks. Cryptography plays a crucial role in protecting sensitive information by converting readable data into an unreadable format, ensuring confidentiality, integrity, and authenticity [8,9].

Traditional encryption techniques rely on mathematical and structural concepts derived from graph theory and set theory.Graph theory, introduced by Harary [5], provides a strong foundation for representing relationships, while fuzzy set theory, introduced by Zadeh [10], handles uncertainty in data. The theoretical foundations of fuzzy sets were further expanded by Kauffman [6].

Fuzzy graphs, first introduced by Rosenfeld [7], combine these two concepts by incorporatingdegreesofmembershipforvertices andedges.Thesestructuresareuseful in modelingcomplex systems with uncertainty and have been widely studied in recentyears [1].Further developments in fuzzy graph theory include uniform vertex and edgefuzzygraphsandtheirstructuralproperties[3,4].Additionally,similarityrelationsand fuzzy ordering concepts introduced by Zadeh [11] play an important role in understanding fuzzy relationships.

Recent research has explored the application of fuzzy graph theory in cryptography.In particular,fuzzygraph–basedencryptiontechniquesprovideanovelandsecuremethod for data transmission [2]. These approaches enhance traditional encryption methods by incorporatinguncertaintyandstructuralcomplexity.

Thisprojectfocusesonthedevelopmentofa fuzzygraph–based8encryptionmethod. In this approach, each character in a plaintext message is mapped to a numerical value and transformed into a fuzzy vertex. The relationships between consecutive characters arerepresentedusingfuzzyedges,formingacompletefuzzygraphstructurethatactsas the ciphertext.

The objective of this work is to demonstrate how fuzzy graph theory can be effectively appliedtocryptographytoachievesecureandreliabledatatransmission.

Preliminaries

Cryptography

Cryptographyisthescienceofsecuringinformation byconvertingreadabledataintoan unreadable form using mathematical techniques.

PlainText

Plaintextreferstotheoriginalreadablemessageordatabeforeencryption.

CipherText

Cipher text is the unreadable and encrypted form of the plain text obtained after applyingan encryption algorithm.

Encryption

Encryption is the process of converting plain text into cipher text using a key to ensure data confidentiality.

Decryption

Decryptionisthereverseprocessofencryption,whereciphertextisconvertedbackinto itsoriginalplaintextusingtheappropriatekey.

FuzzySet

Definition2.1 Let$X$beanon-emptyset.A fuzzyset$A$in$X$isdefinedas

$$A=\{(x,\mu_A(x))|x\in X\},$$

wherethemembershipfunction

$$\mu_A:X\to[0,1]$$

assignstoeachelement$x$adegreeofmembership.

FuzzyGraph

Definition2.2A fuzzygraphisanorderedpair

$$G=(\sigma,\mu),$$

where

$\sigma:V\to[0,1]$ isafuzzysubsetofthevertexset$V$,and

$\mu:E\to[0,1]$ isafuzzyrelationon$V$satisfying

$$\mu(u,v)\leq\min\{\sigma(u),\sigma(v)\}$$

2forall$u,v\in V$.

ExampleofaFuzzyGraph

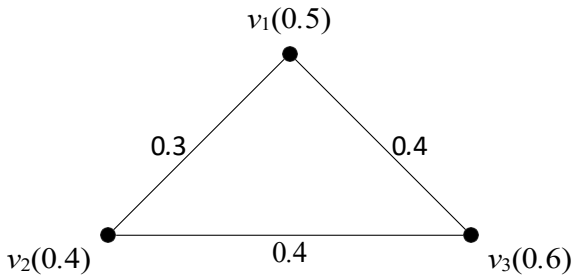

Figure1: G_1

FuzzyGraph–BasedEncryptionusingSpecialCharacters

Definition2.1 Let Pdenote the plaintext space and Cdenote the ciphertext space.Anencryption function is a mapping

such that

forall$x \in P$.

1 SpecialCharacterMappingTable

Each printable ASCII special character is assigned a unique positional value from 1

$$E_k : P \rightarrow C,$$

where$k$representstheencryptionkey.

Definition2.2 Adecryptionfunctionisamapping

$$D_k : C \rightarrow P$$

$$D_k(E_k(x)) = x$$

2

to 32 to facilitate numerical representation in fuzzy graph construction.

Table1:MappingofPrintableASCIISpecial Characters

Character	!	“	#	$	%	&	’	(
Position	1	2	3	4	5	6	7	8
Character	)	*	+	,	-	.	/	:
Position	9	10	11	12	13	14	15	16
Character	;	¡	=	¿	?	@	[	\
Position	17	18	19	20	21	22	23	24
Character	]	^	_	‘	{	—	}	~
Position	25	26	27	28	29	30	31	32

- **Key**$_1$($0 < \text{Key}_1 < 1$) introduces fuzziness and uncertainty, ensuring non-integer vertexmembershipvalues.

- **Key**$_2$(Key$_2 \in$ N)actsasascalingfactortomaintainvert exmembershipvalues within the fuzzy interval $[0,1]$.

Since fuzzy graphs require membership values in the interval $[0,1]$, position values ranging from1to32arenormalizedbydivision.Duringde cryption,multiplicationisusedto reversethisnormalizationandrecoveroriginalpo sitionalvalues.

2 EncryptionAlgorithmforSpecial Characters

This algorithm describes the encryption process for messages consisting of special characters.Each character is represented using its positional value and converted into a fuzzy graph.

Input: Plaintextmessage*M*containingspeci alcharacters

Output: Ciphertextrepresentedasafuzzygr aph*G*

Step1:SelectionofSecretKeys

Choosetwosecretkeys:

$\text{Key}_1 \in (0,1), \text{Key}_2 > 1$

Thesekeys areknown onlytothes enderandr eceiver.

Step2:CharacterMapping

Eachspecialcharacterin*M*ismappedtoitspositi onalvalue:

$$p_i \in \{1,2,...,32\}$$

Since32possiblecharactersareconsidered,nor malizationisperformedusing32.

Step3:VertexMembershipComputati on

Foreachcharacter:$n = \frac{p_i^i}{32}$

$$\sigma(v) = \frac{(n_i + \text{Key}_1)}{\text{Key}_2}$$

Eachcharacterisrepresented asavertex $v_i$withmembership value$\sigma(v_i)$.

Step4:EdgeMembershipComputation

Forconsecutivecharacters:

$$d_i = |p_{i+1} - p_i| \; w = \frac{d_i^i}{32}$$

$$\mu(v_i, v_{i+1}) = \min(w_i, \sigma(v_i), \sigma(v_{i+1}))$$

An edge is drawn between v_i and v_{i+1} with membership value $\mu(v_i, v_{i+1})$.

Step 5: Cipher Construction

The fuzzy graph is constructed as:

$$G = (V, E, \sigma, \mu)$$

For transmission, vertex membership labels may be hidden, and only the fuzzy structure is sent.

Thus, the plaintext is converted into a fuzzy graph representation.

3 Decryption Algorithm for Special Characters

This section presents the systematic procedure used to recover the original plaintext message from the received fuzzy graph representation. The encrypted message is transmitted in the form of a fuzzy graph defined as:

$$G = (V, E, \sigma, \mu)$$

where V represents the set of vertices, E denotes the set of edges, σ is the vertex membership function, and μ is the edge membership function.

Input: Ciphertext represented as fuzzy graph $G = (V, E, \sigma, \mu)$
Output: Reconstructed plaintext message M

Step 1: Key Retrieval and Initialization

The decryption process begins by obtaining the shared secret keys agreed upon during the encryption phase:

$$\text{Key}_1 \in (0, 1), \text{Key}_2 > 1$$

These parameters are essential for reversing the transformation applied to the vertex membership values. An empty string M is initialized to store the recovered characters.

Step 2: Character Recovery Procedure

The vertices are processed sequentially, beginning with the starting vertex v_1. For each vertex v_i, its membership value $\sigma(v_i)$ is extracted.

The positional value corresponding to the special character is computed using the inverse transformation:

$$p_i = [(\sigma(v_i) \times \text{Key}_2) - \text{Key}_1] \times 32$$

The computed value $p_i$is rounded to the nearest integer to eliminate minor numerical deviations caused by floating-point operations.

Each integer value represents the position of a special character in the predefined 32-characterASCIIsubset.Usingtheagreedcharactermappingtable,$p_i$isconvertedinto its corresponding symbol.

Therecovered symbol is appended to the message string M.This procedure is repeated forallverticesin$V$untileverycharacterhasbeenreconstructed.

Step3: Validationof Decryption

Toensurecorrectness,eachrecoveredpositionalvaluemustsatisfy:

$$p_i \in \{1,2,...,32\}$$

If all computed values lie within the valid range, the integrity of the decryption processis confirmed.

FinalOutput

Afterprocessingallvertices,thereconstructedmessageisobtainedas:

$$M=\{p_1,p_2,...,p_n\}$$

Hence, the original plaintext message consisting of special characters is successfully recovered from the fuzzy graph representation.

Model–1: Encryption and Decryption Using Special Characters

This model demonstrates the proposed fuzzy graph based encryption and decryption techniqueusingonlyASCIIspecialcharacters.

Theoriginalmessageistransformedintoa fuzzy graph, which acts as the cipher text, and later reconstructed to obtain the original message.

Plain Text $\xrightarrow{\text{Encryption}}$ Fuzzy CipherGraph $\xrightarrow{\text{Decryption}}$ OriginalPlainText

PlainTextMessage

$$M=@\#\$$$

UsingtheASCIIspecialcharactertable,thepositionalvaluesareobtainedas:

$$p_1=22, \quad p_2=3, \quad p_3=4$$

Letthesecretkeysbe:

$$Key_1= 0.2, \quad Key_2=2$$

EncryptionProcess

VertexMembershipComputation

$$\sigma(v_i)=\frac{32\ \ p_i+\text{Key}^1}{\text{Key}_2}$$

$$\sigma(v_1)=0.4437, \qquad \sigma(v_2)=0.1469, \qquad \sigma(v_3)=0.1625$$

EdgeMembershipComputation

$$\mu(v_i, v_{i+1})=\min\frac{|p_{i+1}-p_i|}{32}, \sigma(v), \sigma(v_{i+1})$$

$$\mu(v_1,v_2)=0.1469, \qquad \mu(v_2,v_3)=0.03125$$

Theencryptedmessageistransmittedasafuzzygraph.

FuzzyGraphCipherRepresentation

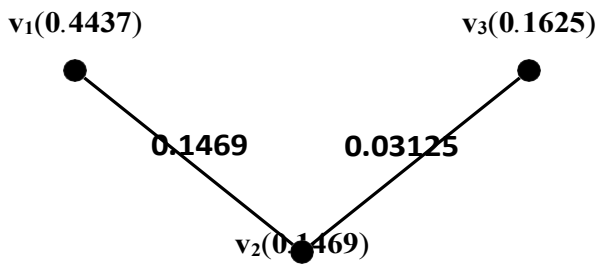

Figure 2:Fuzzy Graph Cipher Representation for Model–1 (Special Characters)

DecryptionProcess

Recovery of Characters In order to recover the original special characters, the inverse transformation is applied to each vertex membership value using the predefined decryption formula:

$$p_i=[(\sigma(v_i)\times \text{Key}_2)-\text{Key}_1]\times 32$$

Sincethecharactersetconsistsof32predefinedspecialsymbols,thescalingfactor32 is used to retrieve the positional value.

Thus,thefirstrecoveredsymbolis@.

Forthefirstvertexv_1,substitutingitsmembership value into the formula gives:

$$p_1=[(\sigma(v_1)\times \text{Key}_2)-\text{Key}_1]\times 32$$

$$p_1=22\Rightarrow @$$

Applyingthesameproceduretothesubsequentvertices:

$$p_2=[(\sigma(v_2)\times \text{Key}_2)-\text{Key}_1]\times 32$$

$$p_2=3\Rightarrow\#$$

$$p_3=[(\sigma(v_3)\times \text{Key}_2)-\text{Key}_1]\times 32$$

$$p_3=4\Rightarrow\$$$

Each computed positional value is mapped to its corresponding special character using thepredefinedASCII-basedsymboltable.

RecoveredMessage

By concatenating the recovered symbols in their original order, the final decrypted message is obtained as:

M=@#$

Hence,theoriginalplaintextmessageissuccessfullyreconstructedfromthefuzzy graph representation.

Model–2: Encryption and Decryption Using Special Characters and Alphabets

This model extends the proposed fuzzy graph based encryption scheme to handle messages containingacombinationofASCIIspecialcharactersandEnglishalphabets.Each characterismappedtoanumericalpositionandrepresentedasavertexinafuzzy graph. The relationships between consecutive characters are represented using fuzzy edge memberships.

PlainTextMessage

$$M=@\text{A}\#$$

$$p_1=22\ (@),\quad p_2=1\ (A),\quad p_3=3\ (\#)$$
$$\text{Key}_1=0.2,\quad \text{Key}_2=2$$

EncryptionProcess

VertexMembershipComputation

Eachcharacterpositionisnormalizedand converted into a fuzzy vertex membership value using the secret keys.

$$\sigma(v_i)=\frac{32^{\frac{p_i+\text{Key}_1}{\text{Key}_2}}-1}{}$$

$$\sigma(v_1)=0.4437,\quad \sigma(v_2)=0.1156,\quad \sigma(v_3)=0.1469$$

EdgeMembershipComputation The fuzzy edge membership between consecutive characters is computed as:

$$\mu(v_i, v_{i+1}) = \min\left(\frac{|p_{i+1} - p_i|}{32}, \sigma(v), \sigma(v_{i+1})\right)$$

$$\mu(v_1, v_2) = 0.1156, \qquad \mu(v_2, v_3) = 0.0625$$

Theencryptedmessageistransmittedintheformofafuzzygraph.

FuzzyGraphCipherRepresentation

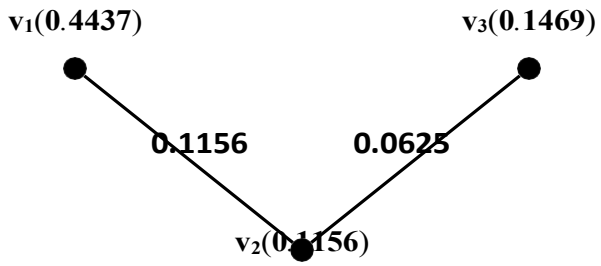

Figure 3:Fuzzy Graph Cipher Representation for Model–2 (Special Characters and Alphabets)

Decryption Process

RecoveryofCharacters

$$p_1 = [(\sigma(v_1) \times \text{Key}_2) - \text{Key}_1] \times 32$$

$$p_1 = 22 \Rightarrow @$$

$$p_2 = 1 \Rightarrow A, \qquad p_3 = 3 \Rightarrow \#$$

RecoveredMessage

$$M = @A\#$$

Thus,theoriginalplaintextmessagecontainingbothspecialcharactersandalphabets issuccessfullyreconstructedfromthefuzzygraph.

Model–3:EncryptionandDecryptionUsingNumbersandSpecial Characters

This model demonstrates the effectiveness of the proposed fuzzy graph based encryption technique for messages containing numeric digits and ASCII special characters.Each character is mapped to a numerical position value and represented as a fuzzy vertex, while therelationshipbetweenconsecutivecharactersi smodeledusingfuzzyedges.

PlainTextMessage

$$M=79\$\%\&!$$

p_1=7 (7), p_2=9 (9), p_3=4 ($), p_4=5 (%), p_5=6 (&), p_6=1(!)

Key_1= 0.2, Key_2=2

EncryptionProcess

VertexMembershipComputation Fordigits:

$$\sigma(v_i)=\frac{10^{p_i}+\text{Key}_1}{\text{Key}_2}$$

Forspecialcharacters:

$$\sigma(v_i)=\frac{32^{p_i}+\text{Key}_1}{\text{Key}_2}$$

$$\sigma(v_1)=\frac{(7/10+0.2)}{2}=0.4500,$$
$$\sigma(v_2)=\frac{(9/10+0.2)}{2}=0.5500,$$
$$\sigma(v_3)=\frac{(4/32+0.2)}{2}=0.1625,$$
$$\sigma(v_4)=\frac{(5/32+0.2)}{2}=0.1781,$$
$$\sigma(v_5)=\frac{(6/32+0.2)}{2}=0.1938,$$
$$\sigma(v_6)=\frac{(1/32+0.2)}{2}=0.1156$$

EdgeMembershipComputation

Edgesareestablishedonlybetweenconsecutive vertices belonging to the same character category. Thus, Digit–Digit and Special–Special connectionsareallowed,whereasDigit–Specialconnectionsarenotpermitted.

Thefuzzyedgemembershipbetweentwovalidconsecutiveverticesiscomputedas:

$$\mu(v_i,v_{i+1})=\min\left(\frac{|p_{i+1}-p_i|}{N},\sigma(v_i),\sigma(v_{i+1})\right)$$

where

$$N=\begin{cases}10, & \text{fordigits}\\ 32, & \text{forspecialcharacters}\end{cases}$$

Digit–DigitEdge:

Between$v_1$andv_2:

$$\mu(v_1,v_2)=\min\left(\frac{|9-7|}{10},0.4500,0.5500\right)$$

$$=\min(0.2000,0.4500,0.5500)=0.2000$$

Digit–SpecialCase:

Between$v_2$andv_3:

Sinceonevertexrepresentsadigitandtheotherrepresentsaspecialcharacter,no edge is formed.

Noedgeisestablished

Special–SpecialEdges:

Between$v_3$andv_4:

$$\mu(v_3,v_4)=\min\left\{\frac{|5-4|}{32},0.1625,0.1781\right\}=0.0313$$

Between$v_4$andv_5:

$$\mu(v_4,v_5)=\min\left\{\frac{|6-5|}{32},0.1781,0.1938\right\}=0.0313$$

Between$v_5$andv_6:

$$\mu(v_5,v_6)=\min\left\{\frac{|1-6|}{32},0.1938,0.1156\right\}=0.1156$$

FuzzyGraphCipherRepresentation

Theencryptedmessageisrepresentedasafuzzygraph$G=(V,E,\sigma,\mu)$,whereeachvertex corresponds to a character and its membership value represents the encrypted form of the plaintextsymbol.Edgesaredrawnonlybetweenconsecutivecharactersofthesametype.

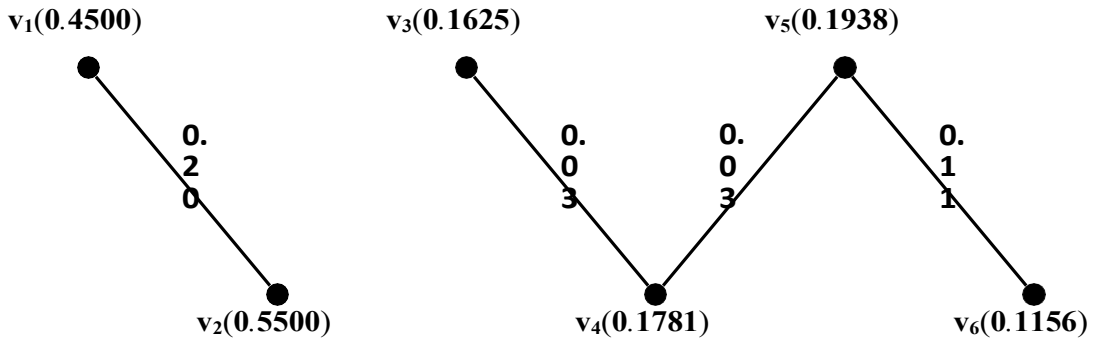

Figure 4:Fuzzy Graph Cipher Representation for Model–3 (Digits and SpecialCharacters)

DecryptionProcess

Theoriginalplaintextisrecoveredbyapplyingtheinversetransformationtoeachvertex membership value.

Thegeneral decryption formulais:

$$p_i = [(\sigma(v_i) \times \text{Key}_2) - \text{Key}_1] \times N$$

where

$$N = \begin{cases} 10, & \text{fordigits} \\ 32, & \text{forspecialcharacters} \end{cases}$$

DigitRecovery For v_1(Digit7):

$$p_1 = [(0.4500 \times 2) - 0.2] \times 10$$

$$= (0.9000 - 0.2) \times 10$$

$$= 0.7000 \times 10 = 7$$

For v_2(Digit9):

$$p_2 = [(0.5500 \times 2) - 0.2] \times 10$$

$$= (1.1000 - 0.2) \times 10$$

$$= 0.9000 \times 10 = 9$$

SpecialCharacterRecovery For v_3(\$):

$$p_3 = [(0.1625 \times 2) - 0.2] \times 32$$

$$= (0.3250 - 0.2) \times 32$$

$$= 0.1250 \times 32 = 4 \Rightarrow \$$$

For v_4(%):

$$p_4 = [(0.1781 \times 2) - 0.2] \times 32$$

$$= (0.3562 - 0.2) \times 32$$

$$= 0.1562 \times 32 = 5 \Rightarrow \%$$

For v_5(&):

$$p_5 = [(0.1938 \times 2) - 0.2] \times 32$$

$$= (0.3876 - 0.2) \times 32$$

$$=0.1876\times32=6\Rightarrow\&$$

Similarly,forv_6(!):

$$p_6=[(0.1156\times2)-0.2]\times32$$

$$=(0.2312-0.2)\times32$$

$$=0.0312\times32$$

$$=1\Rightarrow!$$

RecoveredMessage

Byconcatenatingallrecovered values:

$$M=79\$\%\&!$$

Thus, the original plaintext message is successfully reconstructed from the fuzzy graphrepresentation.

Model–4: Encryption and Decryption Using Special Characters, Numbers and Alphabets

Thismodeldemonstratestheeffectivenessofth eproposedfuzzygraphbasedencryption technique for messages containing a mixture of special characters, numeric digits and alphabetic symbols.Each character is mapped to a numerical position value and represented as a fuzzy vertex, while the relationship between consecutive characters belonging to the same category is modeled using fuzzy edges.

PlainTextMessage

$$M=\#\%79HE$$

Thepositionvaluesofthecharactersaredeterminedasfollows:

Forspecialcharacters(fromthegivenspecialcharacterpositiontable):

$$p_1=3(\#),\qquad p_2=5(\%),$$

Fordigits:

$$p_3=7(7),\qquad p_4=9(9),$$

Foralphabets(A=1,B=2,...,Z=26):

$$p_5=8(H),\qquad p_6=5(E)$$

Thechosensecretkeysare:

$$\text{Key}_1=0.2,\qquad \text{Key}_2=2$$

EncryptionProcess

VertexMembershipComputation The vertex membership value depends on the category of the character.

Fordigits:

$$\sigma(v_i)=\frac{10^{p_i}+\text{Key}1}{\text{Key}2}$$

Foralphabets:

$$\sigma(v_i)=\frac{26^{p_i}+\text{Key}1}{\text{Key}2}$$

Forspecialcharacters:

$$\sigma(v_i)=\frac{32^{p_i}+\text{Key}1}{\text{Key}2}$$

Substitutingtherespectivevalues:

$$\sigma(v_1)=\frac{(3/32+0.2)}{2}=0.1469,$$
$$\sigma(v_2)=\frac{(5/32+0.2)}{2}=0.1781,$$
$$\sigma(v_3)=\frac{(7/10+0.2)}{2}=0.4500,$$
$$\sigma(v_4)=\frac{(9/10+0.2)}{2}=0.5500,$$
$$\sigma(v_5)=\frac{(8/26+0.2)}{2}=0.2538,$$
$$\sigma(v_6)=\frac{(5/26+0.2)}{2}=0.1962$$

Edge Membership Computation

Edges are established only between consecutive vertices belonging to the same character category.Thus, Special–Special, Digit–Digitand Alphabet–Alphabet connections are allowed. However, no edges are formed between Special–Digit, Digit–Alphabet or Alphabet–Special combinations.

Thefuzzyedgemembershipbetweentwovalidconsecutiveverticesiscomputedas:

$$\mu(v_i,v_{i+1})=\min\left(\frac{|p_{i+1}-p_i|}{N},\sigma(v_i),\sigma(v_{i+1})\right)$$

where

$$N=\begin{cases}10, & \text{fordigits}\\ 26, & \text{foralphabets}\\ 32, & \text{forspecialcharacters}\end{cases}$$

Special–SpecialEdge:

Between$v_1$andv_2:

$$\mu_2(v,v)=\min\left(\frac{|5-3|}{32},0.1469,0.1781\right)$$

$$=\min(0.0625,0.1469,0.1781)=0.0625$$

Digit–DigitEdge:

Between$v_3$andv_4:

$$\mu_4(v,v)=\min\left(\frac{|9-7|}{10},0.4500,0.5500\right)$$

$$=\min(0.2000,0.4500,0.5500)=0.2000$$

Alphabet–AlphabetEdge:

Between$v_5$andv_6:

$$\mu_6(v,v)=\min\left(\frac{|5-8|}{26},0.2538,0.1962\right)$$

$$=\min(0.1154,0.2538,0.1962)=0.1154$$

CrossCategoryCases:

Between $v_2$and v_3, and between $v_4$and v_5, no edge is established since the charactersbelong to different categories.

FuzzyGraphCipherRepresentation

Theencryptedmessageisrepresentedasafuzzygraph$G=(V,E,\sigma,\mu)$,whereeachvertex corresponds to a character and its membership value represents the encrypted form of the plaintextsymbol.Edgesaredrawnonlybetweenconsecutivecharactersofthesametype.

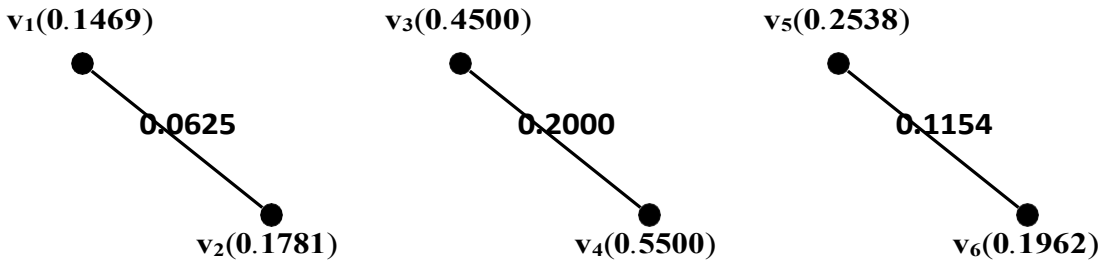

Figure5:FuzzyCipherGraphRepresentationforMixedCharacterMessage

DecryptionProcess

Theoriginalplaintextisrecoveredbyapplyingtheinversetransformationtoeachvertex membership value.

Thegeneral decryption formulais:

$$p_i=[(\sigma(v_i)\times \text{Key}_2)-\text{Key}_1]\times N$$

where

$$N = \begin{cases} 10, & \text{for digits} \\ 26, & \text{for alphabets} \\ 32, & \text{for special characters} \end{cases}$$

Applying the above formula to each vertex:

$v_1 \Rightarrow 3 \Rightarrow \#$
$v_2 \Rightarrow 5 \Rightarrow \%$
$v_3 \Rightarrow 7 \Rightarrow 7$
$v_4 \Rightarrow 9 \Rightarrow 9$
$v_5 \Rightarrow 8 \Rightarrow H$
$v_6 \Rightarrow 5 \Rightarrow E$

Recovered Message

By concatenating all recovered characters:

$$M = \#\%79HE$$

Thus, the original plaintext message is successfully reconstructed from the fuzzy graph representation.

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