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*Abstract*—A multiple component carrier (CC) solution has been agreed as the underlying structure of the Long Term Evolution - Advanced (LTE-A) systems, which are currently being standardized by the 3rd Generation Partnership Project (3GPP). In this deployment, the bundling of Modulation and Coding Scheme (MCS) and Hybrid Automatic Repeat Request (HARQ) parameters across multiple CCs is foreseen to maintain the feedback signaling comparable with the one of the previous LTE Release 8. This paper focuses on the transmission over multiple CCs in LTE-A Uplink. Issues related to the bundling of the link level parameters is discussed and a simple Codeword (CW) mixing strategy is proposed to boost the spectral efficiency performance while keeping low feedback overhead. Results show that, combined HARQ/MCS bundling can achieve the same performance of HARQ only bundling when used together with our proposed CW mixing strategy, with the advantage of a lower feedback overhead. CW mixing also leads to similar spectral efficiency when the bundling is performed over 2 and 3 CCs. The use of a turbo Successive Interference Cancellation (turbo SIC) receiver further improves the spectral efficiency, especially when antenna gain imbalance (AGI) occurs.

*Index Terms*—LTE-A, multiple CCs, OFDM, DFT-s-OFDM, MIMO, MMSE, turbo SIC

## I. INTRODUCTION

The Long Term Evolution - Advanced (LTE-A) systems are currently being standardized by the $3^{rd}$ Generation Partnership Project (3GPP) and aim at peak data rates of 1 Gbit/s in the downlink and 500 Mbits/s in the uplink [1]. Such ambitious targets can only be achieved by using advanced Multiple Input Multiple Output (MIMO) antenna techniques together with wide spectrum allocation, up to 100 MHz. Furthermore, backwards compatibility with the previous LTE Release 8 [2] is also required in order to allow a smooth migration between the two technologies, at the same time reducing the standardization efforts.

A multiple component carrier (CC) solution has been agreed in the 3GPP Work Item (WI) as the underlying structure for the LTE-A spectrum [3]. In this deployment, the 100 MHz bandwidth is divided in 5 chunks of 20 MHz, each of them keeping the LTE numerology for what concerns number of subcarriers as well as the subcarrier spacing. The LTE multiple access schemes [2], Orthogonal Frequency Division Multiplexing (OFDM) for the downlink and Discrete Fourier Transform-spread-OFDM (DFT-s-OFDM) for the uplink, have now to cope with the new spectrum deployment.

NxDFT-spread-OFDM (NxDFT-s-OFDM) has been agreed as uplink scheme for LTE-A [1]. As shown in Fig.1, up to 5 Release 8-like encoded data blocks are independently DFT-spread before being mapped over the CCs. With the assumption of maintaining the same parametrization (i.e., subcarrier spacing) for each of the CCs, a single Inverse Fast Fourier Transform (IFFT) can be used to generate the time domain signal. With this solution, the transmissions over multiple CCs can be seen as parallel LTE Release 8 transmissions as described in [4]. It has been shown than this technology preserves a lower Peak-to-Average Power Ratio (PAPR) than NxOFDM [5].

The wide spectrum allocation leads to an increase of the feedback signaling since the parameters which are needed to properly setup the communication chain should now be sent per CC. Bundling of the frequency parameters across multiple CCs is therefore foreseen to reduce the feedback overhead and keep it comparable with LTE Release 8 [6]. In this paper, we focus on the transmission over multiple CCs in LTE-A Uplink. Issues related to the bundling of the frequency parameters are discussed and a simple CW mixing strategy is proposed with the aim of boosting the link performance while keeping low feedback overhead.

The paper is structured as follows. Section II introduces the main link level features which are needed to enable efficient transmission with the support of feedback signaling. The bundling of the signaling parameters over multiple CCs is discussed in Section III together with our proposed CW mixing strategy. Section IV presents a wide set of link level simulation results. Finally, Section V resumes the conclusions.

## II. LINK LEVEL FEATURES REQUIRING A FEEDBACK CHANNEL

The targeted high data rates of LTE-A can only be obtained with the support of a feedback channel which ensures the proper setting of the transmission parameters. The two main link level techniques of the 3GPP radio access technologies requiring the aforementioned signaling are described in the following subsections.
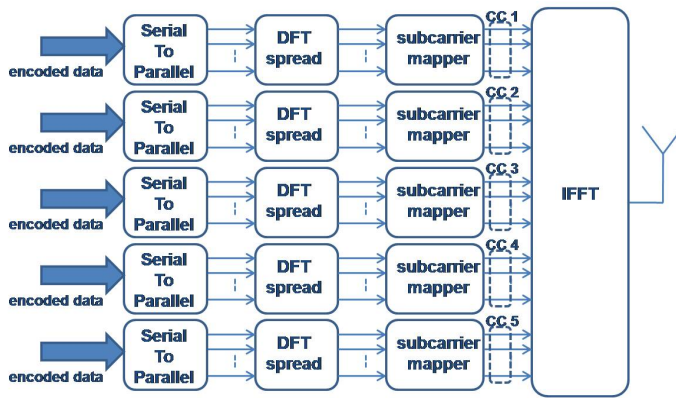
Fig. 1.   NxDFT-s-OFDM signal generation.

## A. Adaptive Modulation and Coding (AMC)

Often referred with the general term "Link Adaptation", this technique allows to adapt the amount of data to be sent to the instantaneous channel conditions [7]. In the uplink, the Base Station (BS) computes the Signal-to-Noise Ratio (SNR) of the User Equipment (UE) depending on a previously transmitted sounding reference signal (SRS), and selects the Modulation and Coding Scheme (MCS) leading to the highest expected throughput with respect of a certain Block Error Rate (BLER) target. The index of the selected MCS is then fed back to the UE through signaling. The UE can therefore achieve robustness to the noise and the channel fades in case of poor radio conditions by using low order MCSs (e.g. QPSK with coding rate 1/3), and leverage its throughput in case of highly reliable channels by using high order MCSs (e.g., 64QAM with coding rate 4/5).

## B. Hybrid Automatic Repeat Request (HARQ)

HARQ is basically a physical layer packet retransmission strategy which exploits the error detection capabilities of the 3GPP radio access technologies [8]. In LTE a cyclic redundancy code (CRC) is appended to the information bits of each CW to check if the detection process has been successful. In case of correct detection, an ACK message is sent to the UE through signaling, otherwise a NACK message is sent and the UE has to retransmit the CW. The fact that this operation is carried out at level 1 of the protocol stack reduces the latency between the retransmissions with respect to the traditional ARQ protocols at Medium Access Control (MAC) layer. Two types of retransmission strategies are usually considered:

1) Chase combining: the same CW is used for both transmission and retransmissions.
2) Incremental redundancy: when the CW is re-transmitted, its coding rate is decreased to make it more robust to the channel. Furthermore, for non-constant amplitude MCSs like 16QAM a re-arrangement of the bits in the QAM constellation is used with the aim to improve the reliability of the information bits.

## III. BUNDLING OF LINK LAYER PARAMETERS

The MCS's index and the ACK/NACK (A/N) messages increase however the feedback overhead in the downlink signaling. In LTE Release 8, a single CW is mapped over the whole transmission bandwidth, and thus only a single MCS index is fed back. In LTE-A it is assumed that each CW is mapped over a CC [1], and it is still under discussion whether the MCS index should be sent per CC or one for the whole user bandwidth. The first solution can make a better use of the frequency selectivity of the channel, but it also increases up to 5 times the feedback overhead. At the same time, also the HARQ process feedback can be made per CC or over the whole bandwidth. In the second case, all the CWs over the used CCs set must be retransmitted even only one of them is not correctly decoded.

The following alternatives will be considered here:

1) *no bundling*: a single MCS field and A/N message per CC (Fig.2(a)). This solution allows to easily cope with the different channel gains over the CCs, however, it is the most expensive solutions in terms of feedback overhead.
2) *HARQ bundling*: the MCS is still selected per CC, but the A/N message is sent per the whole used CC set (Fig.2(b)).
3) *HARQ/MCS bundling per Antenna*: a single MCS field and A/N message per the whole used CC set (Fig.2(c)).
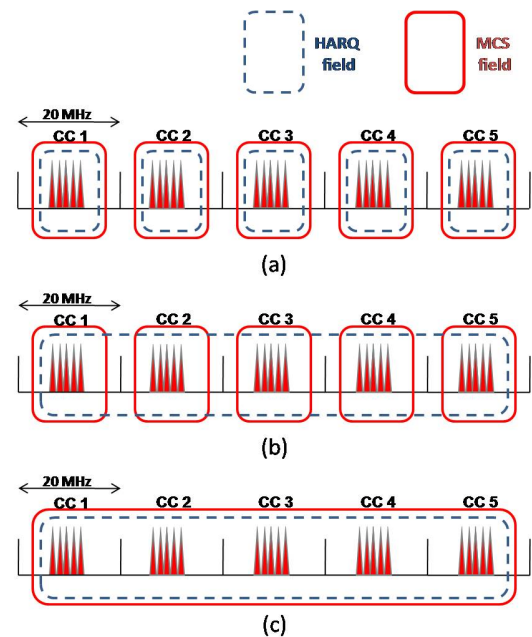


Fig. 2.   Bundling of HARQ and MCS fields.

In case of MCS bundling, the MCS to be used in the UE is computed as a function of the SNR values of the SRSs which are transmitted over multiple CCs. Since the data over multiple CCs are expected to experiment uncorrelated fading because of the frequency separation, the selected MCS might

| | 1 CC | 2 CCs | 3 CCs | 4 CCs | 5 CCs |
|---|---|---|---|---|---|
| *no bundling* | 5 | 10 | 15 | 20 | 25 |
| *HARQ bundling* | 5 | 9 | 13 | 17 | 21 |
| *HARQ/MCS bundling* | 5 | 5 | 5 | 5 | 5 |

not be the one leading to successfull transmission on all CCs, and hence force retransmission of all CWs.

To avoid this problem, we propose to use a *CW mixing strategy over the CCs*: the data belonging to a certain CW are permuted over different CCs on a time symbol basis, as shown in Fig. 3. In this way, the channel gain is averaged over CWs transmitted by the antenna, and the selected MCS is a more valid predictor of the experienced throughput. Furthermore, the SNR-averaging provided by the CW mixing reduces the number of unnecessary retransmissions since the CWs mapped over different CCs have now instantanously the same probability to be correctly decoded. It can be shown that, since the mixing is performed on a CW basis, the PAPR of the signal is not affected.
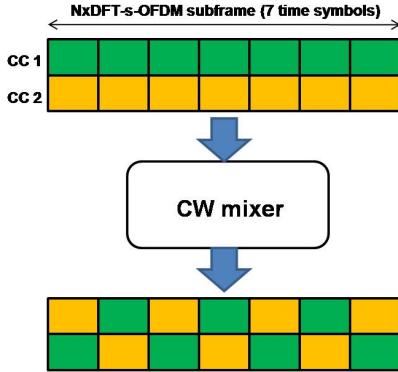


Fig. 3.   CW mixing strategy for 2 CCs.

The feedback overhead per antenna required for supporting the aforementioned solutions is described in Table 1, assuming 10 MCSs' options (therefore requiring 4 bits of feedback for indexing plus 1 bit for A/N message). It can be noted that *HARQ/MCS bundling* keeps constant the feedback overhead over different number of CCs.

Even though the UE might transmit on up to 5 CCs, it is preferable that its transmission bandwidth does not exceed 3 CCs. As noticed in [9], in the power limited uplink a wider transmission bandwidth capability does not necessarily contribute to an increase of the throughput because of the lower power spectrum density. In our evaluation we will therefore consider transmission on up to 3 CCs.

## IV. PERFORMANCE EVALUATION

The link level performance of the multiple component carrier transmission is evaluated by using an LTE compliant MATLAB simulator. The main simulation parameters are gathered in Table 2. We consider a 2x2 MIMO scheme, as an expected candidate scheme for LTE-A uplink. Each CW is mapped over a single CC; this means, up to 6 CWs are transmitted in 3CCs case. An effective transmission bandwidth of 25 Resource Blocks (RBs) per CC, corresponding to around 5 MHz, is further assumed. A Typical Urban 20 Paths channel model [10] with a coherence bandwidth of around 350 kHz is used in the simulations. A spatial correlation of 0.1 in the UE and 0.6 in the BS is considered, reflecting reality where the UE is usually closer to the scattering sources such as buildings, trees, etc. than the BS, and therefore the channel has wider angular spread and lower spatial correlation than in the BS [11]. A 5 ms delay, corresponding to 10 transmission slots, is assumed between the selection of the MCS and the precoder in the BS and its application in the transmitter. A maximum of 3 retransmissions is considered for the HARQ algorithm, which uses the Incremental Redundancy option. Perfect channel knowledge is assumed at the BS receiver, for which we consider the following 2 options:

1) Linear receiver: it is based on the traditional Minimum Mean Square Error (MMSE) equalization [4].
2) Turbo Successive Interference Cancellation (Turbo SIC) receiver: it exploits iteratively the detection of the CWs to enhance the link performance but at the expense of an increase in the computational complexity. In this receiver, for each CC the CW which experiences the better channel condition is selected for detection first, then, it is re-encoded for the purpose of removing its interference contribution from the CW experiencing the weaker channel. In this manner, the disadvantaged CW has increased probability to be correctly decoded. For further details, we refer to [12]. This process can be repeated for a number of iterations. In our simulations, the number of iterations is fixed to 2 to limit the computational complexity.

For the link parameters bundling, the options described in the previous section are considered. The MCS to be used in the next transmission is computed according to the following rule:

$$MCS_{sel} = arg\,max_{i:BLER_i < BLER_{target}}$$
$$\{(1 - BLER_i) \times B_i \times ECR_i\} \quad (1)$$

where $B_i$ and $ECR_i$ are the number of bits per symbol and the effective coding rate for the *i*-th MCS, respectively, and the $BLER_i$ values are obtained by mapping an effective Signal-to-Noise ratio (SNR) over Additive White Gaussian Noise (AWGN) curves. The effective SNR is computed by applying the known Exponential Effective SIR Mapping (EESM) model [13] over the estimated SNRs per subcarrier. However, when MCS bundling over multiple CCs is considered, the BLER target has to be modified in the way that each of the bundled CW has the same BLER target of no bundling case. This can be done by defining an equivalent BLER target as follows:

TABLE II
SIMULATION PARAMETERS

| Carrier frequency | 2 GHz |
|---|---|
| Sampling frequency | 15.36 MHz |
| Subcarrier spacing | 15 KHz |
| Number of CCs | 1, 2, 3 |
| FFT size | 6144 |
| Used subcarriers | 300 per CC |
| CP length | $5.2^a/4.68^b$ $\mu s$ |
| Slot duration | 0.5 ms |
| Symbols per slot | 7 |
| Antenna configuration | 2x2 |
| User speed | 3 kmph, 50 kmph |
| MCS settings | QPSK: 1/6, 1/3, 1/2, 2/3 |
| | 16QAM: 1/2, 2/3, 3/4 |
| | 64QAM: 2/3, 4/5 |
| Channel code | 3GPP Rel.8 compliant Turbo code |
| | with basic rate 1/3 |
| Turbo decoder iterations | 8 |
| Receiver scheme | MMSE, turbo SIC |
| BLER target | 10% |

[a]First NxDFT-s-OFDM symbol in a slot.
[b]$2^{th} - 7^{th}$ NxDFT-s-OFDM symbol in a slot.

$$BLER_{target,eq.} = 1 - (1 - BLER_{target})^{N_{CC}} \qquad (2)$$

where $N_{CC}$ is the number of bundled CWs. By using $BLER_{target,eq}$ in the selection of the MCS to be used by the $N_{CC}$ CWs, we ensure that each of the CWs preserves, in average, the desired $BLER_{target}$.

Fig. 4 shows the spectral efficiency performance of HARQ bundling option assuming 2 CCs and linear MMSE receiver. Note that the position of the 2 CCs in the spectrum doesn't affect the link performance since the frequency separation between the data mapped over adjacent or disjoint CCs is much larger than the coherence bandwidth of the TU20 channel. No bundling results (i.e., HARQ process per CC) are also included for the purpose of comparison. At low speed (3kmph) the HARQ bundling leads to a loss of around 0.5 dB with respect to no bundling, which increases up to 1.8 dB at 50 kmph. The CW mixing has negligible impact in the 3kmph case, but allows to almost fully overcome the performance gap with no bundling for high speed.

The spectral efficiency performance of HARQ/MCS bundling are shown in Fig.5, still assuming linear MMSE receiver, and 3kmph. The losses with respect to no bundling increase up to 2 dB. However, CW mixing allows to achieve approximately the same performance of only-HARQ bundling while saving a significant feedback overhead. No relevant differences in the trends have been noticed at 50 kmph.

Fig.6 shows the performance of the turbo SIC receiver, considering also the impact of the antenna gain imbalance (AGI) [14]. This is an effect which is quite likely to appear in

the uplink due, for instance, to the grip of the handeld device. HARQ/MCS bundling option combined with CW mixing is considered. For no AGI, turbo SIC receiver leads to a gain of around 4 dB over linear MMSE receiver. Furthermore, turbo SIC receiver shows higher gain for high AGI, nulling the performance gap between the different AGI configurations in high SNR region. This is due to nature of the turbo SIC processing, since when AGI is effective the CWs transmitted by the high gain antenna are more likely to be correctly decoded with relatively higher effect in removing their interference contribution from the CWs transmitted by the low gain antenna.
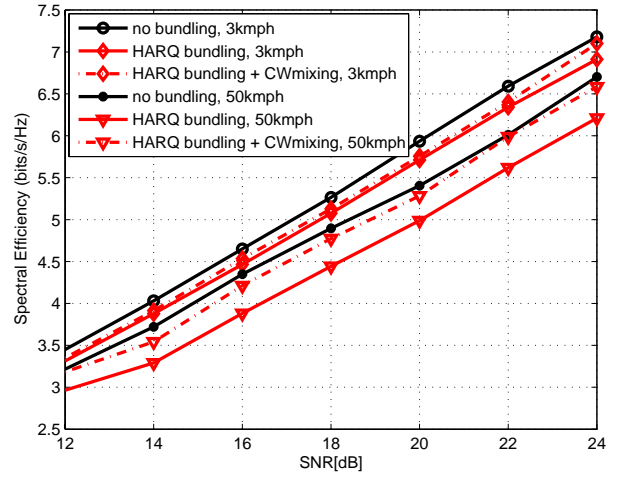


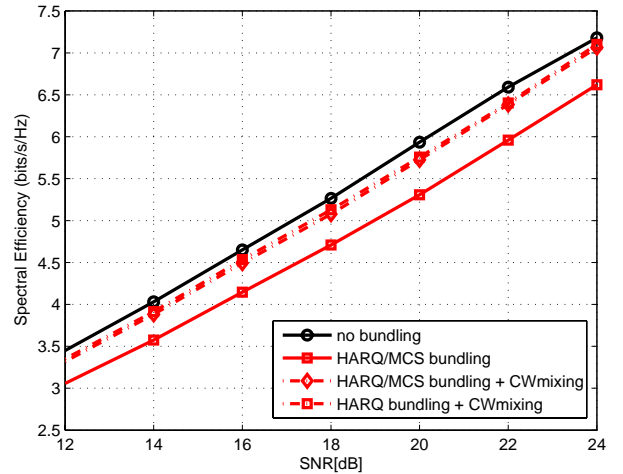Fig. 4. HARQ bundling performance with 2CCs and linear MMSE receiver.



Fig. 5. HARQ/MCS bundling performance with 2 CCs and linear MMSE receiver, 3kmph.

The performance comparison between transmission over 2CCs and 3CCs is shown in Fig.7, assuming no AGI, turbo SIC receiver and UE speed of 3kmph. The HARQ/MCS bundling leads to a loss with respect to no bundling up to 1.8
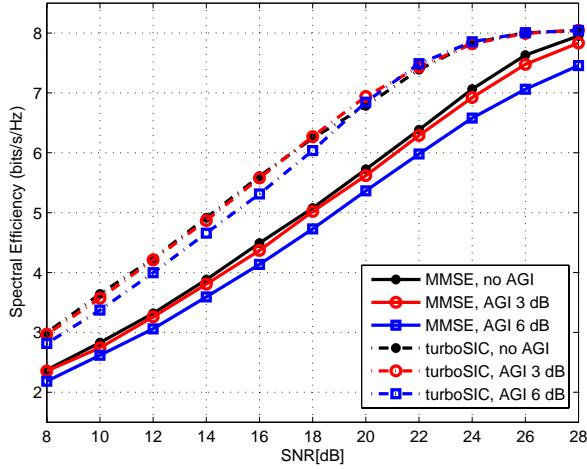
Fig. 6. Turbo SIC vs. MMSE performance with different AGI configurations and HARQ/MCS bundling + CW mixing option, 3kmph.
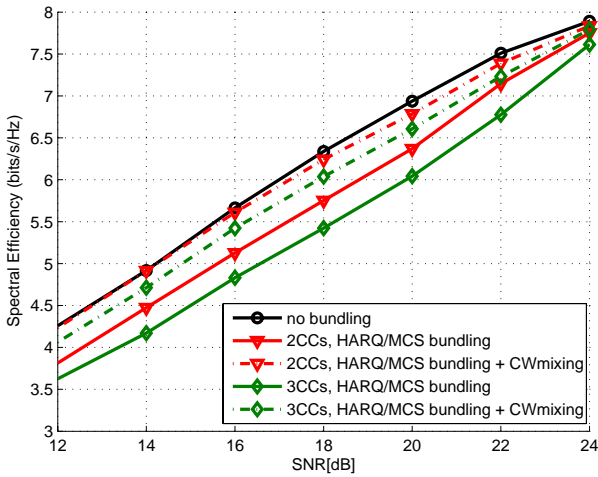


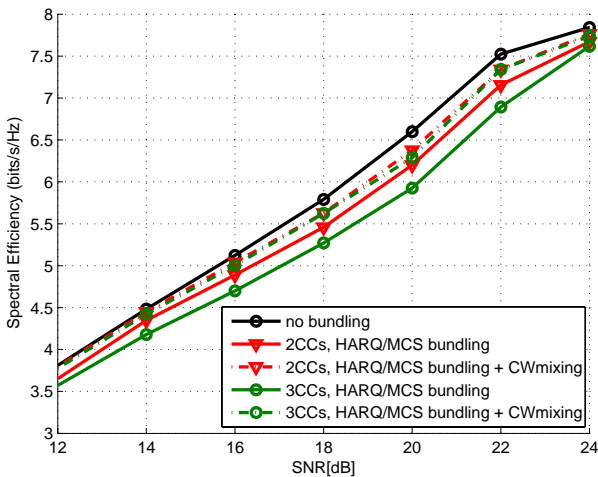Fig. 7. 2CCs vs. 3CCs performance at 3kmph with turbo SIC receiver.



Fig. 8. 2CCs vs. 3CCs performance at 50kmph with turbo SIC receiver.

dB and 2.3 dB for 2CCs and 3CCs, respectively. CW mixing allows again to boost the performance, recovering most of the loss (2 dB). Hence for 2CCs, we obtain approximately the performance of no bundling. At 50 kmph (see Fig.8), the losses of the HARQ/MCS bundling is reduced to 1 dB and 1.5 dB for 2CCs and 3CCs, respectively. Transmission over 2CCs and 3CCs shows here the same performance when CW mixing is applied.

## V. CONCLUSIONS

In this paper, we focused on the transmission over multiple CCs in LTE-A Uplink, and we discussed the impact of the bundling of link level parameters on the spectral efficiency performance. Both HARQ bundling and combined HARQ/MCS bundling are considered, and a CW mixing strategy over CCs is proposed to improve the performance while keeping a low feedback overhead. Results show that HARQ/MCS bundling can achieve the same performance of HARQ only bundling when combined with CW mixing, with the advantage of a much lower feedback overhead. CW mixing also allows to obtain similar spectral efficiency when the bundling is performed over 2 and 3 CCs, and especially for high speed. The adoption of a turbo SIC receiver has been shown to be effective to further boost the spectral efficiency, in particular when AGI occurs.

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