MULTICAST BEAMFORMER DESIGN FOR MIMO CODED CACHING SYSTEMS

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ABSTRACT

Coded caching (CC) techniques have been shown to be conveniently applicable in multi-input multi-output (MIMO) systems. In a $K$-user network with spatial multiplexing gains of $L$ at the transmitter and $G$ at every receiver, if each user can cache a fraction $\gamma$ of the file library, a total number of $GK\gamma + L$ data streams can be served in parallel. In this paper, we focus on improving the finite-SNR performance of MIMO-CC systems. We first consider a MIMO-CC scheme that relies only on unicasting individual data streams, and then, introduce a decomposition strategy to design a new scheme that delivers the same data streams through multicasting of $G$ parallel codewords. We discuss how optimized beamformers could be designed for each scheme and use numerical simulations to compare their finite-SNR performance. It is shown that while both schemes serve the same number of streams, multicasting provides notable performance improvements. This is because, with multicasting, transmission vectors are built with fewer beamformers, leading to more efficient usage of available power resources.

Index Terms— Coded caching, MIMO multicasting

1. INTRODUCTION

Wireless networks are under mounting pressure to bear exponentially increasing volumes of multimedia content [1] and to support the imminent emergence of new applications such as wireless immersive viewing [2, 3]. For the efficient delivery of such multimedia content, coded caching (CC) was proposed in [4] as a means of increasing the data rates by exploiting cache content across the network. In a single-stream downlink network of $K$ users, each capable of caching a portion $\gamma \leq 1$ of the entire file library, CC enables boosting the achievable rate by a factor of $K\gamma + 1$ through multicasting carefully created codewords such that each user can use its cache content to remove unwanted parts from the received signal. As a result, with CC, the achievable degrees of freedom (DoF) is increased from one to $K\gamma + 1$. The multiplicative factor $t \equiv K\gamma$ is also called the coded caching gain.

Motivated by the growing importance of multi-antenna wireless communications [5], the authors in [6, 7] explored the cache-aided multiple-input single-output (MISO) setting, revealing that for a downlink MISO setup with cache-enabled users and the transmitter-side multiplexing gain of $L$, the cumulative DoF of $t + L$ is achievable. Many subsequent works then explored various implementation challenges of MISO-CC schemes, including but not limited to, optimal beamformer design [8–10], exponentially growing subpacketization [11, 12], and applicability to dynamic setups [13, 14].

Compared to MISO setups, using CC in multiple-input multiple-output (MIMO) communications has been less investigated. In [15,16], information-theoretic approaches were used to find upper bounds to the achievable DoF in MIMO-CC setups, and it was revealed that multiple antennas at the receiver side could increase the DoF over MISO settings. Similarly, the authors in [17] proposed a low-complexity solution to construct MIMO-CC schemes building on any given scheme available for MISO setups. It was shown that for the simple case of a MIMO setting with a single transmitter and multiple receivers with spatial multiplexing gains of $L$ and $G$, respectively, if $\frac{L}{G}$ is an integer, the cumulative DoF of $GL + L$ is achievable. In other words, multiple receive antennas enable a multiplicative boost in the coded caching gain.

In this paper, we study the finite-SNR performance of MIMO-CC schemes. We first explain how optimized unicast beamformers could be designed for the scheme in [17] using a similar approach to [8]. Then, we discuss how the underlying MIMO structure could be used to decompose the system into multiple parallel MISO setups (or single-antenna, if $L = G$), and how this decomposition could enable transmitting several multicast codewords simultaneously. While both considered schemes deliver the same number of streams in each transmission, we expect the scheme with multicasting to have better performance in the finite-SNR regime as it requires fewer beamformers in each transmission (hence, the usage of available power resources is more efficient). Finally, numerical simulations are used to verify this assumption.

Throughout the text, we use the following notations. For integer $J$, $\{J\}$ is the set of numbers $\{1, 2, \cdots, J\}$. Boldface upper- and lower-case letters indicate matrices and vectors, respectively, and calligraphic letters denote sets. For two sets $\mathcal{K}$ and $\mathcal{T}$, $\mathcal{K}\setminus\mathcal{T}$ is the set of elements in $\mathcal{K}$ that are not in $\mathcal{T}$.
2. SYSTEM MODEL

We consider a MIMO setup with $K$ users, $L$ antennas at the transmitter, and $G$ antennas at each receiver. The spatial multiplexing gains at the transmitter and receivers are set to $L \leq L$ and $G \leq G$; i.e., the transmitter can deliver $L$ data streams and each user can receive $G$ data streams simultaneously. This requires that the channel matrices $\mathbf{H}_k \in \mathbb{C}^{G \times L}$ from the transmitter to every user $k \in [K]$ have ranks not smaller than $G$, and the cumulative channel matrix formed by the vertical concatenation of individual channel matrices as $\mathbf{H} = [\mathbf{H}_1^H : \mathbf{H}_2^H : \cdots : \mathbf{H}_K^H]^H$ to have a rank larger than or equal to $L$. Each user has a cache memory of size $MF$ bits and requests files from a library $\mathcal{F}$ of $N$ files, each with size $F$ bits. For notational simplicity, we use a normalized data and requests files from a library $\mathcal{F}$.

Following a similar structure as [7], we split each file into $(\frac{K}{t})$ subfiles $W_p$, where $P \subseteq [K]$ can be any subset of users with $|P| = t$. Then, in the cache memory of user $k \in [K]$, we store $W_p$, $\forall W \in \mathcal{F}$, $\forall P : k \in P$.

At the beginning of the delivery phase, every user $k$ announces its requested file $W(k) \in \mathcal{F}$ to the server. The server builds and transmits a vector $x(K)$ for every subset of users $K \subseteq [K]$ with $|K| = t + \eta$ (transmissions are, e.g., in consecutive TDMA slots). Each $x(K)$ is built to deliver $G$ parallel data streams to every user in $K$, resulting in the total DoF of $G(t + \eta) = GL + L$. After transmitting $x(K)$, every user $k \in K$ receives $\mathbf{y}_k(k) = \mathbf{H}_k x(K) + \mathbf{z}_k$, where $\mathbf{z}_k \in \mathbb{C}^{G \times 1}$ is the additive white Gaussian noise (AWGN) with power $N_0$. Then, receive beamforming vectors $\mathbf{u}_{k,g} \in \mathbb{C}^{G \times 1}$, $g \in [G]$ are used to produce stream-specific received signals $y_{k,g}(K) = \mathbf{u}_{k,g}^H \mathbf{y}_k(k)$. Let us use $s_{k,g}$ to denote the stream $g$ at user $k$, and define the equivalent channel vector for the stream $s_{k,g}$ as $h_{k,g} = (\mathbf{u}_{k,g}^H \mathbf{H}_k)^H$. Then, defining $z_{k,g} = \mathbf{u}_{k,g}^H \mathbf{z}_k$, we have

$$y_{k,g}(K) = h_{k,g}^H x(K) + z_{k,g}. \quad (1)$$

Transmission vectors $x(K)$ are built using the delivery algorithm of the considered MIMO-CC scheme. In this paper, we study two schemes with the same number of parallel data streams but with different transmission strategies: unicasting and multicasting.

3. DATA DELIVERY WITH UNICASTING

For data delivery with unicasting, we consider the MISO scheme in [7] as the baseline and use the stretching mechanism in [17] to apply it to MIMO setups. As a result, we first split every subfile $W_p$ into $Q = (\frac{K}{t})$ smaller parts $W_p^q$, $q \in [Q]$, and then, split every resulting part $W_p^q$ into $G$ subpackets $W_p^{g,q}$, $g \in [G]$. The index $g$ does not affect our analysis in this paper and is removed for notational simplicity. The transmission vector $x(K)$ is built as

$$x(K) = \sum_{\mathcal{T} \subseteq K} \sum_{k \in \mathcal{T}} \sum_{g \in [G]} W_p^q \cdot \mathbf{w}_{R(K, T, k, g)}^T, \quad (2)$$

where $\mathbf{w}_{R(\cdot)}$ denotes transmit beamformers and

$$\mathcal{R}(K, T, k, g) = \bigcup_{\bar{k} \in K \setminus T} \{\mathbf{s}_{\bar{k}, g}\} \bigcup_{\bar{g} \in [G]} [\{g\}] \quad (3)$$

represents the set of streams over which the interference is suppressed by beamforming. As a quick explanation, using $x(K)$, we transmit $G(t + 1)\frac{(t + \eta)}{t}$ subpackets, and all these subpackets can be decoded simultaneously as the interference caused by each of them is either suppressed by beamforming or could be reconstructed and removed using the cache content. The following example clarifies this procedure.

**Example 1.** Consider a MIMO setup where spatial multiplexing gains at the transmitter and receivers are $L = G = 2$, and the coded caching gain is $t = 1$ (i.e., $t + \eta = 2$). Let us consider the transmission vector serving users 1 and 2, assuming they have requested files $A$ and $B$, respectively. It is built as

$$x(\{1, 2\}) = A_1^2 \mathbf{w}_{s_{1,2}} + A_2^2 \mathbf{w}_{s_{1,1}} + B_1^2 \mathbf{w}_{s_{2,2}} + B_2^2 \mathbf{w}_{s_{2,1}} \cdot (4)$$

and delivers four subpackets to users 1 and 2 in parallel (note that the brackets for sets $\mathcal{R}(\cdot)$ are removed for notational simplicity). Let us review the decoding process for the first subpacket for user 1, i.e., $A_1^2$. Using (1), the respective stream-specific received signal for this subpacket is

$$y_{1,1}(\{1, 2\}) = h_{1,1}^H x(\{1,2\}) + z_{1,1}$$

$$= A_1^2 h_{1,1}^H \mathbf{w}_{s_{1,2}} + A_2^2 h_{1,1}^H \mathbf{w}_{s_{1,1}} + I_c + z_{1,1},$$

where the interference term $I_c = B_1^2 h_{1,1}^H \mathbf{w}_{s_{2,2}} + B_2^2 h_{1,1}^H \mathbf{w}_{s_{2,1}}$, can be fully reconstructed and removed using the cache content of user 1. By definition, the remaining interference term $A_2^2 h_{1,1}^H \mathbf{w}_{s_{1,1}}$ is also suppressed by beamforming, and hence, $A_1^2$ is decodable at user 1. Following the same process, all the other three streams could also be decoded successfully.

In [17], zero-forcing (ZF) unicast beamformers are used to completely null out the interference, i.e., transmit and receive beamformers are built such that $h_{k,g}^H \mathbf{w}_{R(K, T, k, g)} = 0$ for every $s_{k,g} \in \mathcal{R}(K, T, k, g)$. Of course, ZF is not an appropriate choice, and we need to design optimized beamformers in finite-SNR [8]. This can be done using alternating optimization together with the successive convex approximation

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1. $L$ and $G$ are limited not only by the number of antennas but also by practical constraints such as the number of available baseband chains.

2. Similar to [17], we assume that channel multipliers $h_{k,g}^H \mathbf{w}_{R(\cdot)}$ could be estimated at the receivers, e.g., using downlink precoded pilots.
(SCA) [8]. To do so, at each step, we fix either transmit or receive beamformers to their latest known values, find the optimal solution for the other one, and repeat this procedure until convergence. Here, due to lack of space, we review the beamformer design process only for the symmetric case of \( L = G \) (i.e., \( \eta = 1 \)) and leave the general formulation for the extended version of this paper. The reason is that if \( \eta > 1 \), each receiver has to decode multiple subpackets over each stream through an equivalent user-specific multiple access channel (MAC) [8], and hence, linear MMSE receivers would no longer work. However, if \( \eta = 1 \), after solving for optimal transmit beamformers, receive beamformers can be simply calculated as

\[
\mathbf{u}_{k,g} = (\mathbf{H}_k \mathbf{W}_k \mathbf{H}_k^H + N_0 I)^{-1} \mathbf{H}_k \mathbf{w}_{R(k,k,g)},
\]

where \( \mathbf{W}_k \equiv [\mathbf{w}_{R(k,k,k,1)}; \ldots; \mathbf{w}_{R(k,k,k,G)}] \) is formed by concatenating all the \( G \) transmit beamformers used to send data to user \( k \) (note that when \( \eta = 1 \), \( T = K \)).

Now, assuming receive beamformers are fixed, to calculate optimal transmit beamformers, we note that the SINR for decoding subpacket \( W_{T \setminus \{k\}}^g(k) \) at user \( k \in K \) is

\[
\lambda_{k,g} = \frac{|\mathbf{h}_{k,g}^H \mathbf{w}_{R(k,k,g)}|^2}{\sum_{g \in [G]\{g\}} |\mathbf{h}_{k,g}^H \mathbf{w}_{R(k,k,g)}|^2 + N_0}
\]

and the rate optimization problem will be

\[
\max_{\mathbf{w}_{R(k,k,g)}} \min_{k,g} r_{k,g}
\]

s.t. \( r_{k,g} \leq \log(1 + \lambda_{k,g}), \forall k \in K, g \in [G] \),

\[
\sum_{k \in K} \sum_{g \in [G]} |\mathbf{w}_{R(k,k,g)}|^2 \leq P_T,
\]

where \( P_T \) is the total available transmit power. This problem is non-convex and can be solved, e.g., using SCA [8].

4. DATA DELIVERY WITH MULTICASTING

The primary goal of multicasting in the MIMO-CC scheme is to improve the finite-SNR performance. This is because, with multicasting, fewer beamforming vectors are needed for the transmission and the average power allocated to each beamformer is increased. Of course, this has a more prominent effect in finite-SNR as the rate is power-limited in this regime. Similar results for MISO setups are found in [18, 19].

To illustrate multicasting opportunities, we decompose the MIMO system into \( G \) parallel MISO systems (or single-antenna, if \( L = G \)), as shown in Figure 1. This requires splitting subfiles \( W_T \) into subpackets \( W_{T \setminus \{k\}}^g \) following the same process as in Section 3, and building the multicast-enabled transmission vector \( \hat{x}(K) \) as

\[
\hat{x}(K) = \sum_{T \subseteq K} \sum_{g \in [G]} X_T^g \mathbf{w}_{R(K,T,g)},
\]

where, using \( \oplus \) to represent the bit-wise XOR operation in the finite field, we have

\[
X_T^g = \bigoplus_{k \in T} W_{T \setminus \{k\}}^g(k),
\]

\[
\hat{R}(K, T, g) = \bigcup_{k \in K \setminus T} \{s_{k,g}\} \bigcup_{g \in [G]} \{s_{k,g}\}.
\]

Note that the \( q \) index is again removed for simplicity. As a quick explanation, instead of unicasting individual subpackets, we deliver \( G \) parallel codewords to every subset of users \( T \subseteq K \) with size \( |T| = t + 1 \). Each codeword is built using the same XOR method as [7] and includes subpackets for every user in \( T \). Every \( x(K) \) delivers \( G(t+1) \) codewords, hence, the same number of \( G(t+1) \) subpackets as the unicasting scheme of Section 3. The following example clarifies data delivery with the proposed scheme.

Example 2. Consider the network in Example 1. Instead of using unicast transmission as in (4), we can transmit two codewords \( X_{1,2}^1 = A_1 \oplus B_1 \) and \( X_{1,2}^2 = A_2 \oplus B_2 \) using

\[
\hat{x}([1, 2]) = X_{1,2}^1 \hat{w}_{s_1, s_2} + X_{1,2}^2 \hat{w}_{s_1, s_2}.
\]

Then, for decoding \( A_1 \) at user 1, this user has to first extract \( X_{1,2}^1 \) from the stream-specific received signal

\[
\hat{y}_{1,1}([1, 2]) = X_{1,2}^1 \hat{h}_{1,1} \hat{w}_{s_1, s_2} + X_{1,2}^2 \hat{h}_{2,1} \hat{w}_{s_1, s_2} + z_{1,1},
\]

which is possible as the interference term \( X_{1,2}^2 \hat{h}_{1,1} \hat{w}_{s_1, s_2} \) is suppressed by beamforming. Finally, after extracting \( X_{1,2}^1 \), user 1 can decode \( A_1 \) by removing \( B_1 \) which is available in its cache memory. Using the same procedure, all four subpackets could be decoded successfully.

We can use a similar procedure as unicasting to design optimized beamformers for the multicasting scheme. Again, due to lack of space, we only review this process for the symmetric case of \( L = G \) (hence, \( T = K \)). With this assumption, updating received beamformers is possible using the same linear MMSE receiver in (5). However, to find optimal transmit
beamformers, instead of using the SINR value in (6) for decoding subpackets, we need to use the SINR term for extracting codeword $X_k^t$ at user $k$, given as

$$\hat{\lambda}_{k,g} = \frac{[h_{k,g}^H \hat{w}_{R(k,K,g)}]^2}{\sum_{g \in [K]|\{g\}} [h_{k,g}^H \hat{w}_{R(k,K,g)}]^2 + N_0}.$$  \hspace{1cm} (12)

Finally, the rate optimization problem could be written as

$$\max \sum_{k \in [K], g \in [G]} \min \hat{r}_{k,g}$$

$$\text{s.t.} \quad \hat{r}_{k,g} \leq \log(1 + \hat{\lambda}_{k,g}), \forall k, g \in [G],$$

$$\sum_{g \in [G]} [\hat{w}_{R(k,K,g)}]^2 \leq P_T.$$  \hspace{1cm} (13)

Comparing (13) with (7), the number of required beamformers for every transmission is reduced by a factor of $|K| = t+1$. As a result, we expect a performance boost as the average power allocated to each beamformer is increased. On the other hand, from (12) and (6), it can be seen that every beamformer appears more times at the interference sum (denominators of the SINR terms), by the same factor of $t+1$. This results in more constraints as we search for the optimal beamformer, hindering the performance improvement expected by the power gain. However, as will be shown by simulation results, the overall performance improvement is still noticeable – especially in the finite-SNR regime.

5. SIMULATION RESULTS

We use numerical simulations to compare the performance of the proposed schemes. For reference, we also simulate another setup, called virtual MISO, where the antenna array at the receiver side is used only for achieving a beamforming gain. For this setup, we use the MISO-CC scheme of [7], and for every user $k$, set the receive beamforming vector $\hat{u}_k$ as the eigenvector corresponding to the strongest eigenmode (i.e., the largest eigenvalue) of $\mathbf{H}_k$. The goal of simulating the virtual MISO setup is to analyze the performance gains achieved by the proposed MIMO-CC schemes. All the simulations are done for a network of $K = 8$ users with CC gain $t = 1$, and optimized beamformers are used for transmissions.

In Figure 2, we have compared the performance of the virtual MISO setup with the proposed MIMO-CC scheme with multicast transmissions. The MIMO scheme outperforms the virtual MISO setup for all values of $L$ and $G$, and the performance gap of the two schemes becomes larger at higher SNR or as $L$ and $G$ grow. This is due to the larger DoF of MIMO-CC schemes, where the CC gain $t$ is multiplied by $G$. Note that the DoF value has a more prominent performance effect in the high-SNR regime [8, 19].

In Figure 3, we have compared the performance of the two MIMO-CC schemes considered in this paper. One scheme is based on unicasting subpackets, and the other incorporates multicasting codewords. As can be seen, multicasting provides superior performance, as fewer beamformers are needed for transmission, and the average power allocated to each beamformer increases. Moreover, the (relative) improvement is more prominent in finite-SNR (e.g., up to 30% for the considered network with $L = G = 4$ at 5dB), which is also expected as the rate is power-limited in this regime.

6. CONCLUSION AND FUTURE WORK

In this paper, we focused on improving the finite-SNR performance of coded caching schemes for MIMO systems. We studied two schemes with the same number of parallel streams (i.e., with the same DoF) but with different unicast and multicast transmission strategies. We discussed how optimized beamformers could be designed for each scheme and used numerical simulations to compare their performance. It was shown that with multicasting, the performance could be improved noticeably, especially in the finite-SNR regime.

Future extensions include applying results to the non-integer $t$ case and the non-symmetric ($L \neq G$) scenario. We also target designing MIMO-CC schemes with multicasting but without requiring the complex successive interference cancellation (SIC) structure at the receiver.
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