Distributed Coordination of Co-Channel Femtocells via Inter-Cell Signaling With Arbitrary Delay

Ji-Hoon Yun, *Member, IEEE*, and Kang G. Shin, *Life Fellow, IEEE*

***Abstract*—To achieve high spatial reuse of spectrum resources with limited inter-layer/cell *interference*, co-channel femtocells must be coordinated with the underlying macro- and other femtocells in using radio resources. While inter-cell signaling can coordinate femtocells by providing the status information of neighbor cells explicitly, signaling delay—which may result from a limited signaling rate to reduce the resulting overhead, network latency, etc.—and its impact on the behavior of distributed coordination has not been explored before. In this paper, we propose a new architecture for the distributed coordination of co-channel femtocells based on asynchronous inter-cell signaling, called *asynchronous coordination of co-channel femtocells* (ACoF). ACoF improves solutions iteratively; femtocells update radio resource usage based on the received information, which usually gets outdated due to delayed signaling and asynchronous update behavior. ACoF allows each femtocell to adjust its signaling rate depending on its local conditions for fine-grained cost minimization, but at the expense of higher degree of inconsistency of femtocells' knowledge. Despite such asynchrony and inconsistency, the solution yielded by ACoF is guaranteed to converge to a global optimum under a certain condition of configuration parameters, which we prove theoretically. We design the optimization method of per-cell signaling rate for both wired and over-the-air signaling. Finally, we present a joint muting and transmit power adjustment scheme designed for ACoF and evaluate its convergence behavior and performance gain.**

***Index Terms*—Femtocell, co-channel deployment, interference coordination, inter-cell signaling.**

I. Introduction

HETEROGENEOUS networks (HetNets) have emerged as a cost-effective means to enhance cellular coverage and capacity while offloading macrocells in wireless cellular networks [1]. HetNets represent cellular deployments with heterogeneous types of small cells overlaid on each macrocell. In particular, a *femtocell* is a small indoor coverage area under the control of a low-power base station (BS) which is installed on the subscriber's premise and typically connected to an operator's core network via public Internet connections, such as digital subscriber line (DSL) or cable modem. Femtocells benefit both subscribers and operators, including better service coverage and higher indoor data throughput for subscribers, macrocell offloading and indoor coverage improvement at low capital and operational costs for operators. These femtocells are usually allocated a carrier frequency overlapping with the underlying macrocells' frequency, called *co-channel deployment*, to enhance the total capacity of a cellular network via high spatial reuse of spectrum resource.

As co-channel femtocells may have coverage areas overlapping with macrocells as well as other femtocells, the radio resource usage of a femtocell may greatly affect the performance of other cells and thus inter-cell coordination becomes key to the overall network performance; femtocells need coordination with the underlying macrocells as well as between themselves such that they protect other cells' ongoing user services from the interference they and their users cause while achieving as high spatial reuse of spectrum resources as possible within each cell. To achieve such inter-cell coordination in a distributed manner, sharing the status information and exchanging control messages between cells are essential, thus necessitating inter-cell signaling; for example, the LTE and LTE-Advanced specifications define an inter-cell signaling interface, called X2, for this purpose [2].

A. Asynchrony of Inter-Cell Signaling

In the current cellular systems (e.g., LTE), cell-to-cell signaling for coordination of co-channel femtocells is enabled over *wired* networks with or without traversing intermediate core network nodes, such as a femtocell gateway. *Over-the-air* (OTA) signaling between cells can be considered as an alternative; BSs broadcast and listen to signaling messages for coordination via the air interface.

A challenge associated with femtocell coordination—which is important but has not been recognized well in the literature—is the delay of inter-cell signaling and its impact on distributed coordination. When a femtocell BS (FBS) updates its radio resource usage, its neighbor cells may not know the change of this FBS's status for a certain period of time since a signaling message conveying the change is not received immediately, which we call *asynchronous* signaling. Asynchronous signaling results from diverse causes, e.g., a cell may limit the rate of inter-cell signaling to reduce associated

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J.-H. Yun is with the Department of Electrical and Information Engineering, Seoul National University of Science and Technology, Seoul 139-743, Korea (e-mail: jhyun@seoultech.ac.kr).

K. G. Shin is with the Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, MI 48109-2121 USA (e-mail: kgshin@eecs.umich.edu).

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costs, signaling messages may experience delay in traversing networks, each cell may have a different number of neighbor cells, etc. FBSs often have a limited backhaul speed and thus the cost of frequent signaling over such a slow backhaul could be high since the link bandwidth available for user traffic may be restricted. OTA signaling also incurs considerable costs since a FBS or a user device suspends ongoing service to listen to other cells' broadcast. The asynchrony of inter-cell signaling leads to *inconsistency* of FBSs' knowledge of the true information and makes cells operate with the outdated information on others, affecting the convergence of distributed coordination. Moreover, if cells have individual signaling rates to account for their specific signaling costs, inconsistency may become worse.

B. Contributions

In this paper, we propose a new architecture for the distributed coordination of co-channel femtocells based on asynchronous signaling and resource control between cells, called **A***synchronous* **Co***ordination of* **Co***-channel* **F***emtocells* (ACoF), which is applicable to, but not restricted to, OFDMA-based cellular systems. Two main features of ACoF are (1) radio resource coordination of femtocells via asynchronous inter-cell signaling and (2) optimization of the per-cell signaling rate that accounts for accompanied cell-specific costs. The problem associated with each feature is formulated as an optimization problem, and an algorithm to solve each problem is designed to optimize system performance and guarantee convergence.

The problem of coordinating radio resources is solved by individual femtocells, and the resulting solution parameters are exchanged between femtocells via asynchronous inter-cell signaling to generate better solutions iteratively, under the constraint that macrocell users should experience a limited level of interference only from nearby femtocells. The rate of signaling is cell-specific for fine-grained minimization of signaling costs, but at the expense of more inconsistency in femtocells' knowledge. Despite such asynchrony and inconsistency, ACoF is guaranteed to converge to a global optimum, which we prove analytically. ACoF allows each femtocell to determine the control variables based on local information, requiring inter-cell signaling between neighbor cells only and thus realizing distributed coordination.

For optimization of the signaling rate, we capture the cost of either wired or OTA signaling. Since the cost may differ between cells, each femtocell adjusts its own signaling rate depending on its local condition, such as neighbor cells, connected users' locations, etc. For OTA signaling, we consider a hybrid of FBS-sniffed and user-assisted methods for listening to OTA broadcast signals and capture the activation costs (service interruption and energy consumption) of the two listening methods.

In summary, this paper makes the following contributions.

- Design of a novel architecture, called ACoF, that coordinates marco- and femto-cells via asynchronous signaling.
- Analysis of ACoF's convergence and derivation of the convergence condition in terms of each femtocell's local parameters.
- Characterization of the costs associated with wired signaling and a hybrid listening scheme for OTA signaling.
- Design of a scheme for resource coordination via inter-cell signaling.

The rest of this paper is organized as follows. Section II describes related work and Section III illustrates the behavior of femtocell coordination with asynchronous signaling. Section IV describes a system model. Section V details the framework of ACoF and an update algorithm with a convergence analysis, and Sections VI and VII describe optimization of signaling costs and a coordination scheme, respectively. Section VIII evaluates ACoF via detailed simulations, and Section IX concludes the paper.

II. Related Work

There have been numerous proposals to resolve the femtocell interference problem using various methods. Stand-alone approaches try to solve the problem without relying on inter-cell signaling. Examples include femtocell sectorization [3] and uplink attenuation [4]. An open or hybrid access strategy that allows a FBS to serve nearby macrocell users utilizing full or part of resources, thus reducing the interference they experience and generate, has also been studied extensively [5]–[7].

Some researchers exploit a macrocell's feedback based on which femtocells adjust their usage of radio resource. Vikram *et al.* [8] proposed a non-cooperative power-control architecture for both macro- and femto-cells while the maximum transmit power within femtocells is restricted according to the macrocell's feedback. Jo *et al.* [9] proposed to adjust the transmit power of femtocell users in proportion to the interference level fed back by macrocells. However, they focused on protection of a macrocell's uplink only without providing any convergence analysis. Yun and Shin [10] developed a self-organizing femtocell management architecture also using a macrocell's feedback and provided a comprehensive convergence analysis. Kang *et al.* [11] designed a game-theoretic algorithm based on a similar architecture.

There have also been recent proposals targeting OFDMA systems. A comparative study of orthogonal and co-channel deployments of OFDMA femtocells was reported in [12]. Sundaresan and Rangarajan [13] proposed femtocell management models that allocate orthogonal time-frequency resources among close cells with and without constraint relaxation. Jin and Li [14] proposed a cognitive WiMAX femtocell architecture that exploits cognitive sensing and multi-hop transmission.

Some other proposals use methods other than radio resource coordination. Lopez-Perez *et al.* [15] proposed an intra-cell inter-frequency handover approach that, when a macrocell user suffers from a nearby femtocell's interference, the serving macrocell hands the user over to a less-interfered frequency channel. A decentralized carrier frequency assignment strategy was proposed in [16] and [17]. *Range extension*, which expands the handover ranges of overlaid small cells [18], can also be considered as a possible solution to address the interference problem. An algorithm of joint range adaptation and resource

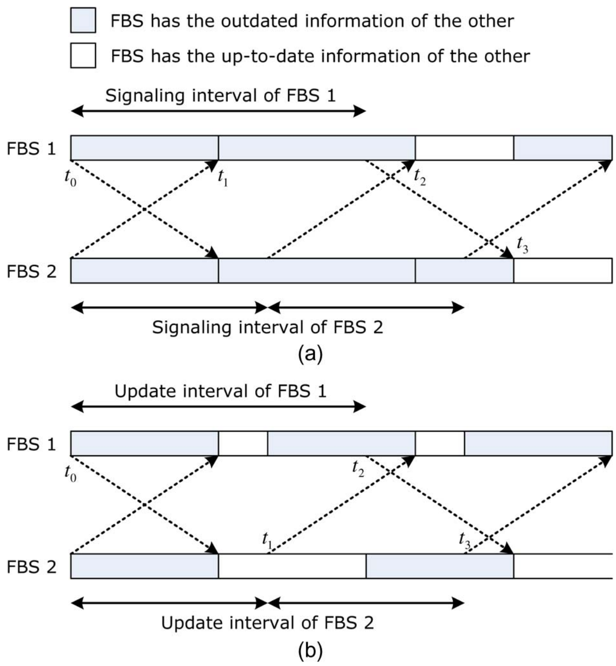

Fig. 1. Example of asynchronous coordination between two FBSs. (a) Periodic signaling and immediate update; (b) Immediate signaling and periodic update.

allocation was proposed in [19] for the purpose of interference mitigation and load-balancing between cells.

There exists a rich body of research on distributed asynchronous power control, which relaxes the need for strict time synchronization and also allows different users to update their power at different rates [20]. Since Foschini and Miljanic [21] proposed an algorithm, there have been many extensions considering discrete power levels [22], time-varying channel conditions [23], Kalman filter [24], etc. Yates [25] provided a general framework for uplink power control by identifying a broad class of iterative power control systems. However, these approaches considered a limited set of objective functions and constraints (e.g., minimization of the sum of powers with fixed target signal-to-interference ratios). One approach to asynchronous operation with more general objective functions is for each user to selfishly attempt to maximize his utility, which can be modeled as a non-cooperative N-person game [26]. For this, the analysis of the resulting *Nash equilibrium* is needed to ensure its existence and optimality along with the design of an algorithm converging to it. Possible utility functions for a non-cooperative power control game were investigated in [27].

III. Asynchrony of Femtocell Coordination

We illustrate an example of femtocell coordination with delayed signaling in Fig. 1 where two neighboring FBSs update their usage of radio resources based on the information they have at the time of update. In this example, we consider two extreme cases: (a) a cell signals its status information to neighbor cells periodically and updates its resource usage upon reception of the other cell's signaling; and (b) a cell signals its status information to neighbor cells as soon as the status changes and updates its resource usage periodically. The former represents the case when the signaling overhead is a dominating cost while the latter assumes that the overhead of updating radio resource usages is significant. Both cases assume that inter-cell signaling accompanies a fixed transmission latency. FBS 2 has a shorter signaling or update interval than FBS 1 has. In the figure, gray and white bars indicate the intervals during which a FBS has outdated and up-to-date information, respectively, of the other.

At t_0, both FBSs update their resource usage and signal the changes to each other, but each has the outdated information of the other before receiving the signal from the other. In Case (a), both FBSs receive the signal from each other and update the resource usage again at t_1. So, the radio resource usage of each has been changed from the signaled one and remains unchanged until they receive another signaling from each other at t_2 and t_3. In Case (b), FBS 2 has a shorter update interval and updates its resource usage at t_1 based on the updated information of FBS 1. However, FBS 1 updates at t_2 based on the outdated information of FBS 2 since signaling from FBS 2 has not yet arrived. At t_3, FBS 2 also updates based on the outdated information. As shown in this example, FBSs often operate with the outdated information of other cells due to asynchronous signaling. We will capture and analyze the impact of such a phenomenon on the behavior of distributed coordination of femtocells.

IV. System Model

A. Network Model

This section describes the network architecture under consideration. We consider a typical two-layer femtocell network in which femtocells are overlaid on a macrocell. The macrocell and the set of femtocells C are assumed to use an identical radio access technology based on OFDMA and a common frequency band. Cell i operates under the control of BS i. A user is connected to and served by either a macro- or femtocell. The set of macrocell users (MUs) and that of femtocell users (FUs) are denoted by M and N, respectively; N is divided into the set N_i of users being served by femtocell i and the number of users in N_i is denoted by n_i. The frequency band is composed of multiple resource blocks (RBs), each of which is a set of contiguous subcarriers and also the minimum scheduling granularity, and the set of given RBs is denoted by K.

The *neighbor cells* of a cell are defined as those cells that establish a signaling interface to the cell for the purpose of coordination. Let C_i be the set of neighbor cells (neighbor set for short) of cell i which is not included in C_i, and c_i be the number of cells in C_i. We define d_{ij} as the indicator of the inclusion of cell j in C_i, i.e., $d_{ij} = 1$ if $j \in C_i$ and $d_{ij} = 0$ otherwise ($d_{ii} = 0$ since $i \notin C_i$). We assume that, if cell j is a neighbor of cell i, the reverse relationship also holds, i.e., $i \in C_j$ if $j \in C_i$. Then, d_{ij} is commutative, i.e., $d_{ij} = d_{ji}$.

B. Signaling and Update Model

In what follows, we model a general behavior of asynchronous signaling and update using mathematical notations.

We define x_l as a variable that is updated by a cell[1] and the vector of all variables as $\mathbf{x}$; $x_l(t)$ is the value of x_l at time slot t and $\mathbf{x}(t)$ is the corresponding vector. Let V_i be the set of all variables under cell i's control and v_i be the number of variables in V_i. We further define $\mathbf{x}_i$ as the vector of x_l for $l \in \bigcup_{j \in C_i} V_j$. To describe the asynchronous behavior of femtocells, we adopt notations similar to Bertsekas' [28].

Let S_{ji} and D_{ji} be the interval and the network latency, respectively, of signaling to cell i from neighbor cell j. Then, the maximum delay of signaling from cell i to cell j is expressed as $S_{ji} + D_{ji}$. We define the upper bound of signaling delay cell i experiences for its neighbors as B_i:

$$B_i \geq \max_{j \in C_i} (S_{ji} + D_{ji}). \quad (1)$$

In other words, cell i's knowledge of $\mathbf{x}_i$ is not older than B_i time slots. Since S_{ji} and D_{ji} may differ between (i, j) pairs, B_i may also differ between cells. Due to such asynchronous inter-cell signaling, femtocell i has knowledge, at any time t, of a vector $\mathbf{x}_i^i(t)$ that is an outdated version of $\mathbf{x}_i(t)$. If an element of $\mathbf{x}_i^i(t)$ is denoted by $x_l(\tau_l^i(t))$ where $\tau_l^i(t)$ is cell i's reception time of the latest signaling of x_l before t, this is expressed formally as

$$\max\{0, t - B_i + 1\} \leq \tau_l^i(t) \leq t. \quad (2)$$

We assume that a femtocell updates the variables under its control at a rate equal to, or higher than $1/B_i$, i.e., femtocell i performs at least one update of $x_l, l \in V_i$ during consecutive B_i time slots. We let T^i be the set of times when femtocell i performs an update of the variables.

Inter-cell signaling is done over a wired network or the air (OTA). For simple configuration in wired signaling, we assume that S_{ji} is set equal to $B_i - D_i$ for $\forall j \in C_i$ where $D_i = \max_{j \in C_i} D_{ji}$ since increasing S_{ji} reduces the cost. Enabling inter-cell OTA signaling requires the implementation of two functional components—broadcasting and listening. To broadcast a cell's information, modification of the legacy system information (SI) format [29] is required and some unused SI fields can be redefined for the inclusion of the coordination information. Femtocell's listening of OTA signaling can be implemented in two ways—(1) *FBS-sniffed*: a FBS switches to a sniffing mode (a.k.a. network-listen mode) and decodes other cells' SI broadcast; or (2) *user-assisted*: user terminals overhear cells' SI broadcast and report it to their serving cells.[2] While broadcasting OTA signals results in only a marginal increase of a SI message's length, listening to them may interrupt connected users' services; typical implementations of the sniffing mode require a FBS to suspend ongoing user services during OTA listening due to otherwise strong interference from itself, and the user-assisted method still requires a user to suspend his service during listening and also consume additional battery power. Therefore, the rate of listening should be determined while taking such associated costs into account. We assume that OTA broadcasting is more frequent than listening (since the cost is much lower) and thus B_i is equal to FBS i's listening interval; FBS i listens to the OTA signaling of each of neighbor cells once every B_i time slots while listening slots are randomly distributed among B_i slots. We also assume that a FBS can decode the OTA signals broadcast by its neighbor FBSs and, if FBS i can decode FBS j's broadcast, the reverse is also true.

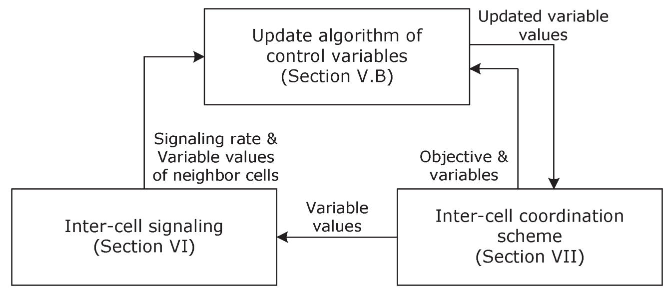

Fig. 2. Framework of ACoF for each cell.

V. Framework and Update Algorithm of ACoF

In this section, we describe a framework of ACoF. We then design a core algorithm for variable update and derive a condition for its convergence.

A. Framework

ACoF is composed of three components as depicted in Fig. 2. The main component is the algorithm (the top box) that updates control variables for radio resource assignment iteratively to optimize the objective function defined by the inter-cell coordination scheme (the bottom right box). When the variables are adjusted by the update algorithm, the inter-cell coordination scheme applies them to radio resource assignment. The updated variable values are then forwarded to the inter-cell signaling component (the bottom left box) so that they are shared with neighbor cells via signaling. The inter-cell signaling component also determines the rate of signaling to optimize signaling costs and reports it to the update algorithm along with the values of neighbor cells' control variables. The update algorithm determines its update rate based on the reported signaling rate. The components of ACoF are detailed in Sections V-B–D, VI, and VII, respectively.

B. Problem Formulation

A general form of the problem that ACoF's update algorithm solves is expressed as

$$P1: \quad \max_{\mathbf{x}_C} \quad U(\mathbf{x}_C)$$
$$\text{s.t.} \quad g_i(\mathbf{x}_C) \leq 0, \ i = 1, \ldots, m$$
$$x_l \in \left[x_l^{\min}, x_l^{\max}\right]$$

[1]These variables are defined by an inter-cell coordination scheme as illustrated in Section VII.

[2]Most COTS modem solutions for FBS support the sniffing mode, mainly for FBS's self-configuration. In LTE systems, user-assisted listening of other cells' overhead messages is available in limited self-configuration scenarios, such as automatic neighbor relation (ANR) [30].

where U is the utility function and $\mathbf{x}_C$ is the vector of all the variables x_l controlled by cells in a network to configure the usage of radio resources (as defined in Section VII); the inequalities $g_i(\mathbf{x}_C) \leq 0$ are the constraints to be satisfied. If there exists a central controller equipped with the status information of all cells in a network and $P1$ is a convex optimization problem, it can solve $P1$ by solving the equations obtained from the corresponding *Karush-Kuhn-Tucker* (KKT) conditions. However, we consider a fully-distributed system and hence assume that each femtocell has the limited information of neighbor cells only. Therefore, finding a solution of $P1$ is not straightforward. Our approach is to let each femtocell solve a local problem iteratively such that the collective solution gets closer to and finally reaches a global optimum of $P1$. For this purpose, we transform P1 into another problem ($P2$), which is easier to be transformed into an iterative version.

We relax the constraints of $P1$ using Lagrange multipliers and denote the corresponding Lagrangian as $L(\mathbf{x}_C;\mathbf{x}_L)$ where $\mathbf{x}_L$ is the vector of Lagrange multipliers. The Lagrange dual function L_{dual} of Lagrangian L is obtained as

$$L_{\mathrm{dual}}(\mathbf{x}_L) := \sup_{\mathbf{x}_C} L(\mathbf{x}_C;\mathbf{x}_L) \tag{3}$$

and, conversely, the infimum of the Lagrangian with respect to Lagrange multipliers, denoted by L_{primal}, is

$$L_{\mathrm{primal}}(\mathbf{x}_C) := \inf_{\mathbf{x}_L} L(\mathbf{x}_C;\mathbf{x}_L). \tag{4}$$

We can then formulate another problem as:

$$P2: \quad \min_{\mathbf{x}_C,\mathbf{x}_L} \quad L_{\mathrm{dual}}(\mathbf{x}_L) - L_{\mathrm{primal}}(\mathbf{x}_C),$$

which ACoF's update algorithm solves, instead of $P1$. The rationale behind this choice is given as the following proposition.

Proposition 1: The optimum of $P2$ is also the solution of the constraint-relaxed version of $P1$.

Proof: Minimizing $L_{\mathrm{dual}} - L_{\mathrm{primal}}$ corresponds to minimizing L_{dual} and maximizing L_{primal}. So, the optimum of $P2$ is the *optimal duality gap* of the relaxed problem and is thus obtained at the minimum of L_{dual} and the maximum of L_{primal}. □

C. Update Algorithm of Control Variables

To solve $P2$ iteratively, we define the transient versions of L_{dual} and L_{primal}, respectively, as

$$\begin{aligned} L_{\mathrm{dual}}\left(\mathbf{x}_L(t)\right) &:= L\left(\mathbf{x}_C(t-1), \mathbf{x}_L(t)\right), \\ L_{\mathrm{primal}}\left(\mathbf{x}_C(t)\right) &:= L\left(\mathbf{x}_C(t), \mathbf{x}_L(t-1)\right) \end{aligned} \tag{5}$$

and the difference of the above functions, which is the *transient duality gap* and denoted by $F(\mathbf{x}(t))$, as

$$F\left(\mathbf{x}(t)\right) := L_{\mathrm{dual}}\left(\mathbf{x}_L(t)\right) - L_{\mathrm{primal}}\left(\mathbf{x}_C(t)\right). \tag{6}$$

where $\mathbf{x}$ is the combined vector of $\mathbf{x}_C$ and $\mathbf{x}_L$. The proposed update algorithm of ACoF iterates on a vector $\mathbf{x}(t)$; x_l is updated by cell i if $l \in V_i$ according to[3]

$$x_l(t+1) = \min\left\{\left[x_l(t) + \gamma_l s_l(t)\right]^+, x_l^{\max}\right\} \tag{7}$$

where γ_l is a positive step-size of update and determines how much x_l changes by an update; $s_l(t)$ is the update direction and $x_l^{\max}$ is the upper limit of x_l. We let

$$s_l(t) = \begin{cases} -\nabla_l F\left(\mathbf{x}^i(t)\right) & t \in T^i \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

where ∇_l is the differentiation operator with respect to x_l. That is, the algorithm is based on *gradient descent* [31]. $\mathbf{x}^i(t)$ is femtocell i's latest knowledge of variables of all other cells at time t, but, as we will assume next, femtocell i requires only those of neighbor cells (i.e., $\mathbf{x}_i^i(t)$) to obtain $\nabla_l F$, $l \in V_i$.

D. Convergence Analysis

We prove that ACoF guarantees convergence if γ_l is chosen from a specified range. First, we make the following assumptions, which are shown to be valid for the muting-based inter-cell coordination scheme considered in Section VII.

Assumption 1: The convergence of ACoF depends solely on the convergence of its update algorithm (the inter-cell signaling component updates the signaling rate less frequently than the update algorithm updates the control variables).

Assumption 2: $P1$ is a convex optimization problem.

Assumption 3: $\nabla_l F, l \in V_i$ depends on $\mathbf{x}_i$ only, and hence we redefine $\nabla_l F(\mathbf{x})$ as $f_l(\mathbf{x}_i)$.

Assumption 4: f_l is *Lipschitz continuous* in $\mathbf{x}_i$ for $l \in V_i$. That is, there exists a finite constant K_1^l, called the *Lipschitz constant*, such that

$$\left|f_l(\mathbf{x}_i) - f_l\left(\mathbf{x}_i^i\right)\right| \leq K_1^l \left\|\mathbf{x}_i - \mathbf{x}_i^i\right\|. \tag{9}$$

We can then prove the convergence of ACoF as follows.

Proposition 2: The 2-norm distance between $\mathbf{x}_i^i(t)$ and $\mathbf{x}_i(t)$ is bounded as

$$\left\|\mathbf{x}_i^i(t) - \mathbf{x}_i(t)\right\| \leq \sum_{j\in C_i}\sum_{l\in V_j}\sum_{\tau=t-B_i}^{t-1} \gamma_l \left|s_l(\tau)\right|. \tag{10}$$

Proof: See the Appendix. □

Proposition 3: ACoF is convergent, i.e., $\nabla_l F \to 0$ for all l, if γ_l is chosen to meet the following inequality:

$$0 < \gamma_l < \Gamma_l \tag{11}$$

where

$$\Gamma_l^{-1} := K_2^l + \frac{K_1^l B_i}{2}\sum_{j\in C_i} v_j + \frac{1}{2}\sum_{j\in C_i} B_j \sum_{l'\in V_j} K_1^{l'} \tag{12}$$

and $K_2^l := \frac{v_i^+}{4}[(K_1^l)^2 + 1]$ when $v_i^+ := \sum_{j\in C_i} v_j$ and $l \in V_i$.

[3] $[x]^+ = \max\{x, x^{\min}\}$ where $x^{\min}$ is the lower limit of x.

Proof: See the Appendix. □

Proposition 4: If ACoF converges, i.e., γ_l is configured to meet Eqs. (11) and (12) of Proposition 3, it converges to the global optimum of $P1$.

Proof: Since $\nabla_l F$ is obtained as $\nabla_l L_{\text{dual}}$ when x_l is a problem variable and $\nabla_l L_{\text{primal}}$ when x_l is a Lagrange multiplier, $\nabla_l F = 0$ for $\forall l$ leads to $\nabla_l L_{\text{dual}} = \nabla_l L_{\text{primal}} = 0$, which meets the KKT conditions of $P1$. Since $P1$ is a convex problem, this is sufficient for the converged solution to be globally optimal. □

Note that, as can be seen in Eq. (12), the convergence condition of ACoF depends on each femtocell's local conditions only, thus enabling distributed configuration of γ_l. Eqs. (11) and (12) also imply that as the interval of inter-cell signaling and variable update increases (i.e., asynchrony of femtocells gets severer), the update step-size should set smaller for convergence.

Remark: Proposition 3 is a sufficient condition of convergence, i.e., it does not imply that ACoF diverges if $\gamma_l \geq \Gamma_l$. In spite of this, we can still use it as a basis for parameter configuration. For example, γ_l can be set as $\delta\Gamma_l$ where $\delta < 1$ matches the above condition while $\delta \geq 1$ explores choices beyond it for possibly faster convergence. We will study further the effect of δ in this approach in Section VIII.

VI. Optimization of Per-Cell Signaling Costs

In this section, we characterize the costs of wired and OTA signaling methods, and then find a cell-specific signaling rate by minimizing the total costs.

A. Signaling Over Wired Backhaul

When inter-cell signaling messages are exchanged over the wired backhaul, the associated signaling cost depends mainly on the sending and receiving rates of signaling. We define the signaling cost of cell i, denoted by G_i, as

$$G_i(\{B_i\}) := \sum_{j\in C_i}\frac{1}{S_{ij}} + \sum_{j\in C_i}\frac{1}{S_{ji}} + \omega_1 B_i + \omega_2\sum_{l\in V_i}\gamma_l^{-1}$$
$$= \sum_{j\in C_i}\frac{1}{B_j - D_j} + \frac{c_i}{B_i - D_i} + \omega_1 B_i + \omega_2\sum_{l\in V_i}\gamma_l^{-1}$$

where the first and second terms are the total sending and receiving rates of signaling, respectively, and the last terms are the costs of late convergence; ω_1 and ω_2 are balancing constants. If γ_l is chosen proportionally to Γ_l according to Proposition 3, then G_i can be rewritten after algebraic simplification as

$$G_i(\{B_i\}) := A^0 + \frac{c_i}{B_i - D_i} + B_i A_i^2 + \sum_{j\in C_i}\left(B_j A_{ij}^2 + \frac{1}{B_j - D_j}\right) \tag{13}$$

where

$$A^0 := \omega_2\sum\nolimits_{l\in V_i} K_2^l,\quad A_i^2 := \omega_1 + \omega_2\sum\nolimits_{l\in V_i} K_1^l \sum\nolimits_{j\in C_i} v_j,$$
$$A_{ij}^2 := \omega_2 v_i \sum\nolimits_{l'\in V_j} K_1^{l'}. \tag{14}$$

The target problem is formulated as

$$P3: \min_{\{B_i\}\succeq D_i}\sum_{i\in C} G_i(\{B_i\}). \tag{15}$$

The last term of Eq. (13) can be manipulated as

$$\sum_{i\in C}\sum_{j\in C} d_{ij}\left(B_j A_{ij}^2 + (B_j - D_j)^{-1}\right)$$
$$= \sum_{i\in C}\left(B_i\sum_{j\in C} d_{ji}A_{ji}^2 + (B_i - D_i)^{-1}\sum_{j\in C} d_{ji}\right)$$
$$= \sum_{i\in C}\left(B_i\sum_{j\in C_i} A_{ji}^2 + (B_i - D_i)^{-1}c_i\right) \tag{16}$$

where the first equality is obtained by exchanging i and j and applying the commutativity of d_{ij} stated in Section IV. Therefore, $P3$ is rewritten as

$$P3' \min_{B_i\geq D_i}\left(\frac{2c_i}{B_i - D_i} + B_i\left(A_i^2 + \sum_{j\in C_i} A_{ji}^2\right)\right) \tag{17}$$

showing that cells are not coupled with others in deciding B_i and thus each cell can decide optimal B_i individually. Since the objective function of $P3'$ is convex, we set its derivative to 0 and obtain the optimum B_i^* as

$$B_i^* = \max\left\{\left[\frac{2c_i}{A_i^2 + \sum_{j\in C_i} A_{ji}^2}\right]^{\frac{1}{2}} + D_i, 1\right\}. \tag{18}$$

B. Signaling Over the Air

Let b_{BS} and b_U be the time durations required to decode an OTA signaling message by a BS and a user, respectively; $\alpha_{y,j} \in [0, 1]$, $y := i \in C$ or $n \in N$ is the activation rate of FBS or FU y's OTA listening to cell j; $\beta_{y,j} \in \{0, 1\}$ indicates if y can decode cell j's OTA signal ($\beta_{y,j} = 1$ means y can decode cell j's signal). Then, the ratio of bandwidth reduction of user n due to service interruptions resulting from OTA listening, denoted by Ω^n, is expressed as

$$\Omega^n(\boldsymbol{\alpha}, B_i) = \sum_{j\in C_i}\frac{b_{BS}}{B_i}\alpha_{i,j}\beta_{i,j} + \sum_{j\in C_i}\frac{b_U}{B_i}\alpha_{n,j}\beta_{n,j}. \tag{19}$$

We define the cost associated with OTA listening in cell i, denoted by G_i, as

$$G_i(\{\alpha_{y,j}\}, B_i) := \sum_{n\in N_i}\Omega^n(\boldsymbol{\alpha}, B_i) + \frac{\omega_0}{B_i}\sum_{n\in N_i}\sum_{j\in C_i}\alpha_{n,j} + \omega_1 B_i + \omega_2\sum_{l\in V_i}\gamma_l^{-1}$$

where the second term is the cost for energy consumption of user devices and the last two terms are the costs for late convergence; ω_0, ω_1 and ω_2 are balancing constants. Similarly, if γ_l is chosen proportionally to Γ_l, then G_i is rewritten as

$$G_i\left(\{\alpha_{y,j}\}, B_i\right) := A^0 + \frac{1}{B_i}\sum_{j\in C_i}\sum_{y\in i,N_i}\alpha_{y,j}A^1_{y,j} + B_iA^2_i + \sum_{j\in C_i}B_jA^2_{ij} \quad (20)$$

where A^0, A^2_i and A^2_{ij} are obtained same as Eq. (14) while $A^1_{y,j}$ is given by

$$A^1_{y,j} := \begin{cases} b_{BS}n_i\beta_{ij} & y := i \in C \\ b_U\beta_{nj} + \omega_0 & y := n \in N_i. \end{cases} \quad (21)$$

$\alpha_{y,j}$ needs to be determined such that the OTA broadcast of each neighbor cell should be received at least once in interval B_i and a FU should not spend the whole time slots on listening. Taking these constraints into account, we formulate the target problem as:

$$\begin{aligned} P4: \quad & \min_{\{\alpha_{y,j}\},\{B_i\}} \sum_{i\in C} G_i\left(\{\alpha_{y,j}\}, B_i\right) \\ \text{s.t.} \quad & \alpha_{i,j} + \sum_{n\in N_i}\alpha_{n,j} \geq \beta_{i,j},\ j\in C_i \\ & \sum_{j\in C_i} b_U\alpha_{n,j} \leq 1,\ n\in N_i \\ & 0 \leq \alpha_{y,j} \leq \beta_{y,j},\ y\in N_i. \end{aligned} \quad (22)$$

We can divide $P4$ into the following two subproblems according to the associated problem variables:

$$P4.1: \min_{\{\alpha_{y,j}\}}\sum_{j\in C_i}\sum_{y\in i,N_i}\alpha_{y,j}A^1_{y,j} \quad (23)$$

with the same constraints as $P4$, which is a linear programming problem and can be solved efficiently using known techniques, and

$$P4.2: \min_{\{B_i\}\succeq 1}\sum_{i\in C}\left(\frac{O^*_{P4.1}}{B_i} + B_iA^2_i + \sum_{j\in C_i}B_jA^2_{ij}\right) \quad (24)$$

with no constraint where $O^*_{P4.1}$ is the objective function value of $P4.1$ with an optimal solution and can be considered constant in $P4.2$. The last term of Eq. (24) can be manipulated similar with Eq. (16) and $P4.2$ is rewritten as

$$P4.2': \min_{B_i\geq 1}\left(\frac{O^*_{P4.1}}{B_i} + B_i\left(A^2_i + \sum_{j\in C_i}A^2_{ji}\right)\right) \quad (25)$$

which has the same form as $P3'$ and thus the optimum B^*_i is obtained similarly as

$$B^*_i = \max\left\{\left[\frac{O^*_{P4.1}}{A^2_i + \sum_{j\in C_i}A^2_{ji}}\right]^{1/2}, 1\right\}. \quad (26)$$

VII. Coordinated Muting Scheme for ACoF

In this section, we present an example inter-cell coordination scheme working under the framework of ACoF. In this scheme, femtocells coordinate the usage of both time and power resources jointly with others, as described below.

- *Coordination of time resource usages*: femtocells remain silent (don't transmit signals) in a fraction of time slots, called *muting*,[4] such that the total utility sum is maximized while a cell-specific ratio of interference-free time slots (where no other neighbor cells transmit) is met. For this, each FBS adjusts per-RB time slot activities.
- *Coordination of power resource usages*: femtocells adjust their transmit powers on a per-RB basis such that the total utility sum is maximized while nearby MUs experience below a specified level of interference.

We consider (i) *asynchronous* muting that the resource usage pattern of a femtocell is randomized in the time axis (to randomize interference to other cells as well as not to require time-synchronization between femtocells), and (ii) *synchronous* muting, but with an emphasis on the former since the design of asynchronous muting within ACoF is more complicated.

In what follows, we formulate the target problem to be solved by ACoF and describe the update algorithm for the muting scheme.

A. Joint Muting and Transmit Power Adjustment

Let $a^n_{i,k} \in [0, 1]$ be the fraction of time slots or *transmission activity* assigned to FU $n \in N_i$ for RB $k \in K$ in femtocell $i \in C$ and $p^n_{i,k}$ be the associated transmit power; $p^n_{i,k}$ is the average power and thus the instantaneous power used in an assigned time slot is given by $p^n_{i,k}/a^n_{i,k}$. For $n \notin N_i$, both $a^n_{i,k}$ and $p^n_{i,k}$ are not defined. We define $\mathbf{a}$ and $\mathbf{p}$ as the vectors of $a^n_{i,k}$ and $p^n_{i,k}$, respectively, for all pairs of (i, k, n). Then, ACoF aims to find $(\mathbf{a}, \mathbf{p})$ that maximizes the sum of all users' utilities. We further define $a_{i,k} \in [0, 1]$ as the fraction of time slots in which femtocell i transmits signals at RB k and $p_{i,k}$ as the average transmit power that femtocell i uses at RB k. They are related to $a^n_{i,k}$ and $p^n_{i,k}$ as:

$$a_{i,k} = \sum_{n\in N_i}a^n_{i,k}, \quad p_{i,k} = \sum_{n\in N_i}p^n_{i,k}.$$

Next, we express a user's achievable transmission capacity in terms of $a^n_{i,k}$ and $p^n_{i,k}$. Let $h^n_{i,k}$ be the channel gain from cell i to user n at RB k. Then, user n's received power at RB k is $h^n_{i,k}p^n_{i,k}/a^n_{i,k}$ and his signal-to-interference-plus-noise ratio (SINR) at RB k, denoted by $\theta^k_{i,n}$, is given by:

$$\theta^k_{i,n} = \frac{h^n_{i,k}p^n_{i,k}/a^n_{i,k}}{I^n_{i,k} + \sigma} := \frac{\Theta^n_{i,k}p^n_{i,k}}{a^n_{i,k}} \quad (27)$$

where $I^n_{i,k}$ is the other-cell interference experienced by user n at RB k; σ is the thermal noise; and $\Theta^n_{i,k} := h^n_{i,k}/(I^n_{i,k} + \sigma)$.

[4] It is called *almost blank subframe* (ABS) in LTE.

Let $\varepsilon_i \in [0,1]$ be femtocell i's target fraction of interference-free time slots. Then, the transmission capacity achieved by FU n at RB k in an interference-free time slot, denoted by $R^n_{i,k}$, is expressed as

$$\begin{aligned} R^n_{i,k} &:= a^n_{i,k}\varepsilon_i(1-\Omega^n)W\log_2\left(1+\theta^n_{i,k}\right) \\ &:= a^n_{i,k}\Lambda^n_i \log\left(1+\theta^n_{i,k}\right) \end{aligned} \tag{28}$$

where W is the bandwidth of one RB; $\Omega^n \in [0,1)$ is FU n's ratio of capacity reduction due to the overhead of inter-cell signaling, and $\Lambda^n_i := \varepsilon_i(1-\Omega^n)W(\log 2)^{-1}$. In $R^n_{i,k}$, $I^n_{i,k}$ includes the interference generated by macrocell only and is independent of $a^n_{j,k}$ and $p^n_{j,k}$, $j \in C_i$. Thus, we approximate $I^n_{i,k}$ of $R^n_{i,k}$ to be constant. Let R^n_i be the sum of $R^n_{i,k}$ for all RBs, which we call FU n's *coordinated channel capacity*. We focus on maximizing the utility function of FU's achieved data rate, denoted by r_n for FU n, within this capacity.

The basic form of the target problem is then formulated as[5]

$$\begin{aligned} P1': \quad & \max_{\mathbf{r},\mathbf{p},\mathbf{a}} \sum_{n\in N} U(r_n) \\ \text{s.t.} \quad & C1'.1: r_n \le R^n_i, \quad i \in C, n \in N_i \\ & C1'.2: a_{i,k} \le 1, \quad i \in C, k \in K \\ & a^n_{i,k} \in [0,1] \\ & p^n_{i,k} \in [0, P^{\max}_i] \end{aligned}$$

where U is the utility function and $\mathbf{r}$ is the vector of r_n; $P^{\max}_i$ is the maximum transmit power of FBS i in a RB. For U, we consider the following family of utility functions parameterized by $\alpha \ge 0$ [32]:

$$U(r_n) = \begin{cases} (1-\alpha)^{-1} r_n^{1-\alpha} & \alpha \ne 1 \\ \log r_n & \alpha = 1. \end{cases} \tag{29}$$

In particular, if $\alpha = 0$, U reduces to r_n. If $\alpha = 1$, proportional fairness among competing users is attained; if $\alpha = 2$, then harmonic mean fairness; and if $\alpha \to \infty$, then max-min fairness [33]. Note that U is concave for $\forall\alpha$. $P1'$ necessitates additional constraints for (1) meeting the femtocell-specific target fraction of interference-free time slots; and (2) protecting MUs against FBSs' interference, which are derived below as $C1'.3$ and $C1'.4$, respectively.

Since the resource usage patterns of femtocells is randomized in the time domain under asynchronous muting, ε_i is related to $a_{j,k}$ for $j \in C_i$ as:

$$\prod\nolimits_{j\in C_i}(1-a_{j,k}) \ge \varepsilon_i, \quad i \in C, k \in K \tag{30}$$

from which, by taking the logarithm of the both sides, a constraint preserving the convexity of the problem is obtained as

$$C1'.3: \sum\nolimits_{j\in C_i} \log(1-a_{j,k}) \ge \hat{\varepsilon}_i.$$

[5]We omit some constraints (e.g., limitation of a cell's total transmit power) to simplify the exposition, but they can also be considered within the proposed framework without effort.

where we define $\hat{\varepsilon}_i := \log \varepsilon_i$. $C1'.3$ becomes $\sum_{j\in C_i} a_{j,k} \le 1$ under synchronous muting with $\varepsilon_i = 1$.

We let F_m be the set of FBSs generating effective interference to MU m and I^m_k be the total interference received by MU m at RB k. To protect MUs against femtocell interference, i.e., letting I^m_k be lower than maximum bearable interference I^{MU}_k for all $m \in M$, we limit femtocells' transmit power by adding the following constraint:

$$C1'.4: I^m_k := \sum_{i\in F_m} h^m_{i,k} p_{i,k} \le I^{\mathrm{MU}}_k, \quad m \in M, k \in K.$$

Then, the following proposition holds.

Proposition 5: $P1'$ with additional constraints $C1'.3$ and $C1'.4$ is a convex optimization problem.

The Lagrangian of $P1'$ is obtained as

$$\begin{aligned} &L(\mathbf{r},\mathbf{p},\mathbf{a};\boldsymbol{\lambda},\boldsymbol{\mu},\boldsymbol{\nu}) \\ &:= \sum_{n\in N} U(r_n) + \sum_{i\in C}\sum_{n\in N_i} \lambda^n_i\left(R^n_i - r_n\right) + \sum_{k\in K}\Phi_k \\ &\quad + \sum_{m\in M}\sum_{k\in K}\nu_{m,k}\left(I^{\mathrm{MU}}_k - I^m_k\right) + \sum_{i\in C}\sum_{k\in K}\xi_{i,k}(1-a_{i,k}) \end{aligned} \tag{31}$$

where $\Phi_k := \sum_{i\in C}\mu_{i,k}\Phi_{i,k}$ and $\Phi_{i,k} := \sum_{j\in C_i}\log(1-a_{j,k}) - \hat{\varepsilon}_i$; $\boldsymbol{\lambda}$, $\boldsymbol{\mu}$ and $\boldsymbol{\nu}$ are the vectors of Lagrange multipliers λ^n_i, $\mu_{i,k}$ and $\nu_{m,k}$, respectively. $P2'$ is then formulated as:

$$P2': \min_{\mathbf{r},\mathbf{p},\mathbf{a},\boldsymbol{\lambda},\boldsymbol{\mu},\boldsymbol{\nu}} \quad L_{\mathrm{dual}}(\boldsymbol{\lambda},\boldsymbol{\mu},\boldsymbol{\nu}) - L_{\mathrm{primal}}(\mathbf{r},\mathbf{p},\mathbf{a}).$$

B. Update Algorithm for the Muting Scheme

In what follows, we derive the derivatives of F which is needed to update a variable in Eq. (8). First, we obtain $\partial F/\partial r_n = -r_n^{-\alpha}$. Next, $\partial F/\partial p^n_{i,k}$ is obtained as

$$\frac{\partial F}{\partial p^n_{i,k}} = -\lambda^n_i \frac{\partial R^n_{i,k}}{\partial p^n_{i,k}} + \sum_{m\in M_i}\nu_{m,k}h^m_{i,k} \tag{32}$$

where

$$\frac{\partial R^n_{i,k}}{\partial p^n_{i,k}} = a^n_{i,k}\Lambda^n_i \frac{1}{1+\theta^n_{i,k}}\frac{\partial \theta^n_{i,k}}{\partial p^n_{i,k}} = \frac{\Lambda^n_i \Theta^n_{i,k} a^n_{i,k}}{a^n_{i,k} + \Theta^n_{i,k} p^n_{i,k}} \tag{33}$$

and M_i is the set of MUs experiencing excessive interference (stronger than I^{MU}_k) in the vicinity of femtocell i, i.e., $m \in M_i$ if $i \in F_m$, and vice versa. Similarly, $\partial F/\partial a^n_{i,k}$ is given by

$$\frac{\partial F}{\partial a^n_{i,k}} = -\lambda^n_i \frac{\partial R^n_{i,k}}{\partial a^n_{i,k}} - \frac{\partial \Phi_k}{\partial a^n_{i,k}} + \xi_{i,k} \tag{34}$$

where

$$\frac{\partial R^n_{i,k}}{\partial a^n_{i,k}} = \Lambda^n_i \left(\log\left(1+\theta^n_{i,k}\right) - \frac{\theta^n_{i,k}}{1+\theta^n_{i,k}}\right),$$

$$\frac{\partial \Phi_k}{\partial a^n_{ik}} = \frac{\partial \Phi_k}{\partial a_{ik}}\frac{\partial a_{ik}}{\partial a^n_{ik}} = \sum_{j\in C}\mu_{jk}d_{ji}\frac{-1}{1-a_{ik}} = \frac{-\sum_{j\in C_i}\mu_{jk}}{1-a_{ik}}.$$

For the Lagrangian multipliers, we have

$$\frac{\partial F}{\partial \lambda_i^n} = \sum_{k\in K} R_{i,k}^n - r_n, \quad \frac{\partial F}{\partial \mu_{i,k}} = \Phi_{i,k},$$
$$\frac{\partial F}{\partial \nu_{mk}} = I_k^{\mathrm{MU}} - I_k^m, \quad \frac{\partial F}{\partial \xi_{ik}} = 1 - a_{i,k}. \tag{35}$$

As shown in the above, $\nabla_l F, l \in V_i$ depends on $\mathbf{x}_i$ only, and hence we can redefine $\nabla_l F(\mathbf{x})$ as $f_l(\mathbf{x}_i)$. In addition, the considered F is Lipschitz-continuous as we will show in the next subsection. Thus, all the assumptions in Section V-C are satisfied and ACoF with the coordinated muting scheme converges to a global optimum according to Propositions 3 and 4 provided that γ_l is chosen within the range specified in Eq. (11).

C. Estimation of the Lipschitz Constant

As shown in Proposition 3, the knowledge of K_1^l is needed to obtain a bound Γ_l. Since a smaller K_1^l enables a larger step-size γ_l and thus faster convergence, we need a good estimate of the Lipschitz constant K_1^l. In this subsection, we propose a method of estimating K_1^l.

Proposition 6: Any constant K_0 satisfying the condition below is the Lipschitz constant of f_l:

$$K_0^2 \geq \sup_{\mathbf{x}_i} \sum_{j\in C_i} \sum_{l'\in V_j} (\nabla_{l'} f_l(\mathbf{x}_j))^2 \tag{36}$$

where $\nabla_{l'} f_l$ is the gradient of f_l with respect to $x_{l'}$.

Proof: Let $\Delta_i \mathbf{x}_i = \mathbf{x}_i - \mathbf{x}_i^i$ and $\Delta_i f_l(\mathbf{x}_i) = f_l(\mathbf{x}_i^i + \Delta_i \mathbf{x}_i) - f_l(\mathbf{x}_i^i)$. Then, for any $\Delta_i \mathbf{x}_i$, the following holds (we shorten $\sum_{j\in C_i}\sum_{l'\in V_j}$ into $\sum_{j\in C_i;l'}$):

$$\begin{aligned}|\Delta_i f_l(\mathbf{x}_i)| &\simeq \left|\sum\nolimits_{j\in C_i;l'} \nabla_{l'} f_l(\mathbf{x}_i)\Delta_i x_{l'}\right| \\ &< \sum\nolimits_{j\in C_i;l'} |\nabla_{l'} f_l(\mathbf{x}_i)| \cdot |\Delta_i x_{l'}| \\ &\leq \sqrt{\sum\nolimits_{j\in C_i;l'} (\nabla_{l'} f_l(\mathbf{x}_i))^2}\sqrt{\sum\nolimits_{j\in C_i;l'} (\Delta_i x_{l'})^2} \\ &\leq \sup\nolimits_{\mathbf{x}_i} \sqrt{\sum\nolimits_{j\in C_i;l'} (\nabla_{l'} f_l(\mathbf{x}_i))^2}\|\Delta_i \mathbf{x}_i\|\end{aligned}$$

where the first approximation follows from the Taylor series and the second inequality follows from the Cauchy-Schwarz inequality. This completes the proof. □

That is, the right side of Eq. (36) can be the smallest K_1^l we can find. To obtain K_1^l accordingly, we derive the second-order partial derivatives of F. We have

$$\frac{\partial^2 F}{\partial x_l \partial x_{l'}} = \begin{cases} -h_{ik}^m & (x_l, x_{l'}) := \left(p_{i,k}^n, \nu_{mk}\right), m \in M_i \\ 0 & \text{otherwise.}\end{cases} \tag{37}$$

and thus, according to Proposition 6, the Lipschitz constants of $\partial F/\partial p_{i,k}^n$ and $\partial F/\partial \nu_{mk}$ are obtained as

$$K_1^l = \begin{cases} \left[\sum_{m\in M_i}\sum_{k\in K} (h_{ik}^m)^2\right]^{1/2} & x_l := p_{i,k}^n \\ \left[\sum_{i\in F_m}\sum_{k\in K} (h_{ik}^m)^2\right]^{1/2} & x_l := \nu_{mk}.\end{cases} \tag{38}$$

Similarly, for $\forall i \in C, \forall k \in K$,

$$\frac{\partial^2 F}{\partial x_l \partial x_{l'}} = \begin{cases} -1/(1-a_{ik}) & (x_l, x_{l'}) := \left(a_{i,k}^n, \mu_{jk}\right), j \in C_i \\ 0 & \text{otherwise.}\end{cases} \tag{39}$$

and the corresponding Lipschitz constant is obtained as

$$K_1^l = \begin{cases} \sqrt{c_i}/(1-a_{ik}) & x_l := a_{i,k}^n \\ \sqrt{\sum_{j\in C_i} n_j}/(1-a_{ik}) & x_l := \mu_{ik}.\end{cases} \tag{40}$$

The second-order derivatives involving the other variables, such as r_n, λ_i^n and $\xi_{i,k}$, are all 0 since $\nabla_l F, l \in V_i$ with respect to them depends on $x_{l'}, l' \in V_i$ only. Thus, their Lipschitz constants are obtained as 0.

Remark: The constants obtained in Eqs. (38) and (40) as well as Γ_l based on them may, however, change over iterations. This may impact the convergence behavior of ACoF since γ_l, which is configured to be fixed, could move out of its valid range before convergence. Therefore, we need to find the *stable* (rarely changing) versions of the constants. From Eqs. (38) and (40), K_1^l is a monotonic increase function of h_{ik}^m and a_{ik}, respectively. Therefore, if we replace h_{ik}^m and a_{ik} with their stable upper bounds, the new versions of K_1^l become larger than before (thus are still valid Lipschitz constants), but stable. We can find an upper bound of h_{ik}^m for $\forall m$ based on measurement history. If h_{ik}^m is measured as the value $z(t)$ at time t, it may vary around $z(t)$ over a short period of time. Therefore, the upper bound of h_{ik}^m can be configured as $z(t) + \kappa$ before the next measurement is made. Here, κ is set such that h_{ik}^m varies below the upper-bound during a short period of time. Since $a_{ik} \leq 1 - \varepsilon_j$ for $\forall j \in C_i$, we have the upper bound of a_{ik} as $\min_{j\in C_i}(1-\varepsilon_j)$.

VIII. Evaluation

To evaluate the effectiveness of ACoF with the coordinated muting scheme, we consider a single-sector macrocell on which multiple femtocells are overlaid. We follow the simulation scenario of 3GPP [34] for femtocell deployment and path-loss models. The radius of a macrocell is 500 m and 10 MUs are randomly placed in the macrocell; the angle and the distance of each to the MBS are randomly chosen with a uniform probability distribution. FBSs are also randomly distributed within a macrocell and a FU is randomly placed at a distance shorter than 50 m from each FBS. We also assume the log-normal shadowing with a standard deviation of 8 dB.

Both MBS and FBSs operate at the frequency band of 2 GHz with the channel bandwidth of 10 MHz. For RB allocation, we assume a simple scheduling design that a random number is generated for each FU-RB pair in every slot and the RB is assigned to the FU if the number is smaller than the corresponding transmission activity determined by ACoF. We assume that the MBS transmits at the power of 40 dBm. The maximum transmit power of FBSs is 20 dBm. If a FBS's pilot signal is received by another FBS with a path loss smaller than 120 dB, it is considered as a neighbor cell of the latter FBS, and vice versa. To restrict the listening overhead of OTA broadcast, the number of neighbor femtocells for a FBS is limited to 5 (chosen

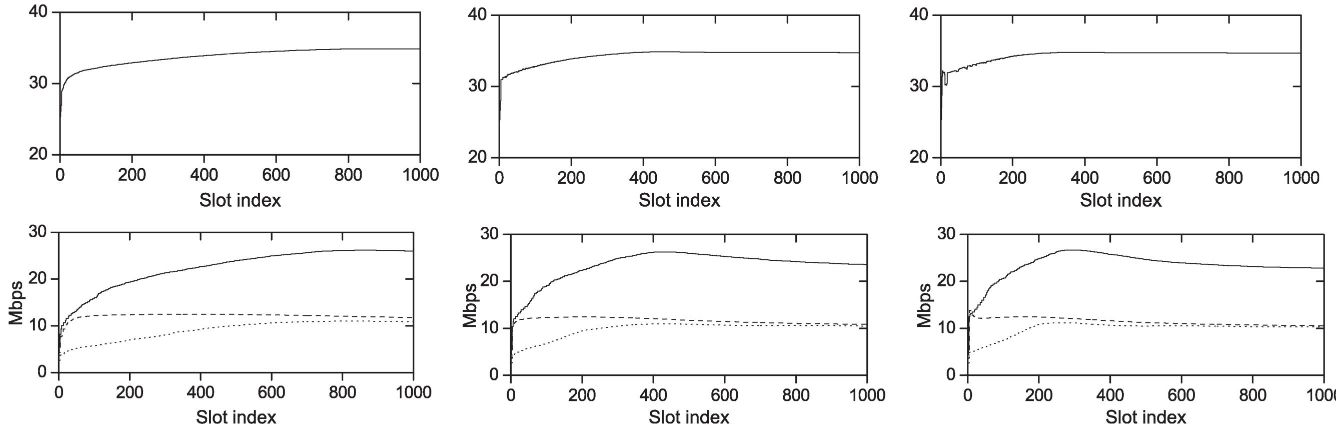

Fig. 3. Time evolution of utility-sum (top) and three user-rate samples (bottom) for $\delta = 0.5$ (leftmost), 1 (middle) and 1.5 (rightmost).

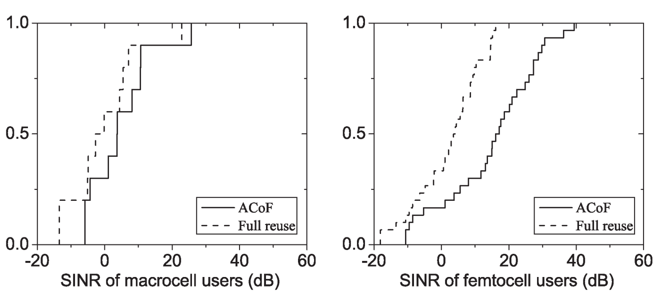

Fig. 4. CDF of the SINR gain of ACoF over full reuse of radio resource within each femtocell.

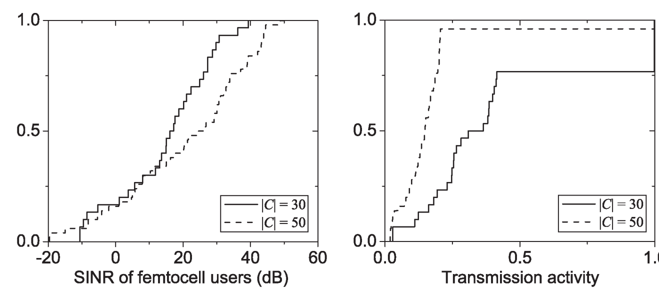

Fig. 5. CDF of FUs' achieved SINR (left) and FBSs' transmission activity (right) under different number of FBSs.

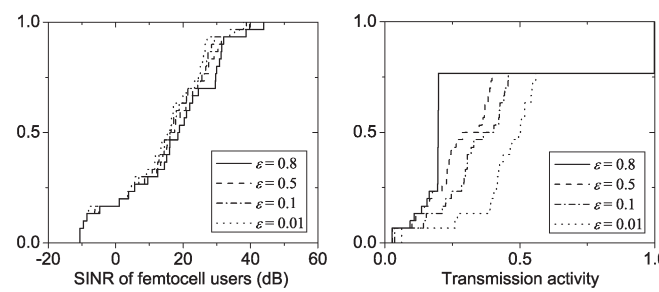

Fig. 6. CDF of FUs' achieved SINR (left) and FBSs' transmission activity (right) under different ε values.

according to the order of received signal strengths). Both b_{BS} and b_U are set to 0.1. For MU protection, the interference threshold I_k^{MU} is configured as -107 dBm. The utility function of $\alpha = 1$ is considered. Unless specified otherwise, the number of FBSs is 30, δ is set to 1.0 and ε_i is 0.3 for all i.

First, Fig. 3 shows the time evolutions of the utility-sum and the data rate of three users under different δ values. The figure shows that larger δ achieves faster convergence, but accompanies overshoot as well as oscillation (as observed in the utility-sum evolution when δ is 1.5). If δ gets larger than a certain threshold (1.6 in our case), the system diverges eventually.

The performance gain of ACoF with the coordinated muting scheme over full reuse of radio resource within each femtocell (i.e., $a_{i,k} = 1$ and $p_{i,k}^n = P_i^{\max}$) is plotted in Fig. 4 for MUs (left) and FUs (right). Since the transmit power of a FBS having a MU in close proximity is restricted by ACoF, MUs achieve higher SINR by up to 7.6 dB. The SINR of FUs is also improved by up to 23 dB. This is achieved by letting each FBS have a certain amount of interference-free time slots in which reliable data transfer at a high transmission speed is available.

Next, the effect of the number of FBSs (denoted by $|C|$) is studied in Fig. 5. The left figure shows that the increasing number of FBSs improves the SINRs of almost all FUs. This is because, as more FBSs are deployed, they are more likely to have neighbor cells and thus get coordinated with other cells. In other words, when $|C| = 30$, around 27% of FBSs have an empty neighbor set and thus use full radio resources with no limitation while possibly producing non-negligible interference to the femtocells in the neighborhood. This can be observed in the right figure; FBSs having no neighbor cell always transmit while the other FBSs use the transmission activity of at most 0.4. When $|C| = 50$, however, most FBSs have neighbor cells and their transmission activities are highly restricted below 0.2.

We also investigate the effect of ε_i in Fig. 6; we assume $\varepsilon_i = \varepsilon$ for $\forall i$. Higher ε makes FBSs to transmit less often (as can be seen in the right figure) and thus produce less interference to others, thus achieving higher SINR (in the left figure). While $\varepsilon = 0.01$ indicates that almost no interference-free time slots will exist, the determined transmission activity is still smaller than 1; this is due to the use of a logarithmic utility function (a femtocell cannot increase its activity over a certain point if other cells are suffering, for user fairness).

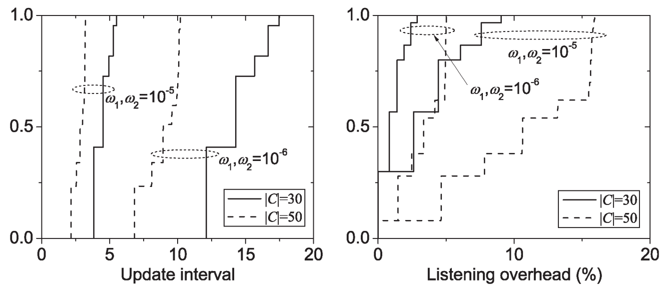

Fig. 7. CDF of FBSs' update interval (left) and overhead of listening to OTA signaling (right) under different number of FBSs and balancing constants.

Finally, we study the distribution of B_i (listening and update interval) and bandwidth overhead Ω^n, both of which are determined by the hybrid listening scheme described in Section VI-B, for different numbers of FBSs and balancing constants ω_1 and ω_2. For simplicity, we consider the case when ω_1 and ω_2 are identical. In Fig. 7, we can observe that femtocells use diverse update intervals due to different local conditions they experience and thus pay a wide range of listening overhead in each deployment case. Since ω_1 and ω_2 correspond to the weighting factor of the convergence-speed term in the cost function, we have smaller update intervals for larger ω_1 and ω_2. Conversely, a larger number of FBSs results in smaller intervals due to the increased number of neighbor cells.

IX. Conclusion

In this paper, we have presented an inter-cell coordination architecture, called ACoF, for large-scale femtocell deployments based on asynchronous signaling between cells. In ACoF, each femtocell updates the usage of radio resource based on the local information received from neighbor cells at a cell-specific signaling rate that may be outdated. Despite such asynchronous and distributed behavior, ACoF guarantees convergence of a network under the given condition of configuration parameters and mitigates inter-layer/cell interference.

There remain several issues to be studied, such as redesign of existing resource coordination schemes within the framework of ACoF, finding a tighter bound of the step size, extending ACoF for implicit signaling (cognition of a local condition without signaling), and designing a new framework with relaxed convergence constraints.

Appendix I
Extended Descent Lemma

The following holds for F[6]:

$$F(\mathbf{x}+\boldsymbol{\gamma}^T\mathbf{s}) \le F(\mathbf{x}) + \boldsymbol{\gamma}^T\nabla F(\mathbf{x}) + \sum_l K_2^l \gamma_l^2 |s_l|^2 \qquad (41)$$

where $K_2^l := \frac{v_i^+}{4}[(K_1^l)^2+1], l \in V_i$ and $v_i^+ := \sum_{j\in C_i} v_j$.

[6]It is used for the proof of Proposition 3. According to the descent lemma in [28], if $\|\nabla g(\mathbf{x}) - \nabla g(\mathbf{y})\| \le K\|\mathbf{x}-\mathbf{y}\|$ for $\forall \mathbf{x},\mathbf{y}$, $g(\mathbf{x}+\mathbf{y}) \le g(\mathbf{x}) + \mathbf{y}^T\nabla g(\mathbf{x}) + \frac{K}{2}\|\mathbf{y}\|^2$ where K is a universal Lipschitz constant for all dimensions of $\mathbf{x}$. Since we consider dimension-specific Lipschitz constants, we call the new lemma by the extended version of this.

Proof: We follow a procedure similar to the one used in [28]. Let $F'(a) = F(\mathbf{x}+a\mathbf{y})$ and $a \in R$. Then,

$$\begin{aligned}
&F(\mathbf{x}+\mathbf{y}) - F(\mathbf{x}) \\
&= F'(1) - F'(0) = \int_0^1 \frac{dF'}{da}(a)da = \int_0^1 \mathbf{y}^T\nabla F(\mathbf{x}+a\mathbf{y})da \\
&\le \int_0^1 \mathbf{y}^T\nabla F(\mathbf{x})da + \left|\int_0^1 \mathbf{y}^T\left(\nabla F(\mathbf{x}+a\mathbf{y}) - \nabla F(\mathbf{x})\right)da\right| \\
&\le \int_0^1 \mathbf{y}^T\nabla F(\mathbf{x})da + \int_0^1 \sum_l |y_l|\,|\nabla_l F(\mathbf{x}+a\mathbf{y}) - \nabla_l F(\mathbf{x})|da \\
&\le \int_0^1 \mathbf{y}^T\nabla F(\mathbf{x})da + \int_0^1 \sum_{i\in C;l} |y_l| K_1^l a \|\mathbf{y}_i\| da \\
&= \mathbf{y}^T\nabla F(\mathbf{x}) + \sum_{i\in C;l} K_1^l |y_l| \|\mathbf{y}_i\| \int_0^1 a da \\
&= \mathbf{y}^T\nabla F(\mathbf{x}) + \frac{1}{2}\sum_{i\in C}\sum_{l\in V_i} K_1^l |y_l| \left(\sum_{j\in C_i}\sum_{l'\in V_j} |y_{l'}|^2\right)^{1/2} \\
&\le \mathbf{y}^T\nabla F(\mathbf{x}) + \frac{1}{2}\sum_{i\in C}\sum_{l\in V_i} K_1^l |y_l| \left(\sum_{j\in C_i}\sum_{l'\in V_j} |y_{l'}|\right) \\
&\le \mathbf{y}^T\nabla F(\mathbf{x}) + \frac{1}{4}\sum_{i\in C}\sum_{l\in V_i}\sum_{j\in C_i}\sum_{l'\in V_j} \left[\left(K_1^l\right)^2 |y_l|^2 + |y_{l'}|^2\right]
\end{aligned}$$

where the last inequality follows from the Cauchy-Schwarz inequality.[7] □

Appendix II
Proof of Proposition 2

The gap between a cell's true status x_l and the status x_l^i known to cell i at time t is bounded as

$$\begin{aligned}
\left|x_l^i(t) - x_l(t)\right| &= \left|x_l\left(\tau_l^i(t)\right) - x_l(t)\right| \\
&= \left|\sum_{\tau=\tau_l^i(t)}^{t-1} \gamma_l s_l(\tau)\right| \le \sum_{\tau=\tau_l^i(t)}^{t-1} \gamma_l\left|s_l(\tau)\right| \\
&\le \sum_{\tau=t-B_i}^{t-1} \gamma_l\left|s_l(\tau)\right|. \qquad (42)
\end{aligned}$$

Therefore, we obtain

$$\begin{aligned}
\left\|\mathbf{x}_i^i(t) - \mathbf{x}_i(t)\right\| &= \left(\sum_{j\in C_i}\sum_{l\in V_j}\left|x_l^i(t) - x_l(t)\right|^2\right)^{1/2} \\
&\le \left(\sum_{j\in C_i}\sum_{l\in V_j}\left(\sum_{\tau=t-B_i}^{t-1}\gamma_l\left|s_l(\tau)\right|\right)^2\right)^{1/2} \qquad (43)
\end{aligned}$$

which becomes Ineq. (2) by applying the fact $x^2+y^2 \le (x+y)^2$ for $x, y \ge 0$. □

[7]$\left(\sum_{i=1}^n x_i\right)^2 \le n\sum_{i=1}^n |x_i|^2$.

APPENDIX III
PROOF OF PROPOSITION 3

Applying the extended descent lemma and performing algebraic manipulations,

$$\begin{aligned}
&F(\mathbf{x}(t+1)) \\
&= F\left(\mathbf{x}(t)+\boldsymbol{\gamma}^T\mathbf{s}(t)\right) \\
&\le F(\mathbf{x}(t)) + \sum_l \gamma_l s_l(t)\nabla_l F(\mathbf{x}(t)) + \sum_l K_2^l\gamma_l^2 s_l^2(t) \\
&= F(\mathbf{x}(t)) + \sum_{i\in C;l} \gamma_l s_l(t)\nabla_l F\left(\mathbf{x}^i(t)\right) \\
&\quad + \sum_{i\in C;l}\gamma_l s_l(t)\left(\nabla_l F(\mathbf{x}(t)) - \nabla_l F\left(\mathbf{x}^i(t)\right)\right) + \sum_l K_2^l\gamma_l^2 s_l^2(t) \\
&\le F(\mathbf{x}(t)) - \sum_l \gamma_l\left|s_l(t)\right|^2 + \sum_l K_1^l\gamma_l s_l(t)\cdot\left\|\mathbf{x}_i(t)-\mathbf{x}_i^i(t)\right\| \\
&\quad + \sum_l K_2^l\gamma_l^2\left|s_l(t)\right|^2. \qquad (44)
\end{aligned}$$

Substituting Ineq. (2) in the above equation to obtain

$$\begin{aligned}
&F(\mathbf{x}(t+1)) \\
&\quad\le F(\mathbf{x}(t)) - \sum_l \gamma_l\left(1-K_2^l\gamma_l\right)\left|s_l(t)\right|^2 \\
&\qquad + \sum_{i\in C;l}\sum_{j\in C_i;l'}\sum_{\tau=t-B_i}^{t-1} K_1^l\gamma_l\left|s_l(t)\right|\gamma_{l'}\left|s_{l'}(\tau)\right|. \qquad (45)
\end{aligned}$$

We then rewrite the last term using the inequality $2\gamma_l|s_l(t)|\gamma_{l'}|s_{l'}(\tau)| \le (\gamma_l|s_l(t)|)^2 + (\gamma_{l'}|s_{l'}(\tau)|)^2$ as

$$\begin{aligned}
&\frac{1}{2}\sum_{i\in C;l}\left(B_i\sum_{j\in C_i} v_j\right)K_1^l\gamma_l^2\left|s_l(t)\right|^2 \\
&\quad + \frac{1}{2}\sum_{i\in C;l}\sum_{j\in C;l'} d_{ij}\sum_{\tau=t-B_i}^{t-1} K_1^l\gamma_{l'}^2\left|s_{l'}(\tau)\right|^2 \\
&= \frac{1}{2}\sum_{i\in C}\sum_{l\in V_i}\left(B_i\sum_{j\in C_i} v_j\right)K_1^l\gamma_l^2\left|s_l(t)\right|^2 \\
&\quad + \frac{1}{2}\sum_{j\in C}\sum_{l'\in V_j}\sum_{i\in C}\sum_{l\in V_i} d_{ji}\sum_{\tau=t-B_i}^{t-1} K_1^l\gamma_{l'}^2\left|s_{l'}(\tau)\right|^2 \\
&= \frac{1}{2}\sum_{i\in C}\sum_{l\in V_i}\left(B_i\sum_{j\in C_i} v_j\right)K_1^l\gamma_l^2\left|s_l(t)\right|^2 \\
&\quad + \frac{1}{2}\sum_{i\in C}\sum_{l\in V_i}\sum_{j\in C_i}\sum_{l'\in V_j}\sum_{\tau=t-B_j}^{t-1} K_1^{l'}\gamma_l^2\left|s_l(\tau)\right|^2 \qquad (46)
\end{aligned}$$

and thus obtain

$$\begin{aligned}
&F(\mathbf{x}(t+1)) \\
&\le F(\mathbf{x}(t)) - \sum_{i\in C}\sum_{l\in V_i}\gamma_l\left[\left(1-K_2^l\gamma_l-\frac{K_1^l\gamma_l B_i}{2}\sum_{j\in C_i} v_j\right)\left|s_l(t)\right|^2\right. \\
&\qquad\left. + \frac{1}{2}\sum_{j\in C_i}\sum_{l'\in V_j}\sum_{\tau=t-B_j}^{t-1} K_1^{l'}\gamma_l\left|s_l(\tau)\right|^2\right]. \qquad (47)
\end{aligned}$$

By adding these inequalities for different t, we obtain

$$F(\mathbf{x}(t+1)) = F(x(0)) - \sum_{\tau=0}^{t}\sum_l \gamma_l(1-\gamma_l/\Gamma_l)\left|s_i(\tau)\right|^2 \qquad (48)$$

where Γ_l is defined as Eq. (12). Suppose that $\gamma_l \in (0, \Gamma_l)$. $F_\infty := \lim_{t\to\infty} F(x(t))$ is nonnegative since it is the optimal duality gap. Thus, if we let t approach infinity, the above inequality becomes

$$\sum_{\tau=0}^{\infty}\sum_l \gamma_l(1-\gamma_l/\Gamma_l)\left|s_l(\tau)\right|^2 \le F(x(0)) < \infty \qquad (49)$$

which implies that $\lim_{t\to\infty} s_l(t) = 0, \forall l$ since γ_l and $1-\gamma_l/\Gamma_l$ are finite positive constants. □

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Ji-Hoon Yun (M'11) received the B.S. degree in electrical engineering from Seoul National University (SNU), Seoul, Korea, in 2000, and both the M.S. and Ph.D. degrees in electrical engineering and computer science from SNU in 2002 and 2007, respectively. He is currently an Assistant Professor in the Department of Electrical and Information Engineering, Seoul National University of Science and Technology (SeoulTech), Seoul, Korea. Before joining SeoulTech in March 2012, he was with the Department of Computer Software Engineering, Kumoh National Institute of Technology (KIT) as an Assistant Professor. He was a Postdoctoral Researcher in the Real-Time Computing Laboratory (RTCL), The University of Michigan, Ann Arbor, MI, USA, in 2010 and a Senior Engineer at the Telecommunication Systems Division, Samsung Electronics, Suwon, Korea from 2007 to 2009. His current research focuses on wireless networks and efficient computing of mobile devices.

Kang G. Shin (S'75–M'78–SM'83–F'92–LF'12) is the Kevin & Nancy O'Connor Professor of Computer Science in the Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, MI, USA. His current research focuses on QoS-sensitive computing and networking as well as on embedded real-time and cyber-physical systems.

He has supervised the completion of 75 PhDs, and authored/coauthored more than 830 technical articles, a textbook and more than 30 patents or invention disclosures, and received numerous best paper awards, including the Best Paper Awards from the 2011 ACM International Conference on Mobile Computing and Networking (MobiCom'11), the 2011 IEEE International Conference on Autonomic Computing, the 2010 and 2000 USENIX Annual Technical Conferences, as well as the 2003 IEEE Communications Society William R. Bennett Prize Paper Award and the 1987 Outstanding IEEE Transactions of Automatic Control Paper Award. He has also received several institutional awards, including the Research Excellence Award in 1989, Outstanding Achievement Award in 1999, Distinguished Faculty Achievement Award in 2001, and Stephen Attwood Award in 2004 from The University of Michigan (the highest honor bestowed to Michigan Engineering faculty); a Distinguished Alumni Award of the College of Engineering, Seoul National University in 2002; 2003 IEEE RTC Technical Achievement Award; and 2006 Ho-Am Prize in Engineering (the highest honor bestowed to Korean-origin engineers).

He was a co-founder of a couple of startups and also licensed some of his technologies to industry.