Secure Broadcasting With Side-Information

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Abstract—In this paper, we derive information-theoretic performance limits for secure and reliable communications over the general two-user discrete memoryless broadcast channel with side-information at the transmitter. The sender wishes to broadcast two independent messages to two receivers, under the constraint that each message should be kept confidential from the unintended receiver. Furthermore, the encoder has side-information - for example, fading in the wireless medium, interference caused by neighboring nodes in the network, etc. - provided to it in a noncausal manner, i.e., before the process of transmission. We derive an inner bound on the capacity region of this channel, by employing an extension of Marton’s coding technique used for the classical two-user broadcast channel, in conjunction with a stochastic encoder to satisfy confidentiality constraints. Based on previously known results, we discuss a procedure to present a schematic of the achievable rate region. The rate-penalties for dealing with side-information and confidentiality constraints make the achievable region for this channel strictly smaller than the rate regions of those channels where one or both of these constraints are relaxed.

I. INTRODUCTION

In the theory of cooperative communications, side-information has been used as a basis for user-cooperation, which has been actively pursued as a key enabling technology to meet the demands of higher data-rates and efficient utilization of radio-frequency spectrum. User cooperation is especially popular in wireless networks with multiple nodes, where a particular node expresses its willingness to share its data (or other resources) in a causal or noncausal manner. One such multiple node network is the broadcast channel (BC)\cite{1}, which has received vast attention since its inception into network information theory. Characterization of performance limits for BC has been an active area of research, with Marton deriving the best known inner bound on the capacity region for the general two-user discrete memoryless version of the channel\cite{2}. Some of the most prominent information-theoretic results on BC have been summarized in\cite{3}.

Yet another issue in wireless communications, owing to the broadcast nature of the wireless medium, is related to information security. That is, the broadcast nature of wireless networks facilitates malicious or unauthorized access to confidential data, denial of service attacks, corruption of sensitive data, etc. An information-theoretic approach to address problems related to security has gained rapid momentum, and is commonly referred to as information-theoretic confidentiality or wireless physical-layer security\cite{4}.

A. Our contribution

In this paper, we consider a general two-user BC with (i) side-information at the transmitter and (ii) confidential messages. The sender, denoted S, has two messages $m_1$ and $m_2$ intended for two destinations, denoted $D_1$ and $D_2$, respectively, such that $m_1$ (resp. $m_2$) has to be kept confidential from $D_2$ (resp. $D_1$). Furthermore, the encoder at S has noncausal knowledge of random parameters - for example, fading in the wireless medium, interference caused by neighboring nodes in the network, etc. We present an inner bound on the capacity region by deriving a set of achievable rate pairs for secure and reliable communications, by considering the discrete memoryless version of this channel.

The achievability theorem is proved by employing an extension of Marton’s coding technique, used to derive a rate region for the general two-user BC, in conjunction with a stochastic encoder at S to satisfy confidentiality constraints. We also discuss a procedure for presenting a schematic of the achievable rate region; our arguments are motivated by well-known results for Gel’fand-Pinsker’s (GP) channel with random parameters\cite{5} and wiretap channel with side-information\cite{6}. Results demonstrate that, owing to rate-penalties for dealing with side-information and satisfying confidentiality constraints, the achievable rate region for our communication setup is strictly smaller than the rate regions of the classical two-user BC and BC with noncausal side-information.

B. Related work

An inner bound on the capacity region for BC with noncausal side-information at the transmitter has been presented in\cite{2}, where Marton’s achievability scheme has been extended to the case of state-dependent channels. It is also shown that, in the case of Gaussian channels, the capacity region coincides with that of the same channel without states. In\cite{8}, the degraded BC with random parameters at the encoder are considered under two separate scenarios: When the states are available in a noncausal manner, and when side-information is provided in a causal manner. Capacity bounds are derived for the channel with noncausal states, and the bounds are shown to be tight when the non-degraded user is informed about the channel parameters. For the causal case, a single-letter characterization of the capacity region is derived.

Characterization of performance limits for BC with side-information at the receivers have also been addressed in the
The channel input and outputs, respectively; memoryless and is characterized by the conditional distribution. 

\[p \quad \text{memoryless and is characterized by the conditional distribution} \]

\[P(Y_2|x_{i1},x_{i2},x_{i3}) = \prod_{j=1}^{N} P(y_2|y_1,y_3|x_{i1},x_{i2},x_{i3}) \]

\[C_{\text{feedback}}(2^{R_1},2^{R_2};N) \]

The average probability of decoding error for the code, averaged over all codes, is \(P_e(N) = \max\{P_{e,1}(N),P_{e,2}(N)\}\), where, 

\[P_{e,t}(N) = \sum_{m} \sum_{w \in W^N} \left( \frac{1}{2^{NR_1+R_2}} \Pr \left[ g_t(Y_t^N) \neq m_t | \text{m sent} \right] \right),\]

where \(m = (m_1,m_2)\). A rate pair \((R_1,R_2)\) is said to be achievable for the channel \(C\) if there exists a sequence of \((2^{NR_1},2^{NR_2}),N,P_e(N)\) codes \(\forall \epsilon > 0\) and sufficiently small, such that \(P_e(N) \leq \epsilon\) as \(N \to \infty\) and the following weak-secrecy constraints \(14\) are satisfied:

\[NR_1 - H(M_1|Y_2) \leq N\epsilon,\]

\[NR_2 - H(M_2|Y_1) \leq N\epsilon,\]

where \(H(\alpha|\beta)\) is the conditional entropy of \(\alpha\) given \(\beta\). The weak-secrecy rate can be replaced by the strong-secrecy key rate without any penalty \(13\). The capacity region is defined as the closure of the set of all achievable rate pairs \((R_1,R_2)\).

M. Result & Discussion

In this section, we present an achievable rate region the channel \(C\). We also discuss, based on previously known results, the procedure adopted to obtain a schematic of this achievable rate region.

A. An achievable rate region

Consider the following auxiliary RVs defined on finite sets: \(U \in U \) and \(V_t \in V_t; t = 1, 2\). Let \(P\) denote the set of all joint probability distributions \(p(w,u,v_1,v_2,x,y)\) that is constrained to factor as follows:

\[p(w,u,v_1,v_2,x,y) = p(w)p(u)p(v_1,v_2|x,w)p(x|w,v_1,v_2)\]

For a given \(p(.) \in P\), an achievable rate region for \(C\) is described by the set \(R_{\text{in}}(p)\), which is defined as the convex-hull of the set of all rate pairs \((R_1,R_2)\) that simultaneously satisfy \(9\) - \(13\).

**Theorem 3.1:** Let \(C\) denote the capacity region of the channel \(C\). Let \(R_{\text{in}} = \bigcup_{p(.) \in P} R_{\text{in}}(p)\). The region \(R_{\text{in}}\) is an achievable rate region for \(C\), i.e., \(R_{\text{in}} \subseteq C\).

The proof of Theorem 3.1 can be found in Appendices A and B.
\[
R_1 \leq I(V_1; Y_1 | U) - \max[I(V_1; Y_2 | U, V_2), I(W; V_1 | U)],
\]
\[
R_2 \leq I(V_2; Y_2 | U) - \max[I(V_2; Y_1 | U, V_1), I(W; V_2 | U)],
\]
\[
R_1 + R_2 \leq I(V_1; Y_1 | U) + I(V_2; Y_2 | U) - I(V_1; Y_2 | U, V_2) - I(V_2; Y_1 | U, V_1) - I(V_2; Y_2 | U) - I(V_1, V_2; W | U).
\]

B. Discussion

For the channel $C$, rate inequalities (16) - (22) and bounds on the binning rates (24) - (26) are combined to obtain the rate region described by (3) - (5). We employ now arguments from Gelfand-Pinsker’s channel with random parameters [5] and wiretap channels with side-information [6] to present a schematic of the rate region (see Fig. 1).

When $R_2 = 0$, the channel resembles a wiretap channel with side-information and $S$ can transmit at the maximum achievable $R_1$ given by (3), denoted by point $A_1$. When $S$ is transmitting at point $A_1$, the maximum achievable $R_2$ is given by the point $B_1 \equiv I(V_2; Y_2 | U) - I(V_2; Y_1 | U, V_1) - \max[I(V_1; Y_2 | U), I(W; V_2 | U)]$; this is obtained by treating the channel as a wiretap channel with side-information. Therefore, the rectangle $O A_1 F_1 B_1$ is achievable. By flipping $R_1$ and $R_2$ and following similar arguments, the points $C_1$, given by (4), and $D_1 \equiv I(V_1; Y_1 | U) - I(V_1; Y_2 | U, V_2) - \max[I(V_1; Y_2 | U), I(W; V_1 | U)]$ are achievable. Hence, the rectangle $O C_1 E_1 D_1$ is also achievable. Since the points $E_1$ and $F_1$ are shown to be achievable, any point which lies on the line $E_1 F_1$ can also be achieved by deriving a bound on the binning rates (see (26), Appendix B). This leads to a sum rate bound given by (5). Finally, owing to convexity of the rate region, any point in the interior of the line $E_1 F_1$ is also achievable. Therefore, an achievable rate region for $C$ is described by the pentagon $O A_1 F_1 E_1 C_1$.

If the confidentiality constraints (1) - (2) are relaxed, the channel $C$ reduces to a broadcast channel with side-information whose rate region is the pentagon OEFGH (see Fig. 2), first characterized by Steinberg and Shamai [7]. It is described by the convex-hull of the set of all rate pairs $(R_1, R_2)$ that satisfy the following inequalities:

\[
R_1 \leq I(V_1; Y_1),
\]
\[
R_2 \leq I(V_2; Y_2),
\]
\[
R_1 + R_2 \leq I(V_1; Y_1) + I(V_2; Y_2) - I(V_1, V_2; W).
\]

Further, in the absence of side-information, i.e., $W = \{\phi\}$, the channel reduces to the classical two-user broadcast channel whose rate region is the pentagon OIJKL, first characterized by Marton [2]. It is described by the convex-hull of the set of all rate pairs $(R_1, R_2)$ that satisfy the following inequalities:

\[
R_1 \leq I(V_1; Y_1) - I(W; V_1),
\]
\[
R_2 \leq I(V_2; Y_2) - I(W; V_2),
\]
\[
R_1 + R_2 \leq I(V_1; Y_1) + I(V_2; Y_2) - I(V_1, V_2; W) - I(V_1; Y_2) - I(V_2; Y_1).
\]

Lastly, if the encoder satisfies confidentiality constraints in the absence of side-information, the channel $C$ reduces to a broadcast channel with confidential messages whose rate region was first characterized by Liu et al. [13]. It is described by the convex-hull of the set of all rate pairs $(R_1, R_2)$ that satisfy the following inequalities:

\[
R_1 \leq I(V_1; Y_1 | U) - I(V_1, V_2; U) - I(V_1; Y_2 | U),
\]
\[
R_2 \leq I(V_2; Y_2 | U) - I(V_2; Y_1 | U) - I(V_1; V_2; W).
\]

Note 3.2: The rate region for BC with side-information [6] - [8] is smaller than that of the classical BC [9] - [11], due to the rate-penalty for side-information. For $I(V_1; Y_2 | U, V_2) > I(W; V_1 | U)$ and $I(V_2; Y_1 | U, V_1) > I(W; V_2 | U)$, the achievable region of channel $C$ is smaller than that for BC with
side-information. The rate region for $C$ is at most as large as that for BC with side-information. This provides the necessary intuition for the dimensions (though, they are not to-scale in Fig. 2) of the pentagon $OIJKL$, which subsumes $OEGFH$ which further subsumes OABCD.

Note 3.3: All the above described rate regions can also be obtained by arguing along lines similar to those used to obtain the rate region for $C$, described by the pentagon OABCD $\equiv OA_1F_1E_2C_1$.

Note 3.4: Outer bounds for the channel model in this paper, as well as for the model considered in [1], have been derived in a followup paper [15].

IV. CONCLUSIONS

We presented an inner bound on the capacity region of a two-user BC with (i) noncausal side-information at the encoder and (ii) confidentiality constraints, such that each message is kept secret from the unintended receiver. The achievability proof involved extension of techniques from Marton’s coding scheme for the general BC and a stochastic encoder to achieve information secrecy. We also discussed a simple procedure to present a schematic of the rate region for this channel and argued that, due to rate-penalties for using side-information and maintaining information-secrecy, the achievable region is strictly smaller than the rate regions for channels where these constraints are relaxed.

APPENDIX A

Here, we present the codebook construction, upper bound the probability of decoding errors and perform equivocation calculations to show that the code satisfies confidentiality constraints. We denote by $A_{\epsilon}^{(N)}(P_\epsilon)$ an $\epsilon$-typical set comprising $N$-sequences picked from a distribution $P_\epsilon$. The encoder at $S$ is given, in a noncausal manner, the $N$-sequence $w$ picked from a distribution $P(w) = \prod_{n=1}^{N} P(w_n)$. Generate a typical $N$-sequence $u$, known to all nodes in the network, picked from the distribution $P(u) = \prod_{n=1}^{N} P(u_n)$. Generate $2^{N[R_t + R'_t + R^*_t]}$ independent $N$-sequences $v_i(i, j, k)$, picked from the distribution $P(v_i[u]) = \prod_{n=1}^{N} P(v_i[t, n | u_n])$. Here, $i \in \{1, \ldots , 2^{NR_t}\}$; $j \in \{1, \ldots , 2^{NR'_t}\}$; $k \in \{1, \ldots , 2^{NR^*_t}\}$. Without loss of generality, $2^{NR_t}$, $2^{NR'_t}$ and $2^{NR^*_t}$ are considered to be integers. The following double-binning scheme is employed:

1) Uniformly distribute $2^{[NR_t + R'_t + R^*_t]} N$-sequences into $2^{NR_t}$ bins, so that each bin indexed by $i_t$ comprises $2^{[NR_t + R'_t + R^*_t]} N$-sequences.

2) Uniformly distribute $2^{[NR'_t + R^*_t]} N$-sequences into $2^{NR'_t}$ sub-bins indexed by $(i_t, j_t)$, so that each bin comprises $2^{NR'_t}$ N-sequences.

To send the message pair $(m_1, m_2)$, $S$ employs a stochastic encoder. In the bin indexed by $i_t$ randomly pick a sub-bin indexed $(i_t, j_t)$. The encoder then looks for a pair $(k_1, k_2)$ that satisfies the following joint typicality condition $E_5 = \{x, v_1(i_1, j_1, k_1), v_2(i_2, j_2, k_2) \} \in A_{\epsilon}^{(N)}(P_{W,[V_1, V_2]}).$ (14)

The channel input is an $N$-sequence $x$ picked from the distribution $P(x|w, v_1, v_2) = \prod_{n=1}^{N} P(x_n | w_n, v_{1,n}, v_{2,n}).$

At the destination $D_t$, given $u$, the decoder picks $k_t$ that satisfies the following joint typicality condition:

$$\{v_t(i_t, j_t, k_t), y_t \} \in A_{\epsilon}^{(N)}(P_{V_t, Y_t} | U_t).$$ (15)

An error is declared at decoder of $D_t$ if it not possible to find an integer $i_t$ to satisfy the condition $E_{D_t} \triangleq \{v_t(i_t, j_t, k_t), y_t \} \in A_{\epsilon}^{(N)}(P_{V_t, Y_t} | U_t).$ From union of events bound, the probability of decoder error at $D_t$ can be upper bounded as follows:

$$P_{e,D_t}^{(N)} \leq P(E_{D_t} | E_5) + \sum_{i_t \neq i_t} \sum_{j_t k_t} P(E_{D_t} | E_5).$$

From the asymptotic equipartition property (AEP) [16], $\forall \epsilon > 0$ and sufficiently small; for large $N$, $P(E_{D_t}^{(N)} | E_5) \leq \epsilon$ and for $i_t \neq i_t$

$$P(E_{D_t} | E_5) \leq 2^{-N[I(V_t; Y_t) - \epsilon]}.$$ Therefore, we have

$$P_e^{(N)} \leq \epsilon + 2^{N[R_t + R'_t + R^*_t]} 2^{-N[I(V_t; Y_t) - \epsilon]}.$$ For any $\epsilon_0 > 0$ and sufficiently small for large $N$, $P_e^{(N)} \leq \epsilon_0$

if

$$R_t + R'_t + R^*_t < I(V_t; Y_t).$$ (16)

The equivocation at the decoder of $D_2$ is calculated by first considering the following lower bound:

$$H(M_1 | Y_2) \geq H(M_1 | Y_2, U, V_2).$$ (17)

Following the procedure in [13] Section V-B and using the fact that $M_1 \rightarrow (U, V_1, V_2) \rightarrow Y_2$ forms a Markov chain, $\forall \epsilon>0$ becomes

$$H(M_1 | Y_2) \geq H(V_1 | U) - I(V_1; V_2 | U) - H(V_1 | M_1, U, V_2, Y_2) - I(V_1; Y_2 | U, V_2).$$ (18)

Let us consider $\epsilon_l; l = 1, \ldots , 10, \text{ s.t. } \epsilon_l > 0$ and sufficiently small for large $N$. Let us consider now each term in (18):

1) $H(V_1 | U) \overset{(a)}{=} N[R_1 + R'_1 + R^*_1],$

2) $I(V_1; V_2 | U) \overset{(b)}{=} NI(V_1; V_2 | U) + N \epsilon_1.$

3) $H(V_1 | M_1, U, V_2, Y_2) \overset{(c)}{=} N \epsilon_2.$

4) $I(V_1; Y_2 | U, V_2) \overset{(d)}{=} NI(V_1; Y_2 | U, V_2) + N \epsilon_3,$

where (a) follows from the codebook construction, (b) and (d) follow from standard techniques and (c) is proved in Appendix C. We follow a similar procedure to calculate the equivocation at the decoder at $D_1$. Finally, the security constraints (1) and (2) are satisfied by letting

$$R'_1 = I(V_1; Y_2 | U, V_2) - \epsilon_4,$$ (19)

$$R_1 = I(V_1; V_2 | U) - \epsilon_5,$$ (20)

$$R'_2 = I(V_2; Y_1 | U, V_1) - \epsilon_6,$$ (21)

$$R^*_2 = I(V_1; V_2 | U) - \epsilon_7.$$ (22)
Here, we upper bound the probability of encoder error. An error is declared at the encoder of $S$ if it is not possible to find a pair $(k_1, k_2)$ to satisfy the condition $E_S \triangleq \{ (w, v_1(t_1, j_1, k_1), v_2(t_2, j_2, k_2)) \in A_N^{(N)}(P_{W_1, V_1, V_2}) \}$. Let $P_{e, E_S}$ denote the probability of error at the encoder, i.e., $P_{e, E_S} \triangleq \text{Pr}(E_S)$. Let $I$ be an indicator RV that the event $E_S$ has occurred. Let $Q = \sum_{k_1, k_2} I \cdot Q = \mathbb{E}[Q]$ and Var$[Q] = \mathbb{E}[(Q - \bar{Q})^2]$, where $\mathbb{E}(\cdot)$ denotes the expectation operator. $P_{e, E_S}$ can be upper bounded as follows:

$$P_{e, E_S} = \text{Pr}(Q = 0) \leq \text{Var}[Q]/\bar{Q}^2,$$

where $(\cdot)$ follows from Markov’s inequality for non-negative RVs. Consider now

$$\bar{Q} = \sum_{k_1, k_2} \text{E}(1) = \sum_{k_1, k_2} \text{Pr}(E_S) \geq \sum_{k_1, k_2} (1 - \delta(N))^2 2^{-N[I(V_1; V_2) + I(V_1, V_2; W) + \epsilon]},$$

$$= (1 - \delta(N))^2 2^{-N[R_1^* + R_2^* - I(V_1; V_2) - I(V_1, V_2; W) - 4\epsilon]}.$$

Next, consider

$$\text{Var}[Q] = \sum_{k_1, k_2} \sum_{k_1', k_2'} \{ \text{E}[I(k_1, k_2)I(k_1', k_2')] - \text{E}[I(k_1, k_2)]\text{E}[I(k_1', k_2')] \}.$$

We have the following four cases:

1. If $k_1' \neq k_1$ and $k_2' \neq k_2$, then $I(k_1, k_2)$ and $I(k_1', k_2')$ are independent and Var$[Q] = 0$.

2. If $k_1' = k_1$ and $k_2' = k_2$, then $\text{E}[I(k_1, k_2)I(k_1', k_2')] = \text{E}[I(k_1, k_2)] \leq 2^{-N[I(V_1; V_2) + I(V_1, V_2; W) - 4\epsilon]}$.

3. If $k_1' \neq k_1$ and $k_2' = k_2$, then $\text{E}[I(k_1, k_2)I(k_1', k_2')] \leq 2^{-N[I(V_1; V_2) + I(V_1, V_2; W) - 6\epsilon]}$.

4. If $k_1' = k_1$ and $k_2' \neq k_2$, then $\text{E}[I(k_1, k_2)I(k_1', k_2')] \leq 2^{-N[I(V_1; V_2) + I(V_1, V_2; W) - 6\epsilon]}$. 

Substituting for $\bar{Q}$ and Var$[Q]$ in $[23]$, we can show that $P(E_S) \leq \delta(N) \cdot \forall \delta(N) > 0$ and sufficiently small; and for $N$ large, if the following conditions are simultaneously satisfied:

$$R_1^* > I(V_1; V_1) - \epsilon_8, \quad (24)$$

$$R_2^* > I(V_1; V_2) - \epsilon_9, \quad (25)$$

$$R_1^* + R_2^* > I(V_1; V_2) + I(V_1, V_2; W) - \epsilon_{10}. \quad (26)$$

Here, we prove that $H(V_1|M_1, U, V_2, Y_2) \leq N \epsilon_2$. This proof is lifted from [13] Lemma 2 and is provided here for the sake of completeness. Given the MGF $M_1 = m_1$, the decoder at $D_2$ chooses $j_1$ and any $k_1$ such that the following typicality condition is satisfied: $\tilde{E} = \{ (v_1(t_1, j_1, k_1), y_2) \in A_N^{(N)}(P_{V_1, Y_2}) \}$. Note that, since $S$ employs a stochastic encoder, the decoder of $D_2$ is uncertain about the sub-bin index $j_1$. Let $P_{e, 2}^{(N)}$ denote the average probability of error of decoding $j_1$ at $D_2$. Therefore, we have

$$P_{e, 2}^{(N)} \leq P(\tilde{E}|m_1 \text{ sent}) + \sum_{j_1} P(\tilde{E}|m_1 \text{ sent}),$$

where $\tilde{E} \triangleq \{ (v_1, y_2) \notin A_N^{(N)}(P_{V_1, Y_2}) \}$. From joint AEP [16], $P(\tilde{E}|m_1 \text{ sent}) \leq \epsilon, \forall \epsilon > 0$ and sufficiently small for large $N$. And,

$$P(\tilde{E}|m_1 \text{ sent}) \leq 2^{-N[I(V_1; Y_2) + I(Y_2|U, V_2) - \epsilon]}.$$

Therefore,

$$P_{e, 2}^{(N)} \leq \epsilon + 2^{N}2^{-N[I(V_1; Y_2) + I(Y_2|U, V_2) - \epsilon]}.$$

From equivocation calculations, $R_1^* = I(V_1; Y_2|U, V_2) - \epsilon_4$. Picking $\epsilon_4 > \epsilon$, we get $P_{e, 2}^{(N)} \leq \epsilon$. Next, from Fano’s inequality [16], we have

$$\frac{1}{N} H(V_1|M_1 = m_1, U, V_2, Y_2) \leq \frac{1}{N} \left[ 1 + P_{e, 2}^{(N)} R_1^* \right] \leq \frac{1}{N} + \epsilon I(V_1; Y_2|U, V_2) \triangleq \epsilon_2.$$

Finally,

$$\frac{1}{N} \sum_{m_1} P(M_1 = m_1) H(V_1|M_1 = m_1, U, V_2, Y_2) \leq \epsilon_2.$$

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