Joint Multi-Cell Processing for Downlink Channels with Limited-Capacity Backhaul

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***Abstract*— Multicell processing in the form of joint encoding for the downlink of a cellular system is studied under the realistic assumption that the base stations (BSs) are connected to a central unit via finite-capacity links (finite-capacity backhaul). Three scenarios are considered that present different trade-offs between global processing at the central unit and local processing at the base stations and different requirements in terms of codebook information (CI) at the BSs: 1) local encoding with CI limited to a subset of nearby BSs; 2) mixed local and central encoding with only local CI; 3) central encoding with oblivious cells (no CI). Three transmission stragegies are proposed that provide achievable rates for the considered scenarios. Performance is evaluated in asymptotic regimes of interest (high backhaul capacity and extreme signal-to-noise ratio, SNR) and further corroborated by numerical results. The major finding of this work is that central encoding with oblivious cells is a very attractive option for both ease of implementation and performance, unless the application of interest requires high data rate (i.e., high SNR) and the backhaul capacity is not allowed to increase with the SNR. In this latter cases, some form of CI at the BSs becomes necessary.**

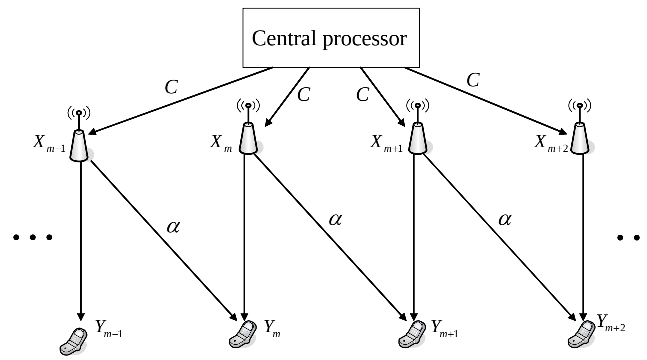

Fig. 1. Linear cellular model of interest characterized by users on the borders between successive cells and finite-capacity links between a central unit processor (that generates the messages to be delivered to each user) and the base stations.

I. Introduction

Multicell processing prescribes joint encoding or decoding of different base stations' (BSs) signals in an infrastructure (cellular or hybrid) network for downlink or uplink, respectively. Traditionally, analysis of the performance of multicell processing has been carried out under the assumption that all the BSs in the network are connected to a central processor via links of unlimited capacity. 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 [1], [2], and [3] a model is studied in which only a subset of neighboring cells is connected to the same central unit for joint processing. In [4] [5] (uplink) and [6] (downlink) a topological constraint is imposed in that there exist links only between adjacent cells, and message passing techniques are implemented in order to perform joint decoding or encoding. Finally, reference [7] focuses on the uplink and assumes that the links between all the BSs and a central processor have finite capacity (*finite-capacity backhaul*).

In this paper, we study a cellular system with finite-capacity backhaul as in [7]. In [7], the uplink of this model was studied in two scenarios: (*i*) the BSs are oblivious to the codebooks used by the mobile stations (MSs) so that decoding is exclusively performed at the central processor; and (*ii*) the BSs are aware of the codebooks used by the local and the nearby MSs. Here, we focus on the downlink and consider three scenarios that, similarly to [7], present different requirements in terms of codebook information (CI) at the BSs and different trade-offs between global processing at the central unit and local processing at the base stations: (*a*) *Local encoding with cluster codebook information (CI)*: in this first scenario, encoding is performed exclusively at the base stations, which are informed by the central processor (over finite-capacity links) about the messages to be transmitted (and possibly about additional information). In order to allow sophisticated encoding techniques such as dirty paper coding (DPC) [8], in addition to the local codebook, every base station is assumed to have available the encoding functions from a number of adjacent cells, similarly to case (*ii*) of [7] (we refer to this situation as "cluster CI")[1]; (*b*) *Mixed central and*

[1]It should be remarked that, when employing DPC, encoding is performed with a more sophisticated encoding strategy than simple look-up on a table of codewords on the basis of the transmitted message. The transmitted signal is in fact a function of the interference sequence to be cancelled. Therefore, a more appropriate term for what we refer to as codebook information (CI) would be encoding function information. We choose the first for simpliciy but this distinction should be kept in mind.

local encoding with local CI: here we assume that each BS is only aware of its own codebook (local CI). Moreover, in order to enable a better handling of inter-cell interference, we allow encoding to take place not only at the base stations, as in the previous case, but also at the central unit; (*c*) *Central encoding with no CI (oblivious BSs)*: here encoding takes place exclusively at the central unit and base stations are oblivious to all the codebooks employed in the system, as in case (*i*) studied in [7] for the uplink.

Achievable rates are derived for all three scenarios by proposing three basic transmission schemes. Performance comparison is carried out in different regimes of interest such as high-backhaul capacity and extreme signal-to-noise ratio (SNR). The performance analysis, corroborated by numerical results, sheds light into the roles of central/ local processing, on one hand, and CI, on the other, as a function of the system parameters.

II. System model

We study the downlink of a cellular system modelled as in Fig. 1, where M cells are arranged in a linear geometry, and one terminal is active in each cell (as for intra-cell TDMA) and is located at the border between successive cells. In this case, each active terminal, say the mth, receives signals from the local mth BS and the previous, $(m-1)$th, BS. This framework is a variation of the Wyner model [9] and has been studied in [10] and later [11] in terms of sum-rate for the case where there are no restrictions on the backhaul connecting the BSs. Deviating from this ideal condition, here we assume that each BS is connected to a central processor via an error-free finite-capacity link of capacity C (bits/ channel use), as in [7]. The model is further characterized by a single parameter to account for intercell interference, namely the power gain $\alpha^2 \leq 1$ (in [10] it was $\alpha^2 = 1$). Accordingly, the signal received at the mth MS is given by

$$Y_m = X_m + \alpha X_{m-1} + Z_m, \tag{1}$$

where X_m is the symbol transmitted at a given discrete time by the mth BS with power constraint $E[|X_m|^2] = P$ and the noise Z_m is a white proper complex Gaussian process with unit power (so that P is the SNR). We remark that we will be interested in asymptotic results where the number M of cells is large, and we refer to [10] for a thorough discussion on the validity of this assumption. Moreover, we focus on Gaussian (nonfaded) channels for simplicity. Finally, we assume that each MS has available CI of the local transmission only, thus ruling out sophisticated joint decoding techniques at the MSs.

Messages $\{W_m\}_{m=1}^{M}$ to be delivered to the respective mth MS are generated randomly and uniformly in the set $\{1, 2, ..., 2^{nR}\}$ at the central processor (see Fig. 1), where R (bits/ channel use) is the common rate of all the messages (*per-cell rate*). We use standard definitions for achievable rates.

III. Reference results

In this section, we review an upper bound on the per-cell rate that can be easily derived from a result presented in [10] for $\alpha = 1$, and later extended by [11] to any $\alpha \leq 1$[2].

Proposition 1 (upper bound): The per-cell capacity of the system is upper bounded by $R_{ub} = \min\{C,\ R'_{ub}\}$ with

$$R'_{ub} = \log_2\left(\frac{1 + (1+\alpha^2)P + \sqrt{1 + 2(1+\alpha^2)P + (1-\alpha^2)^2 P^2}}{2}\right). \tag{2}$$

Proof: Follows by considering a cut-set bound for two cuts, one dividing the central processor from the BSs and one the BSs from the MSs. For the second cut, it is noted that the system is equivalent to the infinite-capacity backhaul case for which the per-cell capacity has been derived in [10] and [11]. ■

It is relevant to notice that the upper bound (2) remains valid even if we allow multiple MSs to be simultaneosly active in each cell (and P is the per-cell power constraint), as it follows easily from [9] and duality arguments [10]. Therefore, whenever achievable rates will be shown in the following to attain (2) in specific regimes, optimality should be intended not only under the restriction of intra-cell TDMA strategies but also for the general case where more MSs can be scheduled at the same time (with a total per-cell power constraint).

For future reference, two further observations on the upper bound (2) are in order. First, it is interesting to study the low-SNR behavior, in the sense of [13]. Accordingly, the minimum energy per bit for reliable communication $E_b/N_{0\min}$, and the corresponding slope of the spectral efficiency [13] are easily shown to be given by

$$\frac{E_b}{N_0}_{\min,ub} = \frac{\log_e 2}{1+\alpha^2}, \quad S_{0,ub} = \frac{2(1+\alpha^2)^2}{1+4\alpha^2+\alpha^4}. \tag{3}$$

This result shows that the power gain with respect to a single-link (interference-free) Gaussian channel (for which $E_b/N_{0\min} = \log_e 2$) due to multicell processing can be quantified in the low-SNR regime by the factor $(1+\alpha^2) \geq 1$ (notice also that the slope $S_{0,ub}$ is a decreasing functions of α^2). A second observation is that the maximum multiplexing gain of the per-cell rate (2) of one requires the capacity C to grow as $C \sim \log_2 P$. In the following, this requirement in terms of capacity C will be compared with that of practical transmission schemes.

IV. Local encoding and cluster CI

In this section, we investigate the case in which encoding is performed locally at each BS. In other words, no encoding is carried out at the central unit, whose only function is to deliver different subsets of messages $\{W_m\}_{m=1}^{M}$ to each BS. Under this assumption, we derive achievable rates based on a transmission scheme first proposed in [14]. Moreover, we comment on the performance in the asymptotic regimes of large backhaul capacity, and extreme SNR, with respect to the upper bound (2).

The considered transmission scheme is inspired by the *sequential* DPC scheme of [14] and works as follows. Every mth

[2]Notice that this result was not given in this form in [11] but can be easily derived from Lemma 3.5 therein.

BS knows its encoding function and the encoding functions of the J BSs preceding it (i.e., BSs $m-i$ with $i=1,...,J$). At the beginning of the transmission block, each BS receives from the central processor $J+1$ messages $\{W_{m-i}\}_{m=0}^{J}$, that is, the local message and the messages of the J preceding BSs. The basic idea is now that, based on these J additional messages and the knowledge of the corresponding encoding functions, the mth BS can perform DPC over these messages and cancel the inter-cell interference achieving the single-user (interference-free) rate $\log_2(1+P)$. As pointed out in [14], in order to implement the sequential DPC scheme correctly, we need to "turn off" every $(J+2)$th BS (e.g., BSs $J+2$, $2(J+2), ...$) and consider the clusters of $J+1$ BSs in between silent BSs. Details can be found in [15].

Proposition 2 (scheme 1): Assuming that every mth BS knows its own encoding function and the encoding function of the J BSs preceding it (cluster CI), the following rate is achievable with local encoding:

$$R_1 = \min\left\{\frac{2C}{J+2}, \left(1-\frac{1}{J+2}\right)\log_2(1+P)\right\}. \quad (4)$$

Proof: See [15].

In the limit of a large backhaul capacity $C\rightarrow\infty$, for fixed cluster size $J+1$, scheme 1 at hand achieves rate $R_1 \rightarrow (1-1/(J+2))\log(1+P)$ and is therefore limited by the loss in multiplexing gain (see also below) that follows from the need to silence a fraction $1/(J+2)$ of the BSs [14]. However, assuming that parameter J can be optimized, then using an asymptotically large cluster size $J\rightarrow\infty$ so that $2C/J > \log(1+P)$, we see that for $C\rightarrow\infty$, scheme 1 is able to achieve the single-link capacity: $R_1\rightarrow\log_2(1+P)$, which is noted to be smaller than the upper bound R_{ub} in (2).

Consider now the regime of large power $P\rightarrow\infty$. In this case, the performance is limited by the backhaul capacity and we have $R_1\rightarrow 2C/(J+2)$, which, if we allow optimization of the cluster size, becomes $R_1\rightarrow R_{ub}=C$ (for $J=0$, that is each cluster consists of only one active cell[3]). Letting C increase with power P, we can also see that the maximal multiplexing gain of scheme 1 is $1-1/(J+2)<1$, and, from (4), achieving this rate scaling requires the backhaul capacity C to grow as $C\sim(J+1)/2\cdot\log_2 P$. Comparing this result with the optimal multiplexing gain of the upper bound (see Sec. III), we see that local encoding entails here a loss in terms of multiplexing gain that can be made arbitrarily small by increasing the cluster size J at the expense of a proportionally more demanding requirement on the scaling of backhaul capacity C.

Finally, we obtain the low-SNR characterization for R_1 as

$$\frac{E_b}{N_{0\,\min}} = \frac{\log_e 2}{1-\frac{1}{2+J}}, \quad S_0 = 2\left(1-\frac{1}{2+J}\right). \quad (5)$$

Comparing this result with (3), we see that in the low-SNR regime the proposed local processing-based scheme falls short of achieving the performance of the upper bound since it fails to take advantage of the inter-cell channel gains α^2, being designed to cancel inter-cell interference. However, by selecting a sufficiently large J it is clear that the single-user performance $E_b/N_{0\min}=\log_e 2$, and $S_0=2$, can be achieved.

[3]This corresponds to the Inter-Cell-Time-Sharing (ICTS) strategy [12]; see also discussion in the next section.

V. Mixed local and central encoding with local CI

In this section, we consider a second scenario where the central unit has encoding capabilities and each BS is aware only of its own codebook (local CI). As in the previous section, we derive an achievable rate under the said assumption and then study its characterization in asymptotic regimes of interest with respect to the upper bound (2). It should be mentioned that rate

$$R_{ICTS} = \min\{C,\ 1/2\log_2(1+P)\} \quad (6)$$

can be straightforwardly achieved under the assumption of local CI by turning off one of every two BSs and using single-user codes for the active BSs (which now see interference-free channels). Notice that this corresponds to the scheme presented in the previous section with $J=0$, and that it follows the Inter Cell Time Sharing (ICTS) approach of [12]. Moreover, in this case, no encoding is carried out at the central processor. It should also be noted that any rate achievable under the assumptions of oblivious cells, studied in the next section, can also be achieved in the less restrictive case of local CI studied here (recall discussion in Sec. I).

In order to improve on R_{ICTS}, we consider the following transmission scheme (to be referred to as scheme 2). As far as the first BS is concerned, the central processor simply sends message W_1 and the BS uses a regular Gaussian codebook transmitting the sequences of n symbols $\mathbf{X}_1$. The central unit then quantizes $\mathbf{X}_1$ using a proper Gaussian quantization codebook with 2^{nR_q} codewords, producing the sequence of n symbols $\hat{\mathbf{X}}_1$. This is delivered, along with the local message W_2, on the limited-capacity link towards the second BS. The latter transmits its message W_2 by performing DPC over the quantized signal $\hat{\mathbf{X}}_1$. The procedure is repeated in the same way for the successive BSs (notice that the central unit must reproduce the transmitted signal $\mathbf{X}_m$, which is possible given that the central unit knows messages, encoding functions and quantization codebooks). Notice that in order to satisfy the capacity constraint on the backhaul links, the quantization rate must satisfy $R_q+R\leq C$. The following proposition quantifies the rate achievable with this scheme.

Proposition 3 (scheme 2): Assuming that every mth BS knows only its own encoding function (local CI), the following rate is achievable with mixed local and central encoding:

$$R_2 = \begin{cases} C & \text{if } C\leq\log_2\left(1+\frac{P}{1+\alpha^2 P}\right) \\ R_2' & \text{otherwise} \end{cases} \quad (7)$$

where

$$R_2' = \log_2\left(1 - \frac{2^C}{\alpha^2 P} + \sqrt{1 + \frac{2^{C+1}}{\alpha^2}\left(2 + \frac{1}{P}\right) + \frac{2^{2C}}{\alpha^4 P^2}}\right) - 1 \quad (8)$$

for $\alpha > 0$ and $\log_2(1+P)$ for $\alpha = 0$.

Proof: See [15].

From (7), we can derive the asymptotic performance of the proposed scheme. For $C \rightarrow \infty$, we have $R_2 \rightarrow \log_2(1+P) < R_{ub}$ (as for R_1), which corresponds to perfect interference pre-cancellation via DPC. For $P \rightarrow \infty$, we have

$$\lim_{P\rightarrow\infty} R_2 = \min\left(C,\ \log_2\left(1 + \sqrt{1 + \frac{2^{C+2}}{\alpha^2}}\right) - 1\right), \quad (9)$$

which is a non-increasing function of α and equals C when $\alpha = 0$. It is noted that the second term of (9) is dominant for $\alpha^2 \geq 1/(2^C - 1)$, in which case R_2, unlike R_1, is asymptotically (with P) smaller that the upper bound C. In particular, with $\alpha^2 = 1$ and increasing C, the rate $R_2 \rightarrow C/2$ for $P \rightarrow \infty$.

By substituting $C = r\log_2 P$ in (4), it can be seen that the multiplexing gain with this choice is given by $\min(r/2, 1)$ so that the optimal multiplexing gain of 1 can be achieved by having $C \sim 2\log_2 P$. This contrasts with the case of local processing studied in the previous section where the optimal multiplexing gain was not achievable. Finally, the low-SNR characterization is given by

$$\frac{E_b}{N_0}_{\min} = \log_e 2, \quad S_0 = \frac{2}{1 + 2\alpha^2 2^{-C}}. \quad (10)$$

where we see that single-user performance in terms of $E_b/N_{0\min}$ is achieved, similarly to the case treated in the previous section, whereas the same can be said for the slope only as $C \rightarrow \infty$ (see also the discussion above).

VI. Central encoding with no CI

Here, we study the case of oblivious BSs (no CI) investigated in [7] for the uplink of the channel at hand. In particular, we assume that encoding is exclusively performed at the central unit and that the BSs are not aware of *any* codebook in the system. We consider the following transmission scheme. The central unit performs joint DPC as in the previous case with the caveat that it assumes a smaller signal-to-noise ratio $\tilde{P}$:

$$\tilde{P} = \frac{P}{\frac{1+(1+\alpha^2)P}{2^C - 1} + 1}, \quad (11)$$

producing the sequences of n symbols $\{\tilde{\mathbf{X}}_m\}_{m=1}^M$. Similarly to the previous section, each $\tilde{\mathbf{X}}_m$ is quantized using a proper Gaussian quantization codebook with 2^{nC} codewords, producing the sequence of n symbol $\hat{\mathbf{X}}_m$. Finally, each sequence $\hat{\mathbf{X}}_m$ is communicated to the mth BS on the limited-capacity link and transmitted by the BS (i.e., $\mathbf{X}_m = \hat{\mathbf{X}}_m$).

Proposition 4 (scheme 3): Assuming that the BSs are oblivious (no CI), the following rate is achievable with central

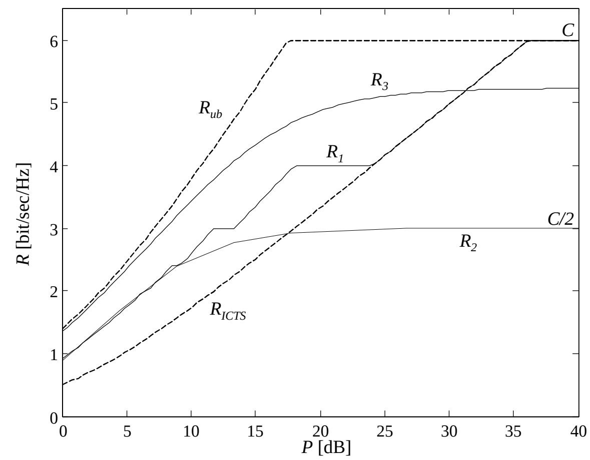

Fig. 2. Rates achievable with local processing and cluster CI (R_1 and R_{ICTS}), with mixed processing and local CI (R_{ICTS}, R_2 and R_3) and with central processing and no CI (R_3) versus P for $C = 6$ and $\alpha = 1$.

encoding:

$$R_3 = \log_2\left(\frac{1 + (1+\alpha^2)\tilde{P} + \sqrt{1 + 2(1+\alpha^2)\tilde{P} + (1-\alpha^2)^2\tilde{P}^2}}{2}\right). \quad (12)$$

Proof: See [15].

In absence of constraints on the backhaul, $C \rightarrow \infty$, unlike R_1 and R_2, the scheme proposed above achieves the upper bound (2) $R_3 \rightarrow R_{ub}$ (since $\tilde{P} \rightarrow P$). Moreover, for $P \rightarrow \infty$ we have

$$\lim_{P\rightarrow\infty} R_3 = C - 1 + \log_2\left(1 + \sqrt{1 - \frac{4\alpha^2}{(1+\alpha^2)^2}(1 - 2^{-C})^2}\right), \quad (13)$$

which is larger than $C-1$ but generally smaller than the upper bound $R_{ub} = C$ (for $P \rightarrow \infty$) unless $\alpha = 0$.

As far as the multiplexing gain (with capacity C scaling with P) is concerned, it can be seen that the optimal multiplexing gain of 1 can be achieved by having $C \sim \log_2 P$. This shows again that central encoding is instrumental in achieving the optimal multiplexing and, compared with scheme 2, presents a reduction by a factor 2 in the required scaling for capacity C. Finally, the low-SNR characterization is given by

$$\frac{E_b}{N_0}_{\min} = \frac{E_b}{N_0}_{\min,ub} \cdot \frac{1}{(1 - 2^{-C})}, \quad S_0 = S_{0,ub} \cdot \frac{1}{1 + S_{0,ub}\frac{2^{-C}}{1 - 2^{-C}}}. \quad (14)$$

This result shows that the power loss due to finite capacity backhaul can be quantified in a simple way in the low-SNR regime by $(1 - 2^{-C})$, which, accordingly to the discussion above, tends to zero for $C \rightarrow \infty$. It is remarked that, interestingly, the low-SNR performance (14) of the scheme at hand coincides with the uplink transmission strategy of [7].

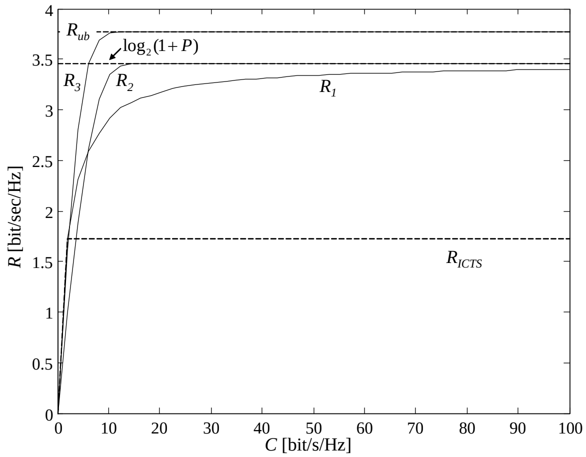

Fig. 3. Rates achievable with local processing and cluster CI (R_1 and R_{ICTS}), with mixed processing and local CI (R_{ICTS}, R_2 and R_3) and with central processing and no CI (R_3) versus C for $P = 10dB$ and $\alpha = 1$.

VII. Numerical results

In the previous sections, we discussed the asymptotic behavior of the proposed techniques, which has shed some light on the performance trade-offs of different assumptions in terms of local/ central processing and CI. In this section, we further investigate the regime of finite capacity C and power P. Fig. 2 shows the rates achievable by local processing and cluster CI (R_1 with optimized J, and R_{ICTS}), by mixed processing and local CI (R_{ICTS}, R_2 and R_3) and by central processing and no CI (R_3) versus the power P for $C = 6$ and $\alpha = 1$. For small-to-moderate power P, the preferred scheme is scheme 3 for its capability of performing joint DPC via central processing. However, as the power increases, we know from the asymptotic analysis that CI, either local (as in ICTS) or cluster (as in scheme 1), plays the leading role. This is confirmed by Fig. 2, where it is clearly shown that R_1 and R_{ICTS} become advantageous over R_3 for $P > 30dB$.

Fig. 3 shows the achievable rates versus the backhaul capacity C for $P = 10dB$ and $\alpha = 1$. The optimal cluster-size J is, as expected from the discussion in Sec. IV, 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 cells, is to be preferred. Also notice that while scheme 2 and scheme 3 attain the respective asymptotic values for $C \simeq 10$, convergence is much slower for schemes based on no central processing.

VIII. Conclusions

This paper has studied the performance of multicell processing for the downlink of a cellular system under the realistic assumption that the base stations are connected to a central processor via finite-capacity (typically wired) links. An interesting issue is the assessment of possible duality results between uplink and downlink channels with limited-capacity backhaul under different assumptions concerning CI and central/ local processing. In this paper, we have provided a downlink transmission scheme that offers the same low-SNR performance as the uplink strategy of [7] for oblivious base stations and the Wyner model, but the general problem remains open.

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