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Robust receivers for base station cooperation systems

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ABSTRACT

In BS (Base Station) cooperation architectures the MTs (Mobile Terminals) in adjacent cells can operate in the same frequency, with the signal's separation and/or MTs detection being performed by a CPU (Central Processing Unit). This results in a substantial improvement in the overall system's capacity and spectral efficiency when compared to conventional cellular systems. To decrease the data load in the backhaul links, the received signals at a given BS must be sampled and quantized before being sent to the CPU, which results in a significant increase of quantization errors. We consider the uplink of BS cooperation schemes employing SC-FDE (Single-Carrier with Frequency-Domain Equalization) modulations and a detection performed through receivers based on the IB-DFE (Iterative Block Decision Feedback Equalization) concept. We present accurate approaches for obtaining the spectral characterization of the quantization noise. Moreover, we propose the design of robust receivers that can take into account the quantization noise effects.[1]

1. Introduction

The frequency spectrum is a scarce and expensive resource and its efficient management will be the key factor in the medium and long term future regarding cellular systems, such as 5G networks. In order to avoid inter-cell interference in conventional architectures, MTs (Mobile Terminals) transmit at distinct frequencies in different cells, which can lead to a lower quality of the system's overall performance due to the reuse factors implemented. Therefore, future cellular systems designs must focus on the improvements of interference-mitigation techniques, namely a cooperation scheme of the elements from the network. Following the cooperation concept, BS (Base Station) cooperation systems are a reliable alternative to the current cellular implementations. In this multi-cell cooperation idea, different cells are no longer considered as separate entities with each MT being assigned a specific BS, but instead users in adjacent cells can share the same physical channel (i.e., they transmit at the same frequency) and the signals between different MTs and BSs are collected and processed by a CPU (Central Processing Unit), so as to perform the user separation and/or interference mitigation. Hence, with BS cooperation it is possible to have a universal frequency reuse and considerable macro-diversity effects, improving the coverage and power requirements in each individual link. In the downlink transmission of BS cooperation systems, considering that a correct signal separation is provided, this is achieved by the implementation of appropriate pre-processing schemes [2,3]. This paper focuses on the uplink transmission, where the global signal contributions from all MTs received at each BS are sent to a CPU that operates the required signal separation and correctly detects data blocks that are then sent to the corresponding BS [4].

Block transmission techniques, jointly with frequency-domain processing schemes are suitable for broadband wireless systems, where the two main techniques include OFDM (Orthogonal Frequency Division Multiplexing) [5] and SC-FDE (Single-Carrier with Frequency Domain Equalization) [6,7]. For the uplink it is preferable to use SC-FDE modulations instead of OFDM. Although they have similar overall signal processing requirements and achievable performances, the receiver complexity is higher for SC-FDE and the transmitter complexity is higher for OFDM. Moreover, the envelope fluctuations of OFDM signals are much higher than the envelope of single-carrier signals with the same constellations, indicating that OFDM is clearly preferable for the downlink while SC-FDE is more suitable for the uplink transmission [8,9].

In this work, the signals from the different MTs received at a given BS are collected, sampled and quantized by an ADC (Analog-to-Digital Converter), with the objective of decrease the overall

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backhaul communication requirements. Posteriorly, at the CPU, the signal separation methodology is performed through frequency-domain receivers based on the IB-DFE (Iterative Block Decision Feedback Equalization) concept [10,11]. Regarding the sampled and quantized signals, the resulting quantization noise can lead to substantial performance degradation, so if the spectral characteristics of the quantization noise is known, it is possible to design robust receivers that can cope with the corresponding degradation. The normal approach for obtaining the PSD (Power Spectral Density) of the quantization noise is to consider it with uniform distribution [12]. However, this approach is only accurate for quantizers with high quantization levels but no saturation effects. Since the signals that are received at each BS present Gaussian-like characteristics, it is possible to obtain the quantization noise variance according to [13], as long as the signal to be quantized has a flat spectrum [14]. Gaussian approximation is reasonable for multipath channels, even with a single user.

However, this approach is only suitable for signals with Nyquist sampling, when the input signal has a rectangular spectrum, and it is important to take into account the intrinsic frequency diversity effects associated to signals with larger than minimum Nyquist band. To overcome this problem, [15] employs an IMP (Inter-Modulation Product) approach to obtain the characterization of the signal being quantized at the corresponding BS. The quantization characteristic is strongly nonlinear, presenting a problem for the IMP approach, since the precision of the PSD of the quantized signal depends on the number of IMPs. Moreover, the quantization characteristic has multiple discontinuities and if the number of IMPs is too high this method increases the numerical computation, making this approach more adequate for smooth nonlinearities. To take advantage of the similarity of Gaussian-like characteristics of the received signals at each BS, [16,1] proposes an approach to obtain a small degree polynomial equivalent nonlinearity that provides signals with approximately the same spectral attributes as the quantized ones. Furthermore, the quantization noise variance that is obtained from the equivalent nonlinearity is very accurate even for oversampled signals. This paper presents robust receivers for evaluating the quantization effects as well as the different approaches for obtaining the statistical characteristics of the quantization noise.

This paper is organized as follows: Section 2 describes the cellular architecture and the receiver design adopted in this paper. Section 3 is concerned with the different approaches for obtaining the spectral characteristics of the quantization noise and Section 4 presents a set of performance results. Section 5 concludes the paper.

Throughout the paper we will adopt the following notations: bold letters denote vectors and matrices; $\mathbf{x}^*$, $\mathbf{x}^T$ and $\mathbf{x}^H$ denote complex conjugate, transpose and Hermitian (complex conjugate transpose) of $\mathbf{x}$, respectively. $\mathbf{I}_N$ denotes a $N \times N$ identity matrix and $\mathbf{e}_p$ is an appropriate column vector with 0 in all positions except the pth position that is 1. The expectation of x is denoted by $\mathbb{E}[x]$.

2. System characterization

Fig. 1 illustrates the adopted cellular architecture considered in this paper. The system corresponds to a BS cooperation scheme characterized by fractionally overlapping cells, where each cell is associated to a specific BS. In this system, P MTs use the same frequency band to transmit the corresponding information (i.e., all MTs share the same physical channel), and there are R BSs that receive the MTs signals and can efficiently cooperate to improve the system's performance. In conventional systems each BS uniquely performs the detection of the signals of its own MTs and considers as interference the remaining information transmitted from the

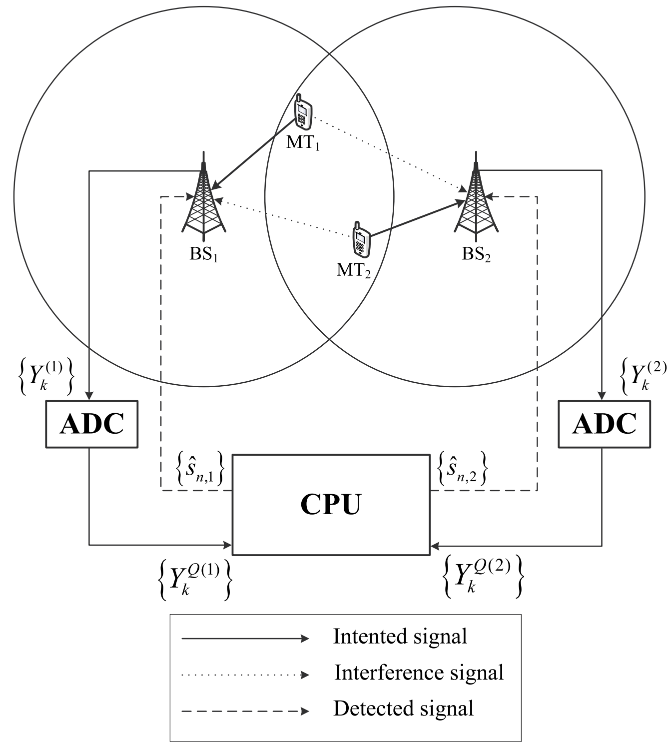

Fig. 1. Cellular scenario.

other MTs, thus discarding it. In turn, with BS cooperation systems the overall signals received at each BS are sent to a CPU that implements the separation of the different signals and then addresses them to the corresponding BS. Hence, the interference issues are managed and mitigated in the CPU. In order to decrease the amount of information to be transmitted in the backhaul link, the signals received at each BS are firstly quantized with an ADC block. In this paper, we assume perfect channel estimation [17] and synchronization, trough the assist of suitable training pilots and/or blocks [18,19].

With respect to transmission, each MT employs an N size block with a SC-FDE modulation scheme. The data block $\{s_{n,p}; n = 0, 1, ..., N-1\}$ is associated with the pth MT ($p = 1, 2, ..., P$), where $s_{n,p}$ corresponds to a QPSK constellation symbol selected from the data following a given mapping scheme (e.g., a Gray mapping rule). Furthermore, the frequency-domain block is $\{S_{k,p}; k = 0, 1, ..., N-1\} = \text{DFT}\{s_{n,p}\}$. In block transmission techniques an adequate cyclic prefix is appended to each data block and it is required to be longer than the overall impulse response, including channel effects as well as transmit and receive filters. However, in BS cooperation schemes it might be necessary to have a slightly longer cyclic prefix to account for different propagation periods between MTs and BSs, since the useful part of each block should overlap. After removing the samples associated with the cyclic prefix, at a given BS r ($r = 1, 2, ..., R$), the useful time-domain received block is given by

$$y_n^{(r)} = \sum_{p=1}^{P} \xi_{p,r} s_{n,p} \circledast h_{n,p}^{(r)} + \nu_n^{(r)}, \tag{1}$$

with $\circledast$ denoting the cyclic convolution regarding n. $h_{n,p}^{(r)}$ indicates the CIR (Channel Impulse Response) connecting the rth BS and the MT p, for the nth time-domain element. The channel noise is denoted by $\nu_n^{(r)}$ and $\xi_{p,r}$ corresponds to a weighting parameter that accounts for the combined effects of power control and propagation loss effects, with the average received power associ-