Imperfect Adaptation in Next Generation OFDMA Cellular Systems

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***Abstract*— Most cellular standards for the forthcoming beyond 3G (B3G) and 4G technologies state Orthogonal Frequency-Division Multiple Access (OFDMA) as the preferred multiplexing technique. OFDMA combines an efficient multiple access 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 fed back from the receivers. However, potential errors and/or delay in the reception of such CQI as well as an imperfect channel estimation may lead to a system performance degradation. This paper analyzes the impact of an imperfect adaptation on a Long Term Evolution (LTE) cellular network.**

***Index Terms*– LTE, OFDMA, AQAM, imperfect adaptation, CQI, feedback channel.**

I. Introduction

Currently, the Third Generation Partnership Project (3GPP) is working on the standardization process of the evolved 3G Cellular Networks [1]. A collaborative process that involves operators, manufacturers and research institutes is currently in progress to discuss views and proposals on the evolution of the Universal Terrestrial Radio Access Network (UTRAN). 3GPP Long Term Evolution (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 that provides 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 channel-aware scheduling at the 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 spectral efficiency while keeping the Bit Error Rate (BER) below a desired target. These techniques require the transmitter to be instantaneously channel-aware so that proper modulation schemes for each user and each frequency sub-band are continuously adapted to the varying channel conditions. In the most common scheme, the channel frequency response is estimated at the receiver and certain Channel Quality Indicators (CQI) for the different sub-bands are fed back to the transmitter.

The adaptation process takes place at the transmitter, which dynamically selects the proper modulation scheme based on the reported CQI. However, the received CQI may be inexact, corrupted or outdated, which potentially leads to a system performance degradation. The main impairments in the adaptation process are summarized as follows:

- *Outdated CQI*: Potential delays introduced by the feedback channel imply that reported CQI does not match current channel state at the time of transmission. This is a further undesirable effect as mobile terminal speed increases, since channel coherence time is shorter. The minimum time allowed between CQI transmissions is determined by the Transmission Time Interval (TTI).
- *Non-exact CQI*: The estimated CQI at the receiver is noisy by nature since perfect channel estimation is not possible. Moreover, as the quantity of information to be feedback has to be bounded, only a reduced set of quantified values can be sent towards the transmitters. Additionally, propagation through feedback channel may introduce errors in the reported CQI, which potentially leads to an erroneous CQI at the transmitter end.

An in-depth study of the performance degradation due to the noisy and outdated channel estimation for single user transmission over flat fading channels can be found in [4]. For High-Speed Downlink Packet Access (HSDPA), several papers address drawbacks related to CQI reports. The main issue to take into account is that, in fast changing channels, the information reported to the base station may become obsolete. The effects of user speed on the reported channel information were studied in [5]. In [6] an improved link adaptation technique that takes into account the reliability of CQI reports is presented; this method introduces a new terminal-specific CQI offset depending on the age of the information. This new offset increases the probability that users with newer reports are scheduled and, therefore, improves the performance of the overall system. Channel information age is also considered in [7], which introduces a scheme to avoid incorrect channel quality information by using a timer and an efficient CQI report timing criterion. When user speed increases, there are both faster changes in channel conditions and higher handover rates. Results show that cell capacity is in the order of 40% worse for user speeds of 20 km/h compared to the reference case of 3 km/h.

In this work, a model based on the current state of LTE specifications [2] has been implemented on top of WM-SIM platform [8] in order to evaluate the effect of imperfect adaptation on system performance. The considered scenario consists of a single cell where a set of mobile terminals report their CQI towards the base station through a feedback channel. The different identified impairments that affect the adaptation process have been evaluated by means of simulations. Concretely, the effects of erroneous and outdated CQI on the performance are studied.

The rest of this paper is structured as follows. In section II a brief description of the LTE cellular technology is presented,

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focusing on both OFDMA and AQAM techniques. Scenario under study and a description of the implemented system can be found in section III. Section IV presents the main sources of adaptation impairments. Simulation results are shown in section V. Finally, section VI gathers the main conclusions and future work.

II. OFDMA Overview

OFDM is a modulation technique widely used to counteract the effects of Inter-Symbol-Interference (ISI) in frequency selective channels [9]. OFDM divides the transmission bandwidth in a large number of sub-bands narrow enough to be considered flat in terms of frequency response. The source symbol sequence is split into lower speed symbol streams transmitted simultaneously on the resulting comb of subcarriers.

An Inverse Fast Fourier Transform (IFFT) efficiently performs the OFDM modulation. 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. This way, OFDM can be considered as a time-frequency squared pattern, where each bin can be addressed independently.

Modulation of each OFDM subcarrier is analogous to that of the conventional Single Carrier (SC) system. Quadrature Phase Shift Keying (QPSK) or M points Quadrature Amplitude Modulation (M-QAM) are the most common schemes. Modulation adaptation allows to maximize spectral efficiency while fulfilling BER service requirements.

When OFDM is also used as user multiplexing technique, the term OFDM Access (OFDMA) is preferred. In this case, resources are allocated to different users in what can be considered as an hybrid TDMA-FDMA technique. The modulation level, i.e. number of bits allocated to each subcarrier, can be periodically modified to track the time variant channel frequency response of each user. Fig. 1 shows an example of the process for three users. The instantaneous SNR measured at each sub-band is presented in the right y-axis and the potential number of bits per symbol in the left y-axis. In this case, the user with maximum modulation level is selected for transmission and has been presented with a different color in the figure.

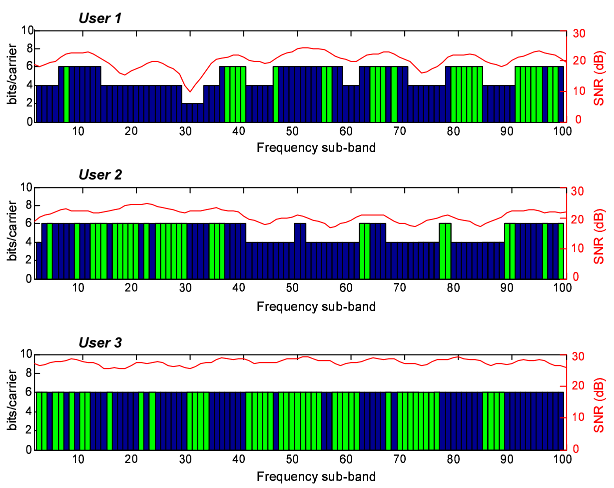


Fig. 1. Snapshot of modulation level for each frequency sub-band.

A. OFDMA in LTE systems

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. For the 20 MHz bandwidth mode, data transmission is performed over 1200 out of a total of 2048 available subcarriers, whereas the rest of subcarriers (848) are used for guard purposes.

Supported data-modulation schemes in LTE downlink are QPSK, 16-QAM, and 64-QAM. For the generic frame structure, the minimum TTI corresponds to the sub-frame duration ($T_{sub-frame} = 1$ ms), which is composed by 14 consecutive OFDM symbols.

Reference symbols (pilots) are spread over the available signalling subcarriers for channel estimation purposes, e.g. 200 pilots are transmitted on the signalling OFDM symbol for the maximum bandwidth configuration.

In LTE, minimum resource allocation unit is a Physical Resource Block (PRB), which consists of $M = 12$ subcarriers assigned along a sub-frame. With the channel information obtained from the reference symbols, CQI are estimated for each PRB at the receiver and feedback to the transmitter for modulation adaptation and resource allocation purposes.

Current LTE specifications define two different modes for a PRB: distributed and localized. In the distributed mode, a PRB is composed by a number of sub-carriers which are spread in the frequency domain in order to obtain frequency diversity. In the localized mode (block-wise transmission) a PRB is composed by contiguous subcarriers, in order to allow the use of adaptive modulation. In this case the modulation level, i.e. number of bits allocated to each subcarrier, is the same for all the subcarriers within a PRB and it can be modified on a sub-frame basis. In this work, only the localized mode has been considered.

III. System Model

The downlink direction of an OFDMA wireless system according to LTE specifications has been addressed. As shown in Fig. 2, a single cell where an evolved Node B (eNode B) is connected to several User Equipments (UE) through a radio channel has been modelled. In the example shown in Fig. 2, channel conditions for UE_1 and UE_2 are different since they are located in different places and they move at different speeds. Therefore, each of them reports a different CQI value (CQI_1 and CQI_2 respectively) to the eNode B. This information about channel conditions will be taken into account to allocate radio resources to each UE.

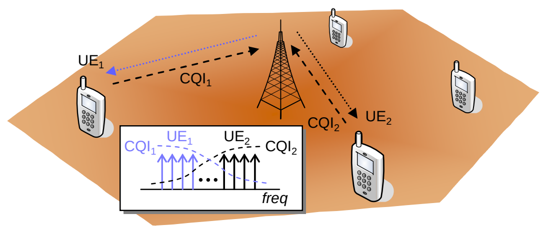


Fig. 2. Scenario under analysis.

The model has been implemented using WM-SIM platform [8]. WM-SIM is a C++ based and data-flow oriented platform that allows to implement and simulate complex models. It allows a modular design of communication systems by means of interconnection of its basic entities: block and system. WM-SIM also includes a repository of predefined blocks.

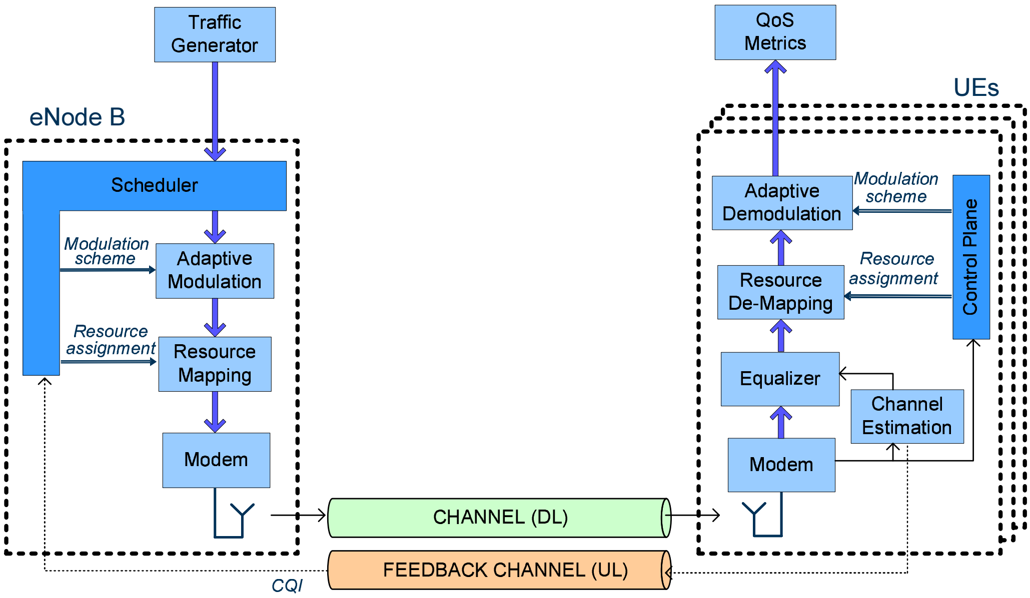


Fig. 3. Downlink OFDMA Wireless System model.

A block diagram of the implemented OFDMA system is shown in Fig. 3, which 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 QoS metrics functionality that collects performance statistics from the simulations as BER or user throughput.

A. Enhanced Node B

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

- *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 by following a certain algorithm. Allocation criteria is based on the CQI reported by each user and a *Best Channel* algorithm have been adopted. Calculation of CQI is performed for each sub-band or PRB (group of 12 consecutive subcarriers) by averaging the SNR value all over the chunk. A modulation scheme is selected for each user and each PRB from the reported CQI value. Once the transmission turn is allocated to a particular UE, a number of bits according to the user and PRB modulation level are extracted from the corresponding queue.
- *Adaptive Modulation.* AQAM is performed using a constant-power and discrete-rate modulation scheme. The modulation level for each user is selected on a subframe basis, according to its estimated instantaneous SNR and target BER (BER_T) values. Reported CQI provides a measurement of the instantaneous SNR (γ) for a particular user and frequency sub-band (PRB). CQI is received at the eNode B from each UE through a feedback channel that introduces a configurable delay and bit error probability. Adaptive modulation is carried out by means of predefined SNR thresholds that determine 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 mapped onto their corresponding constellation. Therefore, different modulation schemes can be used along the OFDM symbol since the information conveyed for each user and PRB may has a different modulation level.
- *Resource Mapping.* According to the scheduling decision, complex data symbols are mapped onto a certain PRB, 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 frequency domain guard intervals.
- *Modem.* The transmission modem performs several tasks before transmitting the signal to the radio interface. Firstly, an IFFT is applied in order to convert the OFDM symbol to the time-domain. Secondly, a cyclic prefix is appended to the OFDM symbol in order to avoid ISI.

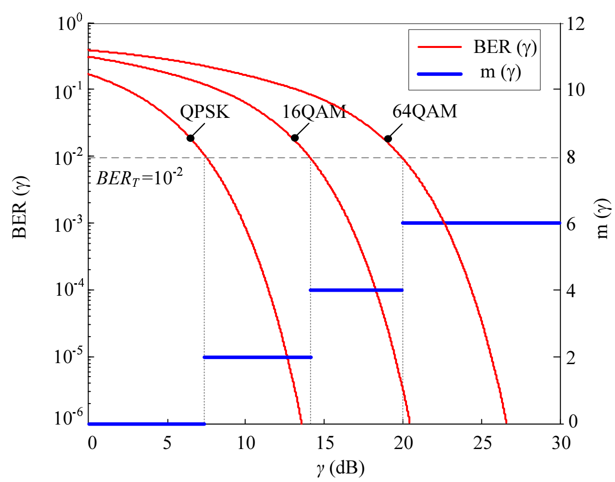


Fig. 4. SNR Thresholds for Adaptive Modulation.

B. Mobile Radio Channel

Downlink and uplink radio channels have been modelled in a very different way. Whereas downlink channel includes a complete frequency-selective multipath model, the feedback channel in the uplink has been simplified in order to focus on delay and bit error effects. As mentioned above, CQI is reported from receivers to the eNode B through feedback channel. Delay and bit errors due to propagation may produce the CQI to be outdated and/or erroneous, leading to a wrong decision in the adaptation process.

1) Downlink 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 [10]. Temporal variations on this profile follow a Rayleigh distribution that affects the instantaneous taps power, while taps delay is 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.

2) Feedback Channel: Propagation through feedback channel may introduce both errors and delay on the reported CQI. Outdated and non-exact CQI are considered in this work as the main problems regarding the modulation adaptation process. Therefore, the implementation of the feedback channel has been simplified to focus on these adaptation impairments. Thus, feedback channel has been modelled as a FIFO queue, which may introduce a configurable delay and certain bit error probability to the reported CQI from each UE.

C. User Equipment

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 signal after being affected by the radio link between the eNode B and the particular UE. Cyclic prefix introduced at the transmitter is removed, and afterwards, an FFT is applied to recover the received OFDM symbol into frequency-domain.
- *Channel Estimation.* Each UE estimates its corresponding channel frequency response as well as the instantaneous SNR of its received signal. A brief description of the considered channel estimation subsystem is provided in section IV.
- *Equalizer.* The estimated channel frequency response is used to compensate the undesirable effects of the radio channel on the received OFDM symbol. In this block, a zero-forcing equalization technique is applied.
- *Control Plane.* Control information is extracted from the first and second OFDM symbols of each subframe. Control data includes resource allocation information and the modulation scheme for each PRB. This information is needed by the Resource De-Mapping and Adaptive Demodulation functionalities for properly recovering user data.
- *Resource De-Mapping.* Received OFDM symbols are combined to compose the original subframe. Resource assignment information provided by the Control Plane allows to identify resource blocks allocated to the particular UE. Once the specific UE blocks are identified, complex data symbols are extracted and then processed by the Adaptive Demodulation functionality in order to recover user data.
- *Adaptive Demodulation.* Complex data symbols are demodulated according to the indicated modulation level to recover the corresponding sequence of bits. Finally, recovered data segment is used for QoS measurements, e.g. Bit Error Rate or user throughput.

IV. Imperfect Adaptation

Two different limitations can be identified in the adaptation process [11], [12], [13]. Firstly, propagation through feedback channel may cause the CQI to be outdated when it is applied to select the modulation level. Besides, the transmitter may receive a non-exact CQI due to imperfect channel estimation and potential errors introduced by the feedback channel. Both impairments may lead to a wrong decision in the selection of the modulation scheme and, as a consequence, to a system performance degradation. In the following sections, the different causes and effects of these adaptation impairments are analyzed.

A. Outdated CQI

The potential delay introduced by the feedback channel imply that reported CQI from the receivers does not match current channel state at the time of transmission. Hence, when the transmitter apply the received CQI to perform the adaptation, the channel may have evolved to a new state. The effect worsens as the mobile terminal speed increases, since channel coherence time shortens. Usually, this delay is considered as a multiple of TTI, which determines the minimum time between CQI reports. A typical delay of 3 TTI is assumed for evaluation in the LTE performance verification process.

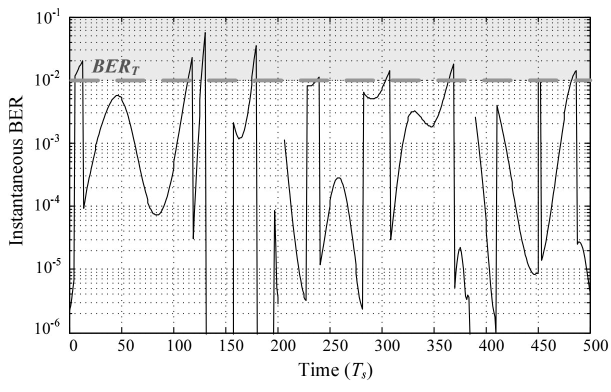


Fig. 5. Instantaneous BER evolution.

An example of the impact of feedback delay is illustrated in Fig. 5, which represents the instantaneous BER as a function of time (normalized to OFDM symbol period T_S) for a single subcarrier. An outdated CQI may cause a wrong decision in the modulation level at the transmitter, and hence, predefined BER requirements may be unfulfilled. It is shown how the instantaneous BER values are above the target BER ($BER_T = 10^{-2}$) during short time intervals. These intervals correspond to those when the selected modulation scheme does not match the current channel conditions.

In order to evaluate quantitatively the effect of using an outdated CQI, different simulations were carried out to obtain the Mean Square Error (MSE) as a function of feedback delay. For a typical flat Rayleigh channel, UE speeds ranging from 5 to 30 km/h and different values of feedback delay up to 8 TTIs (8 ms) were considered. Fig. 6 gathers results from this set of simulations. As expected, a longer feedback delay leads to higher MSE since channel coherence time decreases and, hence, the received CQI becomes further outdated. On the other hand, a higher UE speed imply faster changes on the instantaneous channel state, hence decreasing the temporal correlation between consecutive CQIs.

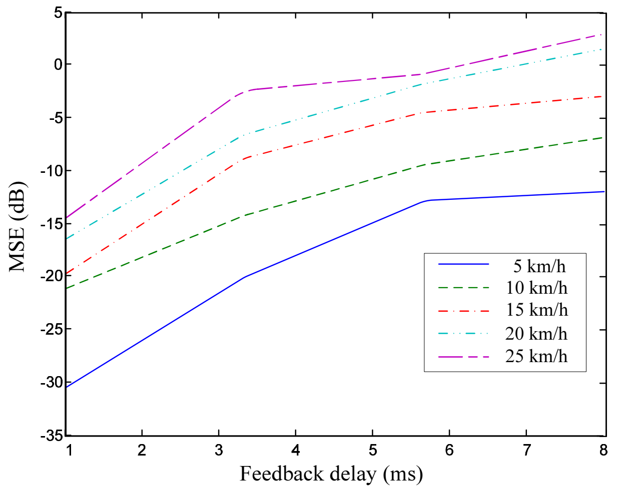


Fig. 6. MSE values due to outdated CQI for different feedback delays and UE speeds.

B. *Non-exact CQI*

Two different causes have been considered for receiving a non-exact CQI at the transmitter.

1) Imperfect Channel Estimation: The estimated CQI value is noisy by nature since perfect channel estimation is not possible. The channel estimation subsystem for the instantaneous SNR described in [4] is here considered. In short, pilot complex symbols (with same average power as data symbols) are spread all over the available subcarriers in a signalling OFDM symbol. A signalling symbol, containing pilot subcarriers, is followed by 6 OFDM data symbols. At the receiver, pilot symbols are extracted; the estimated SNR is obtained from a FIR filtered version of samples of the channel complex envelope followed by a squared norm operation. The obtained MSE for the channel complex envelope estimation can be minimized with the proper filter coefficients selection.

2) Feedback Channel Errors: Propagation through feedback channel may introduce errors in the reported CQI, which potentially leads to an erroneous CQI at the transmitter end. Moreover, as the quantity of information to be feedback has to be bounded, only a reduced set of quantified values can be sent towards the transmitters. The number of bits of the quantification process is still under discussion in the LTE specification process. In this work, a number of 5 bits has been considered for quantification of each CQI and independent bit errors with certain probability are introduced to the quantified values.

V. Simulation Results

Several simulations of the presented model have been carried out in order to study the performance degradation of an LTE system, focusing on the adaptive modulation functionality. In particular, following subsections analyze in detail the impact of outdated and non-exact CQI on the system performance.

Simulations have been carried out on top of WM-SIM simulator [8]. The introduced model has been implemented and simulated by following the design and execution rules defined by WM-SIM environment. Main simulation parameters are listed in Table I. Feedback delay varies from 1 to 5 TTIs (1 to 5 ms), whereas an LTE maximum bandwidth configuration of 20 MHz and 1200 available data subcarriers have been assumed. A QoS requirement has been defined in terms of target BER, set to 10^{-2} and 10^{-3} for different simulations. These values should allow for getting an acceptable QoS under the consideration that no channel coding or retransmission techniques are applied in this work.

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 imply faster temporal changes in channel response and, as a consequence, CQI becomes sooner outdated. On the contrary, CQI from users at lower speeds, i.e. experiencing slowly varying channels, will remain valid for a longer time.

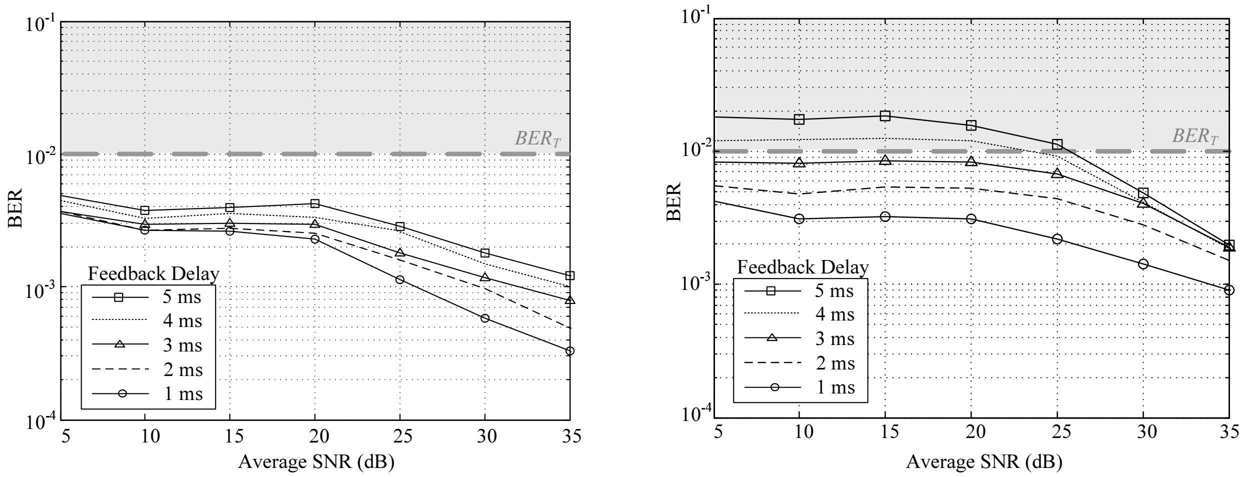
TABLE I
Configuration Parameters

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}

A. *Outdated CQI*

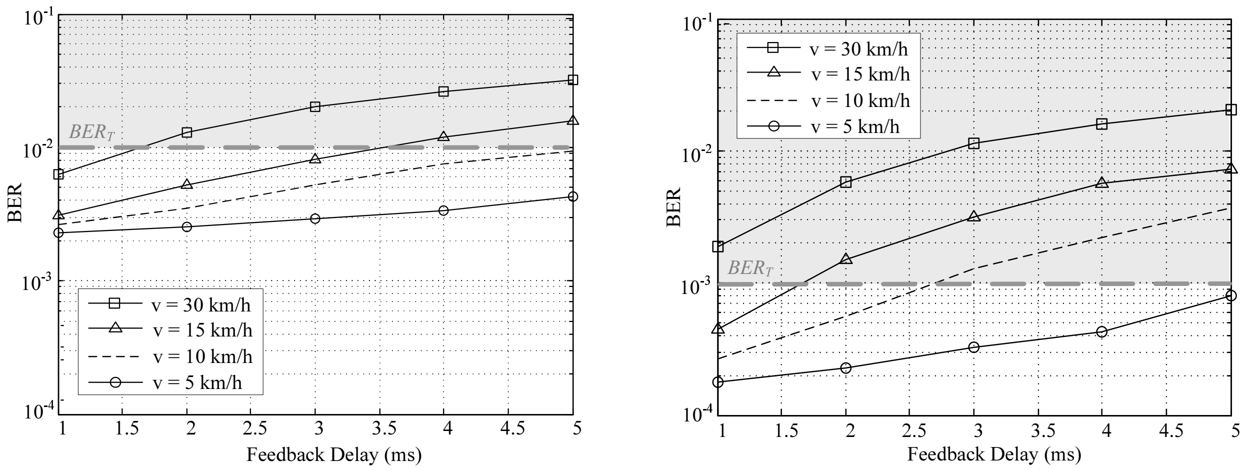
The effect of feedback channel delay on the average BER for different UE speeds and same target BER (10^{-2}) is illustrated in Fig. 7. For a UE speed of 5 km/h (a), channel response has a very slow variation and therefore, feedback channel delay does not affect significantly to the average BER (i.e. BER values remain under the target even for 5 ms delay). However, it is clear how results get worse as the delay increases. When UE moves faster (15 km/h) (b), the effect of feedback delay leads to 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 Fig. 8, the average BER is presented as a function of feedback channel delay for different UE speeds, considering an 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



(a) UE speed: 5 km/h (b) UE speed: 15 km/h

Fig. 7. BER vs. average SNR for different feedback channel delays.



(a) $BER_T = 10^{-2}$ (b) $BER_T = 10^{-3}$

Fig. 8. BER vs. feedback delay for different UE speeds and two cases of target BER.

even for small delays: 1.5 ms is the maximum admissible delay at 30 km/h.

A more restrictive constraint is depicted in Fig. 8(b), where $BER_T = 10^{-3}$. In this case, BER requirements are only fulfilled by pedestrian users (5 km/h). When UE speed is higher (from 10 km/h on) even a small delay causes an average BER higher than the target value (e.g. 2.75 ms at 10 km/h and 1.75 ms at 15 km/h).

B. Non exact CQI

1) Imperfect channel estimation: Effects of imperfect channel estimation on the adaptation process can be derived from Fig. 9. Average BER is depicted for two different mean SNR values (10 and 20 dB) and three different UE speeds (5, 15 and 30 km/h). Channel estimation error is represented in the x-axis in terms of MSE.

Simulation results show that greater MSE in channel estimation imply higher BER values. It is also observed that BER sensitivity against error in channel estimation increases as the average SNR value is higher. That is due to the fact that higher SNR values imply the selection of more dense constellations. Potential errors over these constellations (although less frequent due to a higher SNR value) imply a higher number of erroneous bits. On the other hand, BER

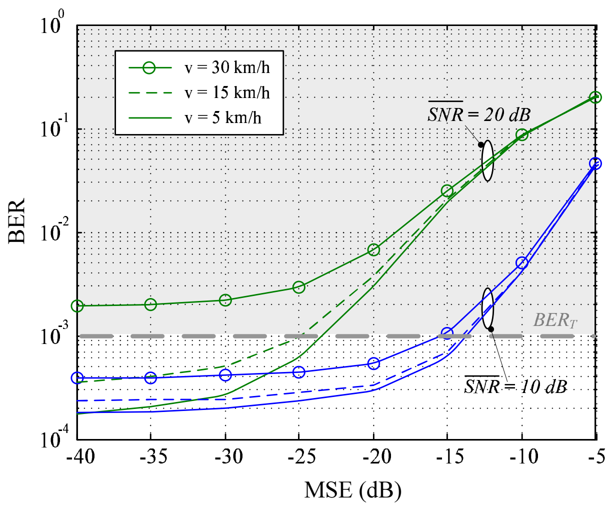


Fig. 9. Imperfect channel estimation.

results for different terminal speeds are similar when MSE is high enough to become the dominant error factor. For instance, when SNR = 10 dB, BER_T is exceeded when MSE is above -15 dB. However, for a higher average SNR (20 dB), BER requirement is unfulfilled with lower MSE values, i.e. -25 dB for 5 km/h and -23 dB for 10 km/h. Finally, for 30 km/h BER requirement is never fulfilled.

2) Feedback channel errors: A model of an imperfect/non-ideal feedback channel make possible to evaluate how the existence of errors in CQI reports affects to system performance. With this purpose, independent bit errors are introduced by the feedback channel with a certain probability.

In order to illustrate this effect, performance between ideal ($P_e = 0$) and extremely noisy ($P_e = 10^{-1}$) feedback channel were compared. Such a comparison was made in terms of average BER and spectral efficiency as depicted in Fig. 10. As shown in the curves, a bit error in the CQI when the channel is poor may provoke the selection of a more dense constellation, leading to a higher spectral efficiency at the expense of increasing BER values. On the other hand, for high SNR an inappropriate selection usually leads to less dense constellations. In this case, spectral efficiency is degraded whereas BER results are not affected so significantly.

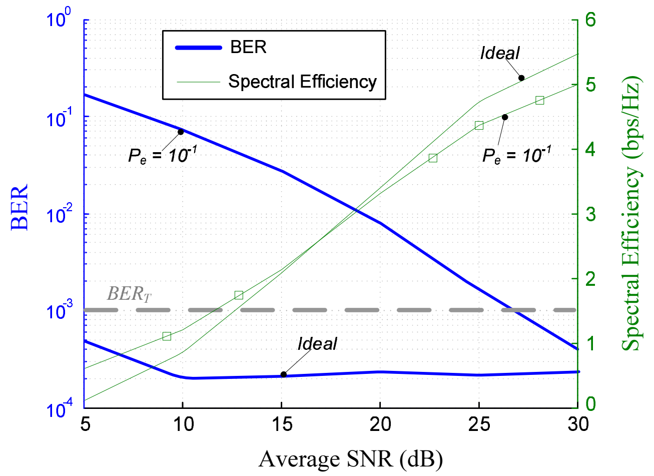


Fig. 10. Comparison between ideal ($P_e = 0$) and noisy ($P_e = 10^{-1}$) feedback channel in terms of average BER and spectral efficiency.

Results for different bit error probabilities (*Pe*) are depicted in Fig. 11. For low *Pe* values (up to 10^{-4} inclusive), BER results are kept under BER_T even for the lowest SNR values. When *Pe* is around 10^{-3}, there is a certain performance degradation. However, when *Pe* increases to 10^{-2} BER results are above BER_T for most of SNR values.

In real systems, CQIs are usually transported over control channels, which are usually protected with a robust channel coding scheme (e.g. convolutional coding with 1/2 rate for LTE [14]). Typical BER values when channel coding is applied are below the ones considered here and, therefore, errors in feedback channel should not be an issue in real systems.

VI. Conclusions and Future Work

The purpose of this paper is to study the impact of imperfect adaptation in next generation OFDMA cellular systems. Concretely, a model based on 3GPP-LTE specifications has been implemented and evaluated by means of simulations. This work has focused on the different impairments in the reported channel state information and their influence on the adaptive modulation functionality.

In the first place, the impact of outdated CQI for different terminal speeds was analyzed. Simulation results show that system performance is very sensitive against outdated CQI, which may cause a wrong selection of the instantaneous modulation scheme. A system performance degradation is detected

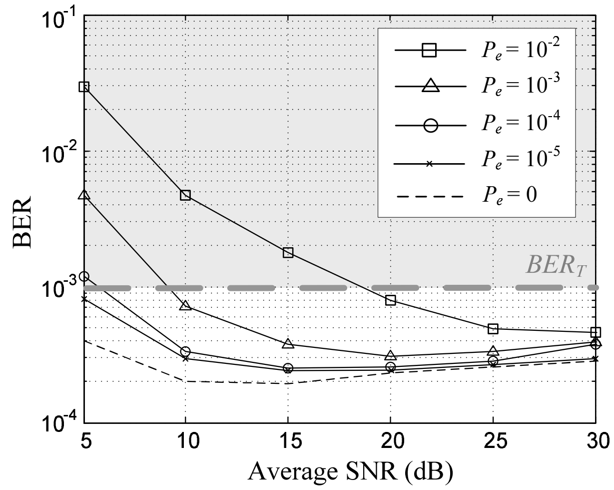


Fig. 11. Impact of feedback channel bit errors on the average BER.

for pedestrian speeds (5 km/h) when feedback channel delay is above 5 ms. However, BER results are kept under the target value if feedback delay is below 5 ms even for a BER_T of 10^{-3}. For higher UE speeds, channel coherence time is shorter, i.e. temporal correlation decreases. Hence, CQI information becomes sooner outdated and average BER results are below the specific target only for low feedback delays.

The effects of non-exact CQI were also studied, both due to imperfect channel estimation and bit errors introduced by feedback channel. Non-exact CQI has also been proved to be a source of performance degradation in the adaptive modulation process. Performance results show that imperfect channel estimation provokes an increment on the average BER. Besides, BER sensitivity against this error increases as the average SNR is higher since a modulation selection error for more dense constellations has a higher cost.

The final purpose of this work is the development of algorithms to estimate and compensate potential errors in adaptive modulation for LTE systems. Future works will include prediction techniques to optimize the system performance even for non-ideal feedback channel conditions.

Acknowledgments

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