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Information Theoretic Security

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Abstract

The topic of information theoretic security is introduced and the principal results in this area are reviewed. The basic wire-tap channel model is considered first, and then several specific types of wire-tap channels are considered, including Gaussian, multi-input multi-output (MIMO), compound, and feedback wire-tap channels, as well as the wire-tap channel with side information. Practical code design techniques to achieve secrecy for wire-tap channels are also introduced. The wire-tap formalism is then extended to the basic channels of multi-user networks, including broadcast channels, multiple-access channels (MACs), interference channels, relay channels and two-way channels. For all of these models, results on the fundamental communication limits under secrecy constraints and corresponding coding schemes are reviewed. Furthermore, several related topics including key agreement through common randomness, secure network coding, authentication, cross-layer design, and secure source coding are discussed.

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1

Introduction

1.1 Confidentiality and Encryption

Security is one of the most important issues in communications. Security issues arising in communication networks include confidentiality, integrity, authentication, and nonrepudiation. Confidentiality guarantees that legitimate recipients successfully obtain source information intended for them, while eavesdroppers are not able to interpret this information. Integrity guarantees that original source information is not modified by malicious actors during its transmission. Authentication ensures that a recipient of information is able to identify the sender from which that information has been sent. Nonrepudiation guarantees that a sender of information is not able to deny having transmitted that information and the recipient is not able to deny having received the information.

Attacks on the security of communication networks can be divided into two basic types: *passive attacks* and *active attacks*. An active attack corresponds to the situation in which a malicious actor intentionally disrupts the system. Alternatively, a passive attack corresponds to the situation in which a malicious actor attempts to interpret source

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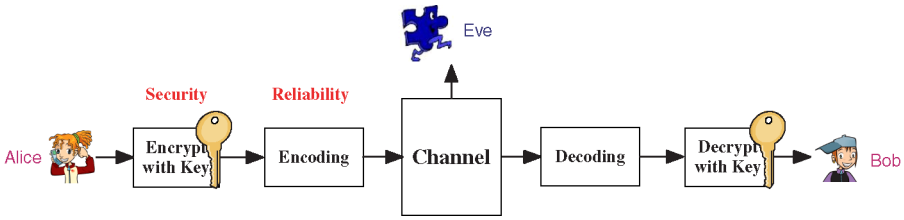

Fig. 1.1 Illustration of encryption with channel coding.

information without injecting any information or trying to modify the information; i.e., passive attackers listen to the transmission without modifying it. This paper focuses primarily on confidentiality issues, and passive attacks are of primary concern in this context.

Conventional techniques for achieving confidentiality in communication networks are based on cryptographic encryption [122, 148], which is depicted in Figure 1.1. In encryption, a transmitter (Alice) uses a key to encrypt source information, i.e., *plaintext*, to convert it into *ciphertext*. The intended receiver (Bob) extracts the original plaintext from the ciphertext by a corresponding key. If an eavesdropper (Eve) has access to the ciphertext, but it does not know the corresponding decryption key, then it cannot obtain the source information. As a practical matter, the eavesdropper can be assumed to have limited time or limited computational resources so that it cannot test all possible keys to extract the source information. This process is illustrated in Figure 1.1, in which additional encoding and decoding steps, which involve physical layer techniques to combat channel transmission errors, are also shown.

Encryption includes two principal types of algorithms: *secret-key encryption* algorithms and *public-key encryption* algorithms. Secret-key encryption is also referred to as *symmetric key encryption*, because the transmitter and the receiver share a common secret key. The transmitter encrypts the plaintext and the receiver decrypts the ciphertext with the same key. For public-key encryption, which is also referred to as *asymmetric key encryption*, the transmitter and the receiver have different keys for encryption and decryption. The transmitter encrypts the plaintext by a public key, which is known publicly to all potential users

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of the network, including any eavesdroppers. The intended receiver maintains a private key corresponding to the public key, with which the receiver can extract the plaintext encrypted by the public key. It is in general mathematically difficult (almost computationally impossible) for other users to derive this private key with only the information about the public key. Hence, in practice, an eavesdropper can obtain no source information without the private key.

As compared to public-key algorithms, secret-key algorithms are computationally efficient, and result in higher data throughput, while presenting challenges for key management, such as secure key storage and distribution [7, 15, 20, 35, 38, 65, 100, 134, 167, 181, 184, 185]. Public-key algorithms are simple in terms of key management, but require considerable computational resources [122]. Hence, hybrid cryptosystems [26, 31] are employed in practice, to facilitate key management and achieve high efficiency, in which a secret key is distributed by public-key algorithms, and encryption and decryption can then use secret-key algorithms. However, several disadvantages of public-key algorithms are of serious concern for hybrid cryptosystems. Besides high computational cost, public-key algorithms are not provably perfectly secure and are vulnerable to the so-called man-in-the-middle attack [122]. Moreover, using public-key algorithms to distribute secret keys adds another layer of complexity in the design of networks.

In addition to these general considerations, providing secure communication over *wireless* networks using cryptographic approaches presents further significant challenges due to: (1) the open nature of the wireless medium, which allows eavesdroppers and attackers to intercept information transmission (in particular, transmission of secret keys) or to degrade transmission quality; (2) the lack of infrastructure in decentralized networks, which makes key distribution difficult; and (3) the dynamic topology of mobile networks (e.g., mobile *ad hoc* networks), which makes key management expensive.

The information theoretic approach to achieving secure communication opens a promising new direction toward solving wireless networking security problems. Such an approach was initiated by Wyner [169] and by Csiszár and Körner [27] in the 1970's, who demonstrated that *confidential messages* can be transmitted securely without using

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an encryption key. Study of the related topic of *secret-key agreement* (including generation and distribution) via information theoretic analysis was later proposed in Maurer's work [115, 116] and in Ahlswede and Csiszár's work [4], which demonstrate that two or multiple legitimate nodes can agree on a key (for encryption later on) kept secret from an eavesdropper. More recently, the emergence and increasing ubiquity of wireless networks, and in particular of networks with minimal infrastructure, have spurred considerable interest in this area. In particular, the promise of this potentially very powerful approach for use in mobile and other wireless networks has been brought to the attention of the wireless networking community.

1.2 Information Theoretic Analysis of Cryptosystems

Information theoretic analysis of secrecy was initiated by Shannon in [145], in which a cryptosystem (see Figure 1.2) was considered. In Shannon's model, a source message W is encrypted to a ciphertext E by a key K shared by the transmitter and receiver. An eavesdropper, which knows the family of encryption functions (keys) and the probability of choosing keys, may intercept the ciphertext E. The system is considered to be *perfectly secure* if the *a posteriori* probabilities of W given E are equal to the *a priori* probabilities of W for all E, i.e., $P_{W|E} = P_W$. It was shown in [145] that the number of different keys must be at least as large as the number of messages to achieve perfect secrecy.

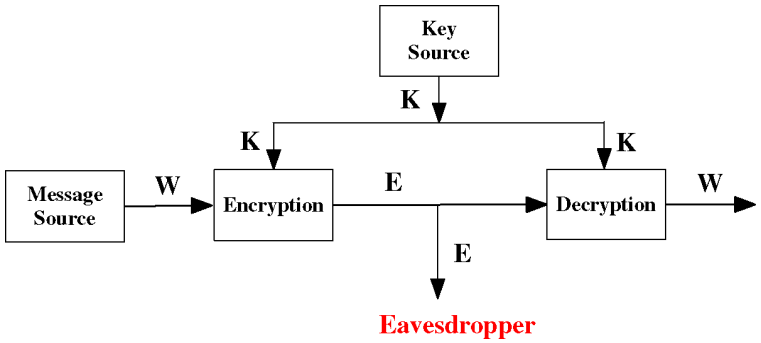

Fig. 1.2 A cryptosystem.

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Furthermore, the *entropy* was introduced to measure the amount of information associated with a message and the amount of uncertainty associated with the possibilities of a key, i.e., $H(W)$ and $H(K)$, respectively. The notion of the *equivocation* was also introduced in [145] to measure the eavesdropper's uncertainty about the message and the key, namely, the conditional entropies $H(W\,|\,E)$ and $H(K\,|\,E)$. (The reader can refer to Appendix A.1 for the definitions and the properties of these quantities.) We note that the entropy of a random variable indicates the average length of a binary sequence (in bits) required to represent the random variable (with small probability of error). Based on the properties of the entropy, we obtain

$$H(K,W) = H(K) + H(W), \tag{1.1}$$

$$H(K,W) = H(K,W,E) = H(K,E) = H(E) + H(K\,|\,E), \tag{1.2}$$

and

$$H(K,W) = H(K,W,E) \geq H(W,E) = H(E) + H(W\,|\,E). \tag{1.3}$$

In the case of perfect secrecy, i.e., $H(W) = H(W\,|\,E)$, (1.1) and (1.3) imply $H(K) \geq H(E)$. Moreover, if $H(E) = H(W)$, then (1.1) and (1.2) imply $H(K) = H(K\,|\,E)$, i.e., no information about the key can be inferred from the ciphertext E. On the other hand, if $H(E) = H(W) + H(K)$, then (1.1) and (1.2) imply $H(K\,|\,E) = 0$, i.e., the key can be determined from E. Hence, the value of $H(E) = H(W) + H(K)$ defines the *unicity distance*, i.e., the minimum length of the ciphertext that guarantees recovery of the key used for encryption.

1.3 Information Theoretic Security

Although the scenarios considered in [145] are cryptosystems, the equivocation, which quantifies how unlikely it is that the eavesdropper can infer source information from its received information, is central to information theoretic security as developed later for systems without using encryption keys [27, 169]. This quantifiable measure also enables secrecy to be jointly considered with the traditional measure of reliability, namely the error probability (at the legitimate receiver), and hence facilitates the application of information theoretic techniques to

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characterize the fundamental communication limits of communication networks under secrecy constraints.

The basic idea of the information theoretic approach to securely transmit conferential messages (without using an encryption key) to a legitimate receiver is to use the inherent randomness of the physical medium (including noises and channel fluctuations due to fading) and exploit the difference between the channel to a legitimate receiver and the channel to an eavesdropper to benefit the legitimate receiver. In this approach, a transmitter intentionally adds structural randomness (stochastic coding) to prevent potential eavesdroppers and attackers from intercepting useful information while guaranteeing that a legitimate receiver can obtain the information. Figure 1.3 illustrates a system that exploits information theoretic security. In this system, the "encryption" and "encoding" of Figure 1.1 are now combined into a single design block for "secure encoding," which guarantees both reliability, i.e., the receiver can successfully decode source messages, and security, i.e., the source messages are guaranteed to be secret from an eavesdropper.

Compared to contemporary cryptosystems, information theoretic approaches to guarantee secrecy have the advantages of eliminating

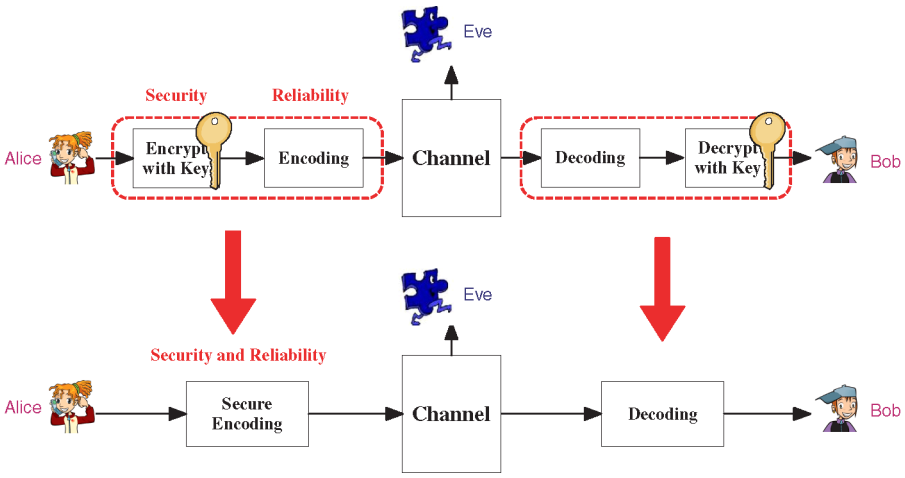

Fig. 1.3 Information theoretic security.

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the key management issue, thereby resulting in significantly lower complexity and savings in resources. Furthermore, compared to public-key algorithms for key management in hybrid cryptosystems, the information theoretic security approaches are less vulnerable to the man-in-the-middle attack [78, 113, 114, 141, 146, 162, 171] due to the intrinsic randomness shared by terminals. Moreover, information theoretic security approaches achieve provable security that is robust to powerful eavesdroppers possessing unlimited computational resources, knowledge of the communication strategy employed including coding and decoding algorithms, and access to communication systems either through perfect or noisy channels.

While information theoretic security approaches exploit physical layer attributes of channel randomness for secure communications, and encryption keys are not necessary, these approaches can also be applied to existing cryptosystems to add an additional level of protection for information transmission or to achieve key agreement (including key generation and distribution) for remote terminals. The idea of applying information theoretic approaches to achieve secret-key (SK) agreement exploits initially shared correlated sources (observations) among legitimate terminals or channel transmission between these terminals. In the simplest model [4, 116], two terminals, each observing correlated source sequences, can agree on a key by communicating over a noiseless public channel using Slepian–Wolf coding [23, 147]. This coding scheme also guarantees that the key is kept secret from an eavesdropper that has access to this public communication. It was also shown in [4] that noisy communication channels can also be exploited to create correlated sequences at the two terminals, thereby allowing them to agree on a secret key.

We note that there is a difference between the two problems of information theoretic security that we mentioned so far, namely, transmission of confidential messages and SK agreement. The latter allows public discussion between legitimate terminals in the process, and secure channel transmission may not be necessary if legitimate terminals share correlated source sequences initially in this latter case. However, there is also a connection between the two problems as secrecy transmission may be used to create a secret key (although without

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public transmission), and an established secret key helps mitigate conditions required for secrecy transmission by transmitting part of the source information by encryption and only the rest of the information via secrecy transmission.

In this paper, we will focus on the problem of transmission of confidential messages, and will address the problem of SK agreement only in one section to illustrate the main idea. We refer the reader to the corresponding references for further details. We also note that in addition to the two problems mentioned above, information theoretic security covers a variety of other topics that are not included in this paper, for example, the identification problem [6, 32], biometric security [60, 61, 79, 80], and the principle of reciprocity [9, 128, 166].

We finally note that the topics we have included in this paper reflect the subjective views of the authors, and should not be considered as a comprehensive overview of information theoretic security and its applications. Within the page limitations of such a work, we can present only selected topics, and thus we focus on what we consider to be the most timely issues.

1.4 Organization of the Paper

This paper provides an overview of how information theoretic approaches are developed to achieve secrecy for a basic wire-tap channel model as well as for its extensions to multi-user networks. In Section 2, we introduce the basic wire-tap channel and derive the secrecy capacity of this channel. We also describe basic coding techniques that achieve the secrecy capacity and introduce the converse methodology to prove the optimality of these techniques. In Section 3, we consider several special classes of wire-tap channels, and discuss the secrecy capacities for these channels. In Section 4, we introduce practical code design techniques that can achieve secrecy over the wire-tap channel. In Sections 5–8, we address extensions of the basic wire-tap channel to several basic multi-user network models including the broadcast channel, the multiple-access channel (MAC), the interference channel, the relay channel and the two-way channel. In Sections 9 and 10, we review several other topics in information theoretic security,

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including key agreement through common randomness, secure network coding, authentication, cross-layer design, and secure source coding. In Appendix A, we present basic definitions and properties from information theory that are used in the main text, for the benefit of the reader who is unfamiliar with these notions.

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