User Cooperation in Heterogeneous Cellular Networks for Improved Spectral Efficiency

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***Abstract*—In this paper we propose user cooperation in Heterogenous cellular networks (HCNs) for combating intra-cell interference and improving downlink spectral efficiency (SE). The main idea we put forward is to employ interference cancellation at users associated to the small cell, when the macrocell transmits simultaneously with the small cell base station (causing intra-cell interference). This allows the decoding of the small cell transmission at several users. Then, in a subsequent time slot, a distributed space time code (DSTC) is used from these users in order to increase the reliability of the transmitted information to the final user. The proposed cooperative transmission scheme is compatible with state-of-the-art resource allocation mechanisms for HCNs. Our results indicate that as the user density is increased, this scheme can improve significantly the SE when compared to a non-cooperative system that does not exploit higher user densities, or a classic cooperative system that operates only during the interference-free time slots.**

***Index Terms*—Heterogenous cellular networks (HCNs), small cells, successive interference cancellation, cooperative protocol, intra-cell interference, 5G.**

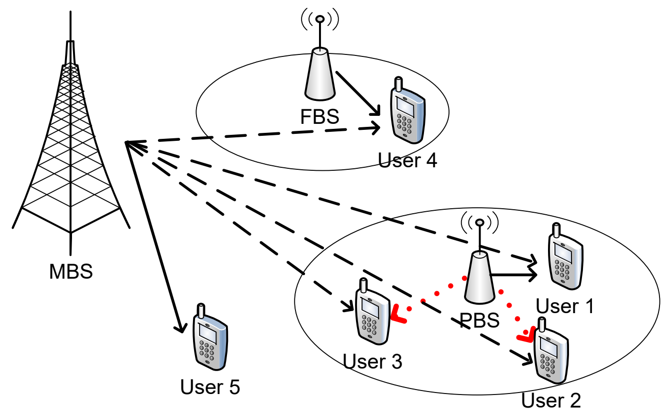


Fig. 1. Illustrating intra-cell interference in a HCN. Solid black arrows indicate the intended source-destination pair. Dashed arrows indicate intra-cell interference during the resources that are shared by the MBS and the PBSs. Users 2,3 also receive the interfering signals plus the PBS data (dotted arrows).

I. Introduction

Heterogenous cellular networks (HCN), a central component of 5G systems, achieve higher spatial reuse through the deployment of low power base stations (BS) like pico BS (PBS) and femto BS (FBS) inside a macrocell. Hence, in HCNs one of the most fundamental problems is that of *intra-cell* interference. Intra-cell interference is caused from the macro BS (MBS) to the users associated to the low power BSs. Fig. 1 illustrates this case where the MBS interferes with the PBS at the picocell users 1,2,3. One strategy for handling this type of interference in HCNs, is time-domain resource partitioning (TDRP) where the macrocell does not transmit for a fraction η of the total available resources. This technique was recently standardized through the introduction of almost blank subframes (ABS) in 3GPP LTE under the more general scheme of enhanced ICIC (eICIC). Users associated to the picocells can achieve higher data rates in these ABSs since interference from the MBS is limited [1].

The optimal allocation of time-domain resources to small cell users under TDRP and for constant η was investigated in [2]. Optimizing the TDRP fraction η together with user association was investigated by Sing and Andrews in [3]. There is a rough guideline that emanates from these state-of-the-art studies, that is also adopted by eICIC in 3GPP [1]: ABS should be allocated to users that require higher SNR (e.g., located at the edge of the small cell), while users close to the PBS can cope better with intra-cell interference and so they are allocated regular subframes (RS). This problem was concretely addressed in [2]. A potential resource allocation under this class of schemes can be seen in Fig. 2. The example in this figure indicates that the PBS will allocate to user 1 a larger fraction of the RS resources, while user 2 receives the larger fraction of the ABS time domain resources. Also user 3 receives only ABS resources.

However, even when state-of-the-art resource allocation schemes under TDRP are used, a fraction $1-\eta$ of the resources must still be allocated to the users associated to the macrocell to ensure umbrella coverage for the complete network (e.g., user 5 in our figure). Also, for several practical deployment scenarios the optimal percentage for $1-\eta$ may be close to 50% [3]. This means that during the downlink regular slots, small cell users will suffer from poor performance regardless of whether they are close or far from the PBS (users 1 and 2 in our example). This observation prompted us to investigate additional techniques to TDRP that can combat interference after it has occurred.

In this paper our goal is to improve downlink spectral efficiency in the small cells in the face of *intra-cell* interference in a dense HCN. The HCN employs TDRP across the tiers together with state-of-the-art resource allocation as we explained in the last paragraphs. We consider a HCN where device-to-device (D2D) communication is allowed. Our high level idea can be explained with the help of Fig. 1 by looking into the transmission of a single information block. What

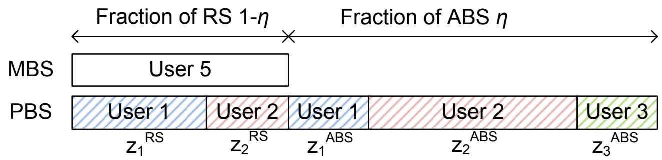


Fig. 2. The fraction of time-domain resources allocated to user i during the ABS and RS is indicated by $z_i^{\text{ABS}}, z_i^{\text{RS}}$ respectively. The proposed transmission mode cannot be used for a time duration higher than $\min(z_1^{\text{ABS}}, z_1^{\text{RS}})$ for user 1.

we propose, is to exercise successive interference cancellation (SIC) at the users associated to a PBS, so that the information block transmitted from the PBS can be decoded at several of them. This is unlike related work that attempts to optimize SIC at the end users [4], [5]. In our example in Fig. 1, the PBS users 2 and 3 will exercise SIC when an information block is transmitted to user 1 by the PBS. Even though the block may not be decodable at the desired user, it can be at other active users in the small cell since SIC performance is sensitive to the instantaneous power of the two interfering signals: The random nature of channel means that SIC leads to successful decoding at a random set of users [6]. The next step is that during an ABS, the helping users forward their received signals to the desired user by applying a distributed space-time code (DSTC). DSTC offers a *cooperative diversity* gain that improves the reliability of the transmission [7] allowing thus a higher rate and SE. To translate this idea into a practical system, there is a need for two steps: First, there is a need to consider the resource allocation in the HCN, since with our scheme the PBS transmission to a user during a RS must be followed by an ABS for cooperative forwarding. Also, our scheme should be used only if it offers higher rate. The second task is to design a practical cooperative protocol.

The main contributions and results of this paper are: 1) We propose a new paradigm for combating intracell interference in HCNs that employ TDRP with cooperative communication and SIC. Our idea is materialized with new cooperative protocol that naturally accounts for multi-user interference [8], [9]. The proposed system is compatible with state-of-the-art 3GPP resource allocation algorithms. 2) Our results indicate that for 100 users and with 4 and 8 PBSs, the spectral efficiency is improved by 13% and 26.8% respectively. Second, as the user density is increased from 100 to 200 users, our system can offer an additional gain of 3% and 11.5% respectively. Hence, our system offers higher gains as more PBSs are deployed, and also as more users join the system. The last is the exact opposite behavior from classic non-cooperative HCNs.

II. System Model and Assumptions

Network Model: The HCN topology that we study in this paper includes a single macrocell with a MBS, the set $\mathcal{J}$ of PBSs, and the users. Each base station j communicates with the set of users $\mathcal{N}_j$. The MBS shuts off its transmissions for a fraction of the resources (ABS) that is denoted with η. During these resources all the picocells transmit and interfere with every active user in the network (including users in other picocells). Thus, we consider *resource reuse* across BSs of the same tier (PBSs in our case) which is one of the main benefits of small cells since it allows spatial reuse. The aggregate average interference power that a node receives from all the small cells BSs during the ABS is denoted as $I_{\text{ABS},i}$ (this includes also the interference from relays in the cooperative mode). During the non-blank resources (RS), both the MBS and PBSs transmit and the aggregate interference power that a node receives besides the MBS signal is denoted as $I_{\text{RS},i}$. **User Model:** The users associate to a BS by using an SINR biasing rule [3]. All the PBSs are assumed to have backlogged data for all the users. **Channel Model:** Every node has a single omni-directional antenna that can be used in half-duplex mode for transmission and reception. We denote the channel from the j-th BS to the r-th user as $h_{j,r}$, and the channel from the r-th user to user i as $h_{r,i}$.[1] We assume that the fading coefficients are independent and $h_{j,r}\sim\mathcal{CN}(0,1)$, $h_{r,i}\sim\mathcal{CN}(0,1)$, i.e., they are complex Gaussian random variables with zero mean and unit variance. All the channels, are considered to be block-fading Rayleigh. The channel coefficients are quasi-stationary, that is they remain constant for the coherence period of the channel that is equal to the transmission length of the complete subframe (Fig. 3). We adopt the LTE frame structure where each subframe is divided into two time slots during which an *information block* of L symbols is transmitted (Fig. 3). We also consider the path loss and shadowing effects according to the LTE channel model [10]: Distance-dependent path loss is given by $L(d) = 128.1 + 37.6\log_{10}(d)$ dB, where d is the distance in Km [10], and the shadowing standard deviation is 8 dB. Additive white Gaussian noise (AWGN) is assumed at every receiver with variance σ^2. **Power Consumption Model:** To perform a fair comparison, the transmission power that the PBS uses in direct transmission P_{PBS}, should be equal in theory to the available transmission power of the PBS named $P_{\text{PBS}}^{\text{COOP}}$ and the transmission power of all the used relays $P_{\text{R}}^{\text{COOP}}$ in the proposed cooperative mode (i.e., $P_{\text{PBS}} = P_{\text{PBS}}^{\text{COOP}} + P_{\text{R}}^{\text{COOP}}$). However, we are even more strict regarding the efficiency of the cooperative schemes and we consider the power consumption at a relay when it overhears the interfering signals. So, for the rest of this document we assume that the total power that each relay user has available is reduced by 50%. Thus, with an equal power allocation between the PBS and the relays, we have that the total available power at all the participating relays is $P_{\text{PBS}}^{\text{COOP}} = P_{\text{PBS}}/2$. **Channel State Information (CSI):** We also assume that users provide only average channel statistics to the BSs.

III. Proposed Cooperative Transmission Mode for Downlink HCN Communication

SIC during RS. With the proposed scheme named *DSTC of interfering signals* (DSTCIF), the interfering transmission between the PBS and MBS during the RS is overheard by the

[1] We distinguish the notation for the users that act as relays to facilitate the description of the proposed protocol.

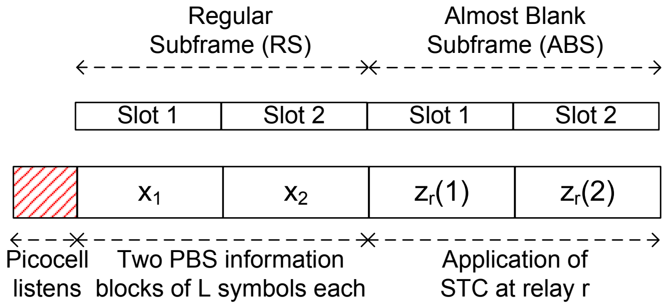


Fig. 3. Frame structure and behavior of the proposed transmission mode during a consecutive regular and a blank subframe. The frame structure is designed to be reminiscent of the LTE-A frame structure. Application of STC in the proposed protocol occurs in the ABS. During the ABS the relays transmit simultaneously in the same time slot.

users in the picocell. Hence, the signal model during the first RS slot (see Fig. 3) is:

$$y_{\text{RS},r}(1) = h_{\text{PBS},r}x_1 + h_{\text{MBS},r}x_{\text{MBS}} + n_{\text{RS,r}} + w_r \quad (1)$$

In this expression w_r is the AWGN sample at the relay. The remaining aggregate interference power that a node r receives is denoted as $I_{\text{RS},r} = \mathbb{E}[|n_{\text{RS,r}}|^2]$. Now the aggregate interference signals typically cannot be decoded, since it is practically impossible even to estimate the channel from multiple sources inside the macrocell and outside. We consider this interference as a constant aggregate term [11], that is measured by the respective user.[2] The same expression holds for the transmission of the second information block x_2 from the PBS during the second slot of the RS. After the end of a RS, a relay user attempts to decode the two blocks x_1, x_2 by employing ordered SIC [6], [9]. That is, the block with the highest energy/bit is decoded first while the other block is treated as noise [12]. If there was no interference from the MBS the following condition shouls be true so that block x_1 from PBS is decoded:

$$\log_2(1 + \frac{P_{\text{PBS}}|h_{\text{PBS},r}|^2}{I_{\text{RS},r} + \sigma^2}) \geq m \Rightarrow \frac{P_{\text{PBS}}|h_{\text{PBS},r}|^2}{(I_{\text{RS},r} + \sigma^2)(2^m - 1)} \geq 1$$

The fractional term in the RHS of the last derivation is essentially the normalized SNR/bit that is required for decoding m bits/symbol. We can get a similar expression for the MBS data and by assuming $\mathbb{E}[|x_1|^2] = \mathbb{E}[|x_{\text{MBS}}|^2] = 1$, we use the following condition so that x_1 is decoded first:

$$\frac{P_{\text{PBS}}|h_{\text{PBS},r}|^2}{2^m - 1} > \frac{P_{\text{MBS}}|h_{\text{MBS},r}|^2}{2^{m_{\text{MBS}}} - 1} \quad (2)$$

In case x_1 is decoded, it is then subtracted from the aggregate signal $y_{\text{RS},r}(1)$.[3] The same SIC scheme is applied for second transmitted block and the associated signal $y_{\text{RS},r}(2)$. Regarding the implementation of the cancellation mechanism it is executed at the block level. The successful decoding of information block x_1 is verified with the use of an error correcting cyclic redundancy check (CRC) code. Thus, upon the successful decoding, and with CSI at the relay (in this example $h_{\text{PBS},r}$), we can completely remove/cancel a complete block from the aggregate received signal $y_{\text{RS},r}(1)$.

Depending on the result, the relay will transmit different information blocks in the two slots of the ABS as illustrated in Fig. 3. We denote the information blocks that the relays transmit as $q_{r,1}$ for the first block which is $q_{r,1}$=x_1, or $q_{r,1}$=0 if the block is not decoded (similarly for $q_{r,2}$). The above notation highlights the fact that a relay user has either available the decoded information or nothing if SIC fails for a block.

Randomized Distributed Space-Time Coding (R-DSTC). Now we describe the actual DSTC operations at the relay that are executed for the information block denoted as q_r. For exposition purposes we select an orthogonal 2x2 Alamouti-type of code for q. Over the two consecutive slots 1, and 2 the r-th relay user transmits:

$$z_r(1) = \boldsymbol{c}_r[g_{r,1}q_{r,1} \quad g_{r,2}q_{r,2}]^T = g_{r,1}c_{r,1}q_{r,1} + g_{r,2}c_{r,2}q_{r,2} \quad (3)$$

$$z_r(2) = \boldsymbol{c}_r[-g_{r,2}q_{r,2}^* \quad g_{r,1}q_{r,1}^*]^T = g_{r,1}c_{r,2}^*q_{r,1}^* - g_{r,2}c_{r,1}^*q_{r,2}^* \quad (4)$$

In the above $\boldsymbol{c}_r$ is the randomization vector that simplifies considerably the distributed implementation of DSTC [7]. Also, $g_{r,1}, g_{r,2}$ are the power scaling coefficients for blocks $q_{r,1}, q_{r,2}$. The available power for all the relays is split equally as P_{R}/M, where M is the number of relays that decoded successfully. The scaling coefficient applied by relay r for information block 1 is $g_{r,1}$=$\sqrt{(P_{\text{R}}/2M)/\,\mathbb{E}[|q_{r,1}|^2]}$ (similarly for block 2). Thus, the relay splits equally the available power P_{R}/M between the two successive STC blocks.

After the STC is applied, the two relays broadcast the ST-coded blocks $z_r(1), z_r(2)$ (as shown in Fig. 3). The channel from the relays to user i is denoted with the $1 \times M$ vector $\boldsymbol{h}$, and remains constant for the entire ABS. Hence, after packing the $z_r(1)$ for each relay into a $M \times 1$ vector $\boldsymbol{z}(1)$, the received signal at the destination over slot 1 is:

$$y(1) = \boldsymbol{h}^T\boldsymbol{z}(1) + n(1) \quad (5)$$

In the above $n(1)$ is the AWGN-plus-interference-sample at the destination over the two consecutive slot transmissions. Similarly for $y(2)$. Similarly with before, the total interference power during the ABSs is denoted as $I_{\text{ABS},i}$. Next, we create the equivalent channel model by taking the complex conjugate of the second column of $\mathbf{y} = [y(1)\ y(2)]$. The resulting signal is denoted as the 2x1 vector $\tilde{\mathbf{y}}$. With the help of (3), (4):

$$\tilde{\mathbf{y}} = \underbrace{\begin{bmatrix} \sum_r g_{r,1}c_{r,1}h_r & \sum_r g_{r,2}c_{r,2}h_r \\ \sum_r g_{r,1}c_{r,2}^*h_r^* & -\sum_r g_{r,2}c_{r,1}^*h_r^* \end{bmatrix}}_{\mathbf{H}} \underbrace{\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} n(1) \\ n^*(2) \end{bmatrix}}_{\mathbf{n}} \quad (6)$$

Decoding. From the received signal model in (6) we calculate the covariance matrix of the noise vector that is the 2x2 matrix $\mathbf{\Sigma_n} = \text{diag}(I_{\text{ABS}} + \sigma^2, I_{\text{ABS}} + \sigma^2)$. For final decoding of the

[2]LTE Rel. 8 already implements the communication of the power of the local interference though the high interference indicator (HII).

[3]It is possible that different rules are used for selecting the symbol to be decoded first or even a completely different IC scheme. Our central concept is to cancel the interference of the MBS and extract the PBS data block.

transmitted blocks we apply linear minimum mean square error (MMSE) equalization for the signal model in (6) that is typically used in MIMO systems:

$$\hat{\mathbf{x}} = \text{HDD}\big((\mathbf{H}^H \boldsymbol{\Sigma}_{\mathbf{n}}^{-1} \mathbf{H} + \mathbf{I})^{-1} \mathbf{H}^H \boldsymbol{\Sigma}_{\mathbf{n}}^{-1} \tilde{\mathbf{y}}\big) \quad (7)$$

In the above $\hat{\mathbf{x}}$ is the result of hard decision decoding and the channel is estimated from the preamble of the STC block [7].

SNR and Achievable Rate. For MMSE equalization we have the well-known result for the instantaneous receiver SNR for decoding block 1 is [12]:

$$\gamma_i^{\text{DSTCIF}} = \frac{1}{[(\mathbf{H}^H \boldsymbol{\Sigma}_{\mathbf{n}}^{-1} \mathbf{H} + \mathbf{I})^{-1}]_1} - 1 \quad (8)$$

This is measured at the receiver when DSCTIF is used. Each user i calculates the average data rate c_i^{DSTCIF} as

$$c_i^{\text{DSTCIF}} = \mathbb{E}[\log(1 + \gamma_i^{\text{DSTCIF}})], \quad (9)$$

i.e., after averaging several measurements of γ_i^{DSTCIF} and informs about this the PBS that is associated, similar to related work [2], [3].

Implementation Aspects. Now if the resource allocation algorithm (described in the next section) has allocated a non-zero fraction of the ABS and RS resources to the user (it might be possible as we stated in the Introduction to allocate only one type of resources to a user, e.g., user 3 in Fig. 2), the PBS must ensure that the resources are allocated as one RS and one ABS subframe back-to-back to the user. This is implemented by indicating through the *ABS period* the type of subframe (ABS or RS) and which users will receive data blocks in specific subframes [2]. This mechanism is already part of the LTE-A specification [1]. The other low-level action that the PBS has to execute is to convert the resource allocation decisions to discrete number of packet transmissions. Finally, we should point out that R-DSTC is fully distributed and implementable in practical systems since it requires no coordination and synchronization between the relays [7].

IV. Resource Allocation in the HCN

Our protocol uses two consecutive subframes in the case that these two types of resources are allocated to a user. If a user is not allocated both RS or ABS resources then this mode cannot be used but only direct transmission. So our approach is to execute *Resource Allocation in the HCN (RAHCN)* based on a state-of-the-art formulation, and depending on these results, to use the DSTCIF mode when it is optimal.

The first step is to calculate the achievable rate during RS and ABS similarly with the way we calculated the rate for DSTCIF given in (9). In particular, the instantaneous SINR between the PBS and user i for ABS is:

$$\gamma_i^{\text{ABS}} = \frac{P_{\text{PBS}} |h_{\text{PBS},i}|^2}{I_{\text{ABS},i} + \sigma^2} \quad (10)$$

The instantaneous SINR during RS for user i is:

$$\gamma_i^{\text{RS}} = \frac{P_{\text{PBS}} |h_{\text{PBS},i}|^2}{I_{\text{RS},i} + \sigma^2} \quad (11)$$

Hence, the final result for the Direct transmission mode above, are the values for $c_i^{\text{RS}}, c_i^{\text{ABS}}$ calculated similarly with (9).

A. RAHCN and DSTCIF

Now we are ready to formulate the problem. Let $z_i^{\text{ABS}}, z_i^{\text{RS}} \in [0,1]$, denote the fraction of the ABS and RS resources that are allocated to user i by the BS that is associated. We pack these variables into vectors of the form $\boldsymbol{z}^{\text{ABS}}=\big(z_i^{\text{ABS}} \geq 0 : i \in \mathcal{N}_j, j \in \mathcal{J}\big)$, and similarly for $\boldsymbol{z}^{\text{RS}}$. Regarding the constraints we have to recall that the total fraction of the ABS resources that are available at the PBSs (there is resource re-use across the PBSs) is η. Thus:

$$\sum_{i \in \mathcal{N}_j} z_i^{\text{ABS}} \leq \eta, \ \forall\, j \in \mathcal{J} \quad (12)$$

$$\sum_{i \in \mathcal{N}_j} z_i^{\text{RS}} \leq 1 - \eta, \ \forall\, j \in \mathcal{J} \quad (13)$$

The proportional-fair HCNRA problem is:

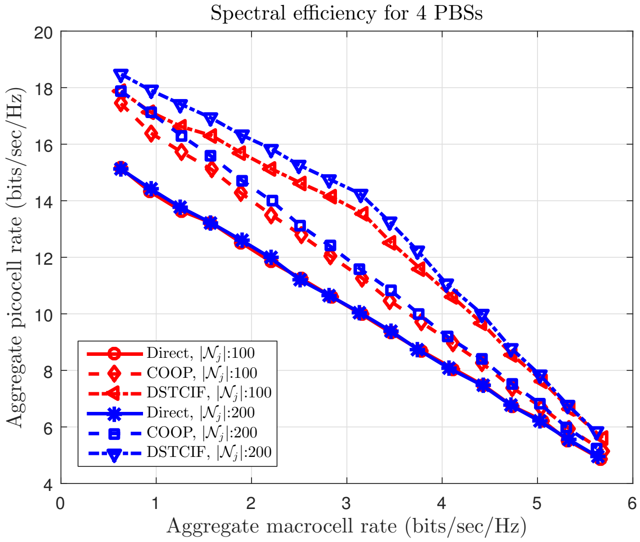
$$\max_{\boldsymbol{z}^{\text{ABS}}, \boldsymbol{z}^{\text{RS}}} \sum_{j \in \mathcal{J}} \sum_{i \in \mathcal{N}_j} \log\left(z_i^{\text{ABS}} c_i^{\text{ABS}} + z_i^{\text{RS}} c_i^{\text{RS}}\right) \text{ s.t. } (12),(13) \quad (14)$$

The problem is convex since the objective is the log of a convex set [13]. This is solved in polynomial time at the PBS. After the optimal vectors $\boldsymbol{z}^{*\text{ABS}}, \boldsymbol{z}^{*\text{RS}}$ have been calculated the PBS converts this decision to discrete packet transmissions. Also, DSTCIF is used for a maximum time duration equal to $\min(z_i^{*\text{ABS}}, z_i^{*\text{RS}})$ for a certain user i. DSTCIF is used if it is better than the direct transmission during the RS and ABS slots. Formally, if the following condition holds: $c_i^{\text{DSTCIF}} > (c_i^{\text{ABS}} + c_i^{\text{RS}})/2$.

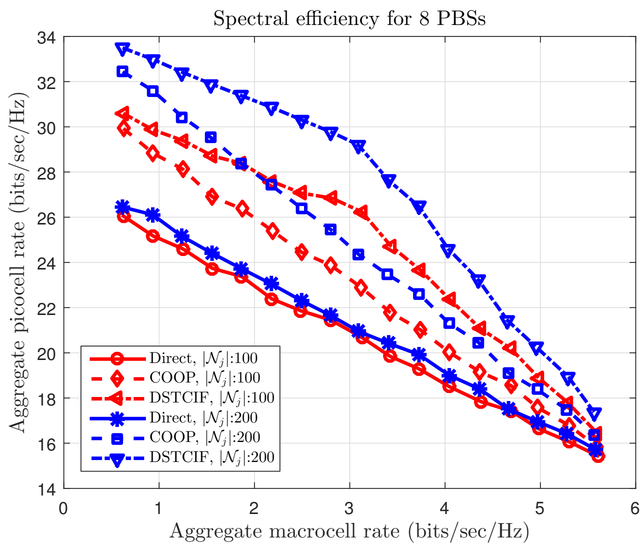
V. Performance Evaluation

Since the use of relays offers diversity gain it might be considered unfair to be compared with a system that applies only direct transmission. Hence, we compare the following three systems: (1) RAHCN+Direct that applies only direct transmissions to the user [2], [3]. (2) RAHCN+COOP where R-DSTC is used during the ABSs in order to extract a diversity gain and improve spectral efficiency (to represent a typical co-operative system). (3) The proposed RAHCN+DSTCIF where RAHCN is used, and DSTCIF is applied opportunistically only when possible. In the remaining ABS subframes a R-DSTC is also applied similarly with (2). In all our figures we measure the aggregate macrocell rate (the rate only from the MBS to its associated users) and the aggregate picocell rate. We run experiments for different values of η in order to obtain these figures. Also in our experiments we set the biasing threshold to 0 dB for all the systems to generate the set $\mathcal{N}_j$ of users that are associated with BS j. Downlink MBS and PBS transmit power are equal to 46dBm and 30dBm respectively. The channel is quasi-static as we already stated. Channel estimation at the receiver is ideal. The user distribution and picocell locations are random and uniform within the complete macrocell.

The results for all systems can be seen in Fig. 4. DSTCIF is superior when compared to COOP and Direct for high user density and low PBS density in Fig. 4(a). As the density of the PBSs is increased in Fig. 4(b), DSTCIF can have higher benefits. The reason is that more users are associated



(a)



(b)

Fig. 4. Aggregate macrocell rate vs. aggregate picocell rate. As we move to the right of the x axis more resources are RS.

to picocells and so more users can enjoy a cooperative transmission. So more picocells leads as expected to better results due to offloading, but user cooperation increases the maximum spectral efficiency. But the most important result is that for constant PBS density we have increasing system performance as the user population grows. This is one of the central points of this paper: With Direct mode we have the same system capacity as the user population grows which is consistent with our expectation since there is resource sharing. However, user cooperation as the density increases leads to higher diversity gain and the higher SNR leads to spectral efficiency improvements. Also note that in the left part of the x axis, where all the resources are allocated to the picocells we have the maximum possible throughput performance in the network ($\eta \approx 1$). In this regime, the performance gap between DSTCIF and Direct or COOP is increased as the number of picocells and users is increased. Also note that the performance gap between our scheme and COOP is limited only because the maximum value of η is also limited.

VI. Conclusions

In this paper we presented a system design for improving the spectral efficiency of HCNs that employ time-domain resource partitioning in the face of intra-cell interference. The central concept is the use of SIC for decoding the PBS data at several small cell users since the information of interest can be available at a several of them. Diversity gain with cooperative DSTC from all the users that successfully decoded offers higher SNR and eventually higher rate. When combined with state-of-the-art resource allocation schemes for HCNs, performance results indicate the significant benefits of our scheme for increasing user densities even when the deployment of picocells does not change. In our future work we plan to investigate different resource allocation schemes.

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