Duality on Timing Alignment and Radio Resources Orthogonality Toward 5G Heterogeneous Networks

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***Abstract*—The heterogeneous network (HetNet) architecture unprecedentedly reusing spectrum faces a critical challenge of interference mitigation among *cells*. For this goal, existing solutions successfully reaching resource orthogonality, however, impose critical assumptions of ubiquitous synchronization among all cells. Lacking of an effective network synchronization scheme, the installation of existing solutions is obstructed. This challenge motivates us to comprehensively study all-embracing solutions including two categories: synchronous and asynchronous based resource orthogonality schemes. In the first category, to be compatible with existing synchronous resource orthogonality techniques, we propose a series of timing alignment schemes by innovations of *gossip algorithm* and *voter algorithm*. In the second category, we avoid the synchronous framework to propose an asynchronous resource management inspired from *game theory*. The equally outstanding performance in both categories reveals an engineering duality on timing alignment and resource orthogonality, to provide foundations and design paradigm shifts toward the fifth generation (5G) HetNet.**

I. Introduction

To fulfill requirements as the fourth generation (4G) and fifth generation (5G) cellular networks, spectrum efficiency of existing systems (e.g., WCDMA, HSPA, and LTE) shall be significantly enhanced. Recently, LTE-A adopts an advanced evolution of the distributive multi-antenna technology: the *heterogeneous network* (HetNet) architecture to fully reuse available spectrum in the spatial domain. In the HetNet, in addition to conventional Macrocells, there is a considerable number of femtocells underlaying Macrocells. However, the key for a successful practice of the HetNet is an effective interference control to prevent unacceptable interference among femtocells and the underlaying Macrocell.

In light of the HetNet architecture in LTE-A, there is no dedicated and direct interfaces between Macrocell base stations (BSs) and femtocell BSs. As a result, centralized coordination between femtocells and Macrocells (inter-tier), and among femtocells (intra-tier), is unavailable. To cope with technical issues of autonomous interference mitigation in the co-channel deployment femtocells (i.e., all Macrocells and femtocells operate on common spectrum), recent research has suggested a variety of promising solutions to effectively achieve resource blocks (RBs) orthogonality among all cells within the HetNet, such as the cognitive radio resource management [1]–[3], statistical spectrum access [4], and auction/game theoretic spectrum access [5]. These solutions are based on an ideal assumption of perfect timing synchronization between femtocells and Macrocells, and among all femtocells. However, achieving this assumption is never an easy task. To enabling ubiquitous timing synchronization in the HetNet such that all cells are synchronized with each other, existing solutions include using Global Positioning System (GPS) and IEEE 1588. However, the GPS signal is very susceptible to penetration loss of building walls, which is infeasible for the indoor deployment. IEEE 1588 is proposed to deliver timing information from a synchronization server to all femtocell BSs through wired backhaul. However, in LTE-A, each femtocell BS connects to the network via users' own connectivity (such as asymmetric DSL or optic fiber lines) through a number of intermediate nodes. As a result, measuring the delay and jitter of packets carrying timing stamps is a very challenging task.

Without proper interfaces to neighboring cells, each femtocell BS can only utilize synchronization signals from Macrocell BSs, or from neighboring femtocell BSs. However, there are two challenges. First, if a femtocell BS can not receive synchronization signals from Macrocell BSs, this femtocell BS should synchronize with the neighbor femtocell BS achieving successful timing alignment with a Macrocell. However, a femtocell BS may not know which one of its neighbor femtocell BSs achieves successful timing alignment with a Macrocell. Second, if none of neighboring femtocells is able to receive synchronization signals from a Macrocell, timing alignment among femtocells still needs to be ensured. To tackle these challenges, there are two options. (i) We shall explore an effective scheme to achieve ubiquitous timing synchronization, for both cases that there is a femtocell BS able to synchronize to a Macrocell, and none of femtocell BSs is able to synchronize to a Macrocell. (ii) We renounce existing synchronous radio resource orthogonality schemes to develop a novel asynchronous resource orthogonality framework. It is difficult to identify the better option, unless we can develop effective schemes for both options. Consequently, in this paper, we devote to propose solutions for both synchronous and asynchronous radio resource orthogonality schemes in the HetNet. For the first option, we propose two potential timing alignment frameworks for femtocells of *gossip algorithm* [6] and *voter algorithm* to achieve ubiquitous synchronization within the HetNet. For the second option, we renounce reaching ubiquitous synchronization in the HetNet. However, without timing alignment, errors in interference estimation and detection dramatically increase. To optimally control interference

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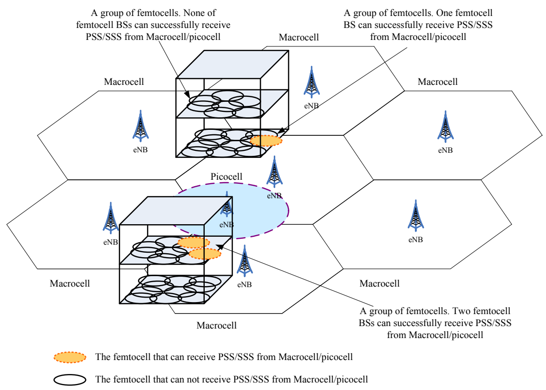

Fig. 1. In the enterprise deployment, femtocells are deployed in groups to provide seamless wireless services. Due to severe penetration loss of signals on building walls, only a small part of femtocells (or even none of femtocells) can receive synchronization signals from Macrocell.

in an autonomous sense, game theory is adopted to develop foundations of an asynchronous resource management. In this paper, our propositions provide sufficient results to evaluate the performance of these two options to select the outstanding framework for the 5G cellular networks.

II. System Model

For all possible deployment scenarios of femtocells, the enterprise deployment can be the most challenging case. As shown in Fig. 1, M femtocell BSs are deployed within a building. To provide continuous wireless services for users with mobility, femtocells are deployed in groups. Each group is composed of a number of femtocells with coverage areas overlapped with each other to form a *quasi-complete graph*. Because of penetration loss, only femtocell BSs located closely to outer walls may receive synchronization signals from Macrocell BSs. Thus, there are two classes of groups: the group of femtocells with a small number of femtocell BSs able to receive synchronization signals from Macrocell BSs, and the group of femtocells without femtocell BSs able to receive synchronization signals from Macrocell BSs.

For femtocell BSs without synchronization signal from a Macrocells BS, an ubiquitous synchronization can only be achieved by synchronizing to neighboring femtocells. However, in LTE-A, communications among femtocell BSs are unavailable. Thus, a femtocell BS does not know whether and which of its neighboring femtocell BSs achieves successful synchronization to a Macrocell BS. For these femtocell BSs, an essential scheme is required to ensure synchronization within a group under following constraints. (i) The knowledge of whether and which of femtocell BSs in a group can synchronize to the Macrocell BS should be avoided. (ii) If none of femtocell BSs can synchronize to a Macrocell BS, synchronization among all femtocells shall be achieved. (iii) The scheme shall yield a low computational complexity.

III. Synchronization within the HetNet

A. Gossip Based Synchronization Scheme

To achieve consensus/convergence of different values taken by each individual, an effective approach from foundations of mathematics is taking the *convex combination* of different values. This is the spirit of the *Gossip Algorithm* [6] widely applied to distributive/in-network computation for the fast averaging problem with continuous changes of connections among nodes and the taken values. The beauties of a low complexity and avoidance of any prior knowledge on nodes in the *convex combination* inspire us to develop a synchronization scheme for femtocells based on *gossip algorithm*.

Gossip Based Synchronization Scheme

Step 1 At each subframe, a femtocell BS decides whether to proceed synchronization according to an independent and identically distributed (i.i.d.) Poisson process (that is, a Poisson clock).

Step 2 Upon the expiration of Poisson clock, a femtocell BS that can receive synchronization signals from a Macrocell BS synchronizes to the Macrocell BS by the conventional synchronization procedure adopted by UEs.

Step 3 Upon the expiration of the Poisson clock, if a femtocell BS can no successfully receive synchronization signals from a Macrocell BS, it randomly selects $n \leq N$ neighboring femtocell BSs to receive the broadcasted synchronization signals, where N is the number of neighboring femtocell BSs in the group. Denote the current timing of the femtocell BS as x_0 and the current timing of the nth neighboring femtocell BSs as $x_1, \ldots, x_n$. x_0 is updated by

$$x_0 = \sum_{i=0}^{n} \lambda_i x_i, \tag{1}$$

where $\sum_{i=1}^{n} \lambda_i = 1$ and $\lambda_i \geq 0$ for all i.

For the femtocell BS that can not receive synchronization signals from the Macrocell, (1) can be described by the equation of the form

$$x_0^{t+1} = W(t)\mathbf{x}^t, \tag{2}$$

where x_0^{t+1} is the timing of the considered femtocell BS after $t+1$ iterations, $\mathbf{x}^t = [x_0^t, x_1^t, \ldots, x_n^t]^{\mathrm{T}}$ and $W(t)$ is an $(n+1) \times (n+1)$ matrix. Please note that, since $\lambda_0, \lambda_1, \ldots, \lambda_n$ are randomly and independently selected across the time, $W(t)$ is independent across the time. Under the enterprise deployment, the following theorem suggests the timing convergence of the proposed gossip based synchronization scheme.

Theorem 1. *For all femtocells under the enterprise deployment adopting our gossip based synchronization scheme, all timings of femtocells converge to a common value.*

Proof: To prove the convergence, we firstly need to show that $W(t)$ is a projection matrix. That is, $W^2(t) = W(t)$. If $W(t)$ is a projection matrix, $W(t)$ shall satisfy

$$\mathbf{1}^T W(t) = \mathbf{1}^T \text{ and } W(t)\mathbf{1} = \mathbf{1}. \tag{3}$$

That is, $W(t)$ shall be *doubly stochastic*. Since the well known Birkhoff-von Neumann theorem suggests that a matrix is *doubly stochastic* if and only if the matrix is a convex combination of permutation matrices. Since x_0^t is updated by the convex combination of $x_0^t, x_1^t, \ldots, x_n^t$, (1) suggests that $W(t)$ is *doubly stochastic*. Therefore, the evolution of x_0^{t+1}

can be expressed by

$$x_0^{t+1} = W(t)\mathbf{x}^t = \prod_{k=0}^{t} W(k)\mathbf{x}^0. \quad (4)$$

Since $W(t)$ is selected independently across the time, the expectation of (4) can be written by

$$\mathbb{E}x_0^{t+1} = \mathbb{E}(\prod_{k=0}^{t} W(k))\mathbf{x}^0 = (\mathbb{E}W)^{t+1}\mathbf{x}^0. \quad (5)$$

Since $\mathbb{E}W$ is a convex combination of $W(t)$, $\mathbb{E}W$ is also *doubly stochastic*. In addition, since femtocells are deployed as a quasi-complete graph, the expected evolution of x_0^{t+1} follows an irreducible and aperiodic Markov chain that has $\sum_{i=0}^{n} \lambda_i x_i^t$ as the stationary distribution. Thus, we complete the proof of convergence to $\sum_{i=0}^{n} \lambda_i x_i^t$ ■

In the gossip algorithm, the convergence rate depends on the network topology. We characterize the convergence rate of the proposed gossip based synchronization scheme as follows.

Definition 1. *The ϵ-convergence time is the earliest iteration in which $\boldsymbol{x}^t$ is ϵ close to the normalized consensus with probability larger than $1-\epsilon$,*

$$T_{con}(\epsilon) = \sup_{\boldsymbol{x}^0} \arg \inf_{t=0,1,\ldots} \{\mathbb{P}(\frac{\|\boldsymbol{x}^t - \sum_{i=0}^{n} \lambda_i x_i^t\|}{\|\boldsymbol{x}^0\|} \geq \epsilon) \leq \epsilon\}. \quad (6)$$

Theorem 2. *The convergence rate of the proposed gossip based synchronization scheme is given by $T_{con}(\epsilon) = \Theta(M^2 \log \epsilon^{-1})$.*

Proof: From [6], it is known that

$$T_{con}(\epsilon) = \Theta(\frac{\log \epsilon^{-1}}{1 - \lambda_2(\mathbb{E}W)}), \quad (7)$$

where $\lambda_2(\mathbb{E}W)$ is the second largest eigenvalue of the matrix $\mathbb{E}W$. For the considered quasi-complete graph deployment, it has been shown that $\lambda_2(\mathbb{E}W) = 1 - \frac{1}{M^2}$ [6]. Therefore, $T_{con}(\epsilon) = \Theta(M^2 \log \epsilon^{-1})$. ■

B. Voter Based Synchronization Scheme

The voter based synchronization scheme is a special case of the gossip based scheme. A femtocell BS updates its timing to that of only one randomly selected femtocell BS. As a result, the number of femtocells with distinct timings can decrease exponentially. Although the voter based synchronization scheme is able to enhance the convergence rate, gossip algorithm suffers from a technical defect. If there is one femtocell BS whose timing synchronization device is out of order, then the timings of all femtocell BSs converge to an error value. To avoid such technical defect, we can introduce the concept of "majority". That is, the minority timing (i.e., the number of femtocell BSs with this timing is the minority in the group) should follow the majority timing in the group. To enable this capability, each femtocell BS (say the ith femtocell BS) holds a counter $C_i^{x_i}$ initially set to 0, where x_i is the timing of the ith femtocell BS, and performs the proposed robust voter based synchronization scheme detailed in the following.

Robust Voter Based Synchronization Scheme

Step 1 At each subframe, a femtocell BS decides to proceed synchronization according to an i.i.d. Poisson clock.

Step 2 Upon the expiration of the Poisson clock, a femtocell BS randomly selects one neighboring (say the ith) femtocell BS to receive the broadcasted synchronization signals.

Step 2a The current timing x_0 is updated by $x_0 = x_i$ if

$$C_i^{x_i} = 0, \ x_0 \neq x_i, \ \text{and} \ C_0^{x_0} = K, \quad (8)$$

where K is a memory threshold of the counter.

Step 2b If $C_0^{x_0} \neq K$, then $C_0^{x_0} = C_0^{x_0} + 1$

Step 2c If $C_i^{x_i} = 0$ and $x_0 = x_i$, then $C_0^{x_0} = 0$.

By appropriately setting K, a femtocell BS updates its timing to that of the neighboring femtocell BS only if the timing of the neighboring femtocell BS has been updated to the majority timing and the femtocell BS has checked about this for K times. By such an enhancement, the error timing from a femtocell BS with an out of order synchronization device is eliminated from the convex combination to avoid impacts to the timing consensus in the group.

IV. Asynchronous Radio Resource Management

Losing synchronization within the HetNet may invoke severe interference. If timing misalignment within the HetNet is a common knowledge in the HetNet, a special autonomous radio resource management strategy may be developed to further improve the performance. Similar to the synchronous design principle, to mitigate interference between the Macrocell and the femtocell, and among femtocells, a femtocell BS shall avoid utilizing radio resources occupied by other cells. To achieve this goal, each femtocell BS should sense the channel for a certain duration $t_{s,i}$ within [0,t_{pac}], and allocates a radio resource to the attached UE only if this radio resource is not occupied in $t_{s,i}$. From the Macrocell's perspective, femtocell BSs shall sense the channel for a sufficiently long period to prevent miss detection. From the femtocells' point of view, a large $t_{s,i}$ is an overhead degrading the throughput of the femtocell. Furthermore, a longer $t_{s,i}$ also yields resource access opportunities to neighboring femtocells if neighboring femtocell BSs adopt a shorter $t_{s,j}$. It is consequently a *sensing-throughput tradeoff* when multiple femtocell BSs simultaneously compete radio resources. Such a sensing-throughput tradeoff can be characterized by formulating the utility function of each (say, the ith) femtocell BS as

$$U_{FEMTO,i} = U_{s,i} + U_{c,i}, \quad (9)$$

where $U_{s,i}$ counts for successful transmissions, while $U_{c,i}$ counts for collisions with the Macrocell. $U_{s,i}$ can be specified by examining two cases. In Case 1, the ith femtocell BS wins the radio resource competition given that ith femtocell BS completes the sensing phase in the first place among all other femtocell BSs. Under the present timing error between the Macrocell and the ith femtocell BS Δt_i due to the lack of knowledge about the Macrocell's timing, the expected payoff of Case 1 is given by

$$U_{s1,i} = \int_{t_{min}}^{t_{max}} \int_{t_{min}}^{g_1} \cdots \int_{t_{min}}^{g_M} [b_i(t_{pac} - t_{s,i} - Y)] \times dF(\Delta t_M) \cdots dF(\Delta t_1) dF(\Delta t_i). \quad (10)$$

In (10), b_i is the transmission data rate of a femtocell BS without interference, $g_j = \min\max \Delta t_i - t_{s,i} + t_{s,j}, t_{max}, t_{max}$ for $j = 1, \ldots, M, j \neq i$ denotes that all other femtocell BSs do not occupy radio resources before i. $F(\Delta t_i)$ is the truncated distributed of Δt_i. Y is a guard interval at the end of all femtocell BSs' subframes.

$$Y = |T_{min}| + |T_{max}|. \quad (11)$$

where $|T_{min}|$ is the minimum amount of time that a femtocell BS could possibly start to sense after the starting point of the subframe of the Macrocell. $|T_{max}|$ is the maximum amount of time that a femtocell BS could possibly start to sense prior to the starting point of the subframe of the Macrocell.

In Case 2, the ith femtocell BS wins the radio resource competition given that all other femtocell BSs belong to either category: (a) i starts to transmit before j, $\forall j \neq i$, and (b) j terminates $t_{s,j}$ in the previous subframe. This case leads to the expected payoff

$$\begin{aligned} U_{s2,i} &= \sum_{\Gamma_{j\neq i} \in \{I_{1,j}, I_{2,j}\}} \int_{t_{min}}^{t_{s,i}} \int_{\Gamma_1} \cdots \int_{\Gamma_M} b_i(t_{pac} - t_{s,i} - Y) \\ &\times \; dF(\Delta t_M) \cdots dF(\Delta t_1) dF(\Delta t_i). \end{aligned} \quad (12)$$

where $I_{1,j} = [t_{min}, g_j]$ stands for the ith femtocell BS in category (a), and $I_{2,j} = [t_{s,j}, t_{max}]$ stands for the ith femtocell BS in category (b). The summation stands for all combinations of femtocell BSs belonging to the two categories. Let θ be the probability that radio resources are occupied by the Macrocell at each subframe, which is a long statistics sensed by femtocell BSs, $U_{s,i}$ in (9) can be expressed by

$$U_{s,i} = (1-\theta)^2 U_{s1,i} + \theta(1-\theta) U_{s2,i} \quad (13)$$

Next, we examine the expected payoff of packet collision due to miss detection (as Case 3), which can be straightforwardly expressed by

$$\begin{aligned} U_{c3,i} &= \int_{t_{s,i}}^{t_{max}} \int_{t_{min}}^{g_1} \cdots \int_{t_{min}}^{g_M} c(t_{pac} - t_{s,i} - Y) \\ &\times \; dF(\Delta t_M) \cdots dF(\Delta t_1) dF(\Delta t_i). \end{aligned} \quad (14)$$

where c is the cost per unit time due to collision. We have

$$U_{c,i} = \theta(1-\theta) U_{c3,i}. \quad (15)$$

Without centralized coordination, femtocell BSs shall act in a distributed manner to determine $t_{s,i}$ that maximizes its own throughput. Such a selfish behavior motivates us to introduce *game theory*. With very limited complexity, determining a fixed sensing duration is an attractive solution. Such a sensing duration falls on the Nash equilibrium strategy that maximizes the utility of each femtocell BS.

Lemma 1. *The equilibrium strategy profile of sensing durations for each femtocell BS is given by* $\mathbf{S}^* = \{t^*_{s,1}, \ldots, t^*_{s,M}\}$ *that satisfies*

$$t^*_{s,i} = \arg_{t_{s,i}} \max U_{FEMTO,i}(t_{s,i}, \mathbf{S}^*_{-i}), \quad (16)$$

where $\mathbf{S}^*_{-i}$ *means the equilibrium strategy profile that does not include the strategy of the* i*th femtocell BS.*

Proof: (16) follows the definition of Nash equilibrium. ■

$U_{FEMTO,i}$ is composed of the benefit term $U_{s,i}$ and the cost term $U_{c,i}$. To maximize $U_{FEMTO,i}$, a parameter termed as the *benefit-to-cost ratio*

$$\gamma_i = \frac{U_{s,i}}{-U_{c,i}} \quad (17)$$

is introduced. Therefore, maximizing $U_{FEMTO,i}$ is equivalent to maximize γ_i. A larger γ_i indicates a larger benefit earned (e.g. the achievable data rate) given a cost paid (e.g. power consumption). For a femtocell BS with a higher γ_i, the potential (packet) collision with Macrocells due to a small sensing duration may be less harmful, since the large data rate in collision-free time intervals compensates the cost of collisions. The optimal sensing duration $t^*_{s,i}$ depends on the sensing duration of other femtocell BSs and γ_i of each femtocell BS. When all other femtoccell BSs protract the sensing duration, a femtocell BS may intend to decrease the sensing duration, as long as its γ_i is sufficiently high to alleviate the risk of collisions with Macrocells. In this game, the equilibrium profile $\mathbf{S}^*$ can be obtained by solving the intersection of all benefit-to-cost ratios of each femtocell BS.

Only maximizing $U_{FEMTO,i}$ for all femtocell BSs is not enough. To maximize the overall network performance, the (normalized) spectrum efficiency shall be maximized. The (normalized) spectrum efficiency can be characterized by

$$\begin{aligned} R &= (1-\theta)^2 \frac{t_{pac} - \mathbb{E}[T_1|\mathbf{S}] - Y}{t_{pac}} + (1-\theta)\theta(1-P_M)^M \\ &+ \theta(1-\theta)(1-P_F^M) \frac{t_{pac} - \mathbb{E}[T_3|\mathbf{S}] - Y}{t_{pac}} + \theta^2 \end{aligned} \quad (18)$$

as a portion of time for transmission without collisions. The first term in (18) aligns to the spectrum efficiency under the Case 1, where $\mathbb{E}[T_1|\mathbf{S}]$ specifies the expected overhead induced by channel sensing of femtocell BSs

$$\begin{aligned} \mathbb{E}[T_1|\mathbf{S}] &= \sum_{i=1}^{M} t_{s,i} \int_{t_{min}}^{t_{max}} \int_{t_{min}}^{g_1} \cdots \int_{t_{min}}^{g_M} \\ &\times \; dF(\Delta t_M) \cdots dF(\Delta t_1) dF(\Delta t_i). \end{aligned} \quad (19)$$

given the strategy profile $\mathbf{S} = [t_{s,1}, \ldots, t_{s,M}]$. The second term in (18) indicates the spectrum efficiency of a transmission in the Macrocell given that all femtocell BSs suspending their transmissions without miss detection. P_M is the probability of miss detection in each femtocell BS. The third term aligns to the spectrum efficiency of Case 2, where

$$\begin{aligned} &\mathbb{E}[T_3|\mathbf{S}] \\ &= \sum_{i=1}^{M} t_{s,i} \sum_{\Gamma_{j\neq i} \in \{I_{1,j}, I_{2,j}\}} \int_{t_{min}}^{t_{s,i}} \int_{\Gamma_1} \cdots \int_{\Gamma_M} b_i(t_{pac} - t_{s,i} - Y) \\ &\times dF(\Delta t_M) \cdots dF(\Delta t_1) dF(\Delta t_i). \end{aligned} \quad (20)$$

and P_F is the probability of false alarm of each femtocell BS. The last term is the spectrum efficiency of a transmission in the Macrocell without femtocell BSs' transmission.

To optimize overall network performance, we emphasize on the equilibrium maximizing R. Fig. 2 illustrates the upper

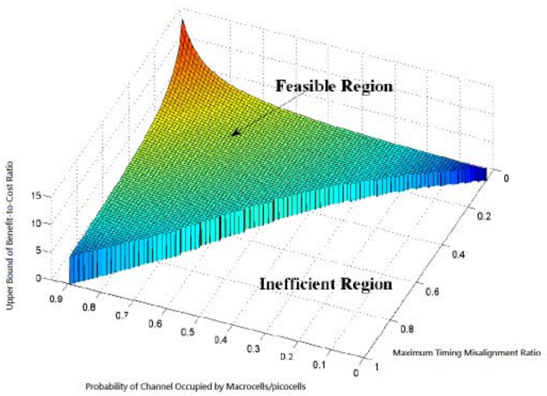

Fig. 2. The region in which the optimal equilibrium exists with respect to different values of the channel availability θ, the maximum timing misalignment $\alpha = t_m/(t_{pac} - Y)$ (where $|t_{max}| = |t_{min}| = t_m$), and the benefit-to-cost ratio.

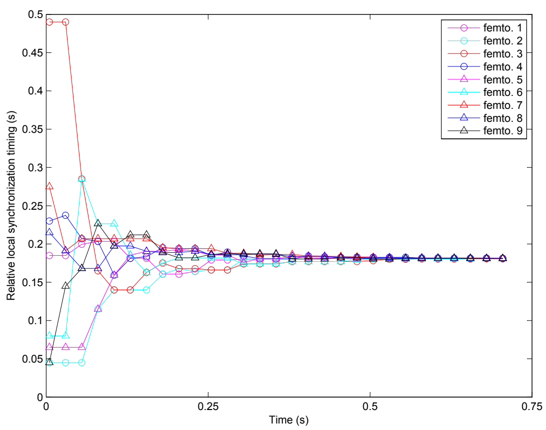

Fig. 3. Timing dynamics of 9 femtocells by adopting the gossip based synchronization scheme.

bound of γ_i for which the optimal equilibrium exists. When θ decreases, we may barely support the optimal equilibrium as indicated by the inefficient region where the optimal equilibrium does not exist. Given a probability of channel occupation by Macrocells, femtocell BSs with a γ_i choose to operate at the optimal equilibrium only if the level of timing misalignment α among femtocell BSs and Macrocells is small.

V. Performance Evaluation

To evaluate the effectiveness of timing alignment, we adopt nine femtocells in a group and none of femtocells can successfully synchronize to a Macrocell. Fig. 3 shows timing dynamics of nine femtocells, and all femtocells achieve timing alignment in 500ms. This performance is very acceptable in practice, as the time required for power-on procedures of a femtocell BS is around the level of seconds.

In Fig. 4, we evaluate the spectrum utilization with different levels of channel occupancy θ and timing misalignment α. The performance is compared with the sensing strategy $t_s = 5\mu s$, which is the minimal length for a reliable sensing result. Fig. 4 shows that a higher spectrum utilization can be achieved by operating at the optimal equilibrium for high θ. However, for low Macrocells traffic intensity, if the maximum timing

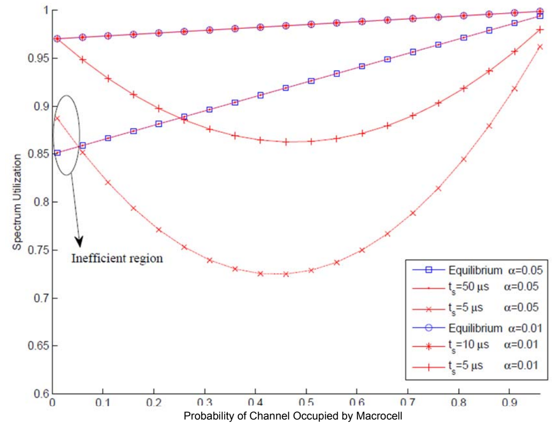

Fig. 4. Spectrum utilization comparison between the proposed asynchronous radio resource management at the optimal equilibrium and the radio resource management without considering the asynchronous nature between Macrocells and femtocell BSs

misalignment α is small, the spectrum utilization at the optimal equilibrium may be inferior to that of one-stage sensing, since a long sensing period from the optimal equilibrium solution leads to a conservative design in view of small probability of Macrocells occupancy. These results show that our asynchronous radio resource management achieves a considerably high spectrum utilization (exceeding 85%) for practice.

VI. Conclusion

In this paper, (i) our synchronization schemes effectively achieve timing consensus in the HetNet without imposing any system impacts to existing LTE-A architecture. Such technical merits eliminate technology gap to practice existing synchronous radio resource orthogonality schemes [1]–[5]. (ii) The practicable spectrum efficiency (exceeding 85%) in our asynchronous resource management also proves the effectiveness of an asynchronous design. These remarks reveal an engineering duality on the timing alignment and resource orthogonality. To mitigate interference, synchronous design and asynchronous design can be equivalent in terms of performance. Our propositions broaden the design principle to open a new research frontier toward the 5G network.

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