A New Distributed Approach for Achieving Clock Synchronization in Heterogeneous Networks

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***Abstract*—Heterogeneous networks have the potential to improve coverage, throughput, and energy efficiency of wireless networks through the use of specialized cellular structures, in particular femtocells and macrocells. However, to reduce interference between different cells, ensure smooth hand-offs from cell to cell, and achieve seamless operation the overall network needs to be synchronized. In this paper a new distributed clock synchronization scheme for heterogeneous networks is proposed that employs the *clock drift ratio (CDR)* information available at user-equipments (UEs) to achieve synchronization between non-interacting femtocells and macrocells. Simulation results show that the proposed scheme can significantly reduce the clock drift between macrocells and femtocells and result in timing synchronization throughout the network without introducing significant overhead.**

***Index Terms*—Heterogeneous networks, two-tier, synchronization, macrocell, femtocell, clock drift, timing offset.**

I. Introduction

Recent studies have shown that a sizable proportion of cellular communications takes place in indoor environments [1], [2]. However, due to significant signal attenuation from the base station to the indoor user, current cellular networks used by operators are not well equipped to fully support high data rates required by users in indoor settings. Heterogeneous networks have the potential to improve the indoor coverage and capacity of cellular networks by employing small, inexpensive, and short range cellular access points or femtocells in conjunction with the existing large base stations or macrocells [1]–[6]. Note that in addition to improving throughput and coverage, femtocells are also capable of improving the energy efficiency of cellular networks at both the base station and end users, which results in reduced costs for operators and longer battery life for users [1], [3]–[7].

The macrocells and femtocells, i.e., the two tiers of a heterogeneous network can be designed to operate in different frequency spectra or can share available spectrum. The former tier relaxes stringent timing synchronization requirements on the network and reduces interference between tiers while the latter more efficiently utilizes the available spectrum and enables smoother operation and deployment. Note that due to the scarcity and cost of spectrum, it may be more advantageous for macrocells and femtocells within the network to operate in the same frequency band [1], [5], [6]. Therefore, to reduce interference between different tiers and ensure smooth hand-offs from tier to tier it is important to ensure that the overall network achieves timing synchronization.

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A. Related work

Unlike macrocells that are equipped with very high accuracy oscillators, the inexpensive hardware requirements of femtocells requires the use of low cost and low accuracy oscillators. Therefore, to achieve timing synchronization between tiers in the network, femtocells need to synchronize their clocks to those of macrocells. Many different schemes have been proposed that seek to achieve timing synchronization in two-tier networks [1]. These methods can be divided into approaches that take advantage of synchronization sources within the network (*internal sensing*), e.g., the signal from neighbouring macrocells [1], femtocells [8], [9], and mobile users [10]–[12] and also the backbone connection [13]–[15] or algorithms that employ synchronization sources from outside the network (*external sensing*), e.g., *global positioning systems (GPS)* [1] and TV signals [16]. The pros and cons of each scheme are briefly summarized below:

- Macrocells are very reliable sources of timing synchronization, since they are equipped with high-accuracy oscillators [1]. However, in most indoor settings the signal from macrocells is significantly attenuated[1]. Therefore, use of macrocell signals for the purpose of synchronizing femtocells can result in delay and/or severe timing offset estimation errors.
- In [8], [9], the signal from neighbouring femtocells is used to achieve synchronization throughout the two-tier network. However, such an approach is only possible if the areas of coverage of many femtocells overlap one another. In addition, the approach in [8], [9] does not provide any means of synchronizing femtocells and macrocells with one another. The latter is essential for

[1]This combined with a potentially free *asymmetric digital subscriber line (ADSL)* backhaul link are the main reasons behind the deployment of femtocells.

successful hand-offs and lower interference between macrocells and femtocells.

- Users that travel between macrocells and femtocells can estimate the timing offsets between different cells, which can be then shared with different access points to achieve synchronization throughout the two-tier network [10]–[12]. However, as shown in this paper and in [9], timing offsets between different tiers in the network are greatly dependent on the oscillator accuracies and vary quickly with time. Thus, even though these decentralized approaches have many advantages, the synchronization accuracies of the schemes proposed in [10]–[12] are greatly affected by the travel patterns of users and can suffer from significant clock bias.
- Use of the IEEE 1588 standard and the backbone network for achieving timing synchronization in two-tier networks has been proposed in [13]–[15]. However, IEEE 1588 is a bandwidth intensive protocol. The backbone network suffers from delays due to the latencies in the *internet protocol (IP)*, and the timing estimation accuracy of such an approach can be adversely affected by the different downlink and uplink speeds of the backbone network.
- Even though a GPS receiver can be a very accurate source of timing synchronization, in most indoor environments the GPS signal is so severely attenuated that it cannot be used for synchronization.
- Broadcast TV signals are widely available in most countries. In addition, given that TV signals are transmitted over lower frequencies, they can easily penetrate most buildings very well compared to GPS signals. Finally, since the receiver only needs to extract the timing information from the TV signal, it can be manufactured at low cost [16]. However, unlike GPS signals, TV signals do not have world wide coverage and the design of TV receivers is area dependent. Moreover, traditional TV signals available in most areas around the world do not contain accurate timing synchronization information [1].

B. Contributions

This paper first formulates the problem of clock synchronization in heterogeneous networks. Next, a new approach for achieving clock synchronization between femtocells and macrocells is proposed that utilizes mobile users to estimate and compensate the *clock drift*, i.e., the deviation with respect to a universal time, between femtocells and macrocells within the network and achieve timing synchronization. Note that unlike the algorithms proposed in [10]–[12] that seek to estimate the *differences in timing, i.e., timing offsets*, between macrocell and femtocells, the proposed approach in this paper estimates the *clock drift ratios (CDRs)* between different tiers. Given that the main sources of clock drift are temperature, voltage, and pressure, and since these sources vary extremely slowly with time, it can be concluded that CDR changes slowly with time [9], [17], [18]. Thus, the proposed algorithm is capable of maintaining synchronization over a longer period of time compared to the schemes in [10]–[12]. Simulation results corroborate the above claim and show that compared to existing algorithms the proposed scheme can achieve and maintain synchronization for a longer period of time throughout the network while, at the same time is not dependent on an external source for timing synchronization.

This paper is organized as follows: Section II formulates the system model for the heterogeneous network. Section III outlines the proposed timing synchronization algorithm while Section IV presents numerical and simulation results.

II. System Model

We assume a two-tier network consisting of macrocells and femtocells. The macrocell or Tier 1 network consists of low density *user-equipments UEs* and femtocells. Each femtocell or Tier 2 network, which is located in an indoor environment also supports a number of UEs within its area of coverage. Due to severe attenuation it is assumed that the signal from macrocell to femtocell is not sufficiently strong to perform accurate timing synchronization, e.g., the femtocell may be located in a tunnel or basement, where it is in the area of coverage of macrocell but has very poor reception, see Fig. 1. UEs in each tier can employ *code division multiple access (CDMA)* or *orthogonal frequency division multiple access (OFDMA)*.

UEs are assumed to have achieved clock synchronization with respect to their existing tiers, which can be achieved by employing pilot signals and timing synchronization algorithms already available for point-to-point systems [19]. Note that this assumption is also in line with existing results in the literature [1], [3]–[7].

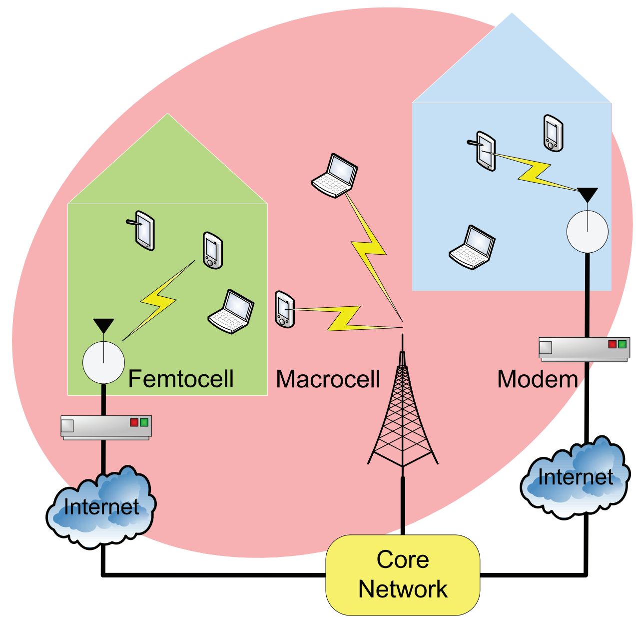

Fig. 1. System model for the multi-relay two-hop cooperative network.

A. Clock Drift Model and Estimation

Each macrocell, femtocell, and UE node has a time reference or local clock which is provided by a hardware oscillator. At universal time T_n the local time, $\bar{T}_n^{[i]}$ at the ith node is modeled as [9]

$$\bar{T}_n^{[i]} = \bar{T}_{n-1}^{[i]} + \int_{T_{n-1}}^{T_n} \varepsilon_i(t)dt, \quad (1)$$

where $\varepsilon_i(t)$ is the ith node's clock drift[2] or instantaneous frequency drift. As shown in [9], [17], [18] and given that the main sources of clock drift are temperature, voltage, and pressure, and since these sources vary extremely slowly with time, throughout this paper it is assumed that clock drift is constant or slowly varying. Furthermore, it is assumed that the CDR between two arbitrary communicating nodes, i and j, $\rho_{i,j}$, which is given by

$$\rho_{i,j} = \frac{\varepsilon_i}{\varepsilon_j}, \quad (2)$$

can be estimated at the receiver side. In (2), ε_i and ε_j denote the clock drifts of the ith and jth nodes, respectively. Note that many algorithms for the estimation of $\rho_{i,j}$ between two point-to-point communicating nodes are proposed in the literature [17], [20], [21], e.g., maximum-likelihood and linear algorithms for estimation of clock drift have been proposed in [17] where it is shown that clock drifts between two nodes can be estimated with very high accuracy. Finally, $\hat{\rho}_{t,r}$ the estimate of $\rho_{t,r}$, is given by

$$\hat{\rho}_{i,j} = \rho_{i,j} + w_{i,j}, \quad (3)$$

where $w_{i,j}$ is the estimation noise modeled as a zero-mean Gaussian random variable with variance $\sigma^2_{w_{i,j}}$. Note that the value of $\sigma^2_{w_{i,j}}$ is affected by many parameters such as *signal-to-noise ratio (SNR)* and estimation method.

III. Clock Synchronization Algorithm

To ensure that a *femtocell base station (FBS)* clock is synchronized with respect to the *macrocell base station (MBS)* overlapping its area of coverage, the CDR between FBS and MBS, $\rho_{\text{MBS},FBS}$, needs to be estimated. The CDR, $\rho_{\text{MBS,FBS}}$ can be subsequently used to adjust the clock and timing of FBS and to ensure that the overall network achieves timing synchronization.

In this paper we propose to use UEs to estimate the CDR between MBS and FBS, $\rho_{\text{MBS,FBS}}$. Let us consider two states: *State A* denotes the scenario where a UE is in a macrocell's area of coverage and *State B* represents the scenario where a UE is in a femtocell's area of coverage. Let $\overline{\text{UE}}$ denote the UE that is moving from *State A* to *State B*. In *State A*, $\overline{\text{UE}}$ can use the algorithms proposed in [9], [17], [18] to estimate the CDR between itself and MBS, $\rho_{\text{MBS},\overline{\text{UE}}}$. Next, the CDR, $\rho_{\text{MBS},\overline{\text{UE}}}$ can be used to achieve and maintain clock synchronization between MBS and $\overline{\text{UE}}$. As $\overline{\text{UE}}$ moves from *State A* to *State B*, it must initiate hand-off, estimate the CDR between itself and FBS, $\rho_{\text{FBS},\overline{\text{UE}}}$, and feedback the previously estimated CDR between UE and MBS, $\rho_{\text{MBS},\overline{\text{UE}}}$, to the FBS. Fig. 2 summarizes the set of CDRs that need to be estimated at each node as $\overline{\text{UE}}$ moves from macrocell, i.e., *State A*, to femtocell coverage, i.e., *State B*.

The CDR between the FBS and $\overline{\text{UE}}$, $\rho_{\overline{\text{UE}},\text{FBS}}$, is estimated and in combination with the CDR between MBS and $\overline{\text{UE}}$, $\rho_{\text{MBS},\overline{\text{UE}}}$,

[2]When $\varepsilon^i(t) = 1$ there is no deviation with respect to universal time.

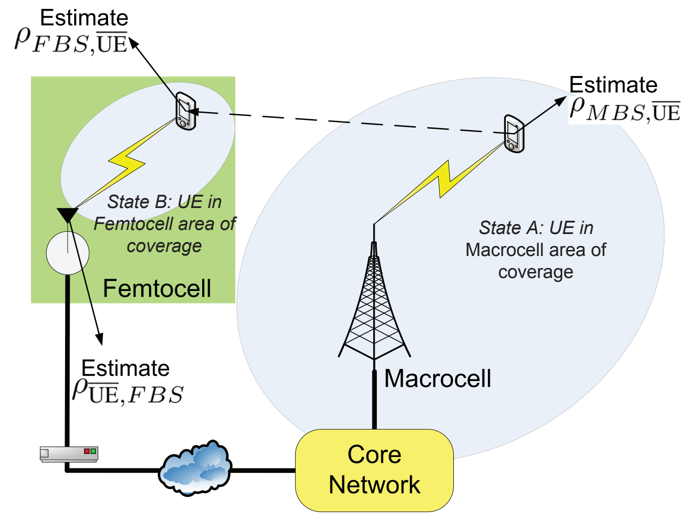

Fig. 2. The CDRs that need to be estimated as the user leaves the macrocell (*State A*) and enters the femtocell (*State B*) coverage.

that is fed back from the $\overline{\text{UE}}$ is used to determine the CDR between FBS and MBS, $\rho_{\text{MBS,FBS}}$, according to

$$\rho_{\text{MBS,FBS}} = \rho_{\text{MBS},\overline{\text{UE}}} \times \rho_{\overline{\text{UE}},\text{FBS}} = \frac{\varepsilon_{\text{MBS}}}{\varepsilon_{\overline{\text{UE}}}} \frac{\varepsilon_{\overline{\text{UE}}}}{\varepsilon_{\text{FBS}}}. \quad (4)$$

Let UE_i denote that ith UE in the area of coverage of the femtocell. Next, the CDR calculated using (4), $\rho_{\text{MBS,FBS}}$ is forwarded to all UEs in the femtocell, where the CDR between UE_i and MBS, ρ_{MBS,UE_i}, is calculated via

$$\rho_{\text{MBS},UE_i} = \rho_{\text{MBS,FBS}} \times \rho_{\text{FBS,UE}_i}, \quad i = 1, \cdots, L. \quad (5)$$

In (5) L denotes the number of UEs within the femtocell's area of coverage. The following remarks are in order:

Figs. 3 a) and b) summarize the synchronization algorithm for UEs and FBSs, respectively.

Remark 1: In (5), it is assumed that the ith UE in the area of coverage of the femtocell has used its link to the femtocell BS to estimate the CDR, $\rho_{\text{FBS,UE}_i}$.

Remark 2: Using (4) and (5), it is possible for every node within the network to estimate its CDR with respect to its current MBS's clock. Subsequently, the estimated CDRs can be used to synchronize each node's timing with the macrocell's timing and achieve synchronization throughout the network.

Remark 3: The proposed clock synchronization algorithm is distributed and can be implemented without any centralized coordination.

IV. Numerical Results and Discussions

In this section simulation results are presented to justify the performance and feasibility of the proposed timing synchronization algorithm. The femtocells are assumed to be equipped with a *temperature compensated crystal oscillator (TCXO)* (frequency accuracy of 1ppm), due to their lower cost [1]. CDR estimation variance, $\sigma^2_{w_{i,j}}$ in (3), is assumed to be a constant and is set to 10^{-4}, which agrees with the results in [9]. The UE's

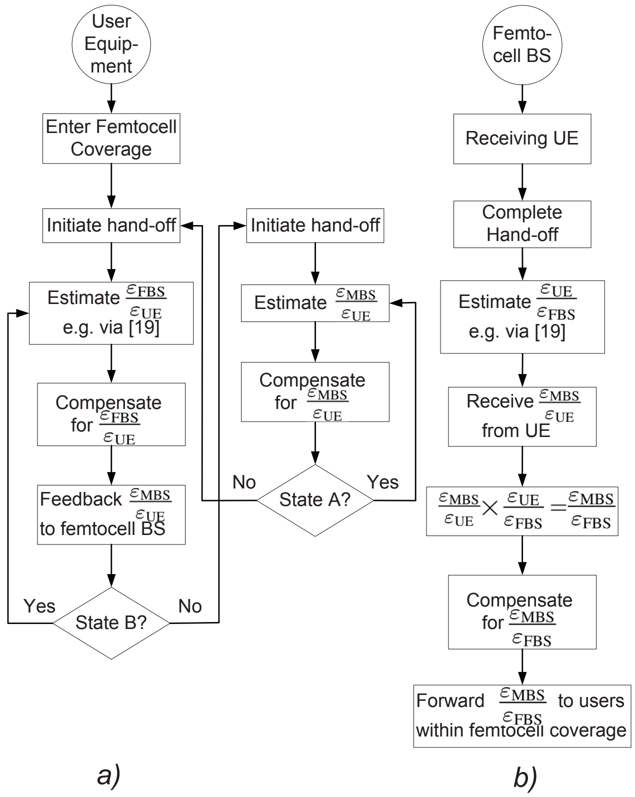

Fig. 3. *a)* UE synchronization process as it enters and leaves macrocells and femtocells and *b)* Femtocell synchronization process as a UE enters its coverage.

transitions from macrocell to femtocell coverage are assumed to be uniformly distributed over the time span $(0, \tau]$, where τ is set to $\tau = [3, 6, 12]$ hours in this section. It is assumed that the network consists of a macrocell, femtocell, and user. Timing offset in Figs. 4-6 is defined as the timing difference between the MBS and FBS clocks. Finally, the results are averaged over 10000 Monte-Carlo simulations.

Fig. 4 compares the timing offset between FBS and MBS when the two systems are not synchronized or when a similar algorithm to the one in [12] is used to estimate and compensate the effect of timing offset as the UE moves between femtocell and macrocell areas of coverage. As anticipated, when employing the algorithm in [12], the timing offset between the MBS and FBS is affected by τ, where the timing offset first increases and then starts to decline until the time span τ is reached.

Note that due to clock drift, if MBS and FBS are not synchronized, the timing offset between the two systems grows linearly with time. As illustrated in Fig. 4, in a short time span this timing offset can become large enough to hinder hand-offs and result in potentially severe interference between the two systems.

Fig. 4 also reveals that through the application of the algorithm in [12], the timing offset between MBS and FBS does not grow without bound over time. However, as depicted in Fig. 4, the estimation performance is poor and is highly dependent on how frequently a UE moves between the two regions. These are the two major shortcomings of the algorithm in [12] that the algorithm proposed in this paper addresses.

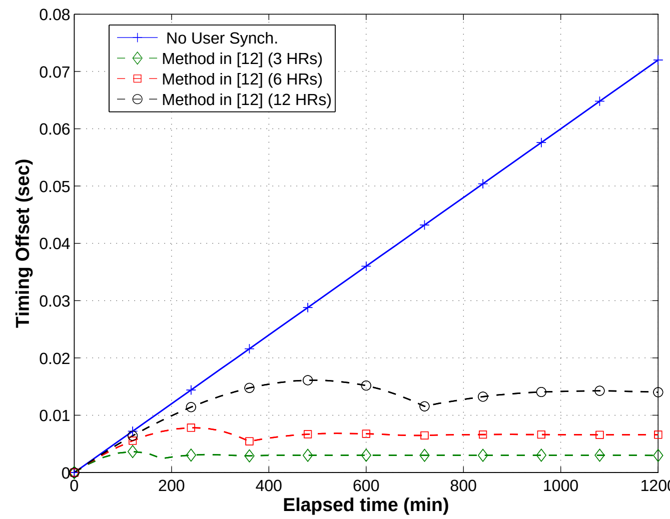

Fig. 4. Timing offset between MBS and FBS for an unsynchronized network and one that is synchronized using the mobile user by estimating the timing offset and compensating its effect periodically.

Fig. 5 illustrates the performance of the proposed timing synchronization algorithm. Note that in the initialization stage of the algorithm, it is assumed that the FBS does not have access to the CDR, $\rho_{MAC,FEM}$. Therefore, similar to the results in Fig. 4, timing offset between FBS and MBS grows with time. However, as the time span, τ, is reached the probability that the UE enters the femtocell's area of coverage approaches 1. When the UE enters the femtocell's area of coverage, $\rho_{MAC,FEM}$ can be estimated and compensated. Thus, after synchronizing the clocks between the FBS and MBS, the timing offset between the two nodes also drops significantly.

The results in Fig. 5 indicate that based on the proposed scheme, from the time that the UE leaves macrocell coverage and enters femtocell's coverage, the timing offset between MBS and FBS is considerably reduced and synchronization is established. Note that unlike the algorithm in [12] depicted in Fig. 4, the proposed algorithm in this paper is capable of maintaining synchronization between the two systems over a long period of time.

Given that the proposed synchronization algorithm is dependent on the UE feeding back $\rho_{\text{MBS,UE}}$ to FBS, it is important to investigate its performance in the presence of quantization error. Fig. 6 illustrates the performance of the proposed timing synchronization algorithm when $\rho_{\text{MBS,UE}}$ is quantized using a 10, 15, and 20 bit uniform linear quantizer ($\tau = 3$ hours).

From the results in Fig. 6, it can be deduced that the proposed algorithm is sensitive to quantization error. Therefore, the choice of quantizer design and accuracy at UE is an important design parameter, which can result in added hardware complexity at the UE and introduce additional feedback.

The following remarks are in order:

Remark 4: In the more practical case where each femtocell and

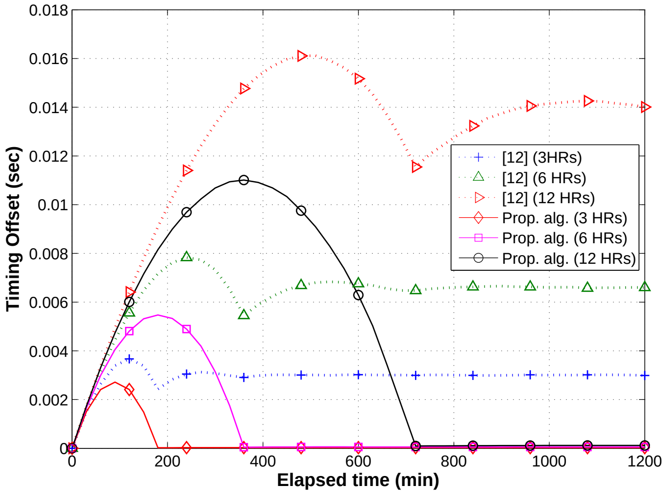

Fig. 5. Timing offset between MBS and FBS for an unsynchronized network and one that is synchronized using the proposed timing synchronization algorithm in this paper.

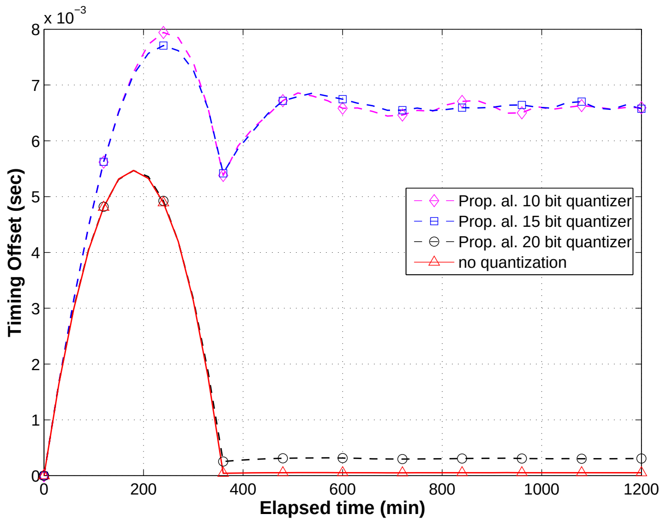

Fig. 6. Timing offset between MBS and FBS for the proposed timing synchronization algorithm with quantized feedback from UE to FBS (τ = 3 hours).

macrocell are supporting multiple users, the proposed synchronization algorithm can be combined with decision combining or gossip averaging algorithms [9] to result in faster convergence and more accurate CDR estimation performance.

Remark 5: The proposed synchronization algorithm can be combined with the algorithms outlined in the Introduction section [1], [8], [13]–[15] to achieve more resilient and accurate timing synchronization. For example, if there is a direct but poor link between FBS and MBS, this link can be used for the estimation of CDR, $\rho_{MAC,FEM}$, where this estimate can be combined with the algorithm proposed in this paper to improve timing synchronization accuracy between FBS and MBS.

V. Conclusions

In this paper a new timing synchronization algorithm based on the estimation of the CDRs between the macrocell and femtocell BSs using the UEs has been proposed. Simulation results show that the proposed algorithm can achieve timing synchronization between nodes within the network and maintain it over a longer period of time, since the CDR does not tend to change very quickly with time. Simulation results also demonstrate that 20 bits of CDR quantization offer considerable improvement over 15 bits, resulting in performance approaching that of infinite precision.

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