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Published in:
Telecommunications (ICT), 2013 20th International Conference on Telecommunications

DOI (link to publication from Publisher):
10.1109/ICTEL.2013.6632081

Publication date:
2013

Document Version
Early version, also known as pre-print

Distributed Synchronization for Beyond 4G Indoor Femtocells

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Abstract—**The exponential growth in indoor data traffic necessitates a massive deployment of small cells, and emphasizes the importance of interference coordination and suppression to realize the full potential of this densification. To be effective however, interference coordination and suppression requires strict time synchronization between the cells. This paper deals with distributed runtime synchronization for Beyond 4G femtocells. A simple random scheduling solution for the clock distribution messages is proposed, as well as different clock update mechanisms. Simulation results for a dense cell scenario with two stripes of apartments show that a 'multiplicative clock update' exhibits an initial large time divergence among neighbor cells, but is able to achieve a lower long-term error floor than 'additive clock update'. Practical implications of the residual time misalignment on the Beyond 4G system design are also addressed.**

Keywords— ***Beyond 4G; femtocells; OFDM; distributed synchronization; beacons' scheduling; clock update; CS-MNS***

I. INTRODUCTION

A massive deployment of small cells (e.g., femtocells) is foreseen as a solution for coping with the exponential increase of the indoor data traffic demand in the upcoming years. A new radio access technology – Beyond 4th Generation (Beyond 4G) following the terminology of the cellular systems evolution - has to be designed for circumventing the limitations of the existing standards in such dense scenarios [1]. A Beyond 4G system should be fully scheduled similar to the current cellular systems and operate over a different band with respect to the micro/macrocells to achieve larger scalability. The usage of advanced features such as Multiple-Input-Multiple-Output (MIMO) antenna technology, fast link adaptation, interference coordination/suppression and optimized frame structure is fundamental for boosting the network throughput. The Time Division Duplex (TDD) mode of separating the uplink (UL) and downlink (DL) is preferred given the possibility of using large unpaired frequency bands, the possibility of exploiting channel reciprocity for reduced feedback overhead, as well as the support of multiple communication links besides the traditional User Equipment-Base Station (UE-BS) access (for instance, Device-to-Device communication).

Time synchronization across multiple BSs is part of the TDD optimization; it allows coordinated operations such as interference management and/or suppression or coordinated multipoint transmission, and can improve the sensing performance, e.g. for mobility across neighbor cells in case of Open Subscriber Group (OSG). In current cellular systems, synchronization across multiple BSs can be obtained by locking their local clocks to the timing signals transmitted by the Global Positioning System (GPS) satellites. However, penetration losses to indoor may strongly limit the accuracy of GPS timing for Beyond 4G femtocells. In principle, macrocell BSs can relay the synchronization signals received from GPS satellites, but the Beyond 4G cells are not necessarily within their coverage area. The alternative is to use distributed network synchronization for Beyond 4G, in which the nodes autonomously agree on a common timeline and maintain it without any centralized coordination.

Distributed synchronization has been widely studied in the academia. Self-organizing algorithms such as firefly synchronization [2] or periodic synchronization [3] target ideal full duplex systems and neglect the problem of maintaining time alignment in the long term by compensating the different clock drifts of the multiple nodes. More practical approaches such as the Timing Synchronization Function (TSF) algorithm [4] used in IEEE 802.11 tracks the fastest clock in the network by correcting the local clock function with the timing of the fastest clock received. Other known solutions are based on control theory principles [5], or Kalman-filter drift estimates [6], mainly targeting wireless sensors networks (WSNs) where the minimization of energy consumption is a vital requirement. To the best of our knowledge, distributed network synchronization algorithms dealing specifically with half duplex scheduled systems are mostly disregarded in the literature.

In this paper, we discuss the suitability of distributed synchronization for a Beyond 4G local area system. The importance of high synchronization accuracy is motivated as part of the Beyond 4G system design. A simple random scheduling solution for the clock distribution messages, or so-called beacon messages, is proposed with the aim of ensuring neighbors visibility, and different approaches for the updating the local clocks are also proposed and evaluated.

The paper is structured as follows. Section II discusses how the achievable synchronization accuracy impacts on the Beyond 4G system design. Section III deals with distributed runtime synchronization, and addresses both issues of beacons exchange among multiple BSs and clock update mechanisms. Simulation results are presented and discussed in Section IV. Finally, Section V resumes the conclusions and states the future work.

II. Impact of Synchronization Accuracy on the Beyond 4G System Design

In a previous paper [1] we have presented requirements and technology components for a Beyond 4G radio system. The maximum data rate is set to 10 Gbps, and the Round Trip Time (RTT) is set to 1 ms. Beyond 4G should support Orthogonal Frequency Division Multiplexing (OFDM) modulation [7] in both UL and DL given its proven multipath mitigation capability as well as its straightforward extension to MIMO antenna techniques.

The ambitious RTT target sets the frame duration to be not longer than 0.5 ms.

While link synchronization between BS and UE is needed for coherent data demodulation, synchronization among neighboring BSs is part of the TDD system optimization. The achievable time alignment accuracy has an impact on the design of the Cyclic Prefix (CP) in the OFDM symbols. It is desirable to maintain the shortest possible CP duration T_{CP}, to reduce the system overhead; on the other hand, T_{CP} should be designed to ensure:

$$T_{CP} > \tau_M + \tau_D + \tau_{HW} + 2\tau_P \quad (1)$$

where τ_M denotes the time misalignment between transmit and receive nodes, τ_D denotes the largest significant excess delay in the channel, τ_P is the propagation delay between transmit and receive node, τ_{HW} is the response time of the hardware filters. In this way, the orthogonality of the subcarriers is preserved and efficient frequency domain processing can be applied [7]. The size of a typical local area cell is anticipated to be around ~50m, resulting in a propagation delay of about 170 ns. Delay spreads of local area indoor channels are typically less than 100 ns for office premises and less than 50 ns for home environment [8], while the hardware response time is of around ~50 ns. This leads to the following requirement:

$$T_{CP} > \tau_M + 0.49\ \mu s \quad (2)$$

A proper characterization of the time misalignment is then fundamental for the definition of the CP duration.

III. Runtime Synchronization

It is straightforward to notice that an initial coarse synchronization across the network nodes can be easily achieved in case of sequential activation of the BSs. As mentioned in the introduction, solutions such as firefly synchronization have been instead proposed for solving the problem of initial synchronization assuming simultaneous activation of the BSs (e.g., after a power shut down).

For the rest of this paper, we will assume that a coarse initial synchronization is already achieved and we focus on the runtime synchronization problem, i.e. how to keep time alignment between the network nodes despite of the different clock functions. For example, current commercial Voltage Controlled Oscillators (VCOs) may feature a nominal accuracy of 1 Part-Per-Million (PPM); this means that, even when aligned in time, two network nodes may take only 1 second before their timing diverts by up to 2 µs. Runtime offset correction procedures are then expected to take place for keeping the different clocks aligned throughout the network. For BS to UE communication, this correction can be pursued in a master-slave fashion. For inter-BS communication without any hierarchy, correction procedures are based on the exchange of beacon messages among the BSs, which react by updating their clock functions according to a predefined update criterion. The half-duplex constraint due to the TDD mode (i.e., each node can only transmit or receive at a time) raises the issue of a proper scheduling of the beacons.

Both beacons' scheduling and clock update issues are discussed in the following subsections.

A. Beacons' scheduling

As mentioned above, synchronization at network level can be achieved by ensuring beacon messages exchange across multiple BSs. The most straightforward way to obtain this in an half duplex scheduled system is to reserve a dedicated time slot for each node. Nodes would transmit their beacons in a round robin fashion, so that each node can read the beacons sent by all its neighbors. However, this approach requires heavy signaling and it is not scalable to a large network.

Let us assume that the beacons of multiple nodes can be multiplexed within the same time symbol, for instance in different frequency blocks or by using orthogonal codes. This is quite feasible since many current systems already feature the required processing for decoding signals that share, even coarsely, the same time resources but are orthogonal in the frequency/code domain. For instance, in the OFDM receive processing the arrival time of multiple beacons can be retrieved and their associated messages decoded in case the CP copes with the requirements mentioned in Section II.

By following a simple random scheduling criterion, each node can decide at each inter-beacon time whether to transmit its beacon with a certain probability p or to receive the beacons eventually sent by the other nodes. The node can transmit its beacon by using one or more of the orthogonal resources, e.g. randomly chosen. By assuming a large available bandwidth or a wide set of orthogonal codes, the scalability to a large number of nodes without too many collisions is obtained by their statistical multiplexing. The principle of random scheduling is shown in Figure 1.

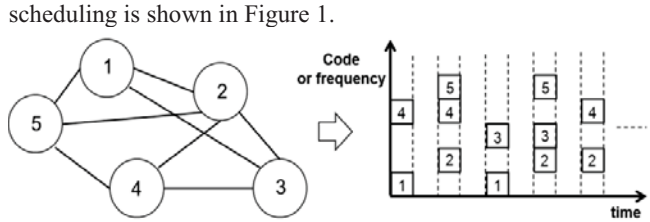

Figure 1. Principle of random scheduling, assuming 5 nodes.

Note that, since the beacons exchange represents an inter-BS communication, it is supposed to happen at a much slower pace than the traditional BS-UE signaling. Moreover, since in Beyond 4G synchronization across multiple BSs is mainly needed for interference management and mobility, we simply need to be time aligned with neighbors which may generate significant reciprocal interference rather than aiming at complete network synchronization. It is worth to mention that the typical energy efficiency requirements of resource

constrained networks such as WSNs [6] are not limiting factors in our Beyond 4G system: in a WSN beacons are sent with low periodicity to save power, whereas here they can be sent frequently, at the same rate as other inter-cell system control information. On the other hand, our pursued accuracy is on the order of fraction of μs, way more ambitious than the typical WSNs targets.

B. Clock update

The time process of the generic *i*-th node in a network can be modeled as follows:

$$c_i(t) = \alpha_i t + \beta_i \tag{3}$$

where α_i represents the drift and β_i the offset with respect to the real time t. It follows that, for an ideal clock, $\alpha_i = 1$ and $\beta_i = 0$. This model neglects jitter and ambient noisy effects; however it can be considered realistic in the long term (minutes) for good modern commercial clocks, e.g. 1 PPM accuracy and below [9]. Upon reception of a beacon, the node needs to update its clock function with the aim of reducing its time misalignment with the neighbor cells. In other words, if the *i*-th node had scheduled its transmission at time $T_i(n\Delta t)$, $n > 1$, where Δt represents the inter-beacon time interval, it will update the transmission time to a corrected value $\tilde{T}_i(n\Delta t)$. Its beacon will be sent over the air at instant

$$t_{air,i}(n\Delta t) = \frac{\tilde{T}_i(n\Delta t) - \beta_i}{\alpha_i} \tag{4}$$

In the following, two different approaches for the clock correction will be presented. In order to simplify the analytical formalism, we will assume that each node can send beacons every inter-beacon time interval Δt.

Additive Update- The most straightforward approach for minimizing the time misalignment between transmit node *j* and receive node *i* is to add an offset to the local timing, i.e.

$$\tilde{T}_i(n\Delta t) = \tilde{T}_i\big((n-1)\Delta t\big) + \Delta t + q_i(n\Delta t) \tag{5}$$

The correction term $q_i(n\Delta t)$ can be defined as follow:

$$q_i(n\Delta t) = \frac{t_{rx,i}(j,(n-1)\Delta t) - \tilde{T}_i\big((n-1)\Delta t\big)}{Q} \tag{6}$$

where Q is a bias term, and $t_{rx,i}(j,(n-1)\Delta t)$ represents the effective time instant in which the beacon sent by node *j* at nominal time $\tilde{T}_j\big((n-1)\Delta t\big)$ is received by node *i*, i.e.

$$t_{rx,i}(j,(n-1)\Delta t) = c_i\left(t_{air,j}\big((n-1)\Delta t\big) + \tau_P(j,i)\right) \tag{7}$$

$\tau_P(j,i)$ represents the propagation delay between node *j* and node *i*.

Basically, each node adds an offset which reduces the timing difference with its neighbors. The usage of the bias term *Q>1* prevents the receive BS to immediately switch its internal timing to the one of the received beacon: this avoids abrupt transitions that may suddenly de-synchronize the affiliated UEs. Since the additive correction only modifies the phase but not the frequency of the clock, the nodes need to perform their update very frequently for avoiding further divergence.

Multiplicative Update- Our multiplicative clock update strategy takes inspiration from the Clock Sampling – Mutual Network Synchronization (CS-MNS) algorithm proposed in [5]. In this case, the corrected timing is given by

$$\tilde{T}_i(n\Delta t) = q_i(n\Delta t)\big(T_i\big((n-1)\Delta t\big) + \Delta t\big) \tag{8}$$

The multiplicative term can be expressed as

$$q_i(n\Delta t) = \frac{1}{s_i(n\Delta t)} \tag{9}$$

where

$$\begin{aligned} &s_i(n\Delta t) \\ &= s_i\big((n-1)\Delta t\big) \\ &+ \frac{T_j\big((n-1)\Delta t\big) - s_i\big((n-1)\Delta t\big)t_{rx,i}(j,(n-1)\Delta t)}{t_{rx,i}(j,(n-1)\Delta t) + Z} \end{aligned} \tag{10}$$

with $s_i(0) = 1 \ \forall i$, and Z is a bias factor. The correction term update is derived from control theory principles, and further details can be found in [5]. Basically, the goal of CS-MNS is to update all the clock functions in the network in a way that

$$\lim_{t\to\infty} q_i(t)c_i(t) = q \ \ \forall i \tag{11}$$

where q denotes a final constant value. In other words, the multiplicative clock update modifies the frequency of the clock functions towards a common convergent value. The bias factor Z can be set empirically with the aim of constraining q within the fastest and the slowest clock in the network (e.g., between -1μs/s and 1μs/s with 1 PPM clocks) [10].

IV. Performance Evaluation

In order to obtain insights on the time misalignment accuracy which can be obtained with the presented runtime synchronization approaches, we simulate their behavior in a dense urban femtocells scenario with two stripes of apartments, where each stripe has 2x10 apartments with size 10 m x 10 m (see Figure 2). This scenario is typically used within the 3rd Generation Partnership Project (3GPP) for interference coordination studies [11].

The main simulation parameters are gathered in Table I. Results are obtained by averaging out the measurements over a number of 500 simulation drops. At each drop, the BSs are deployed in random position in each apartment. Different deployment ratios (DRs) are considered. The DRs represent the probability of having a BS in each apartment. We set a pathloss threshold equal to 70 dB for limiting the node visibility to the potentially significant interferers. This means, each BS only reads the beacons from the BSs towards which the pathloss does not exceed 70 dB. The presence of a pathloss threshold may generate independent network clusters, i.e. independent subsets of nodes which aim at a common timing. Note that two nodes may belong to the same cluster even in case their pathloss relation exceeds 70 dB; this is because they may be connected to a common tree of neighbors. The average cluster size as a function of the DR is shown in Figure 3; the number of nodes per cluster is very small for sparse networks (DR=25%) and tends to increase exponentially with the DR. However, even in case of DR=100% (i.e., 40 BSs in the scenario), the average cluster size is approximately 14.

TABLE I. SIMULATION PARAMETERS

Scenario	dense urban femtocells two stripes with 2x10 apartments
DR	25%, 50%, 75%, 100%
Number of Drops	500
Clock Precision	1 PPM
Maximum Initial Error	within +/- 0.1 μs
Pathloss/shadowing models	taken from [11]
Pathloss Threshold	70 dB
Inter-beacon time	10 ms
Probability of beacon Transmission *(p)*	0.5
Bias factor of additive approach *(Q)*	5
Bias factor of multiplicative approach *(Z)*	100

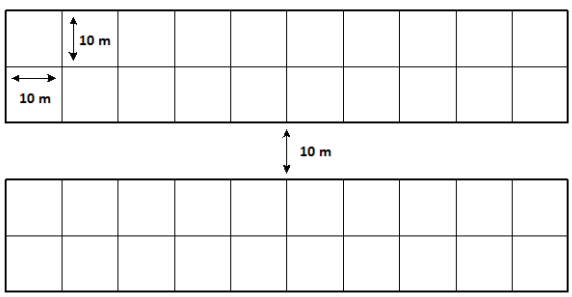

Figure 2. Dense urban femtocells scenario with two stripes of apartments.

Besides the attenuation of the signals, the simulations also take into account the propagation delays between nodes.

Since our focus is on the runtime synchronization, we assume the nodes to have achieved a coarse initial synchronization with a relative error uniformly distributed within +/- 0.1 μs. We then assume a 1 PPM precision of each clock. The inter-beacon time interval is set to 10 ms, which corresponds to 50 Beyond 4G frames. The probability p of sending a beacon at a certain beacon transmission time is set to 0.5. In case a node is not transmitting its beacon, it receives the multiple beacons sent by the other visible nodes and selects randomly the one to consider for its clock update. The bias factor Z for the multiplicative clock update has been empirically set such that the convergent clock slope is constrained by the lowest/fastest clock in the network, i.e. $|q| < 1$ μs/s.

Let us define the time misalignment over air at instant t between node i and node j:

$$\tau_{M,i,j}(t) = \left|t_{air,i}(t) - t_{air,j}(t)\right| \tag{12}$$

An average maximum time misalignment per cluster can then be expressed as follows:

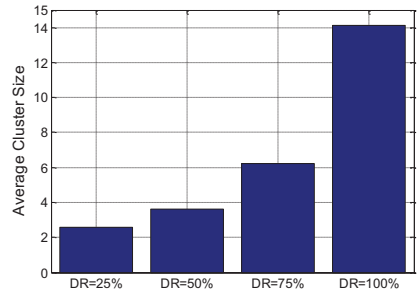

Figure 3. Average cluster size for different DRs.

$$\tau_{M,max}(t) = \frac{1}{N_D}\sum_{r=1}^{N_D}\frac{1}{N_C}\sum_{u=1}^{N_C}\max_{i\in C_u, j\in V_i}\tau_{M,i,j}(t) \tag{13}$$

where N_D denotes the number of drops, N_C the number of independent clusters, C_u is u-th cluster, and V_i is the set of nodes which are visible from node i.

Figure 4 shows the average maximum time misalignment for both cases of additive and multiplicative clock update, assuming different average beacon losses (i.e., the beacon was not received and hence correction not applied), and DR=50%. The multiplicative approach is characterized by an initial divergence of the clocks with leads to a large time misalignment. This is mainly depending on the fact that, at the beginning, the correction factor can amplify the initial error. However, in the long term such misalignment converges towards a value of approximately 25 ns. This residual error floor is due to the impact in the clock update function of the propagation delay between transmit and receive node. The additive clock correction exhibits a higher error floor, which is however constant over time; such error floor is due to the fact that, since this approach does not modify the clock frequency, the nodes tend to misalign their timing before the next correction is made. Note that, in case of multiplicative clock correction, consistent beacon losses (50%) only lead to a slower convergence time, while in the additive approach they impact the magnitude of the error floor. However, the impact of 10% beacons losses is negligible for both approaches.

Figure 5 displays the cumulative distribution function (CDF) of the time misalignment (after 30 seconds, i.e. after convergence is reached) between nodes belonging to the same cluster, assuming 10% beacon losses and multiple DRs. As expected, the additive update leads to higher error floor, which is more sensitive to the DR than the multiplicative update approach. The time misalignment of multiplicative clock update does not exceed 70 ns in 90% of the cases even for DR=100%, while for additive update such value increases up to 180 ns.

By assuming as a reference case DR=50%, for multiplicative clock correction we would need to increase the CP duration of τ_M= 0.04 μs in order to maintain the subcarrier orthogonality in 90% of the cases. However, the initial time divergence of the algorithm would require a longer CP length. The total overhead can be minimized by assuming different CP lengths

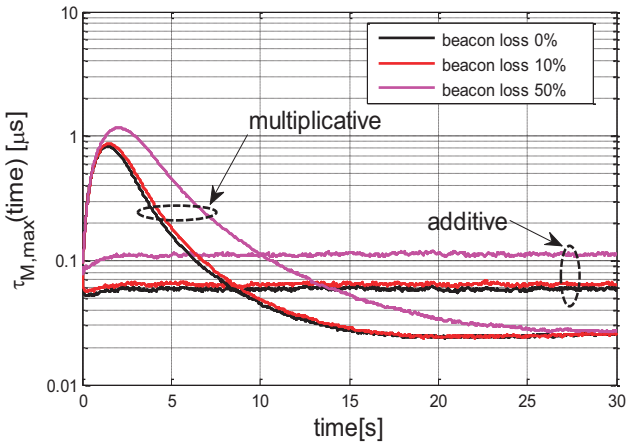

Figure 4. Average max time divergence of multiplicative vs. additive clock correction, assuming DR=50%.

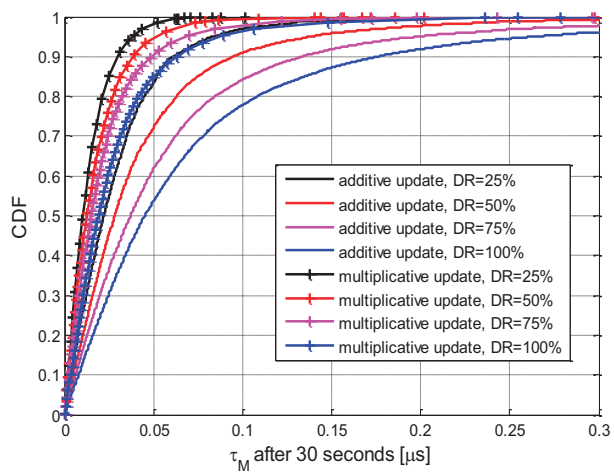

Figure 5. Distribution of time misalignments between pair of nodes, for different DRs, assuming 10% beacons losses.

for control channels (where the beacons are mapped) and for data symbols, with the assumptions that the BS starts sending data only after the time which is required for stabilizing the error floor. According to Section II, the CP length would then be of around 1.5 µs for the control channels and only 0.5 µs for the data symbols. In case of additive clock correction, for the DR=50% reference case we would need to increase the CP duration of around τ_M= 0.1 µs; this holds for both control and data symbols, leading to an overall CP duration of around 0.6 µs. In the remaining 10% of the cases and for higher DRs we may accept some intercarrier interference (ICI) degradation due to power spillover from the CP over the OFDM symbol integration region. However, the effective impact of such ICI should not be critical since it would likely appear between nodes located at a significant distance, whose reciprocal interference is reasonably low. Even though the multiplicative approach would reasonably lead to lower cumulative overhead given the larger number of data symbols with respect to control symbols, we believe it is worth to accept some extra overhead and saving the complexity which is needed for accommodating two different OFDM symbol sizes within the frame.

V. Conclusions and Future Work

This paper discussed the issues of distributed runtime synchronization for Beyond 4G indoor cells. In such half duplex scheduled system aiming at very large capacity it is extremely important to minimize the misalignment error between neighbor nodes, and thereby reduce the system overhead given from the CP. A simple random scheduling solution for the beacons' transmission has been proposed, and two different clock updates mechanism based on multiplicative and additive correction factors have been presented. The additive clock correction leads to a higher error floor than the multiplicative approach, which however suffers from an initial large divergence of the clock timings. Additive clock correction is also more sensitive to the network density. Empirical estimates of the needed CP length have been derived from the simulation results.

Future work will be focused on pursuing hybrid clock update solutions which aim at reducing the initial clock divergence of the multiplicative approach while maintaining its lower error floor. Moreover, further beacons scheduling algorithms will be analyzed for potential improvements. Finally, the proof-of-concept of the proposed solution in a software defined radio testbed will also be addressed.

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