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SUCCESSIVE INTERFERENCE CANCELLATION DECODING FOR THE K-USER CYCLIC INTERFERENCE CHANNEL

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ABSTRACT

The K-user cyclic interference channel can model one scenario in vehicular networks, where all the base stations are arranged along a highway. The k th user is interfered only by the $((k+1) \bmod K)$ th user in the K-user cyclic interference channel. The Han-Kobayashi scheme based rate region, the best inner bound known to date for the two-user interference channel, is extended to the K-user cyclic interference channel, which is obtained by simultaneously decoding the intended messages and a part of the interfered messages at the receiver. In this paper, we show that the simple successive interference cancellation decoding can also achieve this rate region.

Keywords: *Interference Channel, Cyclic Interference Channel, Achievable Rate Region, Successive Interference Cancellation Decoding, Multi-level Encoding*

1. INTRODUCTION

The interference channel, first introduced by Shannon in 1961 [1], models a communication scenario where all user pairs share the same physical medium and the communication of each user pair will be interfered with that of another user pairs. A user pair is usually named a user for short. The interference channel is useful for determining the performance limits of many practical systems such as the wireless networks. However, the capacity region of the two-user interference channel is still unknown except for the following several cases. For the two-user discrete memoryless interference channel, its capacity region is known if the intensity of the interference is strong [2,3,4], if the channel outputs are some deterministic functions of the channel inputs [5], and if the channel satisfies a class of degraded form [6,7]. For the two-user Gaussian interference channel, the capacity regions of very strong and strong interference channels [4,8,9] and the same capacities of noisy interference [10,11,12] , mixed interference [11,13] and one-sided [14] interference channels are known. So far, the best achievable rate region for the two-user interference channel is provided by Han and Kobayashi (HK) [8] using superposition coding in conjunction with simultaneous decoding. A simplified description of the HK rate region, named the CMG rate region, is given in [15] via multi-level encoding and simultaneous decoding. In this paper, we refer to these inner bounds as the HK scheme based inner bounds.

Recently, a special interference channel named the cyclic interference channel was introduced to study the coding problem of a special scenario may appear in vehicular networks, where all the base stations are arranged along a highway or high-speed rail. The cyclic interference channel is motivated by the modified Wyner model that is used to depict the soft handoff scenario of a cellular network [16]. In the K-user cyclic interference channel depicted in Figure 1, the communication of the k th user pair is interfered only by that of the $((k+1) \bmod K)$th user pair . In [17], the HK scheme based inner bounds for the two-user interference channel are extended to the K-user cyclic interference channel, and its all operating points are pointed out to be achieved by successive interference cancellation decoding via taking a geometric viewpoint and using rate-splitting arguments.

Inspired by this, we also focus on the K-user

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discrete memoryless cyclic interference channel in this paper and show that the HK scheme based inner bound of the K -user cyclic interference channel can be achieved by successive interference cancellation decoding via a rigorous and complete achievability proof using random coding arguments. The key idea of the proof is motivated by the equivalence of simultaneous decoding and successive interference cancellation decoding in achieving the capacity region of the multiple access channel (MAC).

Throughout the paper, we use X , x and $\mathcal{X}$ to denote a random variable, its realization and range, respectively. Moreover, a sequence is described as $X^n=(X_1,X_2,...,X_n)$, $X_1^n=(X_{11},X_{12},...,X_{1n})$, and $X_{(0)}^n=(X_0,X_1,X_2,...,X_n)$.

2. CHANNEL MODEL

The K -user discrete memoryless cyclic interference channel is shown in Figure 1, which consists of K input and output alphabets $\mathcal{X}_k$, $\mathcal{Y}_k$, $k=0,...,K-1$ and a collection of conditional probability mass functions $p(y_0,...,y_{K-1}|x_0,...,x_{K-1})$ on $\mathcal{Y}_0\times\cdots\times\mathcal{Y}_{K-1}$. Specially, the marginal distributions of the channel outputs satisfy $p(y_k|x_0,...,x_{K-1})=p(y_k|x_k,x_{(k+1)\ mod\ K})$. It is assumed that transmitter k ($k=0,...,K-1$) wants to send an independent message W_k uniformly distributed over $\mathcal{W}_k$ to its intended receiver. A $((2^{nR_0},...,2^{nR_{K-1}}),n)$ code for the K -user discrete memoryless cyclic interference channel consists of K message sets $\mathcal{W}_k=\{1,2,...,2^{nR_k}\}$, K encoding functions $f_k:\mathcal{W}_k\to\mathcal{X}_k^n$ performed by the corresponding encoder k , and K decoding functions $g_k:\mathcal{Y}_k^n\to\mathcal{W}_k$ performed by the corresponding decoder k. The average probability of error over the codebook is defined as $P_e^{(n)}=\Pr\{(\hat{W}_0,...,\hat{W}_{K-1})\neq(W_0,...,W_{K-1})\}$. A rate tuple $(R_0,...,R_{K-1})$ is said to be achievable for the K -user discrete memoryless cyclic interference channel if there exists a sequence of $((2^{nR_0},...,2^{nR_{K-1}}),n)$ codes with $P_e^{(n)}\to 0$ as $n\to\infty$. The capacity region of the K -user discrete memoryless cyclic interference channel is the closure of the set of achievable rate tuples $(R_0,...,R_{K-1})$.

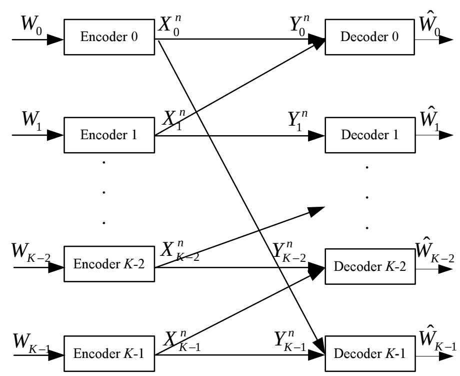

Figure 1: The K -User Cyclic Interference Channel

3. MAIN RESULT

In this section, we will show that the HK scheme based inner bound of the K -user discrete memoryless cyclic interference channel can be achieved by multi-level encoding in conjunction with successive interference cancellation decoding. We rewrite the achievable rate region of the K -user discrete memoryless cyclic interference channel in [17] as follows.

Given a K -user discrete memoryless cyclic interference channel, the random variables take values in $\mathcal{Q},\mathcal{U}_0,...,\mathcal{U}_{K-1}$, respectively. And let $X_0,...,X_{K-1},Y_0,...,Y_{K-1}$ take values in channel input alphabets $\mathcal{X}_0,...,\mathcal{X}_{K-1}$, and channel output alphabets $\mathcal{Y}_0,...,\mathcal{Y}_{K-1}$ respectively. Let $\mathcal{P}$ be the set of all probability distributions on $(Q,U_0,...,U_{K-1},X_0,...,X_{K-1})$ that factor as $p(q,u_{(0)}^{K-1},x_{(0)}^{K-1})=p(q)\prod_{k=0}^{K-1}p(u_k|q)p(x_k|u_k,q)$.

Given a fixed value $p\in\mathcal{P}$, consider $p(q,u_{(0)}^{K-1},x_{(0)}^{K-1},y_{(0)}^{K-1})=p(q,u_{(0)}^{K-1},x_{(0)}^{K-1})\,p(y_{(0)}^{K-1}|x_{(0)}^{K-1})$ on $(Q,U_{(0)}^{K-1},X_{(0)}^{K-1},Y_{(0)}^{K-1})$ and let $\mathcal{R}_k(p)$ be the set of rate tuples $(R_{kp},R_{kc},R_{((k+1)\ mod\ K)c})$ that satisfy

$$R_{kp}\le I(X_k;Y_k|U_k,U_{(k+1)\ mod\ K},Q), \qquad (1)$$

$$R_{kc}+R_{kp}\le I(X_k;Y_k|U_{(k+1)\ mod\ K},Q), \qquad (2)$$

$$R_{kp}+R_{((k+1)\ mod\ K)c}\le I(X_k,U_{(k+1)\ mod\ K};Y_k|U_k,Q) \qquad (3)$$

$$R_{kc}+R_{kp}+R_{((k+1)\ mod\ K)c}\le I(X_k,U_{(k+1)\ mod\ K};Y_k|Q). \qquad (4)$$

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Let $\mathrm{R}^K(p)$ denote the rate tuples $(R_0,\ldots,R_{K-1})$ such that $R_k = R_{kp} + R_{kc}$, where $(R_{kp}, R_{kc}, R_{((k+1)\bmod K)c}) \in \mathrm{R}_k(p)$, for each $k = 0,\ldots,K-1$.

Lemma 1: The set

$$\mathrm{R}^K = \bigcup_{p\in \mathrm{P}} \mathrm{R}^K(p)$$

is an achievable rate region for the K-user discrete memoryless cyclic interference channel.

Proof: We use the coded time sharing technique, multi-level encoding and successive interference cancellation decoding. The formal proof using random coding arguments is given below:

a) Random codebook construction. Fix $p(q)\,p(u_k,x_k|q)\,p(u_{(k+1)\bmod K},x_{(k+1)\bmod K}|q)$. Randomly generate a sequence q^n, drawn according to $\prod_{i=1}^n p_Q(q_i)$. For q^n and $j=k,(k+1)\bmod K$, randomly and conditionally independently generate $2^{nR_{jc}}$ sequences $u_j^n(w_{jc})$, $w_{jc}\in[1:2^{nR_{jc}}]$, each according to $\prod_{i=1}^n p_{U_j|Q}(u_{ji}|q_i)$. For each $u_j^n(w_{jc})$, randomly and conditionally independently generate $2^{nR_{jp}}$ sequences $x_j^n(w_{jc},w_{jp})$, $w_{jp}\in[1:2^{nR_{jp}}]$, each according to $\prod_{i=1}^n p_{X_j|U_j,Q}\left(x_j|u_{ji}(w_{jc}),q_i\right)$.

b) Encoding. To send $w_j=(w_{jc},w_{jp})$, transmitter $j=k,(k+1)\bmod K$ sends the corresponding codeword $x_j^n(w_{jc},w_{jp})$.

c) Decoding. At each receiver a virtual three-user MAC is formed because there are three messages including its own common messages w_{kc}, private messages w_{kp} and the rival's common messages $w_{((k+1)\bmod K)c}$ to be decoded. It is performed in three steps via successive interference cancellation decoding. So we have six decoding orders to decode these three messages. Four decoding orders are left because we can get rid of two meaningless decoding orders where the rival's common messages are decoded at last at the receiver. Also, due to the use of the multi-level encoding technique, we have to decode the common message of each user before decoding its private message. So, we only have two decoding orders, i.e., the rival's common messages, the user's common messages and its own private messages ($\langle w_{((k+1)\bmod K)c}, w_{kc}, w_{kp}\rangle$), and the user's common messages, the rival's common messages and the user's private messages ($\langle w_{kc}, w_{((k+1)\bmod K)c}, w_{kp}\rangle$). Each decoding order determines a rate region named sub-region. The convex hull of the union of these two sub-regions constitutes the rate region of the virtual three-user MAC at each receiver. And the rate region of the K-user discrete memoryless cyclic interference channel is the intersection of the rate regions of these K virtual three-user MACs. Without loss of generality, we only give the proof of one decoding order $\langle w_{((k+1)\bmod K)c}, w_{kc}, w_{kp}\rangle$. The proof of the other decoding order $\langle w_{kc}, w_{((k+1)\bmod K)c}, w_{kp}\rangle$ is similar.

The decoder k declares that $\hat{w}_{((k+1)\bmod K)c}$ is sent if it is the unique message such that $\left(q^n, u^n_{(k+1)\bmod K}(\hat{w}_{((k+1)\bmod K)c}), y_k^n\right)\in \mathbf{T}_\epsilon^{(n)}$, otherwise it declares an error. If such $\hat{w}_{((k+1)\bmod K)c}$ is found, the decoder k finds the unique message $\hat{w}_{kc}$ such that $\left(q^n, u_k^n(\hat{w}_{kc}), u^n_{(k+1)\bmod K}(\hat{w}_{((k+1)\bmod K)c}), y_k^n\right)\in \mathbf{T}_\epsilon^{(n)}$, otherwise it declares an error. If such $\hat{w}_{((k+1)\bmod K)c}$ and $\hat{w}_{kc}$ are found, the decoder k finds the unique message $\hat{w}_{kp}$ such that $\left(q^n, u^n_{(k+1)\bmod K}(\hat{w}_{((k+1)\bmod K)c}), x_k^n(\hat{w}_{kc}, w_{kp}), y_k^n\right)\in \mathbf{T}_\epsilon^{(n)}$, otherwise it declares an error.

d) Analysis of the probability of error. We bound the probability of error averaged over codebooks and messages. By symmetry of the random code generation, the probability of error does not depend on which codeword was sent. So, without loss of generality, we assume that the message pairs $W_k=(1,1)$ and $W_{(k+1)\bmod K}=(1,1)$ were sent. Then the conditional probability of an event given that $W_k=(1,1)$ and $W_{(k+1)\bmod K}=(1,1)$ were sent is defined as

$$\mathrm{P}(\varepsilon) = \mathrm{P}\left(\varepsilon | W_k=(1,1), W_{(k+1)\bmod K}=(1,1)\right).$$

A decoding error occurs only if

$$\varepsilon_1 \equiv \left\{\left(Q^n, X_k^n(1,1), U^n_{(k+1)\bmod K}(1), Y_k^n\right)\notin \mathbf{T}_\epsilon^{(n)}\right\},$$

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$$\text{or } \varepsilon_2 \equiv \left\{ \begin{matrix} \left(Q^n, U^n_{(k+1) \bmod K}(\hat{w}_{((k+1) \bmod K)c}), Y^n_k\right) \in \mathbf{T}_{\epsilon}^{(n)} \\ \text{for some } \hat{w}_{((k+1) \bmod K)c} \neq 1 \end{matrix} \right\},$$

$$\text{or } \varepsilon_3 \equiv \left\{ \begin{matrix} \left(Q^n, U^n_k(\hat{w}_{kc}), U^n_{(k+1) \bmod K}(1), Y^n_k\right) \in \mathbf{T}_{\epsilon}^{(n)} \\ \text{for some } \hat{w}_{kc} \neq 1 \end{matrix} \right\},$$

$$\text{or } \varepsilon_4 \equiv \left\{ \begin{matrix} \left(Q^n, X^n_k(1, \hat{w}_{kp}), U^n_{(k+1) \bmod K}(1), Y^n_k\right) \in \mathbf{T}_{\epsilon}^{(n)} \\ \text{for some } \hat{w}_{kp} \neq 1 \end{matrix} \right\}.$$

Then, by the union bound of events, we have $\mathrm{P}(\varepsilon) \le \mathrm{P}(\varepsilon_1) + \mathrm{P}(\varepsilon_2) + \mathrm{P}(\varepsilon_3) + \mathrm{P}(\varepsilon_4)$. By the law of large numbers (LLN), $\mathrm{P}(\varepsilon_1) \to 0$ as $n \to \infty$. By the packing lemma [18], $\mathrm{P}(\varepsilon_2) \to 0$ as $n \to \infty$ and $R_{((k+1) \bmod K)c} < I(U_{(k+1) \bmod K}; Y_k | Q) - \delta(\epsilon)$ hold, $\mathrm{P}(\varepsilon_3) \to 0$ if $R_{kc} \le I(U_k; Y_k | U_{(k+1) \bmod K}, Q) - \delta(\epsilon)$ and $n \to \infty$, and $\mathrm{P}(\varepsilon_4) \to 0$ as $n \to \infty$ if $R_{kp} \le I(X_k; Y_k | U_k, U_{(k+1) \bmod K}, Q) - \delta(\epsilon)$. Hence, if the following inequalities are satisfied the total average probability of decoding error $\mathrm{P}(\varepsilon) \to 0$ as $n \to \infty$. Actually, that describes a rate sub-region when Q is fixed:

$$R_{kp} \le I(X_k; Y_k | U_k, U_{(k+1) \bmod K}, Q), \quad (5)$$

$$R_{kc} \le I(U_k; Y_k | U_{(k+1) \bmod K}, Q), \quad (6)$$

$$R_{((k+1) \bmod K)c} \le I(U_{(k+1) \bmod K}; Y_k | Q), \quad (7)$$

$$R_{kc} + R_{kp} \le I(X_k; Y_k | U_{(k+1) \bmod K}, Q), \quad (8)$$

$$R_{kc} + R_{((k+1) \bmod K)c} \le I(U_k, U_{(k+1) \bmod K}; Y_k | Q), \quad (9)$$

$$R_{kp} + R_{((k+1) \bmod K)c} \le I(X_k; Y_k | U_k, U_{(k+1) \bmod K}, Q) + I(U_{(k+1) \bmod K}; Y_k | Q), \quad (10)$$

$$R_{kc} + R_{kp} + R_{((k+1) \bmod K)c} \le I(X_k, U_{(k+1) \bmod K}; Y_k | Q). \quad (11)$$

Similarly, according to the other decoding order $\langle w_{kc}, w_{((k+1) \bmod K)c}, w_{kp} \rangle$, we have the other rate sub-region for a given Q:

$$R_{kp} \le I(X_k; Y_k | U_k, U_{(k+1) \bmod K}, Q), \quad (12)$$

$$R_{kc} \le I(U_k; Y_k | Q), \quad (13)$$

$$R_{((k+1) \bmod K)c} \le I(U_{(k+1) \bmod K}; Y_k | U_k, Q), \quad (14)$$

$$R_{kc} + R_{kp} \le I(U_k; Y_k | Q) + I(X_k; Y_k | U_k, U_{(k+1) \bmod K}, Q), \quad (15)$$

$$R_{kc} + R_{((k+1) \bmod K)c} \le I(U_k, U_{(k+1) \bmod K}; Y_k | Q), \quad (16)$$

$$R_{kp} + R_{((k+1) \bmod K)c} \le I(U_{(k+1) \bmod K}, X_k; Y_k | U_k, Q), \quad (17)$$

$$R_{kc} + R_{kp} + R_{((k+1) \bmod K)c} \le I(X_k, U_{(k+1) \bmod K}; Y_k | Q). \quad (18)$$

e) Rate region. According to the convex hull of the union of these two sub-regions, we obtain a rate region of a virtual three-user MAC at receiver k. The rate region of the K-user discrete memoryless cyclic interference channel is the intersection of these K rate regions, which can be described as follows.

$$R_{kp} \le I(X_k; Y_k | U_k, U_{(k+1) \bmod K}, Q), \quad (19)$$

$$R_{kc} \le I(U_k; Y_k | U_{(k+1) \bmod K}, Q), \quad (20)$$

$$R_{((k+1) \bmod K)c} \le I(U_{(k+1) \bmod K}; Y_k | U_k, Q), \quad (21)$$

$$R_{kc} + R_{kp} \le I(X_k; Y_k | U_{(k+1) \bmod K}, Q), \quad (22)$$

$$R_{kc} + R_{((k+1) \bmod K)c} \le I(U_k U_{(k+1) \bmod K}; Y_k | Q), \quad (23)$$

$$R_{kp} + R_{((k+1) \bmod K)c} \le I(U_{(k+1) \bmod K}, X_k; Y_k | U_k, Q), \quad (24)$$

$$R_{kc} + R_{kp} + R_{((k+1) \bmod K)c} \le I(X_k, U_{(k+1) \bmod K}; Y_k | Q), \quad (25)$$

where $k = 0, ..., K-1$.

According to [15], we get rid of those redundant inequalities and then have the simplified inequalities as below.

$$R_{kp} \le I(X_k; Y_k | U_k, U_{(k+1) \bmod K}, Q), \quad (26)$$

$$R_{kc} + R_{kp} \le I(X_k; Y_k | U_{(k+1) \bmod K}, Q), \quad (27)$$

$$R_{kp} + R_{((k+1) \bmod K)c} \le I\left(X_k, U_{(k+1) \bmod K}; Y_k | U_k, Q\right), \quad (28)$$

$$R_{kc} + R_{kp} + R_{((k+1) \bmod K)c} \le I(X_k, U_{(k+1) \bmod K}; Y_k | Q), \quad (29)$$

With this, we complete the proof of the achievability of the rate region for the K-user discrete memoryless cyclic interference channel via multi-level encoding in conjunction with successive interference cancellation decoding.

4. CONCLUSION

The cyclic interference channel models a special scenario that may appear in vehicular networks, where all the base stations are arranged along a highway or high-speed rail. To determine the performance limit of this communication system, the K-user cyclic interference channel is often considered by the information theory researchers. It

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is no wonder that the Han-Kobayashi scheme based inner bound is extended to the K -user cyclic interference channel and this Han-Kobayashi scheme based inner bound is obtained by superposition coding or multi-level encoding in conjunction with simultaneous decoding. In this paper, we give a rigorous achievability proof using random coding arguments to show that successive interference cancellation decoding can also achieve the Han-Kobayashi scheme based inner bound of the K -user cyclic interference channel, which is helpful for us to understand and determine the Han-Kobayashi scheme based inner bound.

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