A Low-Complexity Cache-Aided Multi-antenna Content Delivery Scheme

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Abstract—We study downlink beamforming in a single-cell network with a multi-antenna base station (BS) serving cache-enabled users. Proactive caching and coded delivery provides global caching gains by dividing the files into subfiles and creating multicasting opportunities across users. For a given common rate of the files in the system, we first formulate the minimum transmit power at the BS with beamforming transmission, which corresponds to a multiple multicast problem, as a non-convex optimization problem. While a stationary solution to this problem can be found through successive convex approximation (SCA), the complexity of the problem grows exponentially with the number of subfiles that must be delivered to each user, which itself grows exponentially with the number of users in the system. Therefore, we introduce a low-complexity alternative through time-sharing that limits the number of subfiles that can be received by a user in each time slot. It is shown through numerical simulations that, the reduced-complexity beamforming scheme has minimal performance gap compared to transmitting all the subfiles jointly, and outperforms the state-of-the-art at all SNR and rate values with sufficient spatial degrees of freedom, and in the high SNR/high rate regime when the number of spatial degrees of freedom is limited.

I. INTRODUCTION

Driven by the growing demand for high data rate applications, the fifth generation (5G) of mobile networks are expected to offer a 1000-fold increase in network throughput. With the increasing prevalence of video-on-demand (VoD) services, a significant portion of this explosive growth is due to video content. To accommodate the growing demand, research efforts in efficient video delivery have intensified in recent years. A promising approach to enhance the performance of content delivery is exploiting cache memories across the network. Proactively caching contents at user devices during underutilized off-peak periods can improve the spectral efficiency and reduce the bandwidth requirements, as well as the transmission delay, particularly for VoD services [1].

The coded cache placement and delivery scheme proposed in [2] creates and exploits multicasting opportunities to users with arbitrary demands; thereby achieving a global caching gain. While [2] considered a noiseless broadcast channel, application of coded delivery in real cellular systems requires designing a multicasting strategy over a noisy broadcast channel jointly with the caching and delivery scheme [3], [4]. In this paper we consider a multiple antenna transmitter serving single antenna users, i.e., a MISO broadcast channel. Multicast beamforming, where the multi-antenna base station (BS) in each cell multicasts one or more data streams to one or more user groups, has been extensively studied in cellular networks [5], [6]. Inspired by the multicasting feature of coded content delivery schemes [2], and the high efficiency of multi-antenna beamforming, there have been recent research efforts to incorporate multi-antenna beamforming techniques into cache-aided coded content delivery. In [3], coded delivery is employed along with zero-forcing to simultaneously exploit spatial multiplexing and caching gains. By treating the transmission of coded subfiles as a coordinated beamforming problem, improved spectral efficiency is achieved in [7] by optimizing the beamforming vectors. A reduced-complexity scheme is also presented in [7] by limiting the number of users served at any time.

In this paper, we consider the same problem in [7]. Firstly, a general framework for cache-aided downlink beamforming is formulated, focusing on the minimum required power under user quality-of-service (QoS) requirements. The resultant non-convex optimization problem is tackled by successive convex approximation (SCA), which is guaranteed to converge to a stationary solution of the original nonconvex problem. As noted in [7], the transceiver design and computational complexities increase drastically with the number of coded messages each.
user decodes at any time slot. We propose a novel content delivery scheme which allows flexibly adjusting the number of coded messages each user decodes in each time. Unlike the scheme in [7], our proposed scheme does not limit the number of users served in each time slot, but directly limits the number of messages each user decodes. Our numerical results show that the proposed scheme can provide significant gains in the transmit power, particularly in the high rate/high signal-to-noise ratio (SNR) regime.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider downlink transmission within a single cell, where a BS equipped with $N_t$ antennas serves $K$ single-antenna users. A library of $N$ files $\mathcal{V} \triangleq \{V_1, \ldots, V_N\}$, each of size $F$ bits, is available at the BS. Each user is equipped with a cache of size $MF$ bits, and the caching factor is defined as $t \triangleq MK/N$.

Contents can be placed at users’ caches during off-peak periods without any prior information on user requests, known as the placement phase. We follow the cache placement scheme of [2]: For a caching factor $t \in \{1, \ldots, K-1\}$, we represent $t$-element subsets of $[K] \triangleq \{1, \ldots, K\}$ by $G_1^t, \ldots, G_{t+1}^t$. File $V_i$, $i \in [N]$, is divided into $\binom{K}{t}$ disjoint subfiles $V_{i,G_1^t}, \ldots, V_{i,G_{t+1}^t}$, each of size $F/\binom{K}{t}$ bits. User $k$, $k \in [K]$, caches subfile $V_{i,G_j^t}$, if $i \in G_j^t$, $\forall j \in \{1, \ldots, t+1\}$. The cache content of user $k$ is then given by $\bigcup_{i \in [N]} \bigcup_{j \in \{1, \ldots, t+1\}} k \in G_j^t, V_{i,G_j^t}$.

The delivery phase is performed once the demands are revealed. The file requested by user $k$, $k \in [K]$, is denoted by $V_{d_k}$, where $d_k \in [N]$ is the index of the requested file. Having the placement phase described above, for any demand combination $(d_1, \ldots, d_k)$, we aim to deliver the coded message

$$s_{G_j^{t+1}} \triangleq \bigoplus_{k \in G_j^{t+1}} V_{d_k,G_j^{t+1}\{k\}}$$

(1)

to all users in set $G_j^{t+1}$, for $j \in \{1, \ldots, t+1\}$. Observe that, after receiving $s_{G_j^{t+1}}$, each user $k \in G_j^{t+1}$ can recover subfile $V_{d_k,G_j^{t+1}\{k\}}$ having access to $V_{d_k,g_j^{t+1}\{i\}}, \forall i \in G_j^{t+1}\{k\}$.

We define $S \triangleq \{G_1^{t+1}, \ldots, G_{t+1}^{t+1}\}$ as the set of all the messages, with each message $T \in S$ represented by the set of users it is targeting, and $S_k \subset S$ is the subset of messages targeting user $k$. Subsequently we have $|S| = \binom{K}{t+1}$ messages, and $|S_k| = \binom{K-1}{t}$.

The following example will be used throughout the paper to explain the proposed scheme:

**Example:** Let $N = 5$, $K = 5$, $M = 1$. We have $t = MK/N = 1$. Each file is split into $\binom{K}{t} = 5$ disjoint subfiles of the same size, where we represent file $i$, $i \in [N]$, as

$$V_i = \{V_{i,1}, V_{i,2}, V_{i,3}, V_{i,4}, V_{i,5}\}.$$  

(2)

The cache content of user $k$ is $\bigcup_{n \in [N]} V_{n,k}$, $k \in [K]$, which satisfies the cache capacity constraint. For a demand combination $(d_1, d_2, d_3, d_4, d_5)$, all user demands can be fulfilled by delivering the following $\binom{K}{t+1} = 10$ subfiles:

$$s_{(1,2)} = V_{d_1,(1)} \oplus V_{d_2,(1)}, \quad s_{(1,3)} = V_{d_1,(3)} \oplus V_{d_3,(1)},$$

$$s_{(1,4)} = V_{d_1,(4)} \oplus V_{d_4,(1)}, \quad s_{(1,5)} = V_{d_1,(5)} \oplus V_{d_5,(1)},$$

$$s_{(2,3)} = V_{d_2,(3)} \oplus V_{d_3,(2)}, \quad s_{(2,4)} = V_{d_2,(4)} \oplus V_{d_4,(2)},$$

$$s_{(2,5)} = V_{d_2,(5)} \oplus V_{d_5,(2)}, \quad s_{(3,4)} = V_{d_3,(4)} \oplus V_{d_4,(3)},$$

$$s_{(3,5)} = V_{d_3,(5)} \oplus V_{d_5,(3)}, \quad s_{(4,5)} = V_{d_4,(5)} \oplus V_{d_5,(4)}.$$  

We have $S_1 = \{(1,2), (1,3), (1,4), (1,5)\}$, while $S = \{G_j^t, j \in [10]\}$. $|S_1| = 4$ indicates that four subfiles are intended for user 1. Similarly for other users.

The BS transmits specially designed coded messages to deliver these messages to the users. We assume that the transmission takes place over $B$ time slots, and the transmitted signal at time slot $i \in [B]$ can be written as

$$x(i) = \sum_{T \in S} w_T(i) s_T(i),$$  

(3)

where $s_T(i) \in \mathbb{C}^{1 \times n}$ is the unit power complex Gaussian signal of block length $n$, intended for the users in set $T = G_j^{t+1}$, modulated from the corresponding message $s_{G_j^{t+1}}$, transmitted in time slot $i$, encoded by the beamforming vector $w_T(i) \in \mathbb{C}^{N_t \times 1}$.

The received signal at user $k$ in time slot $i$ is

$$y_k(i) = h_k^H \sum_{T \in S_k} w_T(i) s_T(i) + h_k^H \sum_{T \notin S_k} w_T(i) s_T(i) + n_k(i),$$  

(4)

where $S_k^c$ is the complement of set $S_k$ in $S$, $h_k \in \mathbb{C}^{N_t \times 1}$ is the channel vector from the BS to the $k$-th user, and $n_k(i) \sim \mathcal{CN}(0, \sigma_k^2)$ is the independent additive white Gaussian noise at user $k$. Let $\Pi_{S_k}$ denote the collection of all non-empty subsets of $S_k$, with each element of $\Pi_{S_k}$ denoted by $\pi_{S_k}, j \in [2^{K-1}]$. We denote $S_i \subseteq S$ as the subset of messages transmitted in time slot $i$, i.e., $\mathcal{T} \in S(i)$ if $w_T(i) \neq 0$.

Note that each user may decode more than one message in each transmission slot, and the achievable rate is then bounded by the capacity of the associated Gaussian multiple access channel. Following conditions must be satisfied for successful decoding of all the intended messages at user $k$, $k \in [K]$, at time slot $i$:

$$\sum_{T \in \pi_{S_k}} R_T^i \leq \log_2 \left(1 + \sum_{T \in \pi_{S_k}} \gamma^T_T(i)\right), \forall \pi_{S_k} \subseteq \Pi_{S_k},$$  

(5)

where $R_T^i$ is the rate of the message $s_T(i)$, and $\gamma^T_T(i)$ is the received signal-to-interference-plus-noise ratio (SINR) of message $s_T(i)$ at user $k$ at time slot $i$, given by

$$\gamma^T_T(i) = \frac{|h_k^H w_T(i)|^2}{\sum_{T \in S_k^c} |h_k^H w_T(i)|^2 + \sigma_k^2},$$  

(6)

for any $T \ni k$, or equivalently, any $T \in S_k$. The average rate of message $T$ is defined as

$$\bar{R}_T^i \triangleq \frac{1}{B} \sum_{i=1}^B R_T^i,$$  

(7)
and the rate delivered to user $k$ is $R_k = \sum_{T \in S_k} \bar{R}^T$.

To minimize the time for each user to receive all the desired messages, we assume that all the messages have a common average rate, which results in an equal total rate delivered to all the users, denoted by $R$, due to the combinatorial nature of $S$. Therefore, the common average rate of message is given by $\bar{R}^T = R/(K-1)$, $\forall T \in S$.

A. Total Transmit Power Minimization

Multicast beamforming is employed here as an efficient transmission technique to deliver the coded messages to their intended receivers, and power consumption at the BS is considered as the performance measure. Specifically, a power minimization problem is formulated under the requirement of successfully delivering all the desired files to each user at the prescribed common average rate $\bar{R}^T = R/(K-1)$, $\forall T \in S$. Following the capacity region characterization of Gaussian multiple access channels, constraints in (5) are imposed to guarantee successful decoding of all the messages. Therefore, for any given transmission scheme parameterized by the rates of the subfiles transmitted in each time slot $\theta$, $\forall T \in S$, the minimum average required power under channel $h \doteq \{h_k\}_{k=1}^{K}$, can be obtained as

$$P(\theta, h) = \frac{1}{B} \sum_{i=1}^{B} P_i (R^T (i), h),$$

where $P_i$ is

$$P_i \doteq \min_{\{w_T(i)\}} \sum_{T \in S} \|w_T(i)\|^2$$

s.t.

$$\sum_{T \in \pi_{S_k}} R_i (i) \leq \log_2 \left( 1 + \sum_{T \in \pi_{S_k}} \frac{|\gamma_k(i)|}{F_k} \right), \forall \pi_{S_k} \subseteq S_k, \forall k.$$ (9a)

The optimization problem in (9) is nonconvex due to the constraints in (9b), and hence, it is computationally intractable. In order to obtain an effective feasible solution of the problem (9), we leverage the SCA algorithm [9]. Specifically, given that the nonconvex QoS constraints in (9) can be rewritten as the difference of convex (DC) functions, the SCA algorithm reduces to the conventional convex-concave procedure [9]. Note that the SCA scheme is known to converge to a stationary point of the original problem [9].

The power minimization problem obtained by the SCA algorithm at the $\nu$-th iteration is given as

$$\min \sum_{T \in S} \|w_T(i)\|^2$$

s.t.

$$\frac{\sum_{T \in \pi_{S_k}} R_i (i)}{2^{\nu} - 1} \left[ \sum_{T \in \pi_{S_k}} |h_k^T w_T(i)|^2 + \frac{\sigma_k^2}{F_k} \right] + \sum_{T \in \pi_{S_k}} |h_k^T w_T(i)|^2
- 2 \sum_{T \in \pi_{S_k}} w_T^H (i) h_k h_k^H w_T^H (i) \leq 0, \forall \pi_{S_k} \subseteq S_k, \forall k.$$ (10a)

which can be efficiently and reliably solved by off-the-shelf solvers. Since the convexified constraints in (10a) are stricter than the original ones in (9), the solution obtained at each iteration is feasible for the original problem (9), given an feasible initial point. When the stopping criterion is satisfied, we take the last iteration as the solution of the SCA algorithm.

III. PROPOSED LOW-COMPLEXITY DELIVERY SCHEME

In this section we propose a content delivery scheme with the flexibility to adjust the number of coded messages intended for each user at each time slot. If a maximum of $s$ messages are transmitted to each user in each time slot, then we have $2^s$ constraints per user per time slot in the resultant optimization problem. The computational complexity increases drastically with the number of constraints, rendering the numerical optimization problem practically infeasible. In addition, a multi-user detection scheme, e.g., successive interference cancellation (SIC), needs to be employed at the users, whose complexity also increases with the number of superposed messages at each time slot. A low complexity scheme is proposed in [7] by limiting the number of users to be served in each time slot, thereby indirectly reducing the number of coded messages to be decoded by each user. Instead of confining the subsets of users to be served in each time slot, we propose to directly adjust the number of coded messages targeted to each user.

For example, in the setting of our Example, a straightforward scheme is to transmit all the messages in one time slot. Specifically, we have $B = 1$ and $R^T (1) = R$, $\forall T$. Under this scheme, a total number of $|S| = (K^{K-1}) = 10$ coded subfiles are to be transmitted simultaneously to fulfill user requests in $B = 1$ time slot, with each user decoding $(K-1) = 4$ messages. Accordingly, in the optimization problem in (9), we will have $K \times (2^{|S|-1} - 1) = 75$ constraints.

To alleviate the computational complexity, the low complexity scheme in [7] splits each subfile into $3$ mini-files, and the coded messages are grouped to serve a subset of $K_s = 3$ users in each of the $B = (K_s) = 10$ time slots. Within each time slot, each user needs to decode $2$ messages to recover the corresponding mini-files. Note that the power minimization problem for each time slot can be solved independently; therefore, we would need to solve $10$ smaller optimization problems, each with $3 \times 3 = 9$ constraints.

In contrast, we propose to serve as many users as needed at each time slot while keeping $s$ under a given threshold. In our Example, we can satisfy all the user requests in $B = 2$ time slots, by setting nonzero rate targets for the messages in

$$S(1) = \{s(1,2), s(2,3), s(3,4), s(4,5), s(1,5)\}, \text{ and}$$

$$S(2) = \{s(1,3), s(2,4), s(3,5), s(1,4), s(2,5)\}$$
in time slots 1 and 2, respectively. Note that each user decodes only \( s = 2 \) messages at each time slot, the same as the delivery scheme in [7], requiring the same implementation complexity at the users; however, 5 users are served in each time slot, which results in a significantly smaller number of time slots. Therefore, we need to solve only two optimization problems at the BS, each with \( 5 \times 3 = 15 \) constraints.

In general, since the number of constraints in the optimization problem in [10] increases exponentially with \( s \), the computational complexity of the delivery scheme can be largely alleviated by choosing a small value for \( s \), and the receiver complexity can also be moderated with the reduced use of SIC. The proposed scheme is presented in Algorithm 1 for the general setting.

Algorithm 1 Reduced-complexity delivery scheme

Input: \( N, K, M, s, R \)

Output: \( B, \bigcup_{i=1}^{B} \{ S(i) \} \)

1. Set \( t = \frac{M}{N} \) and generate \( S = \{ \mathcal{G}^{t+1}_1, \ldots, \mathcal{G}^{t+1}_{t+1} \} \)
2. Set \( \tilde{R}^T = R/(K^t + 1), \forall T \in S \)
3. Set \( l = 1 \)
4. while \( S \neq \emptyset \) do
5. Set \( c \triangleq [c_1, \ldots, c_K] = 0, S(i) = \emptyset, \mathcal{C} = S \)
6. while \( c_k \leq s, \forall k \in [K] \) and \( \mathcal{C} \neq \emptyset \) do
7. Set \( T = \arg \max_{T \in \mathcal{C}} |A \cap T| \)
8. Set \( c_k = |A \cap T| \)
9. if \( c_k + 1 \leq s, \forall k \in T \) then
10. Set \( S(i) = S(i) \cup T, S = S \setminus T \)
11. else
12. break
13. end if
14. end while
15. Set \( B = (\frac{K}{t+1})/\gcd(|S(1)|, \ldots, |S(l-1)|) \)
16. for \( i = 1 : B \) do
17. Find \( j \in [l-1] \) such that \( \sum_{n=1}^{j} \frac{|S(n)|}{\gcd} \leq i \leq \sum_{n=1}^{j+1} \frac{|S(n)|}{\gcd} \)
18. Set \( \tilde{R}^T(i) = \begin{cases} \left( \frac{K}{\gcd} \right) \tilde{R}^T, & \forall T \in S(j) \\ 0, & \text{otherwise} \end{cases} \)
19. end for

IV. Simulation Results

In this section, numerical results are presented to demonstrate the effectiveness of the proposed coded delivery scheme with multi-antenna beamforming. We consider a single-cell with radius 500m, and users uniformly randomly distributed in the cell. Channel vectors \( \mathbf{h}_k \) are written as \( \mathbf{h}_k = (10^{-PL/10}) \mathbf{h}_k, \forall k \), where \( \mathbf{h}_k \) denotes an i.i.d. vector accounting for Rayleigh fading of unit power, and the path loss exponent is modeled as \( PL = 148.1 + 37.6 \log_{10}(v_k) \), with \( v_k \) denoting the distance between the BS and the user (in kilometers). The noise variance is set to \( \sigma_k^2 = \sigma^2 = -134 \) dBW for all the users. We set the same rate target for each message \( \tilde{R}^T = R/(K^t + 1), \forall T \in S \), for all the schemes. All simulation results are averaged over 1000 independent trials computed with MOSEK in CVX [10]. The average transmit SNR is calculated as \( \text{SNR} = E_h[P(\theta, h_i)]/\sigma^2 \).

The scheme, in which all the \( \binom{K}{t+1} \) coded messages are sent together in \( B = 1 \) time slot, will be referred to as full superposition (FS). The FS scheme has the best performance given enough number of spatial degrees of freedom, and thus serves as a baseline. However, the FS scheme has the highest complexity as it superposes all the coded messages. To compare our results with those in [7], the same number of coded messages is transmitted to each user in each time slot for both schemes. We note here that the scheme in [7] can be improved by serving disjoint subsets of users simultaneously without increasing the complexity, but the improvement is only applicable when the size of user subset \( K_s \) divides \( K \). Therefore, the scheme in [7] cannot handle certain settings such as the one in the running Example.

We first present the power consumption versus the target rate \( R \) in Fig. 2 for the setting in our Example, assuming that the BS is equipped with \( N_t = 6 \) antennas. The scheme in [7] that satisfies \( s = 2 \) is adopted for fair comparison, where \( K_s = 3 \) users are served in each time slot. We observe that the proposed scheme provides significant savings in the transmit power compared to the one in [7] at all rates. We have also observed in our numerical simulations that solving the optimization problem for our proposed scheme is faster than the one in [7]. The power savings increase with the target rate \( R \) as a result of the increased superposition coding gain. Furthermore, the gap between the proposed scheme and FS is quite small, and remains almost constant with rate. At \( R = 8 \) bps/Hz, the power loss of the scheme in [7] and ours compared to FS is about 12 dB and 1 dB, respectively. Hence, the proposed scheme

![Figure 2. Average transmit SNR as a function of the rate target R for the network with N = K = 5, M = 1, and N_t = 6.](image-url)
provides significant reduction in the computational complexity without sacrificing the performance much.

Fig. 3 considers the average transmit SNR versus the rate target for $N = 4$ files, $K = 4$ users, $M = 1$, and $N_t = 3$ antennas. It is interesting to see that when the target rate is low, the scheme in [7] can slightly outperform both the FS and the proposed schemes. Similar observations are also made in [7]. Due to insufficient spatial degrees of freedom, the FS and the proposed schemes fail to manage the interference between data streams. We conclude that this effect occurs only for low target rates, as the benefit of superposition coding becomes more dominant for high target rates and leads to power savings for both the FS and the proposed schemes. We note that the performance of our scheme coincides with that of the scheme in [7] for $s = 1$, but this does not always happen. For instance, when $s = 2$, the only option in [7] to keep the same level of complexity is to serve 3 users in each time slot.

We finally plot the power loss as a function of $s$ compared to FS in Fig. 4. Assuming $N = 6$, $K = 6$, $M = 1$, we let $s$ take values from $\{1, 2, 3, 4, 5\}$, where $s = 5$ corresponds to the FS scheme in which all the $\binom{K}{s+1} = 15$ coded messages are transmitted in one time slot. On the other extreme, when $s = 1$, the model boils down to the single-cell multigroup multicasting problem, which has the lowest computational and implementation complexity. In general, Fig. 4 can be considered as the trade-off curve between the performance and complexity for each target rate value, both of them increasing with $s$.

V. CONCLUSIONS

We have proposed a low-complexity coded content delivery scheme for a multi-antenna BS serving cache-enabled users. By limiting the number of coded messages targeted at each user in each time slot, the proposed coded content delivery scheme provides the flexibility to adjust the computational complexity of the optimization problem and the receiver complexity in terms of SIC. Compared with the FS scheme, in which all the coded messages are delivered simultaneously, our proposed delivery scheme achieves comparable performance with significantly lower complexity by delivering the coded messages in a time division fashion. It has also been shown that the proposed delivery scheme outperforms another low-complexity scheme proposed in [7] for all values of SNR and rate with sufficient spatial degrees of freedom, while the improvement is limited to high data rate values when the BS does not have sufficiently many transmit antennas. When considering practical implementations, one must choose a suitable value of $s$ that yields an acceptable performance while keeping the complexity feasible.

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