HETNETS: A NEW PARADIGM FOR
INCREASING CELLULAR CAPACITY AND COVERAGE

ON EXPLOITING COGNITIVE RADIO TO MITIGATE INTERFERENCE IN MACRO/FEMTO HETEROGENEOUS NETWORKS

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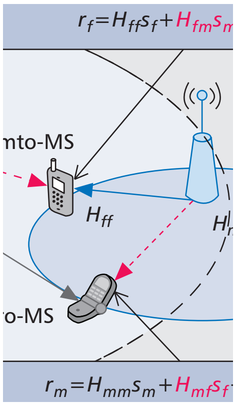

We therefore study possible interference mitigation approaches, including orthogonal radio resource assignment in time-frequency and antenna spatial domains, as well as interference cancellation via novel decoding techniques.

ABSTRACT

To successfully deploy femtocells underlaying the macrocell as a heterogeneous network, which has been proven to greatly improve indoor coverage and system capacity, the cross-tier interference among the macrocell and femtocells as well as the intratier interference among femtocells must be mitigated. However, some unique features present a challenge in interference mitigation in a two-tier heterogeneous network such as random deployment for femtocells, nonexistence of macro-femto backhaul coordination, and mandates allowing no modifications of existing macrocells. Carefully examining the existing distributed information acquisition mechanisms, cognitive radio is the most promising solution for two-tier heterogeneous networks. We therefore study possible interference mitigation approaches, including orthogonal radio resource assignment in the time-frequency and antenna spatial domains, as well as interference cancellation via novel decoding techniques. According to the information acquired by cognitive radio technology, recent innovations such as game theory and the Gibbs sampler have been explored to mitigate both cross-tier and intratier interferences. Performance evaluations show that considerable performance improvement can be generally achieved, and thus demonstrate the potential of applying cognitive radio in mitigating interference.

INTRODUCTION

In order to meet the increasing demands on wireless mobile networks to support data applications with higher throughputs, orthogonal frequency-division multiple access (OFDMA)-based fourth-generation (4G) Long Term Evolution (LTE)-Advanced networks are being developed. In OFDMA, the spectrum is orthogonally divided into time-frequency resource blocks (RBs), which increases flexibility in resource allocation, thereby allowing high spectral efficiency. Exploiting all RBs simultaneously to achieve so-called *universal frequency reuse* becomes a key objective toward deployment of 4G networks.

Heterogeneous network (HetNet) deployment [1, 2] where low-power and small-coverage local nodes are distributed in the coverage of a macro node, is considered as a promising solution. Local nodes such as pico, femto, and relay nodes deployed at coverage holes could extend coverage and increase spectral utilization. Moreover, the small coverage area of a local node facilitates large numbers of concurrent transmissions and improves spatial reuse, therefore potentially yielding enhanced wireless capacity. When all heterogeneous nodes share the same spectrum, two kinds of interference appear:

- **Cross-tier interference**: The aggressor (e.g., a local node) and the victim of interference (e.g., a macro node user) belong to different tiers.
- **Intratier interference**: The aggressor (e.g., a local node) and the victim (e.g., a neighboring local node) belong to the same tier.

Under the impact of interference, some RBs cannot be utilized simultaneously, which challenges HetNet toward universal frequency reuse. Thus, interference mitigation techniques are receiving much attention in both academia and industry, and generally are classified into the following two categories [3]:

- **Interference coordination**: It ensures orthogonality between mutual interfering transmitted signals in the following domains:
  - –Time-frequency: In an OFDMA system, it simply allocates resource at the different RBs.
  - –Location/space: By controlling the transmission power according to the distance to the victim, the aggressor can avoid causing harmful interference to the victim.
  - –Antenna spatiality: Transmissions via uncorrelated spatial paths in multiple-input multiple-output (MIMO) would not disturb each other.

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- **Interference cancellation**: If orthogonality cannot be achieved, coding techniques such as sphere decoding or dirty paper coding (DPC) can be exploited to allow a victim to actively cancel interfering signals from the desired signal.

In this article, one kind of local node deployed at home, known as the femtocell, is investigated due to its attractive benefits for both subscribers and operators. As shown in Fig. 1, each femtocell is composed of a base station (femto-BS) and multiple mobile stations (femto-MSs). The underlaying macrocell is composed of a BS (macro-BS) and multiple MSs (macro-MSs). By deploying femto-BSs, operators can reduce the cost to deploy macro-BSs since traffic loads transfer to femto-BSs. More important, the indoor femto-MSs can enjoy high transmission quality due to the short distance from a femto-BS, and the number of concurrent transmissions that can be accommodated in the network can be increased, therefore yielding enhanced coverage and capacity. Such a macro/femto network is regarded as a two-tier network where the femtocell plays the role of the lower tier that compensates and facilitates the transmission of the higher macrocell tier. According to the deployed location, there are two types of femtocells, standalone and collocated. A standalone femtocell is located far from other femtocells. According to signal attenuation models defined by LTE-Advanced [1, 4], a standalone femtocell only needs to mitigate cross-tier interference from the overlaying macrocell. On the other hand, the coverage of a collocated femtocell overlaps with that of other collocated femtocells. Therefore, a collocated femtocell needs to mitigate both intratier and cross-tier interferences.

However, interference mitigation in such two-tier heterogeneous networks faces practical challenges from the following aspects [5]:

- Random deployment: Since femto-BSs are installed and deployed by users without network planning, they can appear anywhere and act as aggressors.
- Restricted/closed access: Since femto-BSs are paid for by the customers, it is reasonable that only users defined by the owners are allowed to access the femto-BSs. In this case, unauthorized users could only connect to a macro-BS even if a femto-BS exists in the vicinity; thus, users suffer heavy cross-tier interference.
- No coordination between macro-BS and femto-BS: The delay of connection via wired backhaul is too long to admit any cooperation [4], which means that centralized interference mitigation approaches are not feasible.
- Backward compatibility: The legacy macro-MS and macro-BS must be supported for market penetration. Thus, any additional operation on the MS side or the current macrocell protocol is not suggested.

By enabling cognitive radio (CR) technology [6] on femto-BSs to be aware of and adapt to communication environments, the above challenges can be tackled. The macro-BS and CR-enabled femto-BS are analogous to primary and secondary users in the CR model, respectively. With CR capability, a femto-BS could actively acquire knowledge about its environment without the aid of a macrocell in a decentralized fashion and automatically prevent disturbing macro or surrounding femto transmissions.

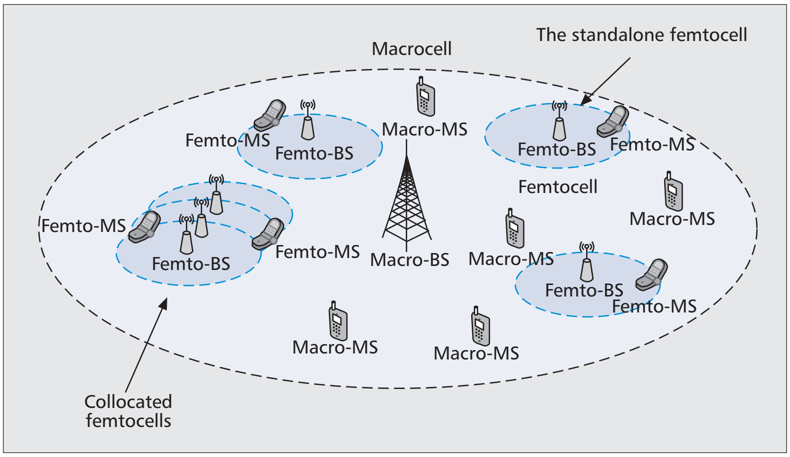

Figure 1. *Network model of the considered two-tier network.*

The aim of this article is to provide an overview of how CR facilitates interference mitigation in two-tier HetNets. A comprehensive comparison of interference mitigation approaches with respect to the requirement of leveraged information is introduced. We also carefully examine the existing information acquisition mechanisms and identify the effects of CR on interference mitigation. We then study possible CR-enabled cross-tier interference mitigation approaches including orthogonal radio resource assignment in the time-frequency and antenna spatial domains, as well as cross-tier interference cancellation via novel decoding techniques. By exploiting information acquired by CR, recent innovations such as game theory and the Gibbs sampler are explored to mitigate intratier interference among femto-BSs. We conduct simulation experiments to evaluate the performance improvement of proposed schemes on interference mitigation. Finally, we conclude this work.

INFORMATION REQUIREMENTS AND ACQUISITION FOR INTERFERENCE MITIGATION

To respectively mitigate cross- and intratier interferences, a femto-BS shall acquire *side information* about the macrocell and surrounding femtocells. The problems that arise regard how much information is required and how to acquire that information. Answering these questions, the role of information in interference mitigation is identified conceptually. The information of other network nodes leveraged by a femto-BS for interference mitigation can be classified as:

- Activity
- Channel condition
- Codebooks
- Messages [6]

If a femto-BS is aware of spectrum activity, it could simply avoid allocating the same RB occupied by a macro-BS, which achieves orthogonality in the time-frequency domain. While the

Orthogonality in time-frequency and antenna spatial domains can be achieved with activity and channel condition information acquired by CR. When codebooks and messages information are further retrieved, cancellation approach can be exploited.

Information required			Type			
Interference mitigation techniques			**Activity**	**Channel condition**	**Codebook**	**Message**
Coordination	Domain of orthogonality	Time-frequency	o			
		Space/location		o		
		Antenna spatiality		o		
Cancellation	Coding techniques			o	o	o

Table 1. *Information requirements for interference mitigation approaches.*

channel condition is known, a femto-BS could adjust its transmission power to ensure that the receiving signals at other nodes' receivers remain below the constraint. Thus, concurrent femto-BS and other node transmissions may occur, which implies that they are orthogonal in the space domain. Alternatively, we could utilize multiple antennas to guide the femto-BS signals away from the other nodes' receivers. Knowledge of other nodes' messages and/or codebooks can be exploited to cancel interference seen at the femto-MS by using coding techniques. We summarize the information required for each kind of interference mitigation approach in Table 1.

In current distributed interference coordination solutions, how to retrieve information for interference mitigation plays a key role in obtaining the performance gains. Typically, the following mechanisms are applied.

Exchanging information among BSs: In this case, the femto-BSs and macro-BS directly exchange information about their allocation usage (e.g., activity), connection behavior (e.g., channel conditions), as well as resource demands (e.g., codebooks or messages). By being aware of the present actions and future intentions of the macro-BS and surrounding femto-BSs, perfect interference mitigation can be achieved. Obviously, common control channel and message exchange procedures shall exist among BSs, typically performed via wired backhaul, which is infeasible due to the constraint of no macro-femto coordination [4]. Moreover, the heavy communication overheads make this mechanism inefficient in dense femtocell deployments.

Receiving measurement reports from femto-MSs: In this case, the femto-MS periodically performs measurements and feeds back reports to its serving femto-BS. By analyzing the report, the femto-BS can acquire activity and channel condition on the immediate environment of each femto-MS, which facilitates interference mitigation. However, performing measurements may consume a lot of power, and may not be feasible for femto-MSs that are typically power limited. Moreover, imposing new operation on the MS side may incur backward incompatibility.

Building CR into femto-BS itself: By adopting traditional spectrum sensing techniques, the detection of the macro-BS and surrounding femto-BS signals can be achieved without any coordination. For example, if the received interference power of an RB exceeds a certain threshold, the femto-BS identifies that the RB is occupied and retrieves activity [7]. Thus, CR-enabled femto-BSs could automatically configure themselves and mitigate both tiers' interferences.

Orthogonality in the time-frequency and antenna spatial domains can be achieved with activity and channel condition information acquired by CR. When codebooks and message information are further retrieved, the cancellation approach can be exploited. Below we discuss possible CR-enabled interference mitigation approaches in detail.

CROSS-TIER INTERFERENCE MITIGATION

This section elaborates on the various cross-tier interference mitigation approaches based on the information acquired by CR.

INTERFERENCE COORDINATION: ORTHOGONALITY IN TIME/FREQUENCY DOMAIN

With activity of the macrocell that indicates which RB is occupied in a frame, each femto-BS prevents allocating these occupied RBs to its femto-MSs. An instinctive approach is proposed at the femto-BS in our previous work [7].

Cognitive Resource Block Management

1. The femto-BS periodically senses the channel to identify which RB is occupied by the macrocell. The sensing period is T_s frames, and each channel sensing persists for one frame. Among the T_s frames, one frame is defined as the *sensing frame* where the femto-BS performs channel sensing. The remaining $T_s - 1$ frames are regarded as the *data frame* for data transmission and reception. Note that the femto-BS can not perform data transmissions and receptions within the sensing frame. We assume that all femtocells are synchronized and have the same frame as the sensing frame.
2. The femto-BS senses the received interference power on each RB within the sensing frame.
   –If the received interference power on an RB exceeds a certain threshold, the RB is identified as being occupied by the macrocell since all femtocells sense at the same time.
   –Otherwise, the RB is unoccupied by the macrocell.
3. In subsequent data frames, the femto-BS only allocates unoccupied RBs sensed in the

sensing frame to its femto-MSs. Please note that the unoccupied RBs may be allocated by collocated femto-BSs at the same time, which incurs heavy intratier interference. We could apply game strategy or the Gibbs sampler, shown later, to mitigate intratier interference.

The received interference power was adopted by Third Generation Partnership Project (3GPP) LTE-Advanced as a mandatory sensing quantity in BSs [8]. Therefore, cognitive resource block management (CRBM) can be applied to LTE-Advanced without any hardware modifications. In addition, the received interference power can be in downlink or uplink, for the femtocell to mitigate interference from the macro-BS to the femto-MS in the downlink case and interference from the macro-MS located within the coverage of the femtocell to the femto-BS in the uplink case.

INTERFERENCE COORDINATION: ORTHOGONALITY IN THE ANTENNA SPATIALITY DOMAIN

If MIMO is supported in the network, we could uncorrelate the MIMO paths between each transmitter-receiver pair, and let macro and femto transmissions happen on different spatial paths. As shown in Fig. 2, the transmitted signal vectors of femto-BS and macro-BS are denoted $\boldsymbol{s}_f \in R^i$ and $\boldsymbol{s}_m \in R^j$, respectively, where i and j are the antenna numbers of the femto-BS and macro-BS, respectively. The $\mathbf{H}_{ff} \in R^{k\times i}$, $\mathbf{H}_{mf} \in R^{k\times i}$, $\mathbf{H}_{fm} \in R^{k\times j}$, and $\mathbf{H}_{mm} \in R^{k\times j}$ are channel matrixes from femto-BS to femto-MS, from femto-BS to macro-MS, from macro-BS to femto-MS, and from macro-BS to macro-MS, respectively, where k is antenna number of an MS. The received signal vectors at femto-MS and macro-MS can be represented as $\boldsymbol{r}_f = \mathbf{H}_{ff}\boldsymbol{s}_f + \mathbf{H}_{fm}\boldsymbol{s}_m + \boldsymbol{n}_f$ and $\boldsymbol{r}_m = \mathbf{H}_{mm}\boldsymbol{s}_m + \mathbf{H}_{mf}\boldsymbol{s}_f + \boldsymbol{n}_m$, respectively, where $\boldsymbol{n}_f \in R^k$ and $\boldsymbol{n}_m \in R^k$ are noise vectors. Thus, for the received vector $\boldsymbol{r}_f$ at a femto-MS ($\boldsymbol{r}_m$ at macro-MS), the $\mathbf{H}_{fm}\boldsymbol{s}_m$ ($\mathbf{H}_{mf}\boldsymbol{s}_f$) is regarded as the cross-tier interference from the macro-BS (femto-MS).

We demonstrate that both the macro-MS and femto-MS can detect the desired signal without cross-tier interference by spatial path separation in the following example. Assume that $i = j = k = 2$, the data vectors of the femto-BS and macro-BS are set as

$$\boldsymbol{s}_f = \begin{bmatrix} \alpha \\ 0 \end{bmatrix} \text{ and } \boldsymbol{s}_m = \begin{bmatrix} 0 \\ \beta \end{bmatrix},$$

respectively, which means that the femto-BS and macro-BS load their data symbols on uncorrelated spatial paths. This way, the received signal vector at the macro-MS can be represented as

$$\boldsymbol{r}_m = \mathbf{H}_{mm}\begin{bmatrix} 0 \\ \beta \end{bmatrix} + \begin{bmatrix} \alpha \\ 0 \end{bmatrix} + \boldsymbol{n}_m.$$

If $\mathbf{H}_{mf}$ can be estimated by the macro-MS, it multiplies the inverse matrix of $\mathbf{H}_{mf}$ with $\boldsymbol{r}_m$ so that the cross-tier interference on the first spatial path is eliminated; thus, signal α is detected. In a similar approach, the desired signal β at the femto-MS can also be extracted on the second spatial path without cross-tier interference. To guarantee that the transmissions of a macro-BS and femto-BSs are separated into different spatial paths, all femtocells need to select the same spatial channel. Since backhaul coordination among femtocells may not practically be possible, a distributed selection approach is more appropriate.

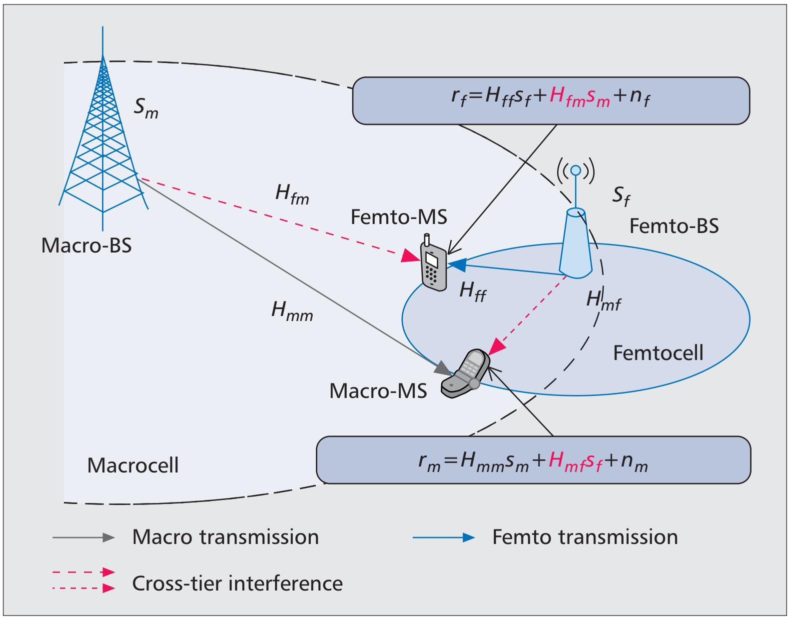

Figure 2. *Signal representation of macro-BS, femto-BS, and MS.*

We model the femto-tier network as an undirected graph, where nodes correspond to femto-BSs, and two femto-BSs are neighbors if they are collocated femtocells. Each femto-BS utilizes a spatial path. Based on such a model, the Gibbs sampler originated from statistical physics [9] provides a distributed procedure for each node to achieve the minimum of the global energy function by utilizing a local energy function. In our scenario, the global energy function is defined as the minus sum of interference in the entire network, while the local energy function is defined as the interference measured at each femto-BS on each spatial path. We would like to maximize the interference to let every femto-BS select the same spatial path. After measuring interference on each spatial path, each femto-BS calculates a set of probabilities for each spatial path, denoting the probability of inducing interference to other BSs if selecting this path. The calculation relates to a temperature parameter T, which is a logarithmically decreasing function of time t. With such a definition of T, the spatial channel with high interference will be chosen with higher probability, the total interference would converge to maximum, and thus every femto-BS would finally select the same path. In the following, we summarize several critical steps in our approach.

Gibbs-Sampler-Based Spatial Path Selection

1. Compute the temperature parameter

$$T = \frac{C}{\log_2(2+t)},$$

where C is a constant.

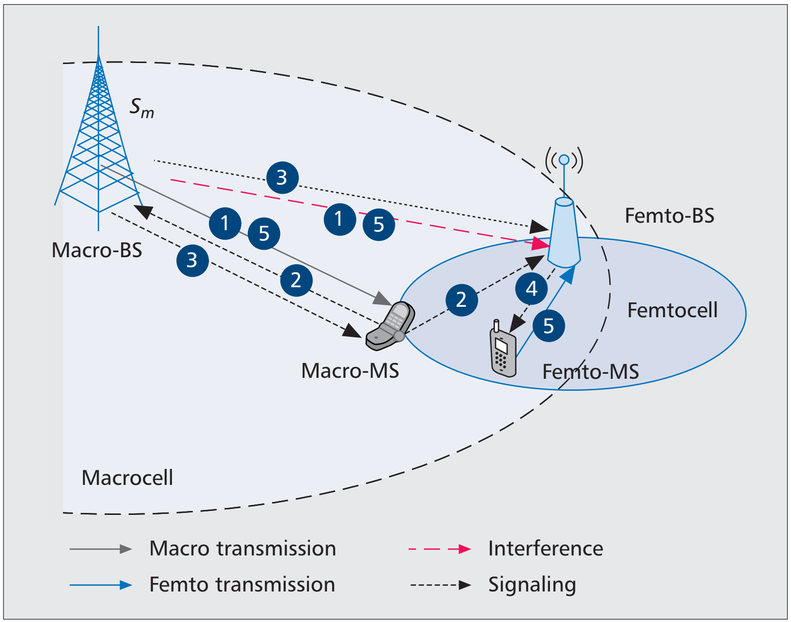

Figure 3. *Procedure of interference cancellation.*

2. Compute local energy for each spatial path.
3. For every spatial path, compute probability of interference by local energy according to Gibbs distribution with temperature T.
4. Sample a spatial path randomly by the interference probability.

INTERFERENCE CANCELLATION: CODING TECHNIQUES

If a femto-BS could acquire more information such as message and codebooks at the macro-BS, interference to femto transmission from the macro-BS could be mitigated by applying some precoding or decoding techniques even if orthogonality is not achieved. Such information can be used at the transmitter side of femto transmission to completely cancel the interference from the macro-BS by performing a precoding technique such as DPC. Here we focus on the alternative approach where interference is subtracted at the receiver side of femto transmission by using decoding techniques and leveraging the opportunity that arises during macro retransmission [10]. Specifically, a femto-BS listens and successfully decodes a macro packet in the initial transmission so that during the retransmissions it can eliminate the interference caused by the macro-BS.

The successful reception of a macro transmission at a macro-MS depends on whether the received signal-to-interference-plus-noise ratio (SINR) is higher than a predefined SINR threshold. In an infrastructure HetNet, the (re)transmissions or (re)receptions of macro and femto packets are centrally scheduled by the macro-BS and femto-BS, respectively, and then informed the scheduling results to each MS. With CR, a femto-BS could actively acquire scheduling results and acknowledgment (ACK)/negative ACK (NAK) feedback information from a macrocell to determine the retransmission periods of the macro packet for concurrent transmission. By summarizing the above results, we propose a novel interference cancellation mechanism in a two-tier network, where the corresponding procedures are illustrated in Fig. 3 and described as follows.

Cognitive Interference Cancellation for Retransmission

1. The CR-enabled femto-BS actively senses when a macro-BS transmits packets to a macro-MS to obtain prior knowledge about the interference (i.e., $x_m^{(t)}$).
2. The CR-enabled femto-BS overhears the feedback ACK/NAK sent by the macro-MS.
   –If it receives an ACK message, the femto-BS discards the knowledge $x_m^{(t)}$ and jumps to step 1.
   –Otherwise, the femto-BS keeps $x_m^{(t)}$.
3. The macro-BS then schedules the failed-decoded packet for retransmission, determines the transmission slot $t + \Delta t$, and informs the scheduling results to the macro-MS, which is also sensed by the femto-BS.
4. The femto-BS utilizes the overheard knowledge to determine the retransmission slot of the macro packet (i.e., $t + \Delta t$), schedules the same slot for femto packet reception, and informs the femto-MS as the transmitter at $t + \Delta t$.
5. During the retransmission slot of the macro packet, the femto-MS uploads a packet to the femto-BS. The femto-BS utilizes the prior information $x_m^{(t)}$ to cancel the interference from the macro-BS $x_m^{(t+\Delta t)} = x_m^{(t)}$ and thus extracts $x_f^{(t+\Delta t)}$ destined to itself.

Since this mechanism exploits the opportunity that arises during macro retransmission, the proportion of its operating time mainly depends on the factors affecting the quality of signal received at the macro-MS (e.g., interference, fast fading, and shadowing). In the two-tier network with unreliable wireless channel and heavy interference, more capacity gain is obtained by this mechanism.

INTRA-TIER INTERFERENCE MITIGATION

After identifying a set of available radio resources orthogonal to that of the macrocell (in time-frequency or antenna spatial domain), the subsequent challenge is that multiple femto-BSs may identify the same set of available RBs, especially when these femto-BSs are located close to each other (known as collocated femto-BSs). In this case, without an effective scheme to share these available radio resources, collocated femto-BSs may suffer heavy intratier interference. In this section, we consequently propose two schemes enabling autonomous coordination of available RBs among collocated femto-BSs.

INTERFERENCE COORDINATION: STRATEGIC GAME FOR COLLOCATED FEMTOCELLS

Since backhaul coordination among femto-BSs for information exchange may not practically be possible in 3GPP LTE-Advanced [4], an instinctive solution for each collocated femto-BS is to randomize RB utilization among the set of available RBs [11]. That is, if there are K_c collocated femtocells and M_a available RBs identified, and each collocated femto-BS utilizes $\lfloor M_a/K_c \rfloor$ available RBs, each collocated femto-BS randomizes the utilization of these $\lfloor M_a/K_c \rfloor$ available RBs. This solution is referred as *equal division*. However, equal division may not be effective when each collocated femtocell has diverse demands.

To determine the maximum number of available RBs that can be utilized by each collocated femto-BS in a distributed way for practical operation, game theory is well suited to be employed as the foundation to facilitate our ultimate goal. Since it is not feasible to distinguish priority among collocated femto-BSs, no collocated femto-BS can make a decision prior to other collocated femto-BS, which motivates adoption of the strategic game (i.e., the one-shot game [12]). Consequently, a strategic game can be formed to find the maximum number of RBs that can be utilized by each collocated femto-BS such that the total number of RBs utilized by all collocated femto-BSs without interference is optimized. In the following, we consequently propose strategic game-based resource block management (SGRBM) for autonomous intratier interference mitigation among collocated femtocells, which replaces step 3 of CRBM, while other steps in CRBM still need to be performed by collocated femto-BSs.

Strategic Game-Based Resource Block Management

1. Each collocated femto-BS finds the corresponding optimum strategy profile according to the developed strategic game, by which each collocated femto-BS can obtain the optimum number of unoccupied RBs (denoted L) available to be allocated to its femto-MSs.
2. In each data frame, each collocated femto-BS can allocate l unoccupied RBs ($l \leq L$) to its femto-MSs, according to the actual demand.
3. These l unoccupied RBs are allocated in a randomized manner.

This scheme achieves better performance than that of equal division, since the optimum decision is autonomously made in each collocated femto-BS by considering all possible decisions that may be made by other collocated femto-BSs. In addition, rather than being calculated online in each collocated femto-BS, the optimal solution can be calculated offline by table lookup as long as the total number of available RBs and the number of collocated femto-BSs are known. With the aid of CR, these two parameters can be acquired at femto-BSs.

INTERFERENCE COORDINATION: GIBBS SAMPLER FOR COLLOCATED FEMTOCELLS

Rather than choose the same spatial path mentioned earlier, here we adopt the Gibbs sampler to achieve orthogonal RB allocation among collocated femto-BSs. With the Gibbs sampler over the graph, the selection of RB by a femto-BS is interpreted as the state of a node, and intratier interference received at a femto-BS from collocated femtocells is regarded as the local energy. The global energy is defined as the total interference all femto-BSs experience from all other femto-BSs, and $p(s)$ denotes the probability that an RB is to be selected. From the mathematical foundation of the Gibbs sampler, we can achieve the minimum global energy function by exploiting the local energy function; that is, each femto-BS will finally allocate the different RBs [13] in a distributed way.

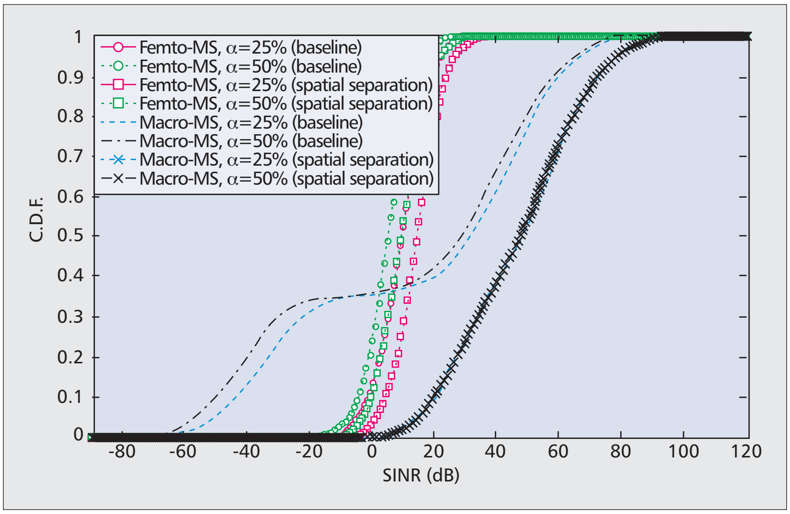

Figure 4. *SINR of macro-MS and femto-MS when 35 percent macro-MS are inside apartment blocks.*

In the following, we consequently propose Gibbs sampler-based resource block management (GSRBM) for intratier interference mitigation among collocated femtocells, which replaces step 3 of CRBM, while other steps in CRBM still need to be performed by collocated femto-BSs.

Gibbs Sampler-Based Resource Block Management

1. Each collocated femto-BS computes the temperature parameter:

$$T = \frac{C}{\log_2(2+t)}.$$

2. Each femto-BS computes local energy for each unoccupied RB.
3. For every RB, compute $p(s)$ according to Gibbs distribution with temperature T.
4. Sample a random variable over all RBs by $p(s)$.

PERFORMANCE EVALUATIONS

We conduct simulation experiments based on Matlab software according to the 3GPP dual-strip model [1]. It includes one macrocell with three sectors and each sector embraces one apartment block. There is one floor in every apartment block, which consists of two strips and total 40 apartments. In each apartment, one femto-BS exists for serving users. The transmission powers of macro-BS and femto-BS are set as 46 dBm and 20 dBm, respectively, and the number of antennas at macro-BS, femto-BS, and users are 2. The setups related to path loss and shadowing are according to the 3GPP dual-strip model in [1, Table A. 2.1.1.2-8]. Please note that it is critical to practically simulate the penetration loss since the signal strength degradation due to the inner wall (the wall inside the apartment block; 5 dB) and outer wall (the wall of the apartment block; 20 dB) can effectively reduce the cross-tier and intratier interference.

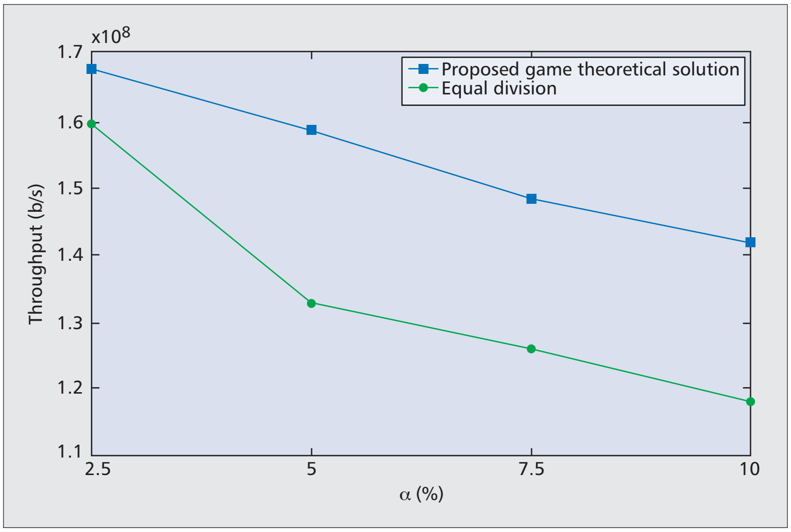

Figure 5. *Overall throughput of all collocated femtocells* (M_a *= 20 RBs).*

Figure 4 investigates the SINR of macro-MS and femto-MS with and without spatial separations to evaluate the performance of orthogonality in antenna spatiality. The *baseline* scheme means that no interference mitigation is applied, while the *spatial separation* scheme denotes the approach proposed earlier. The parameter α denotes the percentage of active femtocells in one apartment block. We observe that as α increases from 25 to 50 percent, femto-MSs suffer higher intratier interference from surrounding active femto-BSs and thus SINR of femto-MS decreases about 3 dB in baseline. For SINR of macro-MS under baseline, the curve has an S shape because the 35 percent of the macro-MSs inside the apartment block suffer more severe cross-tier interference than the other 65 percent of the macro-MSs outside the block. We also observe that the improvement by spatial separation on the SINR of macro-MSs is more significant (about 60 dB), and on the SINR of femto-MSs is slight (about 3 dB). The reason is that spatial path separation could eliminate the cross-tier interference received at macro-MSs from all femto-BSs. Regarding femto-MSs, although cross-tier interference is eliminated, the intratier interference from surrounding femtocells exploiting the same channel still exists and thus limits their performance improvement.

Regarding intratier interference mitigation, we select equal division as the benchmark and consider the following two demand patterns in femtocells:

- **Uniform**: Considering the support of variable bit rate and variable packet length traffic, the number of required RBs in a femtocell may vary in each frame. To generally capture the required RBs, the number of required RBs in each frame is uniformly distributed over 1 to M_a.
- **Burst**: To model the demand of the constant-bit-rate with a burst arrival, the ON-OFF fluid model is adopted. The means of the exponentially distributed holding times in ON and OFF states are 1 and 19 s, respectively. The numbers of required RBs in ON and OFF states are M_a and 1, respectively.

Figure 5 shows the overall throughput of all collocated femtocells (the sum of all throughput of all collocated femtocells) under different ratios of active femtocells in one apartment block, where each (active) collocated femtocell randomly chooses one of two considered demand patterns. Note that α = 2.5 percent indicates that $0.025 \times 40 = 1$ active femtocell exists in an apartment block. The results show that SGRBM outperforms equal division in more general situations.

CONCLUSION

In current two-tier heterogeneous networks, the unique features of random deployment, restricted access, no macro-femto coordination, and backward compatibility challenge interference mitigation toward effective operation. Among the existing decentralized information acquisition approaches, building cognitive radio into femtocell could tackle above challenges. This article provided an overview of the possible CR-enabled interference mitigation approaches to control cross-tier and intratier interference in OFDMA femtocell heterogeneous network. Various approaches have been investigated, including orthogonal radio resource assignment in the time-frequency and antenna spatial domains, as well as interference cancellation via novel decoding techniques. Based on the acquired information, novel techniques such as game theory and Gibbs sampler are exploited to achieve better performances, which shows the potential of applying cognitive radio. Yielding limited complexity and imposing no impact on the state-of-the-art femtocell architecture, the CR-enabled solution can be smoothly applied to 3GPP LTE-Advanced femtocells to serve urgent needs in the standardization progress.

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REFERENCES

[1] 3GPP, "E-UTRA: Further Advancements for E-UTRA Physical Layer Aspects," 3GPP TR 36.814 v9.0.0, Mar. 2010.
[2] A. Ghosh *et al.*, "LTE-Advanced: Next-Generation Wireless Broadband Technology," *IEEE Wireless Commun.*, vol. 17, no. 3, June 2010, pp. 10–22.
[3] G. Boudreau *et al.*, "Interference Coordination and Cancellation for 4G Networks," *IEEE Commun. Mag.*, vol. 47, no. 4, Apr. 2009, pp. 74–81.
[4] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access (EUTRAN); Overall description; Stage 2," 3GPP TS 36.300 v. 9.5.0, Sept. 2010.
[5] M. Yavuz *et al.*, "Interference Management and Performance Analysis of UMTS/HSPA+ Femtocells," *IEEE Commun. Mag.*, vol. 47, no. 9, Sept. 2009, pp. 102–09.
[6] A. Goldsmith *et al.*, "Breaking Spectrum Gridlock with Cognitive Radios: An Information Theoretic Perspective," *Proc. IEEE*, vol. 97, no. 5, May 2009, pp. 894–914.
[7] S.-Y. Lien *et al.*, "Cognitive Radio Resource Management for QoS Guarantees in Autonomous Femtocell Networks," *Proc. IEEE ICC 2010*, May 2010, pp. 1-6.
[8] 3GPP, "E-UTRA Physical Layer Measurements," 3GPP TS 36.214 v. 9.2.0, June 2010.
[9] S. Gemana and D. Geman, "Stochastic Relaxation, Gibbs Distributions and the Bayesian Restoration of Images," *J. Applied Statistics*, vol. 20, no. 5, June 1993, pp. 25–62.
[10] R. A. Tannious and A. Nosratinia, "Cognitive Radio

Protocols based on Exploiting Hybrid ARQ Retransmissions," *IEEE Trans. Wireless Commun.*, vol. 9, no. 9, Sept. 2010, pp. 2833–41.

[11] V. Chandrasekhar and J. G. Andrews, "Spectrum Allocation in Tiered Cellular Networks," *IEEE Trans. Commun.*, vol. 57, no. 10, Oct. 2009, pp. 3059–68.

[12] D. Fudenberg and J. Tirole, *Game Theory*, MIT Press, 1991.

[13] B. Kauffmann *et al.*, "Measurement-Based Self Organization of Interfering 802.11 Wireless Access Network," *Proc. IEEE INFOCOM '07*, May 2007, pp. 1451–59.

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