Digital Signal Processing 81 (2018) 90–99

Contents lists available at ScienceDirect

Digital Signal Processing

www.elsevier.com/locate/dsp

Iterative timing-induced interference suppression in a two-tier OFDMA uplink network

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ARTICLE INFO

Article history:
Available online 23 July 2018

Keywords:
Femtocell
Orthogonal Frequency-Division Multiple Access (OFDMA)
Uplink
Inter-Carrier Interference (ICI)
Precoder
Automatic gain controller
Equalizer
Iterative algorithm

ABSTRACT

Consider a scenario in a two-tier cellular network wherein all subscribers adjust their transmission-times to be synchronously received at the macro base-station (MBS). This transmission timing arrangement causes asynchronous reception of signals and inter-carrier interference (ICI) at the femto base-station (FBS). In this paper, an iterative interference suppression scheme for reducing the ICI at the FBS is presented. By assuming a number of macro-users (MUs) and a single femto-user (FU), the mean square error (MSE) cost-function is first defined, based on which, the closed-forms for 3 underlying parameters, i.e., precoder, equalizer and the automatic gain controller are then derived by proposing a partial derivative-based sub-optimization scheme. To counteract the interrelation of the aforementioned parameters, an iterative algorithm is further proposed which results in finding a local-optimum point of the cost-function. To demonstrate the successful interference suppression performance of the proposed scheme, a per-subcarrier interference power analysis is also derived. The simulation results demonstrate a reasonable convergence after 6 iterations. Moreover, for the proposed scheme, a close bit error rate (BER) performance to that of a system without any timing-induced interference at low and medium SNRs (i.e., <20 dB) and a comparable performance at higher SNRs (i.e., 20 dB & <30 dB) are observed.

1. Introduction

The increasing appetite of cellular users for higher data-rates and sustainable QoS is showing no signs of slowing down over the past decades. On the other hand, more than 50% of voice-calls and 70% of data-download [1] are happening at the indoor environments. Therefore, a more localized solution for the provision of higher capacity particularly to the indoor cellular subscribers had to be proposed by mobile operators. One of the promising solutions was to deploy low-power-short-range nodes, a.k.a., small-cells within the macrocell coverage and as a typical example, *femtocells*. Femtocell is a base station with stringent transmit power constraint, i.e., 10 to 100 mW and hence a shorter coverage range, i.e. 10 to 30 meters [2] that is often bought and installed by the end-users and could be connected to the core of cellular network through a broadband connection by means of the digital subscriber line (DSL), cable modem or via a separate radio frequency backhaul link. The advantages of using femtocells within the cellular network are in several folds. While the use of femtocells can offload a considerable amount of data from macrocells, particularly in the areas with higher localized data-demanding subscribers, they also play an important role in expanding the coverage and increasing the overall network capacity, in comparison with the traditional single-tier cellular networks [1–4].

On the other hand, the latest 3GPP standardized multiple-access scheme that is used as the air-interface on the front-haul link of cellular networks is called orthogonal frequency-division multiple-access (OFDMA) [5–10]. OFDMA is a promising scheme due to its higher resilience to frequency-selective fading, higher flexibility in scheduling of physical resource blocks to different subscribers based on their channel fading status and the relative ease of hardware implementation at the TX and RX sides. Besides its positive points, OFDMA is extremely vulnerable to timing misalignments. If the timing misalignment is greater than the cyclic prefix (CP), the orthogonality between subcarriers would be destroyed and the inter-carrier interference (ICI) as well as the inter-symbol interference (ISI) would occur [11–13].

Consider a scenario wherein a number of cellular subscribers are connected to a two-tier OFDMA-based network, consisting of both macro and femto base stations. In such a scenario, the aforementioned subscribers need to set their uplink transmission time-

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https://doi.org/10.1016/j.dsp.2018.05.014
1051-2004/

origins in a way to ensure all transmitted signals are received at the macro base-station (MBS) in a time-synchronous manner. This transmission timing constraint generally causes asynchronous reception of these signals at an arbitrary femto base-station (FBS) [14] and hence cross-tier interference, i.e. the interference between MBS and FBS, would occur if the timing misalignments of the corresponding macro-users (MUs) are greater than the pre-specified CP length.

Several papers in the literature have considered this problem so far [15–24]. These research works could be divided into two general categories, based on their undertaken approach.

Category I: The schemes within this category generally concentrate on the *analysis* of the timing-induced interference. The most significant works within this category are listed as follows. The analysis of spectrum opportunities detection in the presence of timing misalignment in the OFDMA cognitive radios [15]. Hamdi et al. considered the interference induced by timing misalignment in an OFDMA-based ad-hoc network [16]. They showed that the spectral efficiency can be maximized by adequate guard-intervals and also positioning the fast Fourier transform (FFT) windows in a dynamic manner, for both subband and interleaved subcarrier allocation schemes. In [17], the geometrical 2D contour over which the MUs could generate ICI on the uplink direction was determined. Moreover, the critical distance between the MBS and the FBS, beyond which the FBS would undergo ICI was calculated. A more accurate derivation for the aforementioned contour (than the one in [17]) was proposed in [18]. Moreover, the probability of an MU causing ICI to a given FBS was derived. The results of this research showed that the use of open-access femtocells could help in reducing the uplink interference induced by the timing misalignments. The cumulative distribution function (CDF) belonging to the arrival-times of the MUs' signals at the FBS was derived in [19]. Wang et al. in [20] made an in-detail analysis of the timing-induced interference and based on that derived the close-forms for the average ICI power and the probability mass function (PMF) for the above-mentioned arrival-times by exploitation of a more accurate CDF form than [19]. As the last step in this direction, ICI and IBI (inter-block interference) were analyzed in the uplink direction of heterogeneous cellular networks where multiple macrocells are considered in [21].

Category II: On the other hand, the approaches within the second category have suggested some interference *mitigating* schemes to prevent the ICI induced by the timing-misalignments. Within this category, one of the suggested methods for mitigating the ICI is to increase the CP-length to become greater than required for combating the ISI arisen from the collective effect of both the multipath fading and the timing-offsets [22]. This method maintains the orthogonality between subcarriers at the receiver at the cost of an effective reduction in the spectral efficiency. As the second example within this category, the authors in [23] proposed an approach where the synchronization point at the FBS is set to the instance of first arriving signal. Their proposed method is of a reasonable complexity but further ICI suppression would require some others appropriate accompanying schemes. Looking at it from another perspective, performing synchronization with respect to this point could increase the probability of the ICI occurrence due to the fact that the arrival-time of the first arriving signal is generally earlier than the first arriving MU. This issue would in turn increase the chance of having larger relative-delays than the CP length. As the best performing approach in this category, Wang et al. in [24] proposed a precoding scheme by maximizing femtocell uplink capacity in an OFDMA two-tier network. Based on this method, the effect of interference induced by timing-misalignments is reduced. Despite demonstrating good results in terms of femtocell uplink capacity, an important drawback of this scheme is the severe degradation in ICI suppression behavior on the last two subcarriers, in the presence of one femto-user.

As stated earlier, most of the research works so far either concentrate on timing-induced interference analysis (i.e., Category I above) or they propose ICI mitigating algorithms (i.e., Category II above). To the best of our knowledge, very few works are proposed so far with the purpose of interference suppression to counteract the adverse effects of timing-induced ICI in a two-tier OFDMA uplink network. To further clarify the difference between the proposed scheme and the above two categories, the schemes within the first category do not often propose a particular algorithm to counteract the detrimental effect of timing-induced interference. Instead, they mostly concentrate on formulating the interference signal as well as the measurement of the interference power and how it would affect the overall system performance. On the other hand, within the second category, the concentration is made upon proposing some pre-processing interference mitigating schemes to prevent the occurrence of timing-induced interference. In contrary, the research work presented here would belong to a third category within this context, in the sense that it proposes a post-processing iterative interference suppression scheme with the following details.

This paper presents an iterative scheme for the suppression of timing-induced ICI in a two-tier macro-femto OFDMA uplink network. The major contributions of this paper are in three folds as follows.

1– By assuming a number of MUs and a single precoded femto-user (FU), the mean square error (MSE) cost-function is first defined, based on which, the closed-forms for 3 underlying parameters, i.e., the precoder matrix, the joint deprecoder–equalizer matrix and the gain controller scalar are then derived by proposing a partial derivative-based sub-optimization scheme.

2– It is observed from the closed-forms that the above-mentioned three parameters are inter-related to each other which calls for an appropriate post-processing technique. As a possible solution, an iterative interference suppression scheme is proposed with a reasonable convergence behavior (i.e., 6 iterations) which achieves a bit error rate (BER) performance result close to an interference-free scenario at low and medium SNRs (i.e., $<$20 dB). For higher SNRs ($>$20 dB and $<$30 dB), the BER performance is comparable to the interference-free scenario even for the distances as large as 900 m between MBS and FBS.

3– To further demonstrate the effectiveness of the proposed iterative scheme in terms of interference suppression, the ICI power induced by MUs' timing-misalignments is derived on a per-subcarrier basis. By taking advantage of the close-form for the ICI power, it is semi-analytically shown that the proposed scheme could enhance the signal-to-interference-plus-noise ratio (SINR) indicator by $\approx$ 0.8 dB at SNR = 30 dB and $\approx$0.3 dB at SNR = 25 dB for distances as large as 900 m between MBS and FBS.

The rest of this paper is organized as follows. The system model for a two-tier OFDMA uplink network is presented in section 2. Section 3 contains our proposed iterative interference suppression scheme. We analyze SINR on a per-subcarrier basis in section 4. In section 5, the simulation results are described. Finally, conclusions are drawn in

Notation. In this paper, column vectors and matrices are denoted by lower-case and upper-case boldface italic letters, respectively. $[.]^T$, $[.]^*$ and $[.]^H$ denote matrix transposition, conjugation and conjugate transposition, respectively. tr(.) refers to the sum of diagonal elements of the enclosed matrix. The matrix $\boldsymbol{I}_N$ stands for the $N \times N$ identity matrix and $\mathbf{0}_{N\times M}$ refers to an $N \times M$ zero matrix. Moreover, $\mathbb{C}^{N\times M}$ denotes the $N \times M$ complex matrices and $\mathbb{R}^{N\times M}$ refers to the $N \times M$ real matrices. We represent the complex Gaussian distribution with a mean μ and a variance σ^2 by