Cooperative Rate-Splitting for Secrecy Sum-Rate Enhancement in Multi-antenna Broadcast Channels

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Abstract—In this paper, we employ Cooperative Rate-Splitting (CRS) technique to enhance the Secrecy Sum Rate (SSR) for the Multiple Input Single Output (MISO) Broadcast Channel (BC), consisting of two legitimate users and one eavesdropper, with perfect Channel State Information (CSI) available at all nodes. For CRS based on the three-node relay channel, the transmitter splits and encodes the messages of legitimate users into common and private streams based on Rate-Splitting (RS). With the goal of maximizing SSR, the proposed CRS strategy opportunistically asks the relaying legitimate user to forward its decoded common message. During the transmission, the eavesdropper keeps wiretapping silently. To ensure secure transmission, the common message is used for the dual purpose, serving both as a desired message and Artificial Noise (AN) without consuming extra transmit power comparing to the conventional AN design. Taking into account the total power constraint and the Physical Layer (PHY) security, the precoders and time-slot allocation are jointly optimized by solving the non-convex SSR maximization problem based on Sequential Convex Approximation (SCA) algorithm. Numerical results show that the proposed CRS secure transmission scheme outperforms existing Multi-User Linear Precoding (MU-LP) and Cooperative Non-Orthogonal Multiple Access (C-NOMA) strategies. Therefore, CRS is a promising strategy to enhance the PHY security in multi-antenna BC systems.

Index Terms—Cooperative rate-splitting, physical layer security, relay broadcast channel, secrecy sum rate, success convex approximation

I. INTRODUCTION

COOPERATIVE relaying (CR), introduced in [1], is an efficient technique to improve both the reliability and throughput of wireless networks. Recently, Cooperative Rate-Splitting (CRS), based on the three-node relay channel where the transmitter is equipped with multiple antennas, has been proposed as a more flexible transmission strategy than existing cooperative strategies and its non-cooperative counterpart [2][3]. It achieves an explicit rate region improvement compared to the conventional baseline schemes in a wide range of propagation conditions. CRS is designed based on Rate-Splitting Multiple Access (RSMA), which is a promising multiple access technique that outperforms conventional Space Division Multiple Access (SDMA) and Non-Orthogonal Multiple Access (NOMA) [4][7]. The core of RSMA framework is to split each transmitted message into a common and a private part, and pack all users’ common parts on top of all the private parts. The combined common message is encoded using a codebook shared among all users and it can be decoded by all users, while the private message only can be decoded by the corresponding user. It is worth mentioning that each receiver decodes the common message first by regarding all private parts as interference, and then decodes the each private part after removing the common part via Successive Interference Cancellation (SIC). Such dynamic interference management strategy generalizes the two extreme schemes, i.e., treating all interference as noise and decoding all interference [8]. Hence, RSMA is capable to provide effective enhancement in spectral efficiency, energy efficiency, reliability and Channel State Information (CSI) feedback overhead reduction [3][10].

Due to the broadcast characteristics of wireless communication, data transmission between devices is easily exposed to eavesdroppers, which poses a challenge to secure transmission. Instead of employing cryptographic techniques at the network layer, the Physical Layer (PHY) security enhances confidentiality by utilizing the reciprocity and randomness of the wireless channel. In [11], Wyner proposed the wiretap channel model and demonstrated that the legitimate user can demodulate correctly while ensuring the eavesdropper obtains nothing useful from the message, when the channel quality of the eavesdropper is worse than that of the legitimate receiver. The Wyner’s discrete memoryless eavesdropping channel model is further extended to Broadcast Channels (BCs) [12] and Gaussian channels [13], and it is proved in [12][13] that the confidential capacity of the additive Gaussian channel is the difference between the capacity of the legitimate channel and that of the eavesdropping channel. Existing PHY security transmission technologies mainly include beamforming technology and Artificial Noise (AN) design [14][18]. In particular, the generation of AN needs to spare part of the transmit power to ensure secure transmission.

In this work, contrary to most of the existing works on PHY security which are based on Multi-User Linear Precoding (MU-LP) and NOMA [14][18], we further explore the benefits of CRS for enhancing the PHY security of a multi-antenna BC. Specifically, we employ CRS technique to maximize the Secrecy Sum Rate (SSR) of Multiple Input Single Output (MISO) BC, consisting of a base station, two legitimate users and an eavesdropper. Aiming to maximize the SSR, CRS opportunistically asks the relaying legitimate user with strong
transmissions (U1 → U2, U1 → E). The eavesdropper E wiretaps the signal transmitted to the legitimate users in both transmission phases. Different from the conventional half-duplex mode, two hops, θ is dynamically adapted to the channel condition in this work. During the direct transmission phase (Phase I), S transmits

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

Consider a broadcast cooperative network as shown in Fig. 1 which consists of a base station (S) with NT (NT ≥ 2) transmit antennas, two single-antenna legitimate users (U1, U2), and a potential single-antenna eavesdropper (E). Without loss of generality, we assume that U1 experiences a better channel than U2. Hence, we can regard U1 as a potential relaying user to assist the signal processing of U2 via the Non-regenerative Decode-and-Forward [19] principle. The wireless channels at links S → U1, S → U2, S → E, U1 → U2, U1 → E are expressed as h1, h2, g1, h3, g2, respectively. According to the Rate-Splitting (RS) principle, the message Wk intended to user k is split into one common part Wc,k and private part Wp,k, k = 1, 2. The common parts of both legitimate users are combined into one super common message Wc encoded by a shared codebook, while the private part of each user is processed individually. The resulting encoded three streams s = [sc, s1, s2]T are precoded using P = [pc, p1, p2] ∈ CNT×3, and the superposed transmit signal is

\[
x = Ps = pcsc + p1s1 + p2s2,
\]

where pc ∈ CNT×1 and p1 ∈ CNT×1, k = 1, 2 are the precoding vector for the common stream and the private stream transmitted for Uk, respectively. Supposing that E [ssH] = I, we have tr (PPH) ≤ Pr and Pr is the transmit power constraint at transmit node S.

The relaying user is operating in half-duplex mode, i.e., two consecutive slots are required to complete the communication phases. As shown in Fig. 2, θ (0 < θ < 1) is the fraction of time assigned to the direct transmissions (S → U1, S → U2, S → E), and the remaining is used for the cooperative transmissions (U1 → U2, U1 → E). The eavesdropper E wiretaps the signal transmitted to the legitimate users in both transmission phases. Different from the conventional half-duplex mode with equal-time slot allocation for the two hops, θ is dynamically adapted to the channel condition in this work. During the direct transmission phase (Phase I), S transmits

\[
\gamma_{c,k}^{(1)} = \frac{|h_k^T pc|^2}{|h_k^T h_k|^2 + |h_k^T p_1|^2 + \sigma _e^2}, \quad k = 1, 2.
\]

In the cooperative transmission phase (Phase II), the relaying user U1 forwards the re-encoded common stream sc by employing a different codebook from that of S to U2 at a power level Pr. The received signals at both U2 and eavesdropper E are written respectively as

\[
y_{k}^{(1)} = h_k^T x + ne_k,
\]

\[
y_{c}^{(1)} = h_c^T x + ne_c,
\]

\[
y_{2}^{(2)} = h_2^T \sqrt{Pr} s_c + n_{e2},
\]

\[
y_{c}^{(2)} = h_3^T \sqrt{Pr} s_c + n_{e2}.
\]

The superscript “(2)” represents Phase II. Since the AWGN at the nodes of U2 and E in Phase II, respectively. Based on (5), the SINR of U2 is expressed as

\[
\gamma_{c,2}^{(2)} = \frac{|h_3^T \sqrt{Pr}|^2}{\sigma _e^2}.
\]

To ensure that the common message is decodable at the two legitimate users, the corresponding achievable rate of decoding the common message should be

\[
R_c = \min \{ R_{c,1}, R_{c,2} \},
\]
where $R_{c,1} = \theta \log_2(1 + \gamma_{c,1}^{(1)})$ is the achievable rate of decoding the common stream $s_c$ at $U_1$, and $R_{c,2} = \theta \log_2(1 + \gamma_{c,2}^{(1)}) + (1 - \theta) \log_2(1 + \gamma_{c,2}^{(2)})$ is the corresponding achievable rate at $U_2$.

The legitimate users decode the private messages individually after removing the common part via SIC. Hence, the corresponding SINR and the achievable rate at $U_k$ are written as

\[
\gamma_{p,k}^{(1)} = \frac{|h_k^H p_k|^2}{|h_k^H p_1|^2 + \sigma_k^2}, \quad i \neq k, \quad (9)
\]

\[
R_{p,k} = \theta \log_2(1 + \gamma_{p,k}^{(1)}), \quad (10)
\]

where $i, k = 1, 2$.

As the precoder of the common stream designed at the BS only ensures the decodability of the common stream at the two legitimate users, the eavesdropper $E$ may not be able to decode $s_c$. Hence, the common message can be treated as AN at $E$. To meet this requirement, the condition, i.e., $C_{c,e} \leq R_c$, should be satisfied, where $C_{c,e}$ represents the sum rate of the common message from $S$ to $E$ and from $U_1$ to $E$. The corresponding SINR of private message at $E$ is degraded by the existence of the common message. The receiving SINRs of decoding the common streams at each phase and the private stream at $E$ are written as

\[
\gamma_{c,e}^{(1)} = \frac{|g_{c,e}^H p_{c,e}|^2}{|g_{c,e}^H p_1|^2 + |g_{c,e}^H p_2|^2 + \sigma_{c,e}^2}, \quad (11)
\]

\[
\gamma_{c,e}^{(2)} = \frac{|g_{c,e}^H \sqrt{\theta} p_{c,e}|^2}{\sigma_{c,e}^2}, \quad (12)
\]

\[
\gamma_{k,e}^{(1)} = \frac{|g_{k,e}^H p_k|^2}{|g_{k,e}^H p_1|^2 + |g_{k,e}^H p_2|^2 + \sigma_{c,e}^2}, \quad j \neq k, \quad (13)
\]

respectively, where $j, k = 1, 2$. The corresponding achievable rate of decoding $s_c$ and $s_k$ at $E$ are expressed as

\[
C_{c,e} = \theta \log_2(1 + \gamma_{c,e}^{(1)}) + (1 - \theta) \log_2(1 + \gamma_{c,e}^{(2)}), \quad (14)
\]

\[
C_{k,e} = \theta \log_2(1 + \gamma_{k,e}^{(1)}), \quad k = 1, 2. \quad (15)
\]

Thus, the achievable SSR from $S$ to $U_1$ and $U_2$ is given as

\[
R_{tot}^{sec} = R_{c}^{sec} + R_{p,1}^{sec} + R_{p,2}^{sec}, \quad (16)
\]

where $R_{c}^{sec} = [R_c - C_{c,e}]^+$, $R_{p,1}^{sec} = [R_{p,k} - C_{k,e}]^+$, $k = 1, 2$, represent the achievable secrecy rate of the common message and the private message transmitted to $U_k$, respectively. The operation $[x]^+ = \max\{x, 0\}$.

B. Problem Formulation

In this work, we aim to optimize the precoding $P$ and timeslot allocation $\theta$ with the objective of maximizing the SSR subject to transmit power constraint. Mathematically, the SSR optimization problem is written as

\[
\max_{P, \theta} R_{tot}^{sec} \quad \text{s.t.} \quad C_{c,e} \leq R_c, \quad \text{tr}(PP^H) \leq P_T, 0 < \theta \leq 1, \quad (17a)
\]

where $P_T$ is the maximum transmit power at $S$. The constraint $\theta \log_2(1 + \gamma_{c,1}^{(1)})$ ensures the eavesdropper $E$ is unable to decode the legitimate common message, while $\theta \log_2(1 + \gamma_{c,2}^{(2)})$ presents the transmit power constraint and gives the value range of $\theta$.

III. OPTIMIZATION SOLUTION

Before solving the optimization problem $(17)$, we first analyze its convexity. The max operator is convex, while the max-max is non-convex. Furthermore, the elements in max functions, i.e. $R_c - C_{c,e}$ and $R_{p,k} - C_{k,e}$, are neither convex nor concave. To simplify the original optimization problem, we first decompose $(17)$ to draw the elements out of the max operators below, then we perform a series of linearizations to deal with its non-convexity. We identify four different cases:

Case 1: \[
\max_{P, \theta} R_c - C_{c,e} + R_{p,1} - C_{1,e} + R_{p,2} - C_{2,e}
\]

\[
\text{s.t.} \quad R_{p,1} \geq C_{1,e}, R_{p,2} \geq C_{2,e}, \quad (18a)
\]

\[
R_{p,1} \leq C_{1,e}, R_{p,2} \leq C_{2,e}, \quad (18b)
\]

Case 2: \[
\max_{P, \theta} R_c - C_{c,e} + R_{p,1} - C_{1,e}
\]

\[
\text{s.t.} \quad R_{p,1} \geq C_{1,e}, R_{p,2} \leq C_{2,e}, \quad (19a)
\]

\[
R_{p,1} \leq C_{1,e}, R_{p,2} \geq C_{2,e}, \quad (19b)
\]

Case 3: \[
\max_{P, \theta} R_c - C_{c,e} + R_{p,2} - C_{2,e}
\]

\[
\text{s.t.} \quad R_{p,1} \leq C_{1,e}, R_{p,2} \geq C_{2,e}, \quad (20a)
\]

\[
R_{p,1} \geq C_{1,e}, R_{p,2} \leq C_{2,e}, \quad (20b)
\]

Case 4: \[
\max_{P, \theta} R_c - C_{c,e}
\]

\[
\text{s.t.} \quad R_{p,1} \leq C_{1,e}, R_{p,2} \leq C_{2,e}, \quad (21a)
\]

\[
R_{p,1} \geq C_{1,e}, R_{p,2} \geq C_{2,e}, \quad (21b)
\]

As the non-convexity among all cases are similar, we next specify the optimization framework to solve Problem $(18)$ for simplicity. Note that the method for solving problem $(18)$ can be easily applied to problems $(19)$ - $(21)$. The solution to problem $(17)$ lies in the solution to one problem in $(18)$ - $(21)$ with the highest objective value.

To handle the non-convex problem $(18)$, we first equivalently rewrite $(18)$ as

\[
\max_{P, \theta, \alpha_{c,1}, \alpha_{c,2}} \min\{\alpha_{c,1}, \alpha_{c,2}\} + \sum_k (\alpha_{p,k} - \alpha_{k,e}) - \alpha_{c,e}
\]

\[
\text{s.t.} \quad R_{p,1} \geq \alpha_{p,k}, \quad (22a)
\]

\[
R_{c,k} \geq \alpha_{c,k}, \quad (22b)
\]

\[
C_{k,e} \leq \alpha_{k,e}, \quad (22c)
\]

\[
C_{c,e} \leq \alpha_{c,e}, \quad (22d)
\]

\[
\alpha_{p,1} \geq \alpha_{c,1}, \alpha_{p,2} \geq \alpha_{c,2}, \quad (22f)
\]

\[
\alpha_{c,e} \leq \alpha_{c,1}, \alpha_{c,e} \leq \alpha_{c,2}, \quad (22g)
\]
with auxiliary variable vectors \(\alpha_p = [\alpha_{p,1}, \alpha_{p,2}, \alpha_{p,3}, \alpha_{p,4}]\) and \(\alpha_c = [\alpha_{c,1}, \alpha_{c,2}, \alpha_{c,3}]\) which are introduced to represent the corresponding rates of decoding the common and private streams at legitimate users \(U_1, U_2\) and eavesdropper \(E\), \(k = 1, 2\). The difficulty in solving (22b) is due to the constraints (22b)-(22g). To further expose the hidden convexity of these inequalities, in the derivation below, we introduce several vectors \(\beta_p = [\beta_{p,1}, \beta_{p,2}, \beta_{p,3}, \beta_{p,4}], \beta_c = [\beta_{c,1}, \beta_{c,2}, \beta_{c,3}], \rho_p = [\rho_{p,1}, \rho_{p,2}, \rho_{p,3}, \rho_{p,4}], \rho_c = [\rho_{c,1}, \rho_{c,2}, \rho_{c,3}, \rho_{c,4}], \) where \(\beta_{p,k}, \beta_{c,k}, \rho_{p,k}, \rho_{c,k}\) respectively denote the achievable rates (without \(\theta\)) and the SINR of private and common streams in Phase I at \(U_k\), while \(\beta_{c,k}, \rho_{c,k}\) represent the achievable rate (without \(\theta\)) and the SINR of decoding the private and the common streams in Phase I at \(E, k = 1, 2\). To handle (22b), we rewrite it as
\[
\theta \log_2 (1 + \rho_{p,k}) \geq \alpha_{p,k}, \quad (23a)
\]
\[
\gamma_{p,k}^{(1)} \geq \rho_{p,k}. \quad (23b)
\]
Note that (23b) is equivalently replaced by constraints
\[
\theta \beta_{p,k} \geq \alpha_{p,k}, \quad (24a)
\]
\[
\log_2 (1 + \rho_{p,k}) \geq \beta_{p,k} \Leftrightarrow 1 + \rho_{p,k} - 2\beta_{p,k} \geq 0. \quad (24b)
\]
Based on (23) and (24), (22b) becomes
\[
(22b) \Leftrightarrow \begin{cases} 
\theta \beta_{p,k} \geq \alpha_{p,k}, \\
\gamma_{p,k}^{(1)} \geq \rho_{p,k}, \\
1 + \rho_{p,k} - 2\beta_{p,k} \geq 0. 
\end{cases} \quad (25a)\]
\[
(22b) \Leftrightarrow \begin{cases} 
\theta \beta_{p,k} \geq \alpha_{p,k}, \\
\gamma_{p,k}^{(1)} \geq \rho_{p,k}, \\
1 + \rho_{p,k} - 2\beta_{p,k} \geq 0. 
\end{cases} \quad (25b)\]
\[
(22b) \Leftrightarrow \begin{cases} 
\theta \beta_{p,k} \geq \alpha_{p,k}, \\
\gamma_{p,k}^{(1)} \geq \rho_{p,k}, \\
1 + \rho_{p,k} - 2\beta_{p,k} \geq 0. 
\end{cases} \quad (25c)\]
To deal with the non-convex constraints (25a) and (25b), we adopt the following approximation. For constraint (25a), \(\theta \beta_{p,k}\) is equivalent to \(\theta \beta_{p,k} = 2\left(\theta + \beta_{p,k}\right)^2 - \frac{1}{4} \left(\theta + \beta_{p,k}\right)^2\). Hence, approximated at the point \((\theta^{[n]}, \beta_{p,k}^{[n]})\) by the first-order Taylor expansion of \((\theta + \beta_{p,k})^2, \theta \beta_{p,k}\) is given by
\[
\theta \beta_{p,k} \geq 2\left(\theta^{[n]} + \beta_{p,k}^{[n]}\right) \left(\theta + \beta_{p,k}\right) - \frac{1}{4} \left(\theta^{[n]} + \beta_{p,k}^{[n]}\right)^2 - \frac{1}{4} \left(\theta - \beta_{p,k}\right)^2 \Delta \Phi^{[n]}(\theta, \beta_{p,k}), \quad (26)\]

where the superscript "\(n\)" denotes the \(n\)-th iteration. Therefore, (25a) is rewritten as
\[
\Phi^{[n]}(\theta, \beta_{p,k}) \geq \alpha_{p,k}, \quad (27)\]
where \(k = 1, 2\). As for (25b), we convert it to Difference-of-Convex (DC) form:
\[
|h^H_{p,k} p_i^2 + \sigma_k^2 - |h^H_{p,k} p_i^2|_{\rho_{p,k}}^2| \leq i \neq k, \quad (28)\]
\[
|h^H_{p,k} p_i^2 + \sigma_k^2 - \Psi^{[n]}(p_k, h, \rho_{p,k})| \leq 0, i \neq k, \quad (29)\]
where \(i, k = 1, 2\). To deal with (28), we relax concave parts of the DC constraints with their first-order Taylor expansions. (28) is approximated around the point \((p_k^{[n]}, \rho_{p,k}^{[n]})\) at iteration \(n\) by
\[
|h^H_{p,k} p_i^2 + \sigma_k^2 - \Psi^{[n]}(p_k, h, \rho_{p,k})| \leq 0, i \neq k, \quad (29)\]
Therefore, at iteration \( n \), based on the optimal solution \((g[n], P[n], p[n], \beta[n], \rho_p[n], \rho_c[n])\) obtained from the previous iteration \( n-1 \), we solve the following subproblem:

\[
\begin{align*}
\max_{P, \theta, \beta_p, \rho_p, \beta_c, \rho_c} & \quad \min \{\alpha_{c,1}, \alpha_{c,2}\} + \sum_k (\alpha_{p,k} - \alpha_{k,e}) - \alpha_{c,e} \\
\text{s.t.} & \quad (25a), (27), (29), (30), (32), (33), (22f), (22g), (17c). \tag{34a}
\end{align*}
\]

The proposed SCA-based algorithm is summarized in Algorithm 1.

**Remark 1.** The SSR of the proposed CRS secure transmission is always larger than or equal to that of MU-LP and C-NOMA. In our paper, Non-operative Rate-Splitting (NRS) without user relaying is a special case of the proposed CRS when \( \theta \) is fixed to 1. As discussed in [2], NRS boils down to MU-LP when the power allocated to the common stream is 0, and CRS is more general than NRS and MU-LP. Moreover, CRS reduces to C-NOMA when the common stream encodes the entire message of one of the two users. Therefore, the SSR achieved by the proposed CRS is always larger than or equal to that of MU-LP and C-NOMA.

**A. Convergence Analysis**

Following [20], we briefly demonstrate the convergence of Algorithm 1. Let \( t[n] \) denote the optimal objective, which equals to \( \min \{\alpha_{c,1}, \alpha_{c,2}\} + \sum_k (\alpha_{p,k} - \alpha_{k,e}) - \alpha_{c,e} \) in our paper. Given a feasible initial point, due to the linear expansion in processing the original optimization problem, the solution generated by solving (34) at the iteration \( n-1 \) is the feasible point of (34) at iteration \( n \). Thus, the SCA-based algorithm can yield a non-decreasing sequence, i.e., \( t[n] \geq t[n-1] \). Due to the power constraint in (17c), the series \( \{t[n]\}_{n=1}^{\infty} \) is bounded above, hence, Algorithm 1 guarantees the convergence of the optimization problem (18).

**B. Complexity Analysis**

Due to the exponential cone constraints (25c) and (30c), problem (34) is a generalized nonlinear convex problem. An alternative efficient method is to approximate (25c) and (30c) through a sequence of Second Order Cone (SOC) via the successive approximation method [21, 22], and the SOC Programming (SOCP) can be solved via interior-point methods with complexity \( O([KN_T]^{3.5}) \), where \( K \) is the number of legitimate users. The total number of iterations required for convergence is approximated as \( O(\log(\epsilon^{-1})) \), where \( \epsilon \) is the accuracy of the proposed Algorithm. Therefore, considering the worst case, the computational complexity is \( O(\log(\epsilon^{-1}))|KN_T|^{3.5} \).

**C. Generation of Initial Points**

From the convergence analysis above, it is obvious that if the initial solution \((P[0], g[0], \beta_p[0], \rho_p[0], \beta_c[0], \rho_c[0])\) are feasible to (34), then the problems of the subsequent iterations are also feasible and solvable. Hence, we can solve a simple problem: find \((P, \theta)\) (18b), (18c)), and denote the obtained solutions as \((P[0], g[0])\), while the initial value of the remaining variables can be obtained by replacing the related inequality of (34) by equalities.
V. Conclusion

In this paper, we enhance PHY security in multi-antenna BC by using CRS. We aim at maximizing the SSR subject to transmit power constraint. The result, obtained by utilizing SCA-based algorithm to solve the non-convex problem, shows the proposed CRS secure transmission scheme achieves higher SSR than existing MU-LP and C-NOMA. The benefits of CRS comes from the use of the common message for dual purposes. It not only ensures the secure transmission of the private messages, but also the cooperation between the legitimate users. Therefore, CRS is a promising strategy to improve the PHY security in multi-antenna BC.

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