Optical Cryptosystems

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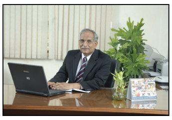

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असतो मा सदगमय ॥ तमसो मा ज्योतिर्गमय ॥ मृत्योर्मामृतम् गमय ॥

- बृहदारण्यक उपनिषद् 1.3.27

'Asato ma sadgamaya, Tamaso ma jyotirgamaya, Mrityorma amritamgamaya'

Oh Almighty! Lead us from the unreal (falsity) to the real (truth),
From darkness to light!
From death to immortality!
–Brihdaranyaka Upanisada 1:3:27 - India

अप्प दीपो भव।

"Appa Deepo Bhavah"
Be a Light unto Yourself.

Gautama Buddha

Dedicated to the memory of my parents
Shrimati Kamini Devi and Shri Balram Prasad Singh

Contents

Preface

In the digital era of contemporary society, information in any form, such as a message, text, data, image, audio, or video, can be treated as wealth. Therefore, securing information is as important as protecting property. In the history of the human race, the significance of security in one form or the other can easily be traced. Though cryptographic techniques have been in use for protecting information for thousands of years, the systematic study of cryptology as a science started around one hundred years ago. Julius Caesar (around 100 BC) was known to use a form of encryption to convey secret messages to his Army Generals. In modern times, digital techniques of information security are already in use wherein there exists scope for further improvements in terms of security level and computation cost.

Owing to the unique features of light, such as parallel processing, high speed, and several degrees of freedom, it is envisaged that information can be highly secured and communicated to the intended recipients or authentic users employing optical technologies. It can be foreseen that with the multifaceted uses of advanced technologies, such as *Artificial Intelligence*, *Big Data*, *Cloud Computing*, and *Internet-of-Things,* security will always remain an important challenge. Technologies provide several opportunities, but, at the same time, they also pose threats to information theft or misuse. Searching for a cyber expert or the attackers who attacked the digital algorithm would be very hard, because they can exist in large numbers anywhere in the world. On the other hand, finding out an attacker in the optics domain would be relatively easier. The security can be in terms of storage, in dissemination of the message, communication/transmission over conventional channels, protection of copyright/ownership, and steganography. Therefore, developments of newer alternative technologies are required to meet the challenges in the domains of scientific investigation.

This book intends to provide a collection of optical technologies for secure storage, secure communication, and the protection of copyright in terms of watermarking. Most of the optical techniques reported in literature can be traced around a double random phase encoding algorithm. Furthermore, many variants of this scheme have been proposed and demonstrated with improvements and different levels of complexity. This book aims to provide help to researchers in the field to get first-hand information of its progress.

This book starts with a general discussion on digital algorithms already in use in chapter 1 with more emphasis on the principles of optical techniques for image/data security in chapter 2. The growth of literature on optical technologies has been exponential with the publication of the first report in 1995. A bar chart has been provided that shows the growth of the literature. Use of fully-phased data provides additional security and robustness against noise, therefore such techniques have been dealt with in chapter 3. There is another aspect associated with security that is called authentication, in which the retrieval of original information is not intended. This can be solved with the use of an optical correlator, called a joint transform correlator, which is discussed in chapter 4. Optical techniques of watermarking and hiding are discussed in chapter 5. Polarization is one of the important properties of light, which is suited to developing a practical system because in this case the parameter that is dealt with is intensity, not the phase. Therefore, storage and transmission of intensity data is easier than phase-only information. This has been detailed in chapter 6.

Digital holography helps record 3D data and recording with digital sensors offers advantages in image/data security. The digital holograms can be stored in a personal computer and transmitted anywhere in the world and can be numerically reconstructed at any point of time. This has been discussed in chapter 7. Processing and security of multispectral data is very important in many applications, particularly in defence, remote sensing, and surveillance. This has been discussed in chapter 8. Chaos has always been very attractive in cryptographic studies in key design. Chapter 9 has been devoted to this topic, which has the ability to combine with other optical technologies. Phase retrieval techniques are important in regenerating object-dependent phase keys used for securing data. There are different algorithms reported in literature, which find use in image security. This has been dealt with in chapter 10.

No cryptographic technique can be considered very strong and useful unless cryptanalysis is carried out. There are several types of attacks reported in literature, which have been stated in terms of optical technologies in chapter 11. The optical technologies differ with digital counterparts, whereby in optical schemes either physical keys are used or keys are designed considering physical parameters as compared to digital keys used in electronic systems. There are various types of keys implemented in optical methods, which are discussed in chapter 12.

In all the chapters, the basic principles have been explained with examples. In some of the chapters, numerical simulation results have been provided for better understanding of the subject. Considering the requirement on some of the relevant topics, MATLAB codes have been provided. At the end of each chapter, a list of relevant literature has been provided.

The book is open to comments, criticisms, and suggestions from the readers in improving the quality of the book for future editions.

Acknowledgement

First of all, I would like to thank my mentors at the Indian Institute of Technology (IIT) Delhi during my doctoral studies. I especially thank my PhD supervisors, Professor Kehar Singh and Professor Joby Joseph, for introducing me to the exciting world of optical information processing research. Over the years they have been much more than just a thesis advisor to me. I am sure that they will be happy to see this book out in print. I must thank Dr G Unnikrishnan from IRDE Dehradun with whom I have had numerous discussions. I wish to extend my sincere thanks to Dr A K Gupta, Ex-Director IRDE Dehradun and Professor R S Sirohi, Ex-Director, IIT Delhi, for their encouragement.

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List of acronyms

AES	Advanced encryption standard
AT	Amplitude-truncated
BE	Beam expander
BR	Bacteriorhodopsin film
BS	Beam splitter
CC	Cross-correlation
CCA	Chosen-ciphertext attack
CCD	Charge-coupled device camera
CGH	Computer generated hologram
CMOS	Complementary metal-oxide semiconductor
COA	Ciphertext-only attack
CPA	Chosen-plaintext attack
CS	Compressive sensing
CT	Computed tomography
1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
DCT	Discrete cosine transform
DES	Data encryption standard
DH	Digital holography
DOE	Diffractive optical element
DRPE	Double random phase encoding
DWT	Discrete wavelet transform
EFJPS	Encrypted fractional joint power spectrum
EMD	Equal modulus decomposition
ERA	Error reduction algorithm
FT	Fourier transform
FFT	Fast Fourier transform
FRT	Fractional Fourier transform
FrT	Fresnel transform
FWT	Fractional wavelet transform
GSA	Gerchberg–Saxton algorithm
GT	Gyrator transform
GWT	Gyrator wavelet transform
HIOA	Hybrid input–output algorithm
HM	Holographic mask
HOE	Holographic optical element
HT	Hartley transform
HWP	Half wave plate
IDEA	International data encryption algorithm
IFT	Inverse Fourier transform
JPS	Joint power spectrum
JTC	Joint transform correlator
KPA	Known-plaintext attack
LC	Liquid crystal
LCT	Linear canonical transform
LCTV	Liquid crystal television
LED	Light-emitting diode

MATLAB	Matrix laboratory
MEMS	Micro-electro-mechanical systems
MO	Microscope objective
MGSA	Modified Gerchberg–Saxton algorithm
MRI	Magnetic resonance imaging
MSE	Mean square error
MZI	Mach–Zehnder interferometer
NIST	National Institute of Standards and Technology
NPCR	Number of pixel change rate
OAC	Optical asymmetric cryptosystem
OD	Optical device
PCE	Peak-to-correlation energy
PCF	Phase contrast filter
PCI	Photon counting imaging
PD	Plastic diffuser
PI	Peak intensity
PK	Private key
POCSA	Projection-onto constraints sets algorithm
POF	Phase-only function
POM	Phase-only mask
PPM	Plasmonic phase mask
PRA	Phase retrieval algorithm
PRX	Photorefractive crystal
PSDOE	Polarization selective diffractive optical element
PSI	Phase-shifting interferometry
PSNR	Peak signal-to-noise ratio
PSR	Peak-to-sidelobe ratio
PT	Phase-truncated
PTFT	Phase-truncated Fourier transform
QPS	Quadratic phase system
QR	Quick response code
QWP	Quarter wave plate
RAM	Random amplitude mask
RE	Relative error
RGB	Red, green, blue
RP	Retardation plate
RPM	Random phase mask
RSAA	Rivest, Shamir, Adleman algorithm
SAA	Simulated annealing algorithm
SC	Symmetric cryptosystems
SHA	Secure hash algorithm
SLM	Spatial light modulator
SNR	Signal-to-noise ratio
SPM	Structured phase mask
SSE	Sum squared error
SWG	Subwavelength grating
UACI	Unified average change in intensity
VAR	Variance
VLC	VanderLugt correlator
WT	Wavelet transform
XOR	Exclusive OR

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Optical Cryptosystems

Naveen K Nishchal

Chapter 1

Digital techniques of data and image encryption

1.1 Introduction

Information security is of paramount importance in today's digitally connected world. This is also called the *digital era*, in which the encryption is being considered as a fast-moving trend. Though advanced modern information security tools, storage, and retrieval mechanisms have been developed there are still enormous challenges posed by hacking tools, unsecure transmission channels, and ubiquity of the Internet. Therefore, there has been a rise in cyber security challenges globally, hence the users must be cyber prepared. Cyber security is impacting the industry. With the advent of advanced technologies such as *Internet-of-Things*, *Cloud Computing*, and *Artificial Intelligence*, it is envisaged that billions of devices would be connected. While such technologies provide several opportunities, they also pose threats to information security. Today most of the global web traffic is encrypted and it is expected that in future almost all the global web traffic will be fully encrypted. While this has enabled much greater privacy and helped prevent data breaches, cyber criminals are using these encrypted channels to propagate malware and exfiltrate data knowing that they can bypass traditional security inspection solutions that do not decrypt traffic [1–4].

The art and science of concealing information/data is called cryptography. The information/data/message to be concealed is called a plaintext (clear text) and the concealed form of message is called a ciphertext (encrypted text). In other words, cryptography is a process of converting plaintext into ciphertext and vice versa. The process of conversion from plaintext to ciphertext is called ***encryption*** and the reverse process that retrieves plaintext from ciphertext is called ***decryption***. The ciphertext is a message that cannot be understood by anyone or is a meaningless message. A cipher is an algorithm used for encryption and decryption. The ciphertext is stored and transmitted to the intended user. The cryptography is not only used for protecting the information from theft or alteration but it is also used for user authentication [5–7].

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A cryptosystem, also referred to as a cipher system, is an implementation of cryptographic techniques and their accompanying infrastructure to provide information security services. Though cryptographic techniques have been in use for protecting information for thousands of years, the systematic study of cryptology as a science started around one hundred years ago. Therefore, cryptology is considered as a young science. Julius Caesar (around 100 BC) was known to use a form of encryption to convey secret messages to his Army Generals. The substitution cipher, known as the Caesar cipher is probably the most mentioned historic cipher in academic literature [3]. In this method, each character of a plaintext is substituted by another character to form the ciphertext. The variant used by Caesar was a shift by three ciphers. Each character was shifted by three places, so the character ‘A’ was replaced by ‘D’ and character ‘B’ was replaced by ‘E’ and so on. The characters would wrap around at the end, so character ‘X’ would be replaced by ‘A’. An example of the character substitution based on Caesar’s algorithm has been shown in figure 1.1.

Figure 1.2 shows the schematic of the modern encryption-decryption process. A plaintext is converted into a ciphertext through the encryption process, which upon use of correct keys returns the decrypted plaintext [4].

A basic cryptosystem has the following components [5]:

- Plaintext
- Encryption algorithm
- Ciphertext
- Decryption algorithm
- Encryption key
- Decryption key.

Figure 1.1. Example of character substitution based on Caesar’s algorithm.

Figure 1.2. Encryption-decryption process.

A plaintext is converted into a ciphertext by applying the encryption algorithm and encryption key. The key space is a string of different keys that can be used to break the algorithm. It is generally accepted that a secure algorithm should use a key with length greater than 100 bits, because the number of bit permutation operations required to try 2^{100} keys is considered to be computationally infeasible for a conventional digital computing technique. A secure encryption algorithm is extremely sensitive to its keys. Various encryption algorithms have been developed and are being practiced. A ciphertext returns the plaintext only after use of the appropriate decryption algorithm and correct decryption key. A slight change to the keys would result in different ciphers. Thus for the successful retrieval of the plaintext, use of the correct decryption key and appropriate decryption algorithm is a must. In different types of cryptosystems, different encryption and decryption algorithms are used and correspondingly different encryption and decryption keys are generated.

While cryptography is the science of securing data, cryptanalysis is the science of analyzing and breaking a secure communication. The professionals involved in the process are called cryptanalysts. They are also called attackers. Attackers always wish to get the access of the encryption-decryption key so that plaintext can be retrieved. In classical cryptanalysis, several things are involved in the process, such as the interesting combination of analytical reasoning, the application of mathematical tools, pattern finding, patience, determination, and luck. With the passage of time, newer and reliable cryptosystems have been developed. On the other hand, attackers have also been creating improved logic to analyze the process to access the data. The pace of the development of information security technology is characterized by the creation of new methods and means of protection in the context of the storage, processing, and transmission of information. To date, much attention has been paid to the development of newer methods of intellectualization of various automated systems.

The cryptology embraces both cryptography and cryptanalysis. The cryptography can provide the following services [6].

- **Confidentiality (secrecy)**: it ensures that no one can read the concealed message except the authentic receiver. The data is kept secret from those who do not have proper credentials, even if that the data travels through an insecure medium.
- **Integrity (anti-tampering)**: it is assured that the authentic receiver has received message and it has not been altered in any way from the original.
- **Authentication**: it helps establish identity for authentication purposes. Actually, the process proves one’s identity.
- **Non-repudiation**: it is a mechanism to prove that the sender really sent this message. Neither the sender nor the receiver can deny the transmission of the message.
- **Access control**: it requires that the access to information resources may be controlled by or for the authentic system.
- **Availability**: it requires that the system assets be available to authorized personnel, as and when needed.

1.2 Types of cryptography

Depending on the common uses, cryptography can be classified into two categories; *symmetric key cryptography* and *asymmetric key cryptography*. Symmetric key cryptography is a classical encryption method. It is referred to as a situation in which the key used for encryption is as used for decryption. In this case, key distribution must be performed prior to data transfer. Therefore, the security key plays a highly significant role because security directly depends on the nature of the key. Asymmetric key cryptography is an advanced encryption method. It is referred to as a situation in which the key used for encryption is different than the key used for decryption. In this case, a pair of keys, public and private keys, are used. The security is very high compared to the classical method of encryption.

Of late, hash functions are also considered as a type of cryptography, which establishes the authenticity of the user [7].

1.2.1 Symmetric key cryptography

Symmetric key cryptography, also known as secret key cryptography or conventional cryptography, refers to an encryption system in which the sender and receiver share a single common key that is used to encrypt and decrypt the message. The process is shown in figure 1.3. The used algorithm is known as the symmetric algorithm or secret key algorithm. The key is defined as a piece of information (a parameter) that determines the functional output of a cryptographic algorithm or cipher. The key used for encrypting and decrypting a message has to be known to all the authentic recipients or else the message could not be decrypted by conventional means [6]. The examples of symmetric key cryptography are discussed below.

- **Data encryption standard (DES)**: the DES was published in 1977 by the US National Bureau of Standards. It uses a 56-bit key and maps a 64-bit input block of plaintext onto a 64-bit output block of ciphertext. 56 bits is a rather small key for today's computing power.
- **Triple DES**: it is an improved version created after overcoming the shortcomings of DES. Since it is based on the DES algorithm, it is very easy to modify existing software to use Triple DES. It has the advantage of proven reliability and a longer key length that eliminates many of the shortcut attacks that can be used to reduce the amount of time it takes to break the DES.
- **Advanced encryption standard (AES)**: the AES is an encryption standard adopted by the US Government. The standard comprises three block ciphers, AES-128, AES-192, and AES-256. Each AES cipher has a 128-bit block size with key sizes of 128, 192, and 256 bits, respectively. The AES ciphers have been analyzed extensively and are now used worldwide.

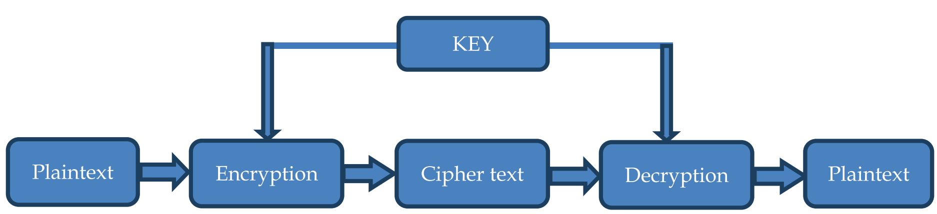

Figure 1.3. Symmetric key cryptography.

- **International data encryption algorithm (IDEA)**: the IDEA was developed in 1991. It uses a 128-bit key to encrypt a 64-bit block of plaintext into a 64-bit block of ciphertext. IDEA's general structure is very similar to DES. It performs 17 rounds, each round taking 64 bits of input to produce a 64-bit output, using per-round keys generated from the 128-bit key.

Key management in symmetric key systems

The symmetric key systems are simpler and faster but their main drawback is that the two parties must somehow exchange the key in a secure way and keep it secure after that. The key management caused a nightmare for the parties using the symmetric key cryptography. The worry was about how to get the keys safely and securely across all users so that the decryption of the message would be possible. This gave the chance for third parties to intercept the keys in transit to decode the secret messages. Thus, if the key was compromised, the entire coding system was compromised and a 'secret' would no longer remain a 'secret'.

1.2.2 Asymmetric key cryptography

Asymmetric key cryptography is also known as public key cryptography. It refers to a cryptographic algorithm which requires two separate keys, one of which is private and another is public. The public key is used to encrypt the message and the private one is used to decrypt the message. This method was developed to address the key management issue of symmetric key cryptography. The process of asymmetric cryptography is shown in figure 1.4. It is a very advanced form of cryptography. Officially, it was invented by Whitfield Diffie and Martin Hellman in 1975. The basic technique of public key cryptography was first discovered in 1973 by the British Clifford Cocks of Communications-Electronics Security Group but this was a secret until 1997. The examples of symmetric key cryptography are discussed below [6].

- **Digital signature standard (DSS)**: the DSS is a digital signature algorithm developed by the US National Security Agency to generate a digital signature for the authentication of electronic documents. DSS was put forth by the National Institute of Standards and Technology (NIST) in 1994.
- **RSA**: (Rivest, Shamir, and Adleman who first publicly described it in 1977) It is an algorithm for public-key cryptography. It is the first algorithm known to be suitable for signing as well as encryption, and one of the first great advances in public key cryptography. RSA is widely used in electronic

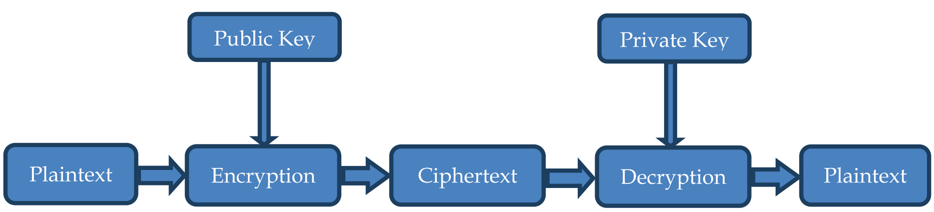

Figure 1.4. Asymmetric key cryptography.

commerce protocols, and is believed to be secure given sufficiently long keys and the use of up-to-date implementations.

- **ElGamal**: ElGamal is a public key method. It is used in both encryption and digital signing. The encryption algorithm is similar in nature to the Diffie–Hellman key agreement protocol and is used in many applications and uses discrete logarithms. ElGamal encryption is used in the free GNU Privacy Guard software.

1.2.3 Hash functions

A cryptographic hash function is a hash function that takes an arbitrary block of data and returns a fixed-size bit string, the cryptographic hash value such that any (accidental or intentional) change to the data will (with very high probability) change the hash value [7]. The data to be encoded is often called the message, and the hash values are sometimes called the message digest or simply digest. The ideal cryptographic hash function has four main properties:

- It is easy to compute the hash value for any given message.
- It is infeasible to generate a message that has a given hash.
- It is infeasible to modify a message without changing the hash.
- It is infeasible to find two different messages with the same hash.

The examples of hash functions are discussed below.

- **Secure hash algorithm (SHA)**: SHA hash functions are a set of cryptographic hash functions designed by the National Security Agency and published by the NIST as a US Federal Information Processing Standard. Because of the successful attacks on MD5, SHA-0 and theoretical attacks on SHA-1, NIST perceived a need for an alternative, dissimilar cryptographic hash, which became SHA-3. In October 2012, the NIST chose the Keccak algorithm as the new SHA-3 standard.

As multimedia, image, and video are becoming increasingly part of modern economy and social companions, ensuring security from malicious interference, theft, and unauthorized use has become the demand of the hour. Encryption of images is one of the well-known mechanisms to preserve confidentiality of images/data over a reliable unrestricted public media, which is vulnerable to attacks. The image encryption algorithms can be classified into frequency-domain and spatial-domain algorithms. Both are able to protect the data/image with a high level of security. Their output encrypted images are either texture-like or noise-like images. From a security point of view, it is an obvious visual sign indicating the presence of an encrypted image that may contain some important information. It is apprehended that this will attract people's attention and can result in a significantly large number of attacks and analysis. The solution has been reported in the form that the original image is transformed into visually meaningful encrypted images. This is because people generally consider these images as normal images rather than encrypted ones.

Securing data/image is important in all the domains including medical diagnosis. There is a fear that patients' computed tomography (CT) and medical resonance imaging (MRI) scan results can easily be changed by hackers, thereby deceiving radiologists and artificial intelligence algorithms that diagnose malignant tumors. The hackers could access to add or remove medical conditions from the scans for the purpose of insurance fraud, ransom, and even homicide. A large number of techniques have been proposed in literature to date, each have an edge over the other, to catch up to the ever-growing need of security. The focus has been devising a mechanism for image encryption that should have the following characteristics.

• **Low correlation**	The value of correlation between the original and the encrypted image should be as low as possible. Ideally its value should be zero.
• **Large key space**	The key size should be very large since the more the key space, the higher the brute force search time would be.
• **Key sensitivity**	The image encryption algorithm should have high key sensitivity. In other words, a slight change in the key value should change the encrypted image significantly.
• **Entropy**	It is a measure of the degree of randomness or disorder. As the level of disorder rises, the entropy rises, and events become less predictable. The minimum entropy value should be zero and it happens when the image pixel value is constant in any location. The maximum value of entropy for an image depends on the number of gray scales. For an image with 256 gray scales, the maximum entropy is log 2(256) = 8. The maximum value happens when all bins of the histogram have the same constant value, or, image intensity is uniformly distributed in [0,255].
Low time complexity	Usually, an encryption algorithm with high computational time is not recommended for practical applications. Therefore, an image encryption algorithm should have low time complexity.

The technology for information security using digital methods is being enhanced by applying more powerful algorithms. Longer key lengths are chosen such that current computers using the best cipher-cracking algorithms would require an unreasonable amount of time to break the key. When encryption key length becomes longer, the processing speed of digital techniques goes down. In order to counter the processing speed and security problem, in 1995 a new technology was proposed that used physical keys employing the principles of classical optics. Owing to the speed of light, it is envisaged that data can be secured at unparalleled speed along with parallel processing. Additionally, optics offers several degrees of freedom that could help encode information more securely [8–14]. Also, there is a natural match between optical processing for optical communications.

With the belief that cryptology based on the optics principle would provide a more complex environment and would be more resistant as compared to purely digital techniques, developing optical cryptosystems have gained much emphasis [13, 14]. Since 1995, a large number of research articles have appeared with so many different techniques. These topics are discussed in detail in the following chapters.

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