A Comparative Study of Cooperation for the Two-user Interference Channel

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Abstract—The interference channel is a model for a wireless network where several source-destination pairs compete for the same resources. When the sources transmit simultaneously the destinations experience unwanted interference. Determining how to optimally manage the interference is a long standing open problem in network information theory. In this talk we review one emerging interference management technique: cooperation. Cooperation can occur among source nodes only (Source Cooperation or Generalized Feedback), or among destination nodes only (Destination Cooperation), or among all nodes (General Cooperation). For the special case of Gaussian noise channels, we compare the different forms of cooperation in terms of symmetric generalized degrees of freedom. When known, we also discuss capacity results to within a constant number of bits.

I. CHANNEL MODEL

A general full-duplex cooperative interference channel is a 2K-node network with inputs $X_0, \ldots, X_{2K-1}$, outputs $Y_0, \ldots, Y_{2K-1}$ and a memoryless channel with transition probability $P := P[Y_0, \ldots, Y_{2K-1} | X_0, \ldots, X_{2K-1}]$. Sources have index 0 to $K-1$ and destinations $K$ to $2K-1$. Message $W_i$ is independent of everything else and uniformly distributed over $[1 : 2^{NR}]$, with $N \in \mathbb{N}$ denoting the block-length and $R_i \in \mathbb{R}^+$ the rate in bits per channel use, for $i \in [0 : K-1]$. Encoding at node $i \in [0 : 2K-1]$ at channel use $t \in [1 : N]$ is a deterministic function $X_{i,t}(Y_{i,t-1})$, with the convention $W_K = \ldots = W_{2K-1} = \emptyset$. Decoding at node $i \in [K : 2K-1]$ after the $N$-th channel use is a deterministic function $W_{i-K}(Y_i^N)$. A rate vector $(R_0, \ldots, R_{K-1})$ is $\epsilon$-achievable if $\max_{i \in [0 : K-1]} P[W_i \neq W_i] \leq \epsilon$ for some $\epsilon \in (0, 1]$. The capacity region is the convex closure of the set of rate vectors that are $\epsilon$-achievable for all $\epsilon > 0$ [1]. In this work we consider the case $K = 2$ only, which is depicted in Fig. 1.

II. MODELS OF COOPERATION

Several cooperation models have been analyzed in literature such as: cooperation only occurs among sources (Source Cooperation, also known as Generalized Feedback), or only among destinations (Destination Cooperation), or among all nodes (General Cooperation). In each case, cooperation can be in-band or out-of-band. For out-of-band cooperation, the network is effectively composed of two parallel networks: the underlying interference channel (from the source inputs to the destination outputs) and the cooperation channel (which is usually assumed to be deterministic/noiseless).

In the following we list some recent journal papers that deal with cooperation for the two-user interference channel and that we will compare in this talk. The interested reader can find the technical details in these works and the list of related preceding publications in the references therein. Some extensions to networks with more than two source-destinations pairs can be found for example in [14], [15].

A. Source Cooperation/Generalized Feedback

The destinations do not have an input to the channel, i.e.,

$$X_K = \ldots = X_{2K-1} = \emptyset.$$  

A.1) Out-of-band. The channel input at source $i$, $i \in [0 : K-1]$, is a two-dimensional vector $X_i := [X_i,d, X_i,s]$, where $X_i,d$ affects the channel outputs at the destinations and $X_i,s$ the channel outputs at the sources. Effectively, there are two parallel channels: the underlying interference channel with transition probability $P[Y_K, \ldots, Y_{2K-1} | X_{0,d}, \ldots, X_{K-1,d}]$ and the cooperation channel with transition probability $P[Y_0, \ldots, Y_{K-1} | X_{0,s}, \ldots, X_{K-1,s}]$. 

Fig. 1. The memoryless cooperative interference channel (channel inputs in green, channel outputs in pink, transmitted messages in black, and decoded messages in blue).
Conferencing Encoders is a special case of out-of-band source cooperation where the cooperation channel is deterministic [2].

Cognition is a special case of conferencing encoders where the channel output at some sources is constant (these sources are known as “primary users”) and the channel output at the other sources is such that all messages can be conveyed in a single channel use (these sources are known as the “cognitive users”) [4],[5].

A.2) In-band. The same inputs affect both the underlying interference channel and the cooperation channel. The cooperation channel is noisy [6],[7],[8],[9].

Noisy Output Feedback is a special case of in-band source cooperation where the channel output at a source is a degraded version of the channel output at its intended destination, i.e., $Y_i = g_i(Y_{i+K}, Z_i)$ for some deterministic function $g_i$ and some random process $Z_i$ representing the “extra noise”, for all $i \in \{0 : K-1\}$ [11]. If the “extra noise” process is deterministic then the channel is known simply as interference channel with feedback [12].

Ultimate Limit of Source Cooperation. By sharing all messages among the sources we obtain an equivalent memoryless broadcast channel with input $X_{eq} := (X_0, \ldots, X_{K-1})$ and outputs $Y_K, \ldots, Y_{2K-1}$, whose capacity (which is not known in general [1]) gives the ultimate gain that can be obtained with source cooperation.

B. Destination Cooperation
The sources do not have an output from the channel, i.e., $Y_0 = \ldots = Y_{K-1} = 0$.

B.1) Out-of-band. The channel output at destination $i$, $i \in \{K : 2K-1\}$, is a two-dimensional vector $Y_i := [Y_{i,d}, Y_{i,s}]$, where $Y_{i,d}$ is affected by the channel inputs from the destinations and $Y_{i,s}$ by the channel inputs from the sources. Effectively, there are two parallel channels: the underlying interference channel with transition probability $P[Y_0,\ldots,Y_{2K-1}|X_0,\ldots,X_{K-1}]$ and the cooperation channel with transition probability $P[Y_{0,d},\ldots,Y_{K-1,d}|X_K,\ldots,Y_{2K-1}]$.

Conferencing Decoders is a special case of out-of-band destination cooperation where the cooperation channel is deterministic [3].

B.2) In-band. The channel outputs are affected by all channel inputs [6],[10].

Ultimate Limit of Destination Cooperation. By sharing all channel outputs at the destinations among the destinations we obtain an equivalent memoryless multiple access channel with inputs $X_0,\ldots,X_{K-1}$ and output $Y_{eq} := (Y_K,\ldots,Y_{2K-1})$, whose capacity region [1] gives the ultimate gain that can be obtained with destination cooperation.

C. General Cooperation
This is the most general case where all nodes cooperate.

C.1) Out-of-band. Channel outputs at the destinations are affected by the channel inputs from the sources only and channel outputs at the sources are affected by the channel inputs from the destinations only. Effectively, there are two parallel channels: the underlying interference channel with transition probability $P[Y_K,\ldots,Y_{2K-1}|X_0,\ldots,X_{K-1}]$ and a cooperation channel with transition probability $P[Y_0,\ldots,Y_{K-1}|X_K,\ldots,Y_{2K-1}]$.

Rate-limited Feedback is a special case of out-of-band general cooperation where the cooperation channel is deterministic [13].

C.2) In-band. All channel inputs affect all channel outputs. To the best of the author’s knowledge the case of in-band general cooperation has not been studied so far.

Ultimate Limit of General Cooperation. By sharing all messages among the sources and all channel outputs at the destinations among the destinations we obtain an equivalent memoryless point-to-point channel with input $X_{eq} := (X_0,\ldots,X_{K-1})$ and output $Y_{eq} := (Y_K,\ldots,Y_{2K-1})$, whose capacity gives the following sum-rate upper bound

$$R_0 + \ldots + R_{K-1} \leq C_{\text{perfect coop.}} := \max_{P[X_{eq}]} I(X_{eq};Y_{eq}).$$

which cannot be improved by feedback, i.e., $C_{\text{perfect coop.}}$ does not depend on $(Y_0,\ldots,Y_{K-1})$.

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REFERENCES


