Cooperative Multi-Cell Networks: Impact of Limited-Capacity Backhaul and Inter-Users Links

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***Abstract*—Cooperative technology is expected to have a great impact on the performance of cellular or, more generally, infrastructure networks. Both multicell processing (cooperation among base stations) and relaying (cooperation at the user level) are currently being investigated. In this presentation, recent results regarding the performance of multicell processing and user cooperation under the assumption of limited-capacity inter-base station and inter-user links, respectively, are reviewed. The survey focuses on related results derived for non-fading uplink and downlink channels of simple cellular system models. The analytical treatment, facilitated by these simple setups, enhances the insight into the limitations imposed by limited-capacity constraints on the gains achievable by cooperative techniques.**

I. Introduction

The performance limitations of conventional cellular wireless networks in terms of throughput and coverage are by now well recognized. This is due to extensive deployment of 2G and 3G systems, and has stimulated the search for new approaches to alleviate these drawbacks. A key technology that has been identified to fulfill this goal is cooperation, to be employed at either the base station (BS) or mobile station (MS) levels. As far as the BS level is concerned, *multi-cell processing* (MCP), sometimes referred to also as a *distributed antenna system*, prescribes joint encoding/decoding of the signals transmitted/received at the BSs through the exploitation of the high-capacity backbone connecting the BSs (see [1][2] for recent surveys on MCP). Cooperation at the MS level in the context of cellular networks has been studied under different names, such as *mesh*, *hybrid* or *multi-hop* cellular networks, and is based on specific forms of relaying by the MSs (see, e.g., [3]).

BS and MS cooperative technologies are enabled by the presence, respectively, of *inter-BS (backbone)* and *inter-MS links* that are not exploited by conventional cellular systems for the purpose of encoding or decoding. These links can be either wireless, orthogonal or not, thus possibly affecting the interference or bandwidth budget of the network, or wired, hence requiring additional deployment efforts.

Analysis of MCP (i.e., BS cooperation) has been so far mostly based on the assumption that all the BSs in the network are connected to a central processor via links of *unlimited capacity*. In this case, the set of BSs effectively acts as a multiantenna transmitter (downlink) or receiver (uplink) with the caveat that the antennas are geographically distributed over a large area. Since the assumption of unlimited-capacity links to a central processor is quite unrealistic for large networks, more recently, there have been attempts to alleviate this condition by considering alternative models. In [4] a model is studied where only a subset of neighboring cells is connected to a central joint processor. In [5][6] a topological constraint is imposed where there exist unlimited capacity links only between adjacent cells, and message passing techniques are employed in order to perform joint decoding in the uplink. Finally, reference [7] focuses on the uplink and assumes that the links between all the BSs and a central processor have limited capacity (*limited-capacity backhaul*). The reader is referred to [8][9] for another framework which deals with practical aspects of limited capacity backhaul cellular systems incorporating MCP.

Information-theoretic analysis of MS cooperation in cellular networks is a more recent development. References include [10][11] where the uplink of a two-hop mesh network is studied with *amplify-and-forward* (AF) cooperation (half-duplex and full-duplex, respectively) and [12] (half-duplex) [13] (full-duplex) where *decode-and-forward* (DF) cooperation is investigated (a thorough tutorial on cooperation techniques can be found in [14]).

Most of the analysis on MCP is based on different variants of a simple and analytically tractable model for a cellular system proposed by Wyner [15] (henceforth, *the Wyner model*, see also [16]). Accordingly, the cells are arranged in either an infinite linear array or in the more familiar two-dimensional hexagonal pattern, and only adjacent-cell interference is present and characterized by a single gain parameter $\alpha \in (0, 1]$ (see Fig. 1). In some cases, we will also refer to a variation of the regular Wyner model, called the *"soft-handoff" model*, where, assuming a linear geometry, MSs are located at the border between two successive cells and thus communicate only with the two corresponding BSs. This model has been proposed in [17] (see also [18]) and later adopted in a number of works [19] - [22]. With simplicity and analytical tractability in mind, the Wyner model provides perhaps the simplest framework for a cellular system that still captures the essence of real-life phenomena such as intercell interference and fading.

In this presentation, we focus on cellular systems abstracted

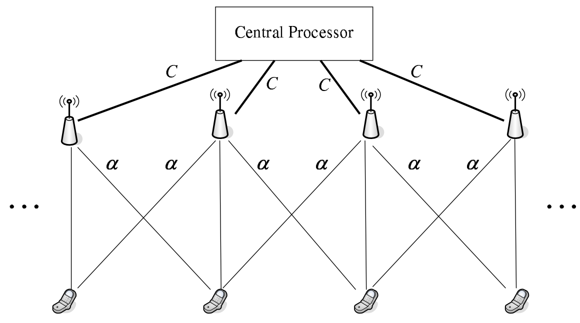

Fig. 1. Linear Wyner model with limited-capacity backhaul.

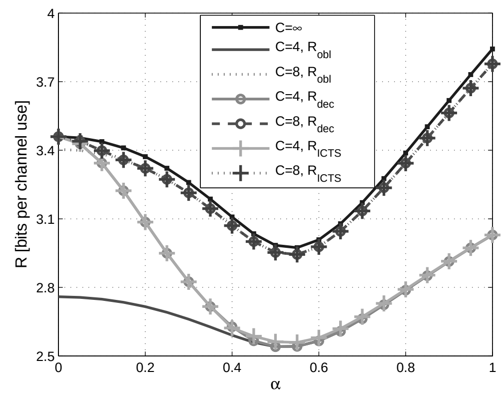

Fig. 2. The uplink achievable rates R_{obl}, R_{dec} and R_{ICTS} are plotted vs. the inter-cell interference α for backhaul capacity $C = 4, 8, \infty$, and user SNR $P = 10$ [dB].

according to the Wyner model, and study the impact of limited-capacity links on both MCP (*limited-capacity backhaul*) and MS cooperation (*conferencing*) for the uplink and the downlink. Moreover, we limit the scope to non-fading Gaussian scenarios and to the case where only one user is active in each cell at any given time (as for *intra-cell TDMA*). It is noted that intra-cell TDMA was proved to be optimal for non-fading channels and the regular Wyner model in [15], but no claim of optimality is made here for the cases of limited-capacity inter-BS and inter-MS of interest.

II. Limited-capacity backhaul

Analysis of MCP with limited-capacity backhaul can be carried out according to different assumptions regarding the knowledge of codebooks (or, more generally, encoding functions) at the BSs (*codebook information, CI*). In the sequel, we will treat separately uplink and downlink channels.

A. Uplink Channel

In [7][23], the uplink of a Wyner model with MCP and limited-capacity backhaul (see Fig. 1) was studied in two scenarios: (*i*) the BSs are oblivious to the codebooks used by the MSs (no CI) so that decoding is exclusively performed at the central processor; (*ii*) the BSs are aware of the codebooks used by the local and the nearby MSs (cluster CI).

With oblivious BSs (case (*i*)), the cellular uplink channel is equivalent to the setup of non-cooperative nomadic MSs communicating with a central receiver via oblivious access points with limited capacity links studied in [24][25]. Focusing on non-fading Gaussian channel and using the tools of [24] combined with the inherent symmetry of the Wyner model, an achievable per-cell sum-rate is given in [7][23] in the form of a simple fixed-point equation. This rate presents an SNR penalty with respect to the performance of the unlimited-capacity setup [15], but it coincides with the cut-set bound (taken over the wireless and wired channels respectively) for high-SNR and high backhaul capacity regimes. For the low-SNR regime, [23] shows that the fixed-point equation characterizing the rate can be approximated to a closed-form solution. Using this result, the low-SNR parameters of this achievable rate, namely the minimum energy per-bit required for reliable communication and respective low-SNR slope [26], can be expressed as functions of the low-SNR parameters of the unlimited setup and the backhaul capacity C.

In the case of cluster CI (case (*ii*) above), an achievable rate is derived in [7][23] by allowing partial local decoding at the base stations. According to this approach, each MS splits its message and transmitted power into two parts: one is intended to be decoded locally by the in-cell BS and transmitted over the limited link to the central processor, while the second part is processed according to the oblivious scheme and is jointly decoded by the central processor. Assuming that each BS is aware of the codebooks of the three MSs received by its antenna (according to the limited-propagation property of the linear Wyner model), it maximizes the local rate by selecting between multiple-access and interference approaches [27]. This local rate appears in the fixed-point equation mentioned earlier since less bandwidth is now available for the oblivious scheme applied for the second message part. Since the resulting overall per-cell rate is non-concave, time-sharing is beneficial. Nevertheless, numerical calculations reveal that a good strategy is to do time-sharing between the two extremes: using decoding at the BSs, with no decoding at the central processor, and doing decoding only at the central processor, rather than using the mixed approach. Since joint decoding is useful only when the BSs' signals are correlated, the improvement in performance over the oblivious scheme is increasing when the interference factor α decreases, assuming that the limited capacity link does not restrict the local rate. Interestingly, it is shown in [7][23] that incorporating inter-cell time-sharing (ICTS) where the cells interfere each other only a fraction of the time (see [27]) does not provide significant improvement over the partial local decoding scheme at hand.

Achievable rates of the three schemes considered, are plotted in Fig. 2 for SNR, $P = 10$ [dB], and several backhaul capacity values, as functions of the inter-cell interference factor α. The gain of the cluster CI scheme R_{dec} over the oblivious scheme R_{obl} when C is low, is prominent for low inter-cell interference. The cluster CI with ICTS scheme

R_{ICTS} provides only a slight improvement over the cluster CI scheme R_{dec}. As expected, for $\alpha = 0$, the rates achieved by the cluster CI and ICTS schemes are optimal, when C is larger than the respective unlimited setup rate (upper bound), since no inter-cell interference is present and local decoding with no ICTS is optimal.

Other settings such as the soft-handoff model and fading channels are also considered in [23] but are not mentioned here for the sake of conciseness.

B. Downlink Channel

Turning to the downlink channel of the system in Fig. 1, MCP in the form of joint encoding in the framework of the soft-handoff Wyner-like model is studied in [28] under the assumption of limited-capacity backhaul. Similarly to [7] [23], three scenarios are considered that present different tradeoffs between global processing at the central unit and local processing at the BSs, with different requirements in terms of CI at the BSs: *(a)* local encoding with CI limited to a subset of adjacent BSs (cluster CI); *(b)* mixed local and central encoding with only local CI; *(c)* central encoding with oblivious cells (no CI). Three transmission strategies are proposed that provide achievable rates for the considered scenarios.

Let us start with the case of cluster CI (case *(a)*). Exploiting the local interference structure of the soft-handoff setup, shutting off one every $(J+2)$th BSs forms isolated clusters of $(J+1)$ cells (see also [29]). Each BS is aware of the codebooks of its cluster's users, while the central processor sends each cluster's messages to all its BSs via the limited capacity links. Having the cluster's CI and messages, each BS performs a form of *dirty paper coding* (DPC) locally (under individual equal per BS power constraint [30]) and transmits its signal accordingly. In [28] two cluster DPC schemes are considered: 1) *sequential* encoding in which each BS invokes DPC to cancel the interfering signal coming from its left neighboring BS; and 2) *joint* encoding in which each BS performs optimal joint DPC within the cluster. It is shown in [28] that the per-cell rate of the joint encoding scheme, although it approaches the cut-set bound when both the limited capacity C and the cluster size $(J+1)$ go to infinity while their ratio converges to some finite constant, is in general lower than the rate of sequential encoding for relatively small values of C.

In case *(b)* of local CI, a scheme is proposed in [28] whereby each BS receives from the central processor through the limited capacity link its local user's message and a quantized version of the signal to be transmitted by its left neighboring BS. By performing local DPC against the quantized signal, where the inherent quantization error is treated as an additional independent Gaussian noise, each BS is then able to reduce the interfering signal (or cancel its quantized version) coming from its left neighboring BS. The per-cell rate of this scheme is given in [28] as the unique solution of a fixed-point equation. The closed-form expression derived in [28] reveals that the rate approaches the cut-set bound only when the SNR is high and the interference level is low.

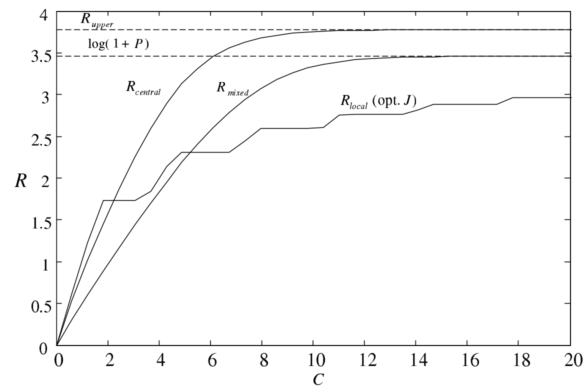

Fig. 3. The downlink achievable rates R_{local}, R_{mixed}, $R_{central}$, and upper bound R_{upper} are plotted vs. the backhaul capacity C for $P = 10$ [dB] and $\alpha = 1$.

With oblivious BSs (case *(c)*), joint DPC under individual equal power constraint is performed by the central processor, which sends quantized versions of the transmitted signals to the BSs via the limited-capacity links. Since the transmitted quantization noise decreases the overall SNR seen by the MSs, joint DPC is designed to meet lower SNR values and tighter power constraints than those of the unlimited setup [17]. As expected, the resulting per-cell rate is shown in [28] to approach the cut-set bound with increasing C. Moreover, also in the high-SNR regime the scheme performs well achieving rates which are less than 1 [bit/ channel use] below the cut-set bound.

The main conclusions of [28] is that central processing, even with oblivious BSs, is the preferred choice for small-to-moderate SNRs or when the backhaul capacity C is allowed to increase with the SNR. On the other hand, for high SNR values and fixed capacity C, a system with oblivious BSs is limited by the quantization noise, and knowledge of the codebooks at the BSs becomes the factor dominating the performance. Therefore, in this regime, transmission schemes characterized by local CI or cluster CI coupled with local processing outperforms central processing with oblivious cells.

Fig. 3 shows the rates achievable by: (a) local processing and cluster CI R_{local} (with sequential DPC and optimized J), (b) mixed (local and central) processing and local CI R_{mixed}, and (c) central processing and no CI $R_{central}$, versus the backhaul capacity C for $P = 10$ [dB] and $\alpha = 1$. It is noted that the optimal cluster-size $(J+1)$ is increasing with the capacity C (not shown). It is seen that if C is large enough, and for relatively small to moderate values of P, scheme 3, which performs central processing with oblivious BSs $R_{central}$, is to be preferred.

III. Conferencing with limited-capacity inter-MS links

We now direct attention to a scenario where BSs perform multi-cell processing (here, with unlimited-capacity backhaul), while the MSs are allowed to cooperate over limited-capacity links (see Fig. 4). These links should be considered as ad-

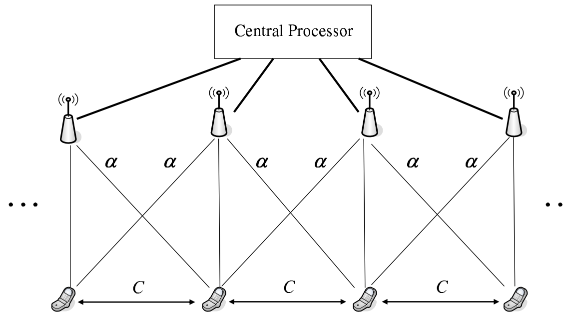

Fig. 4. Linear Wyner model with limited-capacity inter-MS conferencing.

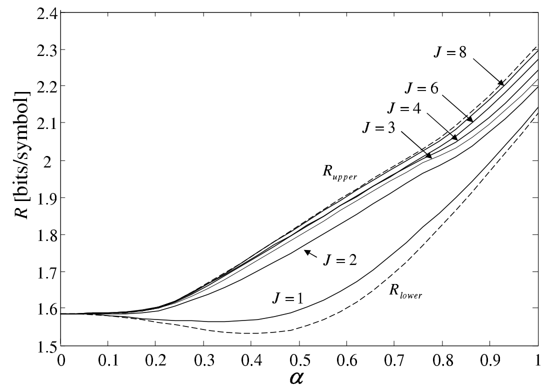

Fig. 5. The achievable rate R (with inter-cell conferencing and intra-cell TDMA), R_{upper}, and R_{lower}, are plotted vs. the inter-cell interference factor α for $P = 3$ [dB], $C = 10$, and several values of J.

ditional spectral resources (orthogonal to the main uplink or downlink channels) that are available for cooperation.

In modeling the interaction among MSs, the framework of conferencing encoders for the uplink [31] (see also [32] for related scenarios) and decoders for the downlink [33] - [36] is followed. Moreover, as stated above, we focus on the non-fading linear Wyner model with intra-cell TDMA so that conferencing channels exist only between MSs belonging to adjacent cells (*inter-cell conferencing*) (reference [37] also considers intra-cell conferencing for the uplink).

Starting with the uplink and multicell decoding (MCP), an upper bound to the per-cell rate is obtained by considering a system with perfect inter-MS cooperation whereby all the MSs are able to exchange the local messages with all the other active MSs in the network. The system at hand is thus equivalent to an *inter-symbol interference* (ISI) channel with channel state information (CSI) at the transmitter (or equivalently an infinite MIMO system with a Toeplitz channel matrix), for which a stationary input with power spectral density obtained via standard waterfilling is known to be optimal (in terms of sum-rate and thus, by symmetry of the system at hand, in terms of per-cell rate). An achievable rate can be derived by considering an extension of the approach in [31] to multiple sources (in the spirit of [38], Sec. VII) [37]. Specifically, rate splitting is performed at each MS so that one message (the *common* message) is communicated to the $2J$ nearby MSs (J on either side) in J rounds of conferencing on the limited-capacity links, so that in the transmission phase cooperative transmission by $(2J+1)$ MSs can take place for every common message. Based on the observation that a stationary input is asymptotically optimal, cooperative transmission can be designed so as to implement an equivalent linear pre-filtering of the transmitted signal, which in the limit of $C \to \infty$ (and $J \to \infty$) allows the upper bound discussed above to be attained via appropriate design of the filter at hand [37]. It is worth mentioning that the number of conferencing rounds J, restricts the time-span of the impulse response of the pre-coding filter.

In Fig. 5 the achievable rate R is plotted vs. the inter-cell gain α along with the lower bound R_{lower} (no cooperation) and upper bound R_{upper} for $C = 10$ and $P = 3$ [dB]. Note that very relevant performance gains can be obtained by increasing the number of conference rounds, especially from $J = 1$ to $J = 2$. Moreover, having sufficient large conferencing capacity C and number of conference rounds J (with $C/J \geq R_{upper}$) enables for the upper bound to be approached. It is worth mentioning that increasing J is always beneficial to obtain a better approximation of the waterfilling strategy. However, due to the limited conferencing capacity C, it is not necessarily advantageous in terms of the achievable rate (not shown).

When considering the downlink, the upper bound on the rate achieved with perfect cooperation is again the rate of an ISI channel with CSI, for which a waterfilling power spectral density of the input is optimal. Since we are interested here in the processing to be performed at the receiving end, that is at the MSs, it is relevant to point out that optimal decoding in case of perfect cooperation can be implemented by means of a Minimum Mean Square Error - Decision Feedback Equalizer (MMSE-DFE) [39]. Moreover, the same per-cell rate (recall the symmetry argument) can also be achieved by moving the DFE part of the equalizer to the transmitter via DPC [40] [41]. An achievable, and asymptotically ($C \to \infty$) optimal, rate can then be obtained by having the central encoder perform DPC to cancel the post-cursor interference, while the MSs exchange quantized versions of the received signals on the conferencing channels in order to enable MMSE filtering on a subset of channel outputs. Analysis of this scenario involves the problem of source encoding with side information on the conferencing channels, and is currently under study.

IV. Concluding Remarks

Three decades after their introduction, the information theoretic understanding of cellular systems is far from being complete. In its full generality, it touches upon the most basic information theoretic models, not yet fully understood. Those comprise combinations of multiple-access, broadcast, interference and relay MIMO frequency selective fading channels, as well as fundamental network information theoretic aspects. With the new setup at hand, which incorporates limited capacity links among MSs, and between BSs and central processor, it is expected that information theory will continue to play a central role in assessing the ultimate potential and limitations of cellular networks as well as in providing fundamental insights into the architecture and operation of future systems.

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