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Cross-tier interference management with a distributed antenna system for multi-tier cellular networks

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Abstract

In a multi-tier cellular communication system, the interference from one tier to another, denoted as cross-tier interference, is a limiting factor for the system performance. In spectrum-sharing usage, we consider the uplink cross-tier interference management of heterogeneous networks using femtocells overlaid onto the macrocells. We propose a variation of the cellular architecture and introduce a novel femtocell clustering based on interference cancellation to enhance the sum rate capacity. Our proposal is to use a distributed antenna system (DAS) as an interface to mitigate the cross-tier interference between the macrocell and femtocell tiers. By placing a DAS remote antenna unit (RAU) near a set of femtocells that experience interference from a macrocell user, the DAS can retrieve the interference symbols and feed them back to the femtocells, where each cell can perform interference cancellation when necessary. In addition, the DAS can forward the recovered data to the macrocell base station (MBS); thus, the macrocell user can reduce its transmit power to reach a RAU located closer than the MBS. By distributing the sensor nodes within the macrocell coverage, the proposed scheme can mitigate the cross-tier interference at different locations for several femtocell clusters. Our simulation results show substantial improvement in the network sum rate capacity.

Keywords: Macrocell; Femtocell; DAS; Cross-tier interference mitigation; Heterogeneous networks; Spectrum sharing; Small cell networks

1 Introduction

Next-generation wireless communication demands enhancement of the cooperation at the multi-tier level to improve the end-user data rate. Cooperation among wireless systems has been demonstrated to be a better alternative for coexisting networks [1]. Contemporary novel wireless network concepts such as heterogeneous networks (HetNets) and multi-tier networks such as femtocells overlaid onto the macrocells require advanced management of the cell load, cross-tier interference, and user access to the spectrum. Spectrum sharing increases to the complexity of meeting the demand in wireless broadband access, thus prompting the emergence of these networks. This process requires the design of spectrum-sharing self-enforcing rules compatible with each individual system [2]. Considering the differences in

the transmit power and the near-far problem in two-tier networks [3], our proposal contributes to the design of a coordinator between the two systems, which manages the cross-tier interference and enhances the ergodic sum rate capacity scaling.

In this study, we focus on the cross-tier interference management between a primary system (PS) and a secondary system (SS) in a spectrum-shared scenario. The PS or macrocell tier is composed of a macrocell base station (MBS) and the mobile users that communicate directly with the MBS by default, denoted as macrocell user equipment (MUE). The SS or femtocell tier consists of femtocells. A femtocell is a low-powered user-deployed base station (FBS) that operates in co-channel with the macrocell to deliver high spectral efficiency in closed- or open-access regime [3] to one or two indoor mobile users, denoted as femtocell user equipment (FUE). The femtocell tier constitutes the core technology of small cell networks [4-6].

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Femtocells constitute an underlay cell network with the macrocells. Because each FBS is exclusively managed by its end-user, mitigating the cross-tier interference coordination similar to that in traditional cellular networks (individually handled by the operators) becomes difficult. Furthermore, the backhaul exchange information between the MBS and the FBSs becomes tedious for a large number of femtocells because the MBS communicates with the femtocells through a gateway. Our proposal aims to address these challenges through the advanced HetNets scheme and innovative femtocell clustering consequent to the proposed introduction of the distributed antenna system (DAS) interface.

We consider the DAS as referred in our references such as [7]. A DAS consists of signal processing modules and remote radio frequency (RF) antenna element modules denoted as remote antenna units (RAUs). Multiple RAUs can share the same signal processing unit denoted as common processing unit (CPU). Each RAU is connected to a CPU by optical fiber. The RAUs are located nearby premises which shelter FBSs. Therefore, different RAUs can cover several small areas in a heterogeneous coverage while sharing the same processing unit. The wired part of the system, made of optical fiber, presents a negligible error rate and delay. The DAS has a common platform role because it can accommodate different wireless service operators and different protocols. Thus, the DAS is an asset for heterogeneous small cell deployment and can be functionally compared to a radio access network (RAN) aggregation system [8]. As RAN aggregation is considered between operators in [8] to improve throughput and spectrum efficiency; this study considers femtocell integration by the DAS interface.

In our system model, the FBSs are small base stations located inside the premises of the customers. In a close access operating regime, such FBSs allow communication with only their registered mobile users. The RAUs of the DAS are antenna elements located outside the premises sheltering the FBSs. We consider a path loss exponent difference between the wireless communications of each FBS and its registered FUE and each RAU and an unregistered (to the FBS) MUE.

Reference [9] proposed a cellular architecture based on the DAS to address the coverage scarcity in HetNets. The sum rate of the network improved because of the DAS, which added more degrees of freedom to the network. Recently, HetNets have been considered [10] to implement efficient architecture for broadband access in relation to LTE [11] where DAS is used as HetNet technology enabling system. Interference mitigation in HetNets was considered in [12] through orthogonal resource allocation and relaying. The ergodic capacity analyses can be found in [7], where downlink DAS was considered in multicell environment. Analysis that features cooperation between DAS antenna element modules and the femtocells located in tall building was presented in [13].

The study in [14] consisted of the cooperation of the base stations equipped with multiple antennas within a cellular system. The proposed interference cancelation was based on multiple antenna signal processing and the exchange of strongly interfering terminal data with the base stations where the received signal decoding remained unsuccessful. The latter base stations performed successive interference cancellation, which used additional multiple antenna processing. Reference [14] assumed that some base stations in the cell can decode multiple user data using their multiple antennas and then exchange the estimated data with the other base stations. Then, the forwarded data were used for interference cancellation when the signal-to-interference-plus-noise ratio (SINR) at the femtocell due to the MUE interference was negligible.

The concept in [14] reflected more of the version of the traditional successive interference cancellation combined with the network MIMO. The traditional successive interference cancellation involved the extraction of the estimated interfering signal from the combined signals and the estimation of the desired signal from the difference. The system model in [14] lacked reliability because one of the base stations could be unable to estimate the signal of a strongly interfering terminal from the received combined signals. In contrast to [14], the study in this paper uses signaling without resorting to multiple antennas. Because femtocells are indoor systems managed by their end users, it is difficult to apply the schemes in [14] or network MIMO to the different femtocell base stations. In addition, given the recent ubiquity of small cell networks [6], our proposal in this paper effectively addresses the cross-tier interference issue in a novel way to the best of the authors' knowledge. Because DAS has already been introduced into cellular systems, we propose to use the DAS as an interface between the macrocell and femtocell tiers, considering uplink transmission to mitigate the cross-tier interference as follows:

- The mitigation at the femtocell side considers a cluster of femtocells. Near the cluster, an MUE that transmits to its MBS drastically subjects the cluster into a high outage probability. When the DAS is connected to the MBS and to each femtocell in the cluster through the optical line, information exchange can be performed for interference cancellation. By placing a RAU in the cluster, the DAS can retrieve the symbols transmitted by the MUE and feed them back to each FBS, thus cross-tier interference can be cancelled at the FBS. The DAS can multicast the feedback to the FBSs in the cluster affected by the same MUE on the basis of each FBS request for feedback. The feedback request can be

based on the evaluation of the SINR at each FBS in the cluster of femtocells.

- At the macrocell side, the interference from the MUE to the femtocells in the cluster can be mitigated by reducing the MUE transmit power because the DAS retrieves the symbols transmitted by the MUE through the nearby RAU located closer to the MUE than the MBS. Such reduction is constrained by the MUE outage probability at the RAU. The introduction of the DAS shortens the radio transmission distance of the MUE. This implies a reduction of its transmit power [15].

In addition to the mitigation of the cross-tier interference made possible by the DAS interface, we can derive consequent benefits from our proposal. Instead of exchanging the related information of the strongly interfering terminal as performed in [14] or resorting to network MIMO as done in [7], our proposed interface directly forwards the MUE transmitted symbols where needed in the femtocell cluster. The traditional MBS-FBS direct connection can be used for interference cancellation [16]; however, as the number of femtocell clusters increases, the macrocell off-loading role of the femtocells [6] is compromised by the induced traffic delay in the backhaul. Furthermore, the signal decoding complexity individually involves each femtocell that requests interference cancellation, in contrast to the schemes in [7,14]. As stated in the outage analysis, to ensure that the feedback system retrieves the symbols of the MUE(s) causing interference at the FBSs, we propose a cross-tier interference avoidance which consists of prohibiting any FUE transmission susceptible of creating significant interference at the RAU involved in the feedback system. The overall novelty and contribution of our proposal is the use of the distributed direct (wired) links between the DAS (through CPUs and RAUs) and the femtocell tier (FBSs). Consequent to our proposal, the sum rate of the small cell networks improves substantially. Such result is confirmed in this study by computer simulations.

The rest of this paper is structured as follows. The system model and the proposed architecture are described in Section 2. The femtocell clustering concept based on the feedback request is presented in Section 3. Section 4 is devoted to the proposed interference management. The computer simulations are discussed in Section 5, and this paper ends with the conclusion in Section 6.

2   System model and proposed architecture

Figures 1 and 2 illustrate our conventional and proposed systems respectively. $Op_x, x = n, m, u$ are telecommunications operators operating in the same region, each having his own MBS. For each operator, frequency

sharing between macrocell and femtocells is considered. Considering the work in [8], we assume that operators can share the DAS through wired optical links connected to the CPUs. We further assume that the RF part of the DAS sensor supports the operator frequency bands. We do not consider the situation where different MBSs share simultaneously the same RAU. Therefore, this study focuses on a macrocell coexistence with femtocells with regard to the cross-tier interference mitigation in presence of the DAS which is an independent interface to the operators. We assume TDD-OFDMA in this paper. The cases presented in this paper are feasible situations for our proposal performance evaluation. As the MUEs are managed by the MBS, if several MUEs are located in the same area, the MBS allocates different frequency bands or time slots for them to communicate. Consequently, we considered one or two MUEs for the cases studied in this paper since we consider frequency sharing in our system model.

2.1   Conventional system: traditional coexistence of the femtocell and macrocell tiers

Each femtocell constitutes an FBS and an FUE (FUE + FBS) as shown in Figure 1. The FBS carries the radio access control of its FUE. Because we assumed a closed regime, the MUE is unable to communicate directly on the wireless link with any FBS. The femtocell radius is on the order of 10 to 50 m. The macrocell tier is composed of the MBS and each MUE randomly distributed in the tier. Each MUE attempts to transmit directly to the MBS.

2.2   Cellular architecture modification

Our proposed modification of the conventional system involves the insertion of the DAS in the benchmark. The DAS is represented in Figure 2 by the CPUs and the RAUs. Each RAU is connected directly to a CPU, which is linked to the MBS. We assume that all RAU-CPU and CPU-MBS links are fiber optic links with negligible delay. Signal processing such as minimum mean square estimation (MMSE) through recursive least square algorithm and symbol demodulation can be performed at each FBS, and each CPU. A logical implementation of a DAS that cooperates with a network operator can be found in [11].

## 3   Proposed concept of an femtocell clustering by DAS

In [16], the interference cancellation considered information exchange directly between MBS and FBS. Because of the number of femtocells in a macrocell, we consider DAS cooperation as a solution to address the drawbacks such as signal decoding complexity and the traffic constraint on a single MBS.

Figure 1 Femtocells overlaid onto legacy macrocells.
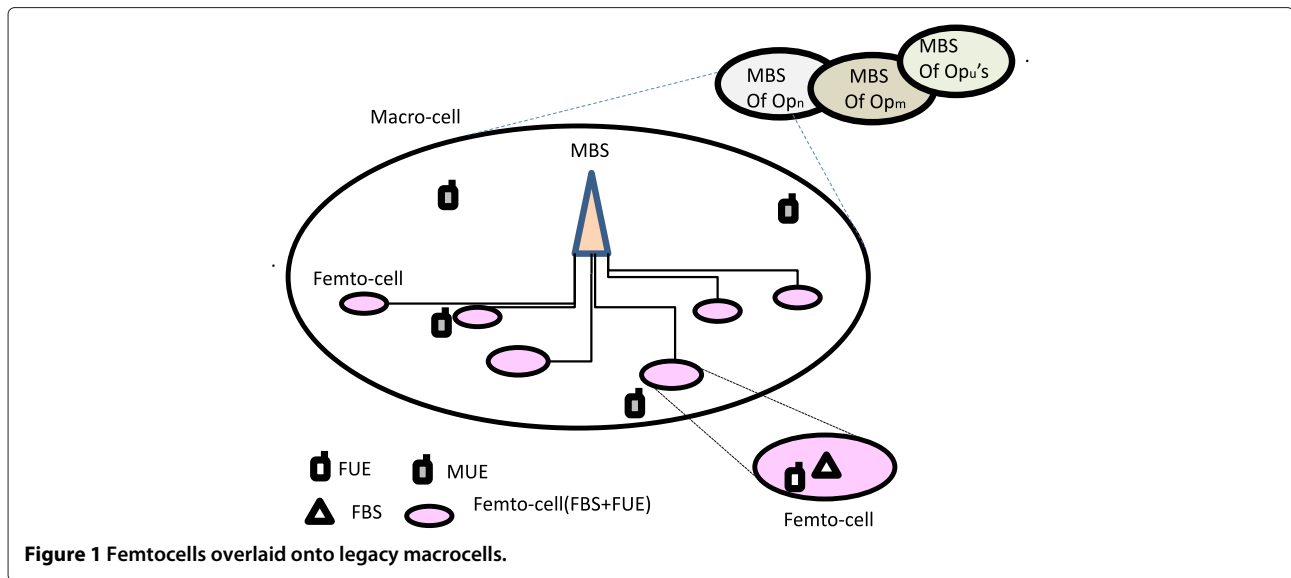
3.1 Femtocell clustering concept

Our proposal considers a virtual cluster concept. Our concept of 'cluster' is defined as an aggregation of several femtocells (FBSs + FUEs) around a DAS sensor node which assists the FBS at the femtocells in the cross-tier interference cancellation. Due to the small radius of a femtocell, we can obtain several femtocells that form a cluster in a random location in the macrocell. Figure 2 shows such clusters, and we denote three of them as FC_i, FC_j, and FC_k associated each with at least a RAU. In FC_j, F_j is a femtocell and R_j is a RAU. Considering such cluster, we derive the following femtocell clustering concept relative to the DAS elements and the interfering MUE near

the cluster. The MUE transmission generates interference at the cluster. Each FBS evaluates its SINR to assess the need to mitigate the interference. We define a femtocell in outage as a femtocell whose FBS has a SINR below a threshold above which symbol decodability is possible. The femtocells in outage can request the cooperation of the DAS for interference mitigation. The DAS selects the femtocells that request interference mitigation. This selection consists of the femtocell clustering by the DAS. The interference mitigation requires that the DAS retrieves the symbols transmitted by the MUE through its RAU(s) and feed them back to the set of selected femtocells. Thus, each femtocell in the femtocells clustered by the DAS

Figure 2 Femtocells overlaid onto legacy macrocells in uplink interference with the added DAS.
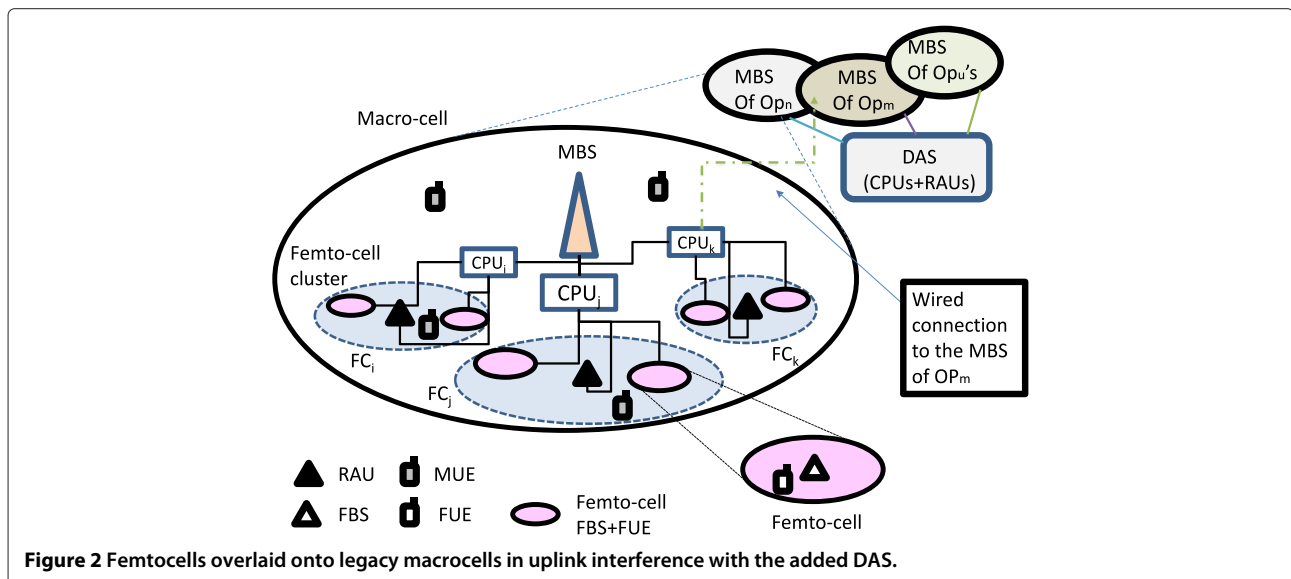
can retrieve its desired signal by interference cancellation which uses the feedback symbols of the interfering terminal(s). Given the distribution of the DAS elements within the macrocell-tier, such cross-tier interference management can be performed in different clusters. This concept generalizes the interference cancellation scheme in [16].
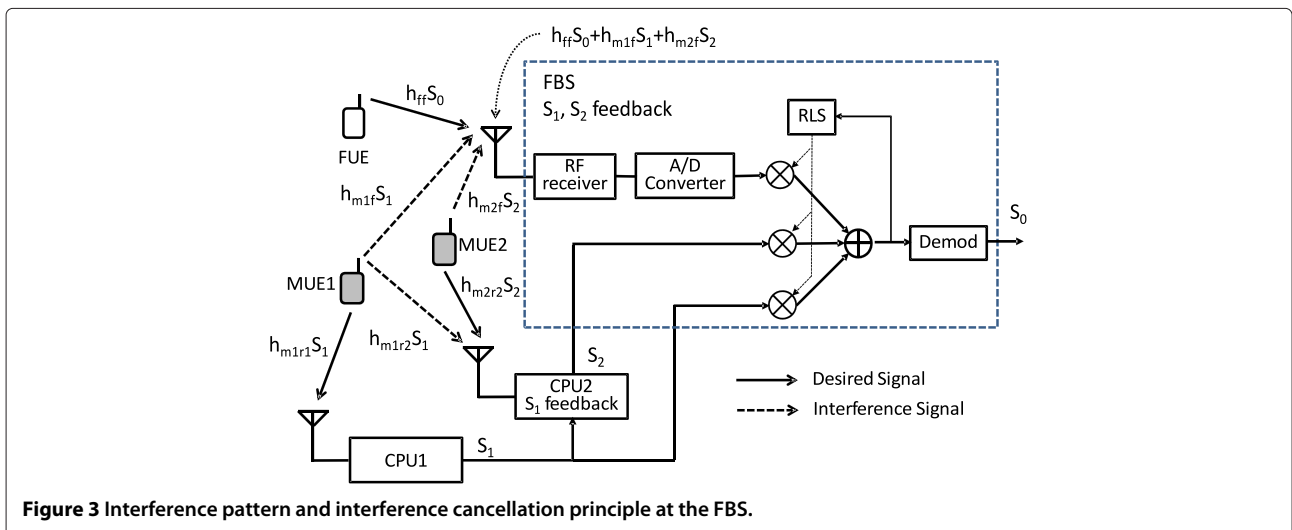
3.2 Interference cancellation patterns

The introduction of the DAS allows cross-tier interference management under different situations. The channel gains are modeled as independently and identically distributed variables with zero mean and a unit variance. The interference cancellation for the femtocells selected by the DAS is illustrated in the following cases:

- Figure 3 shows MUE1 and MUE2 interference at the FBS. On the wireless link, the FBS receives its desired signal S_0 weighted by the channel gain h_{ff} in addition to the signals S_1 and S_2 which are weighted by the channel coefficients h_{m1f} and h_{m2f}, respectively. Simultaneously, the feedback system constituted by CPU1 and CPU2 retrieves the symbols S_1 and S_2 through signal processing and forward them to the FBS. CPU1 receives MUE1 transmitted signal S_1 without interference from MUE2 assumed to be located far enough from CPU1. Then, it demodulates the received signal in order to forward S_1 to both the FBS and CPU2. After receiving S_1, CPU2 performs interference cancellation as detailed in Figure 4 in order to retrieve S_2 from the wireless signal $h_{m1R}S_1 + h_{m2R}S_2$, where h_{m1R} (h_{m2R}) is the channel coefficient between MUE1 (MUE2) and the RAU of CPU1. The FBS can perform interference cancellation using the forwarded symbols S_1 and S_2 to recover S_0.
- Figure 4 shows the feedback system composed of the MBS and a RAU, where h_{m1R} (h_{m2R}) is the channel

coefficient between MUE1 (MUE2) and the RAU of the CPU, and h_{m1M} is the channel coefficient between MUE1 and the MBS. MUE1 is close to the MBS such that interference from MUE2 to MBS is negligible, and MUE2 is close to the RAU linked to the CPU. When both MUEs interfere at the RAU, the MBS can recover S_1 and forward it to the CPU, which can recover the symbol S_2 of MUE2. This process involves a single feedback scheme at the CPU. Then, the two MUE symbols can be forwarded at the femtocells (FBSs connected to the CPU) that experience the interference from the two MUEs.
- Figure 5 shows a similar situation to Figure 4 with the difference that the MBS in Figure 4 is replaced by a RAU. Owing to the presence of the two MUEs and two RAUs sharing a CPU, we propose a power control of the MUEs through the following scheme: MUE2 reduces its transmit power to reach its closest RAU, RAU2. MUE1 transmits to RAU1. The CPU can demodulate the symbol received by RAU1 independently of the signal received at RAU2. The CPU connecting the two RAUs retrieves the MUE symbols to feed them back to the FBS for interference cancellation.

In Figure 5, RAU1 receives the symbol S_1 without interference. Thus, the RLS module can receive the symbol S_1 after demodulation. The equation represents the signals received at the RLS input for interference cancellation. As represented in Figure 5, $hm1r1$ is not required at the RLS input, therefore is not necessary in the following matrix representation of the signals for modeling the interference cancellation process. Such interference cancellation scheme has been proposed in our previous work in [16]. In Figure 5, the signals received by the CPU can be represented as follows:

Figure 3 Interference pattern and interference cancellation principle at the FBS.
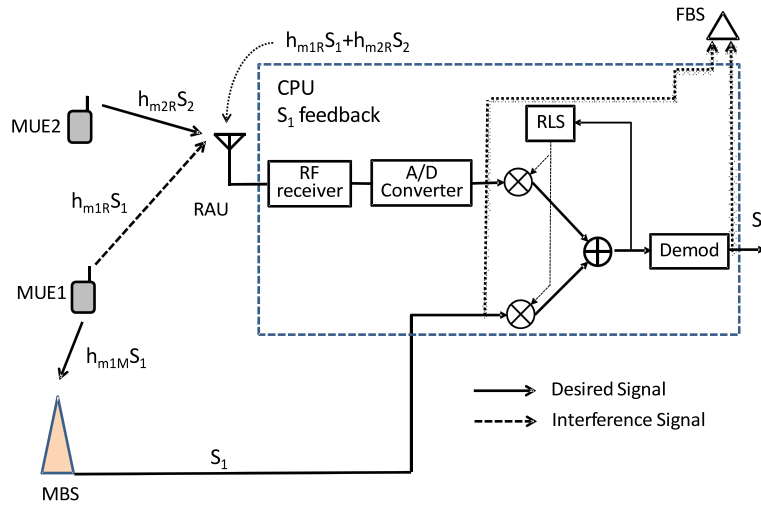
Figure 4 Feedback system with CPU and MBS.

$$\begin{pmatrix} S_2 h_{m2R} + S_1 h_{m1R} + n_R \\ S_1 \end{pmatrix} = \begin{pmatrix} h_{m2R} & h_{m1R} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} S_2 \\ S_1 \end{pmatrix} + \begin{pmatrix} n_R \\ 0 \end{pmatrix},$$

where h_{m2R} and h_{m1R} are the channel coefficients from MUE2 and MUE1, respectively, to RAU2; h_{m1r1} is the channel coefficient from MUE1 to RAU1, and n_R is an AWGN. MUE1 signal at RAU1 is received without interference. S_1 and S_2 can be independently decoded by the signal processing at the CPU because the channel matrix

$$\begin{pmatrix} h_{m2R} & h_{m1M} \\ 0 & 1 \end{pmatrix}$$

is invertible.

Considering that the feedback system can be one of the situations represented in either Figures 4 or 5, we use the notation in Figure 3 to effectively describe the interference management schemes for the rest of this section. FUE transmits the symbol S_0 under channel gain h_{ff} to its related FBS. S_1 and S_2 are transmitted from the two MUE1 and MUE2, respectively. h_{m1f} and h_{m2f} represent the channel gains from MUE1 and MUE2 to the FBS. We consider MUE1 and MUE2 in Figure 3 for the analysis of the S_0 recovery under the interference of two MUEs. We assume that the estimation process of S_0 can be performed as described in [16] by considering the signal feedback from the feedback system to the FBS that receives the combined signal $S_0 h_{ff} + S_1 h_{m1f} + S_2 h_{m2f}$. The interference case that must be considered before the recovery of S_0 by the FBS is described as follows: $(h_{m1r2} S_1 + h_{m2r2} S_2)$
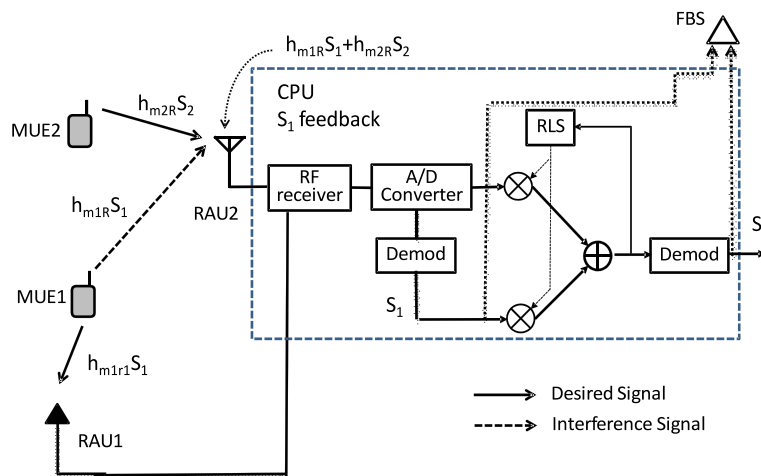
Figure 5 Feedback system with two RAUs.

represents the signal received at the RAU resulting from the transmission of the two MUEs. The feedback of S_1 from the MBS to CPU2 allows a single-symbol detection as in [16]. Assuming correct recovery of S_1 and S_2 at the CPU, each femtocell in the DAS femtocell cluster can perform interference cancellation using the following relationship:

$$\begin{pmatrix} S_0 h_{ff} + S_1 h_{m1f} + S_2 h_{m2f} + n_f \\ S_1 \\ S_2 \end{pmatrix} = \begin{pmatrix} h_{ff} & h_{m1f} & h_{m2f} \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$
$$\times \begin{pmatrix} S_0 \\ S_1 \\ S_2 \end{pmatrix} + \begin{pmatrix} n_f \\ 0 \\ 0 \end{pmatrix},$$

where n_f is an AWGN. The symbols S_1 and S_2 are provided to the FBS by the CPU. The FBS can retrieve S_0 by channel matrix inversion. Such channel matrix inversion is approximated by the RLS algorithm with minimum mean square error equalization. Therefore, the FBS approximates h_{m1f} and h_{m2f} by the RLS algorithm. The detection of S_0 using the above matrices notation was explicitly derived in [16].

3.3 Reception at the RAUs and FBSs

On one hand, the proposed interference management based on the DAS relies on the correct reception of the interfering MUE symbols at the RAU located in the vicinity of both the femtocell cluster and the MUE. On the other hand, the inter-femtocell interference may remain at the FBS although the cross-tier interference is cancelled with our proposed feedback. The restriction on the femtocells transmission due to their closeness to the DAS sensor node is made to allow the DAS sensor node to receive the interfering MUE signal without interference from the close femtocell users.

Thus, we evaluate the probability of successful reception of the transmission of an MUE (FUE) at a RAU (FBS). This evaluation is subject to the MUE (FUE) transmit power control and the combined interference from the set of femtocells that transmit within the cluster. We denote the cardinality of this set by $|\Omega|$. We assume that the femtocells involved in the outage derivation are each located at a distance r from the RAU. Such combined interference is subject to the following analysis:

We denote the set of transmission occurrences in the vicinity of the RAU as $E = \{x_1, x_2 \ldots\}$. Therefore, we obtain $\Sigma = \{\emptyset, \{x_1\}, \{x_1, x_2\} \ldots\}$ as the set of the subsets that can be constructed from E, where $\emptyset$ is an empty set. We define the following function over Σ:

$$f : \Sigma \rightarrow R^+$$
$$\Omega \rightarrow P(X \in \Omega), \tag{1}$$

where Ω is the set of FUE transmission occurrences from the cluster, $P(X \in \Omega)$ is the total probability of the events constituting Ω and R^+ is the set of positive real numbers. To express $P(X \in \Omega)$, we must rely on the DAS femtocell clustering which defines the set of femtocells that request interference mitigation. The cardinality of Ω is given by:

$$\begin{aligned} |\Omega| &= |\{X_s \in \Omega_M\}| + |\{X_n \in \Omega_c\}| \\ &= |\Omega_M| + |\Omega_c| - |\Omega_M \cap \Omega_c|, \end{aligned} \tag{2}$$

where $s, n \in \{1, 2, .. |\Omega|\}$ are the indexes, Ω_M is the set of transmission occurrences interfering at the RAU, and Ω_c is the set that requires symbol feedback from a CPU for interference cancellation. The probability of successful reception at the RAU denoted as $P_s(r, |\Omega_M|)$ is derived from [17] as follows:

$$P_s(r, |\Omega_M|) = e^{-\theta \frac{N_0}{P_{tm}} d^{\lambda_{out}}} \prod_{i=1}^{|\Omega_M|} \frac{1}{1 + \frac{P_i}{P_{tm}} \frac{d^{\lambda_{out}}}{r^{\lambda_{in}}}}, \tag{3}$$

where P_i is the transmit power of the FUE whose transmission is received at the RAU considered in Equation 3, θ is the threshold SINR for successful reception, N_0 is the noise power, P_{tm} is the transmit power of the MUE, d is the distance from the MUE to the RAU, and λ_{out} and λ_{in} are the outdoor and indoor path loss exponents, respectively.

Proof. The SINR of the MUE at the RAU is expressed as

$$\text{SINR} = \frac{P_{tm} d^{-\lambda_{out}} |h_M|^2}{N_0 + \sum_{i=1}^{|\Omega_M|} P_i r^{-\lambda_{in}} |h_i|^2}, \tag{4}$$

where h_M is the channel coefficient between the MUE and the RAU and h_i is the channel coefficient from the ith femtocell to the RAU. The outage probability is given by

$$P(\text{SINR} < \theta) = 1 - P(\text{SINR} \geq \theta), \tag{5}$$

where $P((x) < (y))$ indicates the probability that x is lower than y. Furthermore,

$$P(\text{SINR} \geq \theta) = P(|h_M|^2 \geq \frac{N_0 \theta}{P_{tm} d^{-\lambda_{out}}} + \frac{\sum_{i=1}^{|\Omega_M|} P_i r^{-\lambda_{in}} |h_i|^2}{P_{tm} d^{-\lambda_{out}}}), \tag{6}$$

We note that $|h_M|^2$ and $|h_i|^2$ are exponentially distributed with a variance of one; thus, by computing the moment generating function [18], we can obtain

$$P(\text{SINR} \geq \theta) = e^{-\theta \frac{N_0}{P_{tm}} d^{\lambda_{out}}} M_t(Y), \tag{7}$$

where t is a real number parameter of the moment generating function and Y is defined as:

$$Y = \sum_{i=1}^{|\Omega_M|} P_i r^{-\lambda_{in}} |h_i|^2. \tag{8}$$

$M_t(Y)$ is the moment generating function of the random variable Y and parameter t is defined as

$$
\begin{aligned}
M_t(Y) &= E[e^{tY}] \\
&= \prod_{i=1}^{|\Omega_M|} \int_0^\infty e^{-st} e^{-t} dt \\
&= \prod_{i=1}^{|\Omega_M|} \frac{1}{s+1},
\end{aligned}
\tag{9}
$$

where $s = \frac{\theta P_i r^{-\lambda_{in}}}{P_{tm} r^{-\lambda_{out}}}$ and e^{-t} is the density function of an exponentially distributed random variable with a variance of one. Replacing $M_t(Y)$ by its value in Equation 9 ends the proof. □

4 Proposed interference management in underlay macrocell

As $|\Omega|$ results partially from the cardinality of the terminals that interfere at the RAU, we propose to manage the interference by considering the situation where two different sets of DAS-selected femtocells are linked to different DAS elements as denoted by FC_j and FC_k where the MUE denoted by M_j interferes in both sets. Because interference cancellation can be performed at each element of the DAS femtocell clustered in $\{X_n \in \Omega_c\}$, the resulting sum rate capacity can be written as follows:

$$
C_{\Omega_c} = \sum_{n=1}^{|\Omega_c|} \log_2(1 + \text{SINR}_n),
\tag{10}
$$

where SINR_n is the SINR of $X_n \in \Omega_c$. Because the feedback option is unfeasible with M_j interfering in FC_k, we propose the following time slot based orthogonal resource allocation for the MUE transmissions to improve the network sum rate.

Considering the transmission of an FUE to its FBS, the previous analysis can be applied by substituting the MUE with the FUE and the RAU with the FBS. The set of femtocells surrounding the considered FBS can cause interference and degrade the FBS reception even in the case of feedback. Thus, for a perfect reception at the RAU, we propose to prohibit the FUE transmission close to the RAU as illustrated in Figure 6 used for our simulation model described in Section 5.

4.1 Proposed radio resource allocation for cross-tier interference management in the underlay macrocell

In Figure 2, let us consider M_j and M_k are MUEs interfering at FC_j and FC_k, respectively. In addition, we assume that M_j interferes at F_j and F_k whereas M_k interference is restricted to FC_k. R_j and R_k are RAUs in FC_j and FC_k, respectively. F_j (resp. F_k) is a femtocell in FC_j (resp. FC_k). The interference management through feedback can be achieved as follows: R_j (resp. R_k) retrieves M_j (resp. M_k) transmitted symbols, then CPU_j (resp. CPU_k) feeds back the retrieved symbols to F_j (resp. F_k). Such feedback process is enabled by the following radio resource allocation of the MUEs. Table 1 lists the access of the femtocells and MUEs to FC_j and FC_k partitioned using time slots (TS). For each column, the different TSs
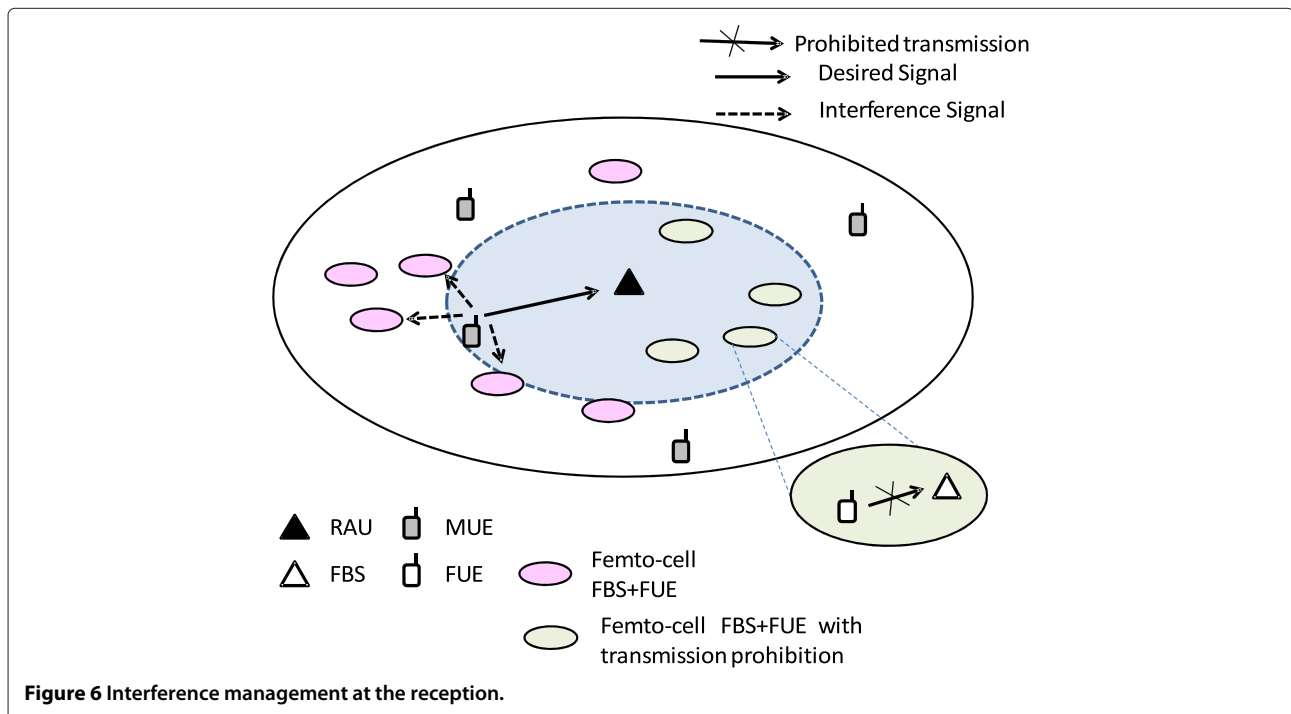

Figure 6 Interference management at the reception.

Table 1 Proposed orthogonal radio resource allocation for interference management

Proposed	Conventional
$TS_1 : M_j, F_j$	$TS_1 : M_j$
$TS_2 : M_k, F_j, F_k$	$TS_2 : M_k, F_j$
...	$TS_3 : F_j, F_k$

are expressed as TS_i, $i = 1, 2, 3$. At each column TS_i, the simultaneously transmitting terminals are denoted as MUE and/or FUE. M_j and F_j can transmit simultaneously during TS_1 because M_j can target the MBS or the RAU. The interference of M_j at F_j can be cancelled by the feedback as illustrated by Figures 4 or 5. In TS_2, the interference from M_j to F_k is avoided and a transmission similar to TS_1 can occur in M_k and F_k whereas F_j is beyond the interference range. F_j and F_k can transmit simultaneously in TS_3. The DAS enables terminal access management and permits cooperation if the MUE access to any femtocell base station is restricted. In the conventional scheme, three TSs are required to avoid interference from the base stations. Because the transmit power decays with the distance, the interference of M_k with F_j is assumed to be negligible.

4.2 Simultaneous transmission without the proposed radio resource allocation

This section describes the conventional scheme of the proposal in Subsection 4.1. We consider FC_j and FC_k in the absence of the proposed radio resource allocation. We assume a simultaneous transmission of all femtocells and MUEs. Considering the DAS elements, the MUEs can transmit at minimum power to reach the RAU. Although F_j and F_k benefit from the interference cancellation from M_j and M_k, respectively, in the DAS femtocell clustering, F_k experiences interference from M_j. In the conventional system, F_j and F_k experience low SINR from the high transmit power of the MUEs.

5 Simulation results and discussion

5.1 Simulation conditions

We use the C language for the simulations presented in this paper. The channel model is a five-path exponential Rayleigh fading. The noise is generated as AWGN. Each user transmits by QPSK modulation to generate the symbols from the binary output of the convolutional encoder. Then, OFDM is applied before the signals enter the channel. The OFDM key parameters are listed in Table 2, and the simulation parameters related to the macrocell-femtocell two-tier network are presented in Table 3 which are similar to those in [3]. The noise is added during signal reception whereas the signal fed back to the base station or the DAS element is free from noise. We use the

Table 2 Simulation conditions

Parameter	Value
Bandwidth	5 MHz
Number of subcarriers	512
Useful symbol time	6.4 μs
Guard interval	1.25 μs
Data modulation	OFDM QPSK
Small-scale channel model	Rayleigh flat fading
Weight estimation algorithm	RLS
Noise	AWGN
Convolutional code rate	1/2
Convolutional code constraint length	7

RLS-based MMSE algorithm to recover the data at the receiver for interference cancellation at CPU and/or FBS. The transmit power, positions, and details of the distance path loss model of each user are listed in Table 3. A fixed loss is chosen instead of considering a random lognormal shadowing. We use the SINR and capacity evaluation from [19]. The sum rate is then evaluated by Equation 10 whose cumulative distribution function (CDF) is used in the simulation results.

5.2 Performance evaluation and discussion

Our simulation system model is illustrated by Figure 6. In Figure 6, MUE is located at random distances from the femtocells in its vicinity. In our simulation, we consider different values of r for the variation of the distance between the MUE and different FBSs under the MUE cross-tier interference. Therefore, we evaluate the performance at the FBS with and without feedback from the feedback system. As represented in Figure 6, the reception of the MUE symbols at the RAU is performed without femtocell interference. In the case of 2 MUEs, we apply the feedback system in Figures 4 or 5 where the MBS or RAU(s) are protected from femtocell interference.

The performance evaluation consists of the computation of the sum rate that considers a femtocell cluster and

Table 3 HUE and MUE femtocell and macrocell parameters

Parameter (variable)	Value
Macrocell radius (R_c)	1,000 m
Femtocell radius (R_f)	30 m
Normalized distance (r)	0.01 to 0.95
Carrier frequency (f_c)	2,500 MHz
Wall penetration loss (P_l)	5 dB
Mobile maximum transmit power (P_{tmax})	23 dBm
Macrocell path loss exponent (λ_{out})	3.8
Femtocell path loss exponent (λ_{in})	3

its neighboring MUE. The sum rate is evaluated using Equation 10 for a given number of mobile terminals. Thus, we add up the rates of the femtocells and MUEs chosen in the situations that illustrate our proposal and the benchmark. For the two MUEs and two RAUs connected to the same DAS signal processing unit, the DAS can recover the MUE transmitted symbols and forward them to the FBSs that require interference cancellation. In the case of a one-sensor node and two MUEs, one MUE can target the RAU and the other transmits directly to the MBS. The DAS can demand data from the MBS for interference cancellation as depicted in Figure 4. In the presence of more than two MUEs, we assume a time slot-based orthogonal resource allocation for the MUE transmissions as explained in Subsection 4.1. Therefore, the FBS can synchronize with the MUE scheduling. We present the results through the CDF of the capacity.

5.3 Spectral bit rate at RAU and FBSs with $|\Omega_M|$

The capacity of the MUE at the RAU or at any FBS is subject to the interference of the surrounding femtocells. Thus, we evaluate the capacity considering the transmitting femtocells, i.e., $\{X_s \in \Omega_M\}$. We present the performance of a receiver considering the presence of surrounding terminal interference and the proposed interference cancellation. In Figure 7, *NF* stands for *No Feedback*, i.e., there is no interference cancellation of the cross-tier interference. The curves with NF represent the benchmark. *WF* indicates *With Feedback*, i.e., the receiver performs interference cancellation using the feedback of the symbols of an interfering MUE. $N = i$ indicates that i FUEs are interfering at the receiver as in the situation where the FBS retrieves its FUE data with the MUE symbols feedback and the interference of the neighboring femtocells.
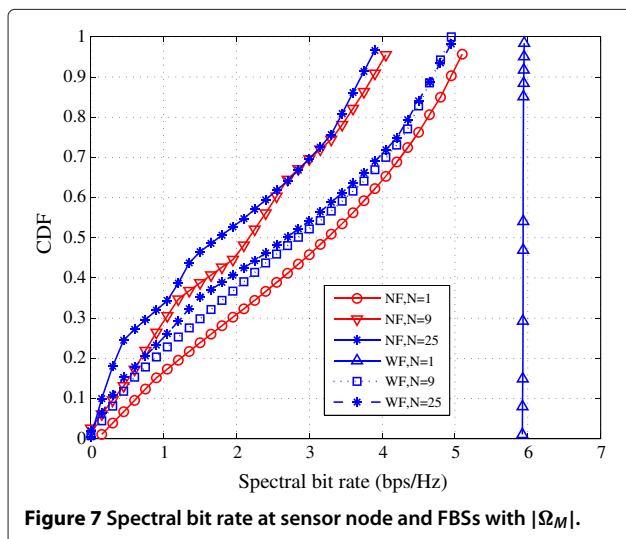
Figure 7 Spectral bit rate at sensor node and FBSs with $|\Omega_M|$.

The curves with WF represent the simulations with interference cancellation by the CPU or the FBS using feedback symbols. The spectral bit rate performance improves with the reduction of the received interference power which decreases in these simulations with the path loss and the interfering terminals are farther located from the receiver.
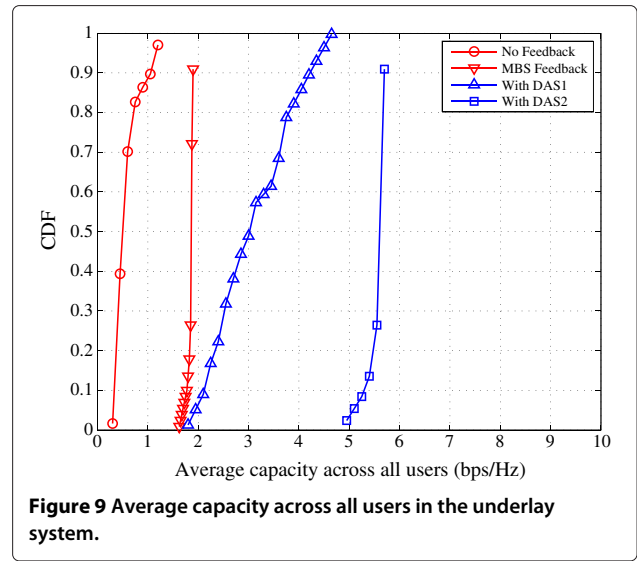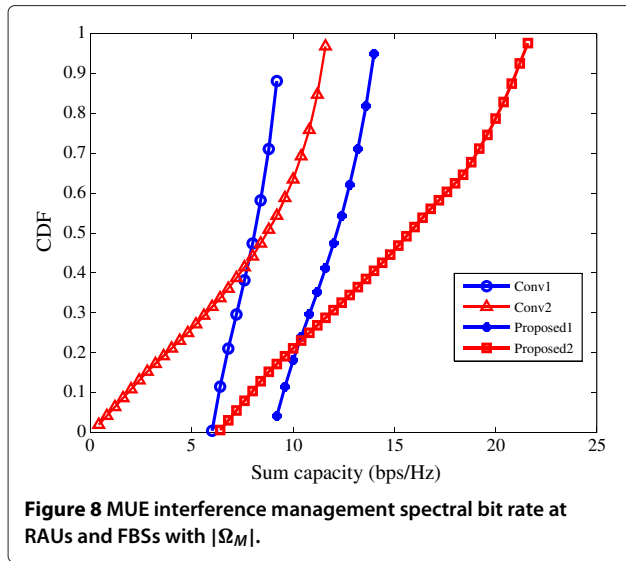
NF, $N = 1$ evaluates the situation where the desired signal of one mobile equipment is received with interference. Such cases is represented in this study by an MUE transmission received at the RAU while another MUE interference occurs at the reception. Another illustration of NF, $N=1$ is the interference of an MUE at an FBS receiving the transmission of its FUE without inter-femtocell interference. WF, $N=1$ represents the interference cancellation performance where the symbols of the single interfering terminal are fed back to the receiver. In this case, the interference is completely removed. This situation illustrates the performance of the feedback system in Figures 4 or 5.

NF, $N = 4$ and NF, $N = 25$ evaluate each the performance at the receiver when the number of interfering mobile terminals increases and without interference mitigation. WF, $N=4$ and WF, $N = 25$ are similar to NF, $N = 4$, and NF, $N = 25$, respectively; with the difference that for NF, $N = 4$ and NF, $N = 25$, the MUE interference at the FBS has its interference cancelled at the receiver whereas the interference from neighboring femtocells affects the performance. The interference mitigation effectively reduces the cross-tier interference to enhance the spectral bit rate.

5.4 Sum rate capacity by proposed radio resource allocation

We consider two MUEs and two femtocells to evaluate the sum rate capacity, as shown in Figure 2 and described in Subsections 4.1 and 4.2. The situation of FC_j and FC_k requires our proposal in 4.1 to improve the sum rate of the two MUEs (M_k and M_j) and the two femtocells (F_j and F_k). We evaluate the CDF of the sum rate capacity resulting from the performance of the MUEs at the RAUs and the corresponding $|\Omega_c|$ femtocells for the situation presented by FC_j and FC_k, as described in Subsections 4.1 and 4.2. conv1 and proposed1 represent the performance of the conventional and proposed systems, respectively, as described in Table 1 and Subsection 4.1. conv2 and proposed2 represent the transmission without the proposed orthogonal radio resource allocation, i.e., MUE simultaneous transmissions presented in Subsection 4.2. In conv2, FC_k experiences interference from the two MUEs whereas in proposed2, it receives feedback from M_k.

In Figure 8, the intersections of conv1 with conv2 and proposed1 with proposed2 occur because of the

Figure 8 MUE interference management spectral bit rate at RAUs and FBSs with $|\Omega_M|$.

Figure 9 Average capacity across all users in the underlay system.

power decay with the distance adopted for each interfering terminal, i.e., as the interfering terminal moves away from the receiving terminal, the interference effect decreases. The proposed resource allocation enhances the DAS femtocell clustering interference mitigation to reduce the combined interference in order to lower the outage probability at the RAU. With the increase in N due to the number of terminals that experience high interference mitigated by feedback, the joint interference cancellation and DAS femtocell clustering yields significant sum rate improvement compared with the conventional system.

5.5 Average capacity across all users in two-tier network
This section shows the effect of inserting the DAS in the two-tier network. The performance metric used in the simulations is the average capacity across all users in the underlay system. The sum rate capacity of the two-tier network can be rewritten as:

$$C_f = \sum_{i=1}^{N_1} \log_2(1 + \text{SINR}_i) + \sum_{j=1}^{N_2} \log_2(1 + \text{SINR}_j), \quad (11)$$

where SINR_i is the average SINR for each femtocell in the DAS clustering, SINR_j is the SINR of an interfering MUE on the femtocells. Equation 11 is an expansion of Equation 10. The benchmark is the conventional system described in Subsection 5.3. We have $N_i \in \{4, 14, 25\}$. We use all the permutations of $\{4, 14, 25\}$ to evaluate Equation 11 with the permutations of the SINR_js. In the Figure 9 simulations, $N_1 = N_2 = 3$. Each element of $\{4, 14, 25\}$ is a number of femtocells clustered by the DAS selection described in Section 3.

Figure 9 shows the CDFs of the average capacity across all users in different scenarios. The average capacity across all users is defined by:

$$C_u = \frac{C_f}{N_1 + N_2}. \quad (12)$$

Without the insertion of the DAS, and $N_2 > 1$, we assume that the radio resource management (by the MBS) assigns orthogonal resource blocks for the MUESs because of their direct transmission to the MBS by default. Thus, there is MUE interference avoidance from the MUEs to the MBS. Each femtocell cluster experiences the interference from one or two MUEs. No Feedback and MBS Feedback represent each the conventional system without the DAS. With No Feedback, each femtocell experiences an MUE interference without interference mitigation. MBS Feedback considers a feedback from the MBS; each cluster which experiences an MUE interference can receive a feedback from the MBS for interference cancellation. However, the feedback is subject to the orthogonal resource allocation applied for the MUEs directly transmitting to the MBS. Because of the MUE transmission scheduling (we assume different time slot allocations in the simulations), the sum rate decreases with N_2. DAS1 and DAS2 represent our proposed modification of the two-tier network with the DAS insertion. With DAS1, the MUEs transmit to their respective RAUs. Thus, there is a simultaneous transmission of the MUEs; besides, the DAS can feedback the symbols of each interfering MUE to the femtocells which experience the interference. DAS2 is similar to DAS1 except that in DAS2, the interference cancellation removes all the cross-tier interference.

With DAS1, more than 90% of all users get each an average capacity of 2 bps/Hz, whereas with the MBS Feedback,

almost all users get each less than 2 bps/Hz. The performance gap obtained by the insertion of the DAS can be interpreted as the traffic unmanageable by the MBS without the DAS.

A synchronization of the transmitting terminals is required in order to achieve our proposed interference cancellation scheme. The FBS and sensor node can adopt the macrocell synchronization by listening to the closest MUE signaling with the MBS. We propose the use of the convex combination algorithm in [20] to update the FBS timing to their nearest neighbors in the wireless interface. Additionally, we propose to feedback the synchronization signaling to the cluster of femtocells from the CPU as the CPU is directly connected to the femtocell cluster without intermediate node.

6 Conclusion

We have presented a novel femtocell clustering in a multi-tier network which was made possible using a proposed HetNet consisting of a DAS on the macrocell and femtocell tiers. We proposed the use of DAS as an interface between the two tiers to manage the cross-tier interference. Consequently, the network cross-tier interference was effectively mitigated, and the sum rate capacity has improved substantially because the DAS femtocell clustering linearly scaled the capacity in proportion of the proposed femtocell clustering and its cardinality. The introduction of a DAS within the macrocell overlaid with the femtocells improved the cross-tier interference management and can be used as a benchmark for future HetNet.

Abbreviations

AWGN, additive white Gaussian noise; DAS, Distributed antenna system; FC, femtocell clustering; HetNets, heterogeneous networks; LTE, long-term evolution; MMSE, minimum mean square error; MUE, macrocell user equipment; OFDM, orthogonal frequency division multiplexing; QPSK, quadrature phase shift keying; RAU, remote antenna unit; RF, radiofrequency; RLS, recursive least square; SINR, signal-to-interference-plus-noise ratio.

Competing interests

The authors declare that they have no competing interests.

References

1. A Ozgur, O Leveque, D Tse, Hierarchical cooperation achieves linear capacity scaling in ad hoc networks, in *IEEE International Conference on Computer Communications (INFOCOM),)* Anchorage (IEEE, New York, 2007), pp. 382–390
2. R Etkin, A Parekh, D Tse, Spectrum sharing for unlicensed bands. IEEE J. Selected Topics Commun. **25**, 517–528 (2007)
3. V Chandrasekhar, M Kountouris, JG Andrews, Coverage in multi-antenna two-tier networks. IEEE Trans. Wireless Commun. **8**, 4316–4328 (2009)
4. H Claussen, LTW Ho, LG Samuel, An overview of femtocell concept. Bell Labs Tech. J. **13**, 221–245 (2008). doi: 10.1002/bltj.20292
5. Y Li, A Maeder, L Fan, A Nigam, J Chou, Overview of femtocell support in advanced WiMAX systems. IEEE Commun. Mag. **49**, 122–130 (2011)
6. JG Andrews, H Claussen, M Dohler, S Rangan, M Reed, Femtocells: past, present, and future. Selected Areas Commun. IEEE J. **30**(3), 497–508 (2012)
7. W Choi, JG Andrews, Downlink performance and capacity of distributed antenna systems in a multicell environment. IEEE Trans Wireless Commun. **6**, 69–73 (2007)
8. Y Kon, M Ito, N Hassel, M Hasegawa, K Ishizu, H Harada, Autonomous parameter optimization of a heterogeneous wireless network aggregation system using machine learning algorithms, in *Consumer Communications and Networking Conference (CCNC),* Las Vegas (IEEE, New York, 2012), pp. 894–898
9. D Castanheira, A Gameiro, Distributed antenna system capacity scaling [coordinated and distributed MIMO]. IEEE Wireless Commun. **17**, 68–75 (2010)
10. RQ Hu, Y Qian, S Kota, G Giambene, Hetnets - a new paradigm for increasing cellular capacity and coverage. IEEE Trans Wireless Commun. **18**, 8–9 (2011)
11. H Li, J Hajipour, A Attar, VCM Leung, Efficient HetNet implementation using broadband wireless access with fiber-connected massively distributed antennas architecture. IEEE Trans. Wireless Commun. **18**, 72–78 (2011)
12. Y Peng, F Qin, Exploring Het-Net in, LTE-advanced system: interference mitigation and performance improvement in macro-pico scenario, in *Proceedings of the IEEE International Conference on Communications Workshops (ICC),* Kyoto (IEEE, New York, 2011)
13. T Alade, Z Huiling, Joint signal processing in femtocell based distributed antenna systems in high buildings, in *Proceedings of the IEEE 72nd Vehicular Technology Conference Fall,* Ottawa (IEEE, New York, 2010)
14. K Balachandran, JH Kang, K Karakayali, KM Rege, NICE: a network interference cancellation engine for opportunistic uplink cooperation in wireless networks. IEEE Trans. Wireless Commun. **10**, 540–549 (2011)
15. T Alade, H Zhu, H Osman, Spectral efficiency analysis of distributed antenna system for in-building wireless communication, in *2011 IEEE 22nd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC),* San Francisco (IEEE, New York, 2011), pp. 2075–2079
16. M Ndong, T Fujii, Cross-tier interference mitigation for self organized-self optimized femtocells, in *Wireless Telecommunications Symposium,* London (IEEE, New York, 2012)
17. M Vu, N Devroye, T Vahid, On the primary exclusive region of cognitive networks. IEEE Trans. Wireless Commun. **6**, 3380–3385 (2009)
18. A Goldsmith, Performance of digital modulation over wireless channels, in *Wireless communications, 1st edition* (university press, New York, USA, Cambridge, 2005), pp. 187–197
19. JG Andrews, A Ghosh, R Muhamed, Orthogonal frequency division multiple access, in *Fundamentals of WiMAX understanding broadband wireless networking, 1st edition.* Edited by Rappaport TS (Prentice Hall, Massachusetts, 2007), pp. 210–211
20. S Lien, H Lee, S Shih, P Chen, K Chen, Network synchronization among femtocells, in *the second GLOBECOM workshop on femtocell networks,* Houston (IEEE, New York, 2011), pp. 248–252