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Achieving Individual Secrecy

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Broadcast Channel with Receiver Side Information: Achieving Individual Secrecy

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Abstract—In this paper, we study the problem of secure communication over the broadcast channel with receiver side information, under the lens of individual secrecy constraints (i.e., information leakage from each message to an eavesdropper is made vanishing). Several coding schemes are proposed by extending known results in broadcast channels to this secrecy setting. In particular, individual secrecy provided via one-time pad signal is utilized in the coding schemes. As a preliminary result, we obtain a general achievable region together with a characterization of the capacity region for the case of a degraded eavesdropper.

I. INTRODUCTION

The broadcast channel is a fundamental communication model that involves transmission of independent messages to different users. In this paper, we consider the secure transmission of independent messages to two receivers which have, respectively, the desired message of the other receiver as side information. The model is shown in Fig. 1. The problem (without an eavesdropper) was originally motivated by the concept of the bidirectional relay channel, where two nodes exchange messages via a relay node. If the relay node decodes both messages, then it can broadcast a common codeword to both nodes each having their own message as side information. In [1], the broadcasting capacity region (without an eavesdropper) has been completely characterized.

The model of the broadcast channel with receiver side information (BC-RSI) with an external eavesdropper has been studied in [2]. The authors proposed achievable rate regions and outer bounds for a joint secrecy constraint, whereby the information leakage from both messages to the eavesdropper is made vanishing. Differently from [2], we review the problem under individual secrecy constraints that aim to minimize the information leakage from each message to the eavesdropper. Although individual secrecy constraints are by definition weaker than the joint one, they nevertheless provide an acceptable security strength that keeps each legitimate receiver away from an invasion of secrecy. In addition, a joint secrecy constraint can be difficult or even impossible to fulfill in certain cases. So, in this paper, our main concern is to characterize the fundamental limits of secure communications under the individual secrecy constraints for the BC-RSI model.

II. SYSTEM MODEL

Consider a discrete memoryless broadcast channel given by

\[ p(y_1, y_2, z|x) \]

with two legitimate receivers and one passive eavesdropper. The transmitter aims to send messages \( m_1, m_2 \) to receiver 1, 2, respectively. Suppose \( x^n \) is the channel input, whilst \( y_1^n \) (at receiver 1), \( y_2^n \) (at receiver 2) and \( z^n \) (at eavesdropper), are the channel outputs. Besides, \( m_2 \) (available at receiver 1) and \( m_1 \) (available at receiver 2), serve also as side information that may help to decode the desired message. (Unless otherwise specified, we use capital letters for random variables and corresponding small cases for their realizations.)

Denote the average probability of decoding error at receiver \( i \) to be \( P_{e,i} \). The rate pair \((R_1, R_2)\) is said to be achievable, if for any \( \epsilon > 0 \), there exists an encoder-decoder such that

\[
\frac{1}{n} H(M_i) \geq R_i - \epsilon
\]

\[
P_{e,i} \leq \epsilon
\]

\[
\frac{1}{n} I(M_i; Z^n) \leq \epsilon,
\]

for \( i = 1, 2 \) and for sufficiently large \( n \). Equation (3) corresponds to individual secrecy constraints. If the coding scheme fulfills a stronger condition that

\[
\frac{1}{n} I(M_1, M_2; Z^n) \leq \epsilon,
\]

then it is said to satisfy the joint secrecy constraint.

We recall the capacity region of the discrete memoryless broadcast channel with receiver side information, when none of the secrecy constraints are taken into account.

**Theorem 1.** ([1, Theorem 1]) The capacity region of the discrete memoryless broadcast channel \( p(y_1, y_2|x) \) with receiver side information is the set of the rate pairs \((R_1, R_2)\) such that

\[
R_1 \leq I(X; Y_1) \quad \text{and} \quad R_2 \leq I(X; Y_2)
\]

over all possible pmf \( p(x) \).
III. INDIVIDUAL-SECRET RATE REGION

A. Secret key approach

Consider the symmetric secret rate region where $R_1 = R_2 = R$, i.e., $M_1$ and $M_2$ are of the same entropy. One can apply a one-time pad approach as proposed in [2]. With this scheme, the following rate region is achievable.

Proposition 2. Any $(R_1, R_2) \in \mathbb{R}^+$ satisfying

$$R_1 = R_2 \leq \min\{I(X; Y_1), I(X; Y_2)\}$$

for any $p(x)$ is achievable.

Proof: Randomly generate $2^nR$ codewords $x^n$ according to $\prod_{i=1}^n p(x_i)$. Given $(m_1, m_2)$, send $x^n(m_k)$ with $m_k = m_1 \oplus m_2$ to the channel. Both receivers can decode reliably by utilizing their side information to extract intended messages if $R_1 = R_2 \leq \min\{I(X; Y_1), I(X; Y_2)\}$.

For the secrecy constraint, we have for $i = 1, 2$,

$$I(M_i; Z^n) \leq I(M_i; Z^n, M_k) = I(M_i; M_k) = 0$$

(7)

where the 1st equality is due to Markov chain $M_i \rightarrow M_k \rightarrow Z^n$; and the 2nd is since $M_k$ is a one-time pad of $M_i$.

Note that the above achievable region is limited by the worse channel. In the following, we consider other coding schemes to enlarge the achievable region beyond the one stated above.

B. Secrecy coding approach

Consider those channel inputs $p(x)$ such that $I(X; Z) \leq \min\{I(X; Y_1), I(X; Y_2)\}$. Assume that $I(X; Y_2) \leq I(X; Y_1)$. For such cases, we split $M_1$ into two parts: one of entropy $nI(X; Y_1) - I(X; Y_2)$ which is secured by using secrecy coding for classical wiretap channels; and the other of entropy $nI(X; Y_2)$ which is secured by capsuling with $M_2$ in a one-time pad (thus $M_2$ is also secured). We obtain the following.

Proposition 3. Any $(R_1, R_2) \in \mathbb{R}^+$ satisfying

$$I(X; Z) \leq R_1 \leq I(X; Y_1), \quad I(X; Z) \leq R_2 \leq I(X; Y_2)$$

(8)

for $p(x)$ such that $I(X; Z) \leq \min\{I(X; Y_1), I(X; Y_2)\}$ is achievable.

Proof: Assume that $R_2 \leq R_1$. We split $M_1$ into two parts, i.e., $M_1 = (M_{1k}, M_{1s})$ with $M_{1k}$ of entropy $nR_2$, the same as $M_2$; whilst $M_{1s}$ of entropy $n(R_1 - R_2)$. Randomly generate $2^{nR_2}$ codewords $x^n$ according to $\prod_{i=1}^n p(x_i)$. Throw them into $2^{n(R_1 - R_2)}$ bins [3] and index them as $x^n(i_{kz}, i_{ks}, i_{zs})$ with $i_k = (i_{kz}, i_{ks}) \in [1 : 2^{n(I(X; Z) - \epsilon)}] \times [1 : 2^{n(R_1 - I(X; Z) + \epsilon)}]$. Correspondingly, split $M_k = (M_{kz}, M_{ks})$. We have

$$H(M_{1s}, M_{kz}|Z^n) = H(M_{1s}, M_{ks}, X^n|Z^n) - H(X^n|M_{1s}, M_{ks}, Z^n)$$

(9)

$$\geq H(M_{1s}, M_{zk}, X^n|Z^n) - H(Z^n) - n\epsilon_1$$

$$= H(X^n) + H(Z^n|X^n) - H(Z^n) - n\epsilon_1$$

(10)

where (a) follows as $H(X^n|M_{1s}, M_{zk}, Z^n) \leq n\epsilon_1$ due to Fano’s inequality and that the eavesdropper can decode $X^n$ reliably, given $(M_{1s}, M_{zk}, Z^n)$; (b) is due to the fact that $H(X^n) = nR_1$; (c) is the fact that $H(Z^n) = nR_2 - I(X; Z) + \epsilon$.

Above inequality implies $H(M_{1s}; Z^n) \leq n\delta(\epsilon)$. In addition, we bound $I(M_{1k} ; Z^n|M_{1s}) \leq I(M_{1k} ; Z^n, M_{1s}) = I(M_{1k}; M_{ks}) = 0$ due to Markov chain $M_{1k} \rightarrow (M_{kz}, M_{ks}) \rightarrow Z^n$. Therefore, we obtain

$$H(M_1; Z^n) = H(M_{1s}; Z^n) + I(M_{1k}; Z^n|M_{1s}) \leq n\delta(\epsilon).$$

This concludes the individual secrecy proof.

Proposition 4. If the channel to the eavesdropper is degraded with respect to the channels of both legitimate receivers, then the individual-secret capacity region is given by the union of $(R_1, R_2) \in \mathbb{R}^+$ pairs satisfying

$$R_1 \leq \min\{I(X; Y_1) - I(X; Z) + R_2, I(X; Y_1)\};$$

$$R_2 \leq \min\{I(X; Y_2) - I(X; Z) + R_1, I(X; Y_2)\},$$

(9)

where the union is taken over $p(x)$.

Proof: With the degraded condition, we have $I(X; Z) \leq \min\{I(X; Y_1), I(X; Y_2)\}$ for any $p(x)$. Denote $R_1$ to be the region achievable by Proposition 3, as defined in (8). Further, denote $R_2 = ((R_1, R_2) : R_1 \geq 0, R_2 \leq I(X; Y_2) - I(X; Z))$ and $R_3 = ((R_1, R_2) : R_1 \leq I(X; Y_1) - I(X; Z), R_2 = 0)$, which are achievable by employing Wyner’s secrecy coding. The achievability of the region in (9) follows from the convex hull of $R_1 \cup R_2 \cup R_3$. The converse follows directly from Theorem 1 together with Proposition 7 provided below.

C. Superposition coding

Consider a degraded broadcast channel where $X \rightarrow Y_1 \rightarrow Y_2$ forms a Markov chain. Then, one can utilize superposition coding to transmit a cloud center to the weak receiver and both the cloud center and satellite codewords to the strong receiver [3]. By utilizing the one-time pad message as the cloud center, one can readily achieve the following region.

Proposition 5. The individual-secret rate region for BC-RSI is achievable for the set of rate pairs $(R_1, R_2)$ such that

$$R_t = I(U; Y_t) \leq I(V; Y_t|U) - I(V; Z|U) + R_t,$$

(10)
over all \( p(u)p(v|u)p(x|v) \), where \( t = \arg\ \min_{i \in \{1, 2\}} \{I(U; Y_i)\} \) and \( \bar{t} = \{1, 2\} \backslash \{t\} \).

Proof: Assume that \( R_2 \leq R_1 \). (This corresponds to the case \( t = 2 \) in which \( I(U; Y_2) \leq I(U; Y_1) \), since \( V \) can be always chosen such that \( I(V; Y_1 | U) - I(V; Z | U) \) is non-negative). Represent \( M_1 \) by \((M_{1k}, M_{1\bar{k}})\), with \( M_{1k} \) of entropy \( nR_{1k} \), the same as that of \( M_2 \) and \( M_{1\bar{k}} \) of entropy \( n(R_1 - R_{1\bar{k}}) \).

Codebook generation: Fix \( p(u), p(v|u) \). First, randomly generate \( 2^nR_{1\bar{k}} \) i.i.d sequences \( u^n(k), k \in [1 : 2^nR_{1\bar{k}}] \), according to \( \prod_{k=1}^{n} p(u_k) \). Secondly, for each \( u^n(k) \), according to \( \prod_{k=1}^{n} p(v_k|u_k) \), randomly generate i.i.d sequences \( u^n(k, s, r) \) with \( (s, r) \in [1 : 2^n(R_{1\bar{k}} - R_{1k})] \times [1 : 2^n(I(V; Z(U)|U) - \epsilon)] \).

Encoding: To send messages \((m_1, m_2)\), choose \( u^n(k) \), where \( k = m_k \triangleq m_{1k} \oplus m_{2\bar{k}} \). Given \( u^n(k) \), randomly choose \( r \in [1 : 2^n(I(V; Z(U)|U)) \) and find \( v^n(k, m_1, r) \). Generate \( x^n \) according to \( \prod_{k=1}^{n} p(x_k|v_k) \), and transmit it to the channel.

Decoding: Receiver 2, upon receiving \( y^n_2 \), finds \( u^n(k) \) such that \((u^n(k), y^n_2)\) is jointly typical. (It is necessary that \( R_2 < I(U; Y_2) \)) With the knowledge of \( m_1 \), decode \( \hat{m}_2 = m_{1k} \oplus k \).

Receiver 1, upon receiving \( y^n_1 \), finds \( u^n(\hat{k})\) such that \((u^n(\hat{k}), y^n_1)\) is jointly typical. (This is possible since \( R_2 < I(U; Y_2) \) \( \leq I(U; Y_1) \).) Corresponding to \( u^n(\hat{k}) \), further find \( v^n(\hat{k}, \hat{m}_2, r) \) which is jointly typical with \( y^n_1 \). With the knowledge of \( m_2 \), decode \( \hat{m}_1 = (m_2 \oplus \hat{k}) \oplus m_{1\bar{k}} \).

Analysis of the probability error: Similar to the analysis of the superposition coding for general discrete memoryless broadcast channels, we have \( P_{e,1}, P_{e,2} \to 0 \) as \( n \to \infty \) if \( R_2 < I(U; Y_2) - \epsilon \) and \( R_1 < I(U; Y_1) - I(V; Z | U) + R_1 - \epsilon \).

Analysis of individual secrecy: For the secrecy of \( M_2 \), due to the Markov chain \( M_2 \to (M_{1k}, M_{1\bar{k}}) \to Z^n \), we have \( I(M_2; Z^n) \leq I(M_2; Z^n, M_{1k}, M_{1\bar{k}}) = I(M_2; M_{1k}, M_{1\bar{k}}) = 0 \), where the last equality is due to the fact that \( M_{1k} = M_{2\bar{k}} \oplus M_{1\bar{k}} \), is independent of \( M_2 \) as its one-time pad encryption.

For the secrecy of \( M_1 \), we have

\[
I(M_1; Z^n) = I(M_{1k}, M_{1\bar{k}}; Z^n) \leq I(M_{1k}; Z^n, M_{1\bar{k}}; M_{1k}) = I(M_{1k}; M_{1\bar{k}}) \leq I(M_{1k}; Z^n, M_{1\bar{k}}, M_{1k}) = I(M_{1k}; Z^n, M_{1\bar{k}}) \leq I(M_{1k}; Z^n) \leq n(R_1 - R_2) - n\delta(\epsilon),
\]

where \( (a) \) is due to the fact that \( I(M_{1k}; Z^n) = 0 \) by following a similar proof of \( I(M_2; Z^n) = 0 \); \( (b) \) follows that \( I(M_{1k}; M_{1\bar{k}}; Z^n, M_{1\bar{k}}) \geq 0 \) and that \( H(M_{1k}|M_{1\bar{k}}, Z^n, M_{1\bar{k}}) = H(M_{1k}|M_{1\bar{k}}, Z^n) = H(M_{1k}) \geq H(M_{1k}|M_{1\bar{k}}, Z^n) \).

To complete the proof that \( I(M_1; Z^n) \leq n\delta(\epsilon) \), we show in the following that \( H(M_{1k}|M_{1\bar{k}}, Z^n) \geq n(R_1 - R_2) - n\delta(\epsilon) \).

\[
H(M_{1k}|M_{1\bar{k}}, Z^n) \geq H(M_{1k}, Z^n|U^n) = H(M_{1k}, Z^n|U^n) = H(M_{1k}, Z^n, V^n|U^n) - H(V^n|U^n, M_{1k}, Z^n) \geq H(V^n|U^n, M_{1k}, Z^n) - H(Z^n|U^n)
\]

where \( (c) \) is due to the fact that \( U^n \) is uniquely determined by \( M_{1k} \); \( (d) \) follows as \( H(V^n|U^n, M_{1k}, Z^n) \leq n\delta(\epsilon) \) due to Fano’s inequality and that the eavesdropper can decode \( V^n \) reliably, given \((U^n, M_{1k}, Z^n)\); and \( H(Z^n|U^n) = \sum_{i=1}^{n} H(Z_i|Z^{i-1}) \leq \sum_{i=1}^{n} H(Z_i|U_i) = nH(Z|U) \).
Decoding: Receiver 1, upon receiving \( y_1^n \), finds \( u^n(\hat{k}) \) such that \( (u^n(\hat{k}), y_1^n) \) is jointly typical. (It is necessary that \( R_k < I(U_1; Y_1) \).) With the knowledge of \( m_1 \) and \( u^n(\hat{k}) \), further find \( v_1^n(\hat{k}, m_1, c_1, r_1), v_{22}^n(\hat{k}, m_2, c_2, r_2) \), which is jointly typical with \( y_1^n \). Decode \( \hat{m}_2 = (m_2k + k, \hat{m}_{12} \).

Receiver 2, upon receiving \( y_2^n \), finds \( u^n(\hat{k}) \) such that \( (u^n(\hat{k}), y_2^n) \) is jointly typical. (It is necessary that \( R_k < I(U_2; Y_2) \).) With the knowledge of \( m_1 \) and \( u^n(\hat{k}) \), further find \( v_1^n(\hat{k}, m_1, c_1, r_1), v_{22}^n(\hat{k}, m_2, c_2, r_2), v_{23}^n(\hat{k}) \), which is jointly typical with \( y_2^n \). Decode \( \hat{m}_2 = (m_{12k} + k, \hat{m}_{12} \).

Analysis of decoding error: For \( P_{e1} \) (similar for \( P_{e2} \)), a decoding error happens iff \( \hat{m}_{12} \neq m_{12} \). The probability of error \( P_{e1} \) is upper bounded as \( P_{e1} \leq Pr(E_{11}^c)Pr(E_{12}^c)Pr(E_{13}^c)Pr(E_{14}^c) \). By the LHN, \( Pr(E_{11}) \) and \( Pr(E_{13}) \) tend to zero as \( n \to \infty \); \( Pr(E_{12}^c) \), by the mutual covering lemma [3], tends to zero as \( n \to \infty \) since the dependence on the number of indices \( m_{12} \) is additive. The 4th term, \( Pr(E_{14}^c) \), by the packing lemma [3], tends to zero as \( n \to \infty \) if \( R_{1c} + R_{2c} + R_{1r} + R_{2r} < I(V_1, V_2; Y_1) - \epsilon \), and \( R_{1c} + R_{1r} < I(V_1, V_2; Z[U] - \epsilon \).

Analysis of individual secrecy: For the secrecy of \( M_1 \) (similar for \( M_2 \)), we follow the steps in (11)-(17) and obtain

\[
I(M_1^n; Z^n) = nR_{1s} - H(M_{1s}|M_k^n; Z^n). \tag{19}
\]

In the following, we show that \( H(M_{1s}|M_{2s}|M_k^n; Z^n) \geq n(R_{1s} + R_{2s}) - n\delta(\epsilon) \) holds if we take \( R_{1c} + R_{2c} = I(V_1, V_2; Z[U] - \epsilon \).

The capacity region of BC-RSI, an obvious upper bound is the capacity region of the BC-RSI without an eavesdropper as given in Theorem 1. Another upper bound follows directly the work of wiretap channel with shared key [5], as stated in the following proposition.

Proposition 7. For any \( R_2 \) in the achievable region, \( R_1 \) is upper bounded by

\[
\max_{U \rightarrow V \rightarrow X \rightarrow (Y_1, Z)} \min\{I(V_1; Y_1) - I(V_1; Z[U] + R_2, I(V_1; Y_1)) \}
\]

If the channel is degraded such that \( X \rightarrow Y_1 \rightarrow Z \), then for any \( R_2 \) in the achievable region, \( R_1 \) is upper bounded by

\[
\max_{X \rightarrow Y_1 \rightarrow Z} \min\{I(X; Y_1) - I(X; Z) + R_2, I(V_1; X; Y_1) \}
\]

Similar results hold for interchanging 1 and 2 above.

IV. CONCLUSION

In this paper, we studied the problem of secure communication over BC-RSI under the individual secrecy constraints. Compared to the joint secrecy constraint, this relaxed setting allows for higher secure communication rates at the expense of having a weaker notion of security. We provide some special case results together with several achievable schemes; whilst the characterization for the general case still remains as an open problem.

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