Impact of Feedback Channel Delay on Adaptive OFDMA Systems

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Abstract. Most standards for the forthcoming beyond 3G (B3G) and 4G technologies state Orthogonal Frequency-Division Multiple Access (OFDMA) as a very promising candidate to be used as a digital modulation scheme. OFDMA combines multiple access techniques with Adaptive Quadrature Amplitude Modulation (AQAM) to maximize system performance while keeping the errors below a certain target. In order to achieve this objective, Channel Quality Indicators (CQI) are fedback from the receivers. However, potential delays in the reception of such CQIs may lead to a system performance degradation. This paper analyzes the impact of CQI feedback delay over a Long Term Evolution (LTE) network.

1 Introduction

Currently, the Third Generation Partnership Project (3GPP) is working on the evolution of the 3G Cellular Networks standardization process [1]. A collaborative process that involves operators, manufacturers and research institutes is in progress to discuss views and proposals on the evolution of the Universal Terrestrial Radio Access Network (UTRAN). LTE specifications are targeting to become a high-data-rate, low-latency and packet-optimized radio-access technology [2]. LTE multiple access in the downlink is based on Orthogonal Frequency-Division Multiple Access (OFDMA), which is a promising technique to provide an efficient access over high-speed wireless networks [3]. LTE will offer broadband wireless access at data rates of multiple Mbit/s to the end-user and within a range of several kilometers. OFDMA at the physical layer, in combination with a Medium Access Control (MAC) layer, provides an optimized resource allocation and Quality of Service (QoS) support for different types of services.

High spectral efficiency in OFDMA environments is achieved by dividing the total available bandwidth into narrow sub-bands to be shared by users in an efficient way. Besides, Adaptive Quadrature Amplitude Modulation (AQAM) is also used to maximize the transmission efficiency while keeping the Bit Error

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Rate (BER) below a desired target. These techniques require the transmitter to be instantaneously channel-aware so that proper modulation schemes and frequency sub-bands are selected dynamically. Thus, the transmitted signal is continuously adapted to the varying channel conditions.

In order to select the modulation scheme for each subcarrier, the channel has to be known at the transmitter. With this objective, Channel Quality Indicators (CQI) are fedback from the receivers to the transmitter. However, potential delays in the reception of CQI through the feedback channel may cause a system performance degradation. Impairments in adaptation due to the delayed reception of CQI were analyzed in [4] for a generic AQAM system. Such delay is a further undesirable effect as mobile terminal speed increases (since channel time-coherence is shorter). Currently, the possibility to concatenate multiple sub-frames into longer Transmission Time Interval (TTI) is being considered in LTE in order to reduce the signalling overhead. However, this would mean a longer delay in the modulation adaptation process.

In this work, a model based on LTE specifications [2] has been implemented on top of WM-SIM [5] in order to evaluate the maximum admissible delay of feedback channel. The model allows to simulate the LTE downlink where CQI is fedback from each User Equipment (UE) to the Enhanced Node-B (eNodeB).

The rest of the paper is structured as follows. In section 2 a brief description of the LTE is presented, focusing on both OFDMA and AQAM techniques and how CQI delays affect performance in this kind of systems. The scenario under study and a description of the implemented system can be found in section 3, whereas simulation results are shown in section 4. Finally, section 5 gathers the main conclusions and future work.

2 OFDMA overview in LTE systems

Orthogonal Frequency Division Multiplexing (OFDM) is a modulation technique widely used to counteract the effects of Inter Symbol Interference (ISI) in frequency selective channels [6]. OFDM divides the transmission band in a large number of sub-bands narrow enough to be considered flat. The symbol sequence is split into lower speed symbol streams transmitted simultaneously on the resulting comb of carriers. Specifically in LTE, several transmission bandwidths from 1.25 to 20 MHz are defined, with a corresponding number of subcarriers in the range from 128 to 2048. At the transmitter, several subcarriers are employed to locate reference symbols in order to allow channel measurements. For the 20 MHz bandwidth mode, the number of useful subcarriers is reduced to 1200 whereas 848 subcarriers are guards and pilots symbols are transmitted over 200 of them.

An Inverse Fast Fourier Transform (IFFT) efficiently performs the modulation process. Its reciprocal process, the forward Fast Fourier Transform (FFT), is used to recover the data as a cyclic extension of the OFDM symbol eliminates the residual ISI. In this way, OFDM can be considered as a time-frequency squared pattern, where each bin can be addressed independently.

Modulation of the OFDM subcarriers is analogous to that of the conventional Single Carrier (SC) systems. Supported downlink data-modulation schemes in LTE are QPSK, 16QAM, and 64QAM. The number of bits allocated to each subcarrier can be modified on a sub-frame basis to simultaneously track the time variant frequency response of the channel and fulfill the BER service requirements. In LTE, the minimum downlink Transmission Time Interval (TTI) corresponds to the sub-frame duration, $T_{sub-frame} = 0.5$ ms, and a sub-frame is composed by a signalling symbol and six data symbols. In addition, a second frame structure is also supported with the intention of providing co-existence with LCR-TDD (Low Chip Rate - Time Division Duplexing). With this alternative frame structure, the sub-frame is enlarged up to 5 ms.

When OFDM is also used as multiplexing technique, the term OFDM Access (OFDMA) is preferred. In this case, a block of bins is assigned to a single user in what can be considered a hybrid TDMA-FDMA technique. In LTE, radio blocks consists of $M = 12$ subcarriers assigned along a sub-frame. With the channel information obtained from the pilot symbols, Channel Quality Indicators (CQI) are estimated at the receiver and fedback to the transmitter for modulation adaptation and resource allocation purposes. Although both block-wise transmission (localized) and transmission on distributed sub-carriers are to be supported in LTE, in this work only blocks consisting of contiguous subcarriers have been considered as fast adaptive modulation is more sensible to the adaptation delay.

2.1 Effects of adaptation delay

In the adaptation process two different impairments can be identified [4]. First, modulation selection is performed using noisy Channel State Information (CSI) as exact channel estimation is not possible. Moreover, Doppler shift may cause different CSI at the time of transmission from that at the time of channel estimation. This work focuses on the second degradation as it is definitively determined by design aspects which can not be modified in prototyping time.

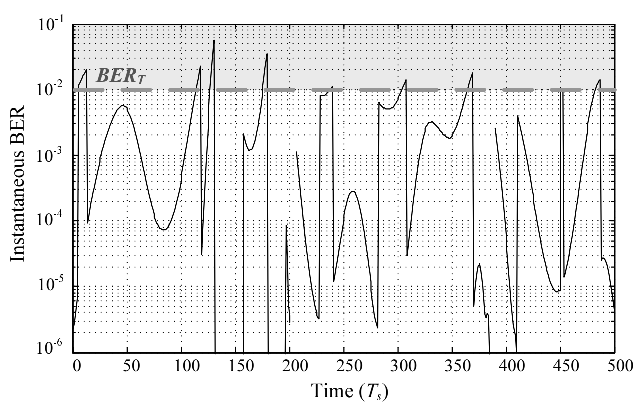

Fig. 1. Instantaneous BER evolution with feedback delay.

The impact of adaptation delay on the instantaneous BER for a single subcarrier is illustrated in Fig. 1. Delay on adaptation may cause a wrong decision in the modulation level at the transmitter and, hence, predefined BER requirements may be unfulfilled. Fig. 1 represents the instantaneous BER as a function of time (normalized to OFDM symbol period T_S). It is shown how the instantaneous BER values are above the target BER ($BER_T = 10^{-2}$) during short time intervals. These intervals corresponds to those when the selected modulation scheme does not match the channel conditions due to the delay on CQI report.

3 System Model

The downlink direction of an OFDMA wireless system has been studied. As shown in Fig. 2, an evolved Node B (eNode B) is connected to one or several User Equipments (UE) through a radio channel. In this example, channel conditions for UE_1 and UE_2 are different since they are located in distinct places and have different speeds. Therefore, each of them report a different CQI values (CQI_1 and CQI_2) to the eNode B. This information about channels conditions will be taken into account to allocate radio resources for each UE.

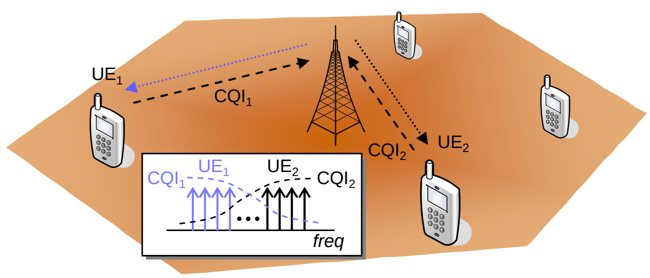

Fig. 2. Scenario under analysis.

The scenario under analysis is modelled using WM-SIM. A block diagram of the implemented OFDMA model is shown in Fig. 3. Model includes the following subsystems: a traffic generator that produces the information flows associated to each user; an eNode B, which implements the main PHY/MAC functionalities at the radio interface; a Rayleigh frequency-selective radio channel; a set of user equipments in charge of processing adequately the received signal; and finally, a Quality of Service (QoS) metrics functionality that collects performance statistics from the simulations (BER, delay, throughput and loss rate in the transmission queues).

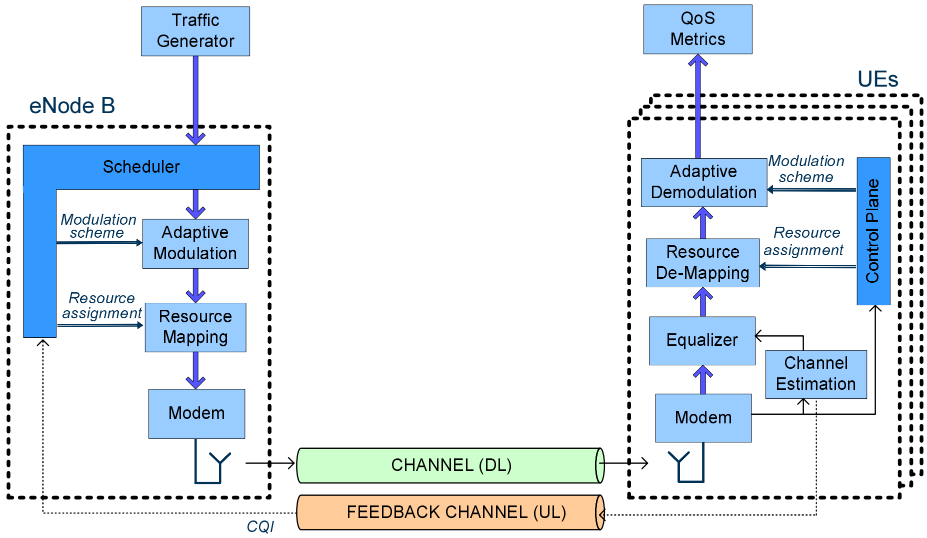

Fig. 3. Downlink OFDMA Wireless System model.

3.1 Enhanced Node B

The eNode B subsystem aims to simulate the basic functionalities of a base station that uses OFDMA technology. This subsystem is made up by four different blocks (as shown in Fig. 3):

- *Scheduler*. Incoming information flows from the traffic generator are stored into N_u First-In First-Out (FIFO) queues (one per user). The cross-layer scheduler is responsible for allocating transmission turns to users following a certain algorithm. Allocation criteria is based on various information like the Channel Quality Indicators (CQI) and/or the queues occupancy. Calculation of CQI is performed for each sub-band (group of 12 consecutive subcarriers) by averaging the SNR value all over the chunk. Once the transmission turn is allocated, a number of bits (according to the UE and chunk modulation level) are extracted from the corresponding queue.

- *Adaptive Modulation*. The modulation level for each user is selected at a subframe rate, according to their estimated instantaneous SNR and target BER values. Instantaneous SNR (γ) is received at the eNode B from each UE through a feedback channel that introduces a configurable transmission delay. No losses are assumed in feedback channel since their effects are beyond the objectives of this study. Adaptive modulation is carried out by means of predefined SNR thresholds that select the proper modulation level $m(\gamma)$ depending on the BER_T, as shown in Fig. 4. Once the scheduler has selected a particular user, the sequence of bits extracted from the queues are

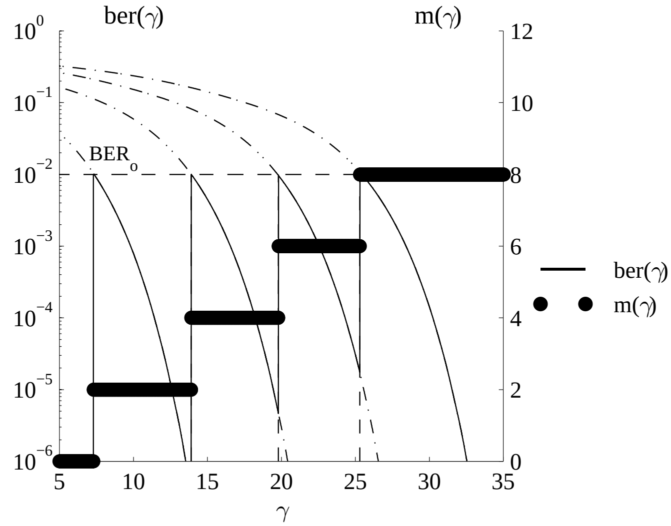

Fig. 4. SNR Thresholds for Adaptive Modulation.

mapped onto their corresponding constellation. Therefore, different constellations can be used along the OFDM symbol since the information conveyed for each user may has a different modulation level.

– *Resource Mapping.* According to the scheduling decision, complex data symbols are mapped on to a certain physical resource block, corresponding to a particular time-frequency area. Thus, the frequency selectivity of the channel can be alleviated. In addition, OFDM symbols are fully conformed, including reference symbols (pilots) and guard periods.

– *Modem.* The transmission modem performs several actions before transmitting the signal to the radio interface. Firstly, the Inverse Fast Fourier Transform (IFFT) is applied in order to convert the OFDM symbol to the time-domain. Secondly, a cyclic prefix is appended to the OFDM symbol to avoid ISI and to minimize temporal synchronization problems between transmitter and receiver.

3.2 Radio Channel

Downlink and uplink radio channels have been modelled in a very different way. While the downlink channel includes a complete frequency-selective multipath model, the uplink scenario (feedback channel) has been simplified in order to focus on the delay effect.

Downlink Radio Channel. A frequency-selective channel is modelled, considering the temporal fading due to multipath propagation [3]. Channel response is assumed to be composed by multiple taps with predefined delays and mean power. This multi-tap configuration determines the mean power profile, which has been set according to the Suburban Macro scenario defined in [7]. Temporal variations on this profile follow a Rayleigh distribution that affects the instantaneous taps power, while taps delays are assumed to be constant.

Additionally, downlink channel includes the effect of noise, modelled as Additive White Gaussian Noise (AWGN) with zero mean at the receive antenna. Noise variance depends on the pre-configured SNR value since constant transmit power has been assumed.

Feedback Channel. As the main purpose of this paper is to analyze the impact of the feedback channel delay on adaptive OFDMA systems, this feedback channel has been modelled as a perfect delay line. This simplification allows to isolate other undesirable effects from the results. Hence, uplink channel has been just modelled as a FIFO queue, which introduces a configurable delay to the CQIs.

3.3 User Equipment Subsystem

Each UE is modelled as an independent subsystem, which processes its received signal through the following blocks sequence (see Fig. 3):

- *Modem* This block receives the transmitted physical signal after being affected by the radio link between the eNode B and a particular UE. Cyclic extension introduced by the eNode B is removed, and afterwards, Fast Fourier Transform (FFT) is applied to recover the received OFDM symbol into frequency-domain.
- *Channel Estimation.* Each UE estimates its correspondent channel frequency response as well as the instantaneous SNR of its received signal. Ideal channel estimation has been assumed in order to isolate the effects of feedback channel delay.
- *Equalization.* The estimated channel frequency response is used to compensate the undesirable effects of the radio channel on the received OFDM symbol. In this block, zero-forcing is adopted as equalization technique.
- *Control Plane.* Scheduling signalling information is extracted from the first and second symbols of a subframe. This information is needed by the Resource De-mapping and Adaptive Demodulation functionalities.
- *Resource De-mapping.* Received OFDM symbols are de-mapped according to the scheduling signalling information. Once a subframe is completed, the data segments allocated to each UE are identified.
- *Adaptive Demodulation* Data segments from each user are demodulated according to the received control information.

4 Simulation Results

Main simulation parameters are listed in Table 1. Different UE speeds have been simulated in order to identify the maximum speed that fulfill the predefined QoS requirements. The users speed vary from 5 Km/h (pedestrian) to 30 Km/h. Higher UE speeds implies faster temporal changes in channel response and, as a consequence, the influence of the feedback channel delay on the transmission adaptation will be greater. On the contrary, CQIs from UEs at lower speeds (i.e. experiencing slow varying channels) will be even less affected by the feedback delay.

Table 1. Configuration parameters

Parameter	Value
FFT Size	2048
Data Sub-carriers	1200
Cyclic prefix length	144 samples
Carrier Frequency	1.8 GHz
Sampling Frequency	30.72 MHz
UE Speed	5-30 Km/h
Feedback Delay	1-5 ms
Target BER	10^{-2} and 10^{-3}

Figure 5 illustrates the effect of feedback channel delay on the average BER for different UE speeds and same target BER (10^{-2}). For a UE speed of 5 Km/h (a), channel response has a very slow variation and therefore, feedback channel delay does not affect significantly (BER values remain under the target even for

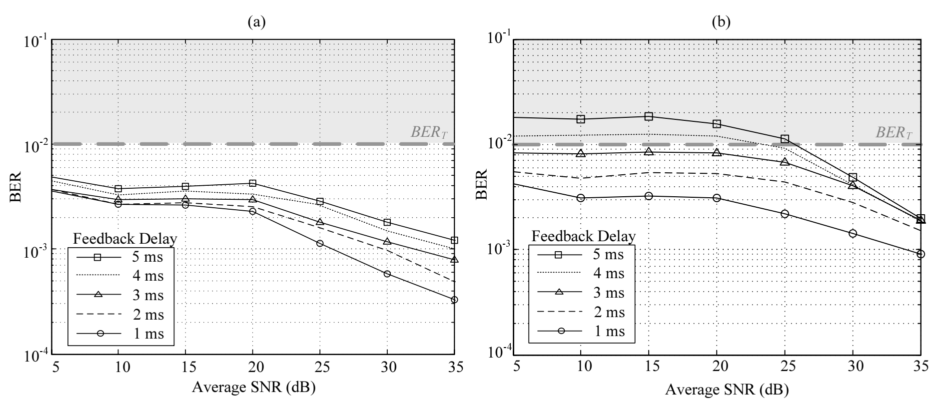

Fig. 5. BER vs. average SNR for different feedback channel delays for: (a) UE speed: 5 Km/h; (b) UE speed: 15 Km/h.

5 ms delay). However, it is clear how results get worse as the delay increases. When UE moves faster (15 Km/h) (b), the impact of delay is greater and there is an important performance degradation. The maximum admissible delay for the feedback link is about 3 ms when the UE moves at 15 Km/h. Shadowed area in the figure represents those BER values above BER_T.

In Figure 6, the average BER is presented as a function of feedback channel delay for different UE speeds and average SNR of 20 dB. In case (a), BER results are always below the $BER_T = 10^{-2}$ for quasi-pedestrian speeds (5 and 10 Km/h). However, for higher UE speeds, BER_T is exceeded even for small delays: 1.5 ms is the maximum admissible delay at 30 km/h.

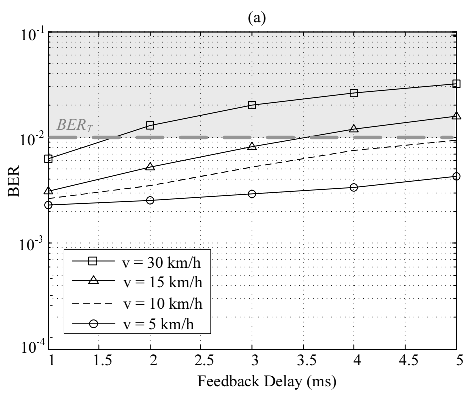

Fig. 6. BER vs. feedback delay when target BER value is 10^{-2} (a) and 10^{-3} (b) for different UE speeds.

For a more restrictive and reliable constraint, e.g. $BER_T = 10^{-3}$, BER requirements are only fulfilled by pedestrian UEs (5 Km/h). When UEs speed is higher (from 10 Km/h on) even a small delay causes a BER higher than the target value (e.g. 2.75 ms at 10 Km/h and 1.75 ms at 15 Km/h).

In the forthcoming B3G or 4G cellular systems, UE speed will be limited in most of the cases to pedestrian values. For this situation, it has been shown how delays in feedback channel are not so restrictive, and system performance does not experience a degradation even for delays up to 5 ms.

5 Conclusions and future work

Along this paper, the impact of CQI feedback delay on an OFDMA system is addressed. As it was foreseen, adaptive modulation is very sensitive to such delays. They may cause a wrong selection of the instantaneous modulation scheme since the CQI used in that selection may not match current channel conditions.

Simulation results show that a system performance degradation is detected for pedestrian speeds (5 Km/h) when feedback channel delays are above 5 ms.

However, BER results are kept under the target value if delays are below 5 ms even for a BER_T of 10^{-3}. When UE speed is higher, channel time coherence is lower, i.e. temporal correlation decreases. Hence, CQI information becomes outdated sooner and average BER results are below the specific target only for low feedback delays.

A complementary study focused on the effects of errors in CQI information for a given delay is an ongoing work. All this work will lead finally to the development of algorithms to estimate and compensate both potential delays and errors in the feedback link. These algorithms will make possible to keep system performance even for non-ideal feedback channel conditions.

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