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Transmission over Multiple Component Carriers in LTE-A Uplink

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Abstract

Long Term Evolution-Advanced (LTE-A) systems are currently being standardized by the 3rd Generation Partnership Project (3GPP) and aim at very high peak data rates of 1 Gbits/s in the downlink and 500 Mbits/s in the uplink. Those ambitious targets can only be achieved by using advanced Multiple Input Multiple Output (MIMO) antenna techniques as well as wide spectrum allocation, up to 100 MHz. A multiple component carrier (CC) structure has been agreed in the 3GPP Work Item (WI) as a solution to extend the 18 MHz bandwidth of the previous LTE Release 8 up to 100 Mhz. The multiple access schemes on both uplink and downlink now have to be adapted to the new spectrum configuration. Furthermore, in the link adaptation design the transmission over multiple CCs would reasonably lead to an increase of the feedback overhead. *Bundling* of the spatial or frequency parameters can keep the overhead low at the cost of lower throughput. In this article, we consider as a study case LTE-A uplink, where the Nx-DFT-spread-OFDM (Nx-DFT-s-OFDM) has been selected as multiple access scheme. The validity of this scheme for the uplink is evaluated in terms of cubic metric (CM), which is an indicator of the power derating needed at the transmitter to avoid the intermodulation distortion. Furthermore, the impact of the *bundling* of the link adaptation parameters on the link performance is discussed considering both linear and turbo Successive Interference Cancellation (SIC) receivers. Two codeword mixing strategies in frequency and spatial domain are also proposed to boost the performance when the bundling is made *per antenna* or *per CC*, respectively. Results show that, when a linear receiver is used in the base station the mixing techniques can increase the spectral efficiency, thus reducing the performance gap to the *no bundling* case which is the most expensive solution in terms of feedback signaling. However, when a

turbo SIC receiver is used, only *mixing over CCs* results to be a valid option to achieve link performance gain.

Index Terms — 3rd Generation Partnership Project (3GPP), Long Term Evolution Advanced (LTE-A), Single Carrier Frequency Division Multiplexing (SC-FDM), Multiple Component Carriers (CCs), cubic metric (CM), linear receiver, Turbo Successive Interference Cancellation (TurboSIC) receiver

I. INTRODUCTION

High data rate transmission is definitely one of the main goals of the future 4th generation mobile communication systems. Ambitious targets of 1 Gbit/s in the downlink and 500 Mbit/s in the uplink are aimed for instance by the Long Term Evolution - Advanced (LTE-A) systems [1], which are currently being standardized by the 3rd Generation Partnership Project (3GPP).

The main purpose of LTE-A is to enhance the previous LTE Release 8 [2], whose specifications were finalized in December 2008. In LTE Release 8 the target data rates are "limited" to 300 Mbit/s in the downlink and 50 Mbit/s in the uplink, and achieved by using an effective transmission bandwidth of 18 MHz as well as a set of features including link adaptation, channel-aware scheduling and adaptive transmission bandwidth. While Multiple-Input-Multiple-Output (MIMO) antenna technologies are expected to take place to meet the downlink target, only single transmit antenna schemes have been standardized for the uplink. The promised data rates of LTE-A foresee instead the usage of a wider transmission bandwidth, up to 100 MHz, as well as MIMO solutions even for the uplink [3]. Furthermore, an evolved radio standard as LTE-A should be also backward compatible with the previous Release in order to allow a smooth migration between the two technologies, at the same time reducing the standardization efforts. An LTE terminal should be able to operate in a LTE-A system without dramatically increasing the control signaling or requiring new protocol stacks. That leads to severe constraints for the multiple access.

A multiple component carriers (CCs) solution has been therefore agreed as underlying structure for the LTE-A spectrum [1]. The 100 Mhz bandwidth is divided to 5 chunks, each of them keeping the LTE numerology for what concerns number of subcarriers as well as the subcarrier spacing.

This wide spectrum structure leads to an increase of the feedback overhead which is needed to properly setup the transmission depending on the instantaneous channel conditions: the *bundling* of link parameters over space or frequency resources is foreseen to reduce this signaling overhead and make it comparable with a single CC technology as LTE.

Regarding the multiple access scheme, Orthogonal Frequency Division Multiplexing (OFDM) has been unanimously selected for the downlink transmission by several standards including LTE, given its robustness of the multipath as well as its flexibility in the resource allocation. The Single Carrier Frequency Division Multiplexing (SC-FDM) technology is instead more suitable for the uplink transmission because of its advantageous low Peak-To-Average Power Ratio (PAPR) property [4]. In SC-FDM, the data symbols are indeed transmitted serially in the time domain rather than in parallel as in OFDM, thus reducing the envelope fluctuations in the transmit waveform.

However, the necessity of coping with a spectrum structure with multiple CCs puts further constraints in the SC-FDM signal generation. It will not be possible to maintain the single carrier property for transmission bandwidth larger than a single CC because the edges of each CC are usually reserved for uplink control channels [5]. Therefore further solutions have been proposed and discussed.

In this article, we focus on the transmission over multiple CCs for uplink transmission; the generation of the uplink signals over wide bandwidth is discussed, as well as the issues of the link adaptation design over the multiple CCs. The article is structured as follows. In Section II, the multiple component carrier scheme is introduced as a solution to cope with the wide spectrum requirement. The evolution of the uplink multiple access scheme to cope with the multiple component carrier structure is discussed in Section III. Section IV focuses on the cubic metric performance of the Nx DFT-s-OFDM signals. Section V discusses the link adaptation design over multiple component carriers. Finally, Section VI presents the conclusions and states the future work.

II. LTE-A SPECTRUM CONFIGURATION

The agreed multiple component carrier structure for the LTE-A spectrum is shown in Fig.1. In this setup, the bandwidth is divided in 5 CCs. As mentioned in the introduction, this structure will allow the development of "low category" User Equipments (UEs) whose maximum reception bandwidth is lower than 100 MHz, e.g. 18 MHz for LTE UEs. Furthermore, it makes possible the flexible spectrum usage (FSU) by allowing the CCs to be controlled by different Base Stations (BSs) [6]. There are two mechanisms to accede the available spectrum:

- 1) Channel bonding: combining multiple adjacent CCs.
- 2) Channel aggregation: combining 2 or several totally separate CCs.

A guard band (GB) is assumed between the CCs, with the aim of avoiding the interference between adjacent CCs. This can prevent dramatical performance degradations, e.g. when a "low category" UE receives in its limited bandwidth while the BS is also transmitting to evolved UEs in the adjacent CCs. Note that a further GB should be left on both sides of the spectrum to avoid interference with systems operating on the adjacent bands.

III. Nx DFT-s-OFDM

The multiple access scheme based on SC-FDM technology has to cope with the proposed spectrum configuration. That leads to some modifications with respect to its typical signal generation.

The baseband transmitter chain of SC-FDM as adopted for instance in Rel.8 LTE uplink is shown in Fig.2(a). With respect to the well-known OFDM chain, we have an additional Discrete Fourier Transform (DFT) block, which spreads each data symbol over all the used subcarriers. It can be easily shown that, the insertion of this block allows to transmit the data symbols serially in the time domain. This also implies, the power amplitude of the transmit signal tends to be lower than in OFDM. This way to generate the SC-FDM signal is often referred in literature as well as in the technical documentation as DFT-spread-OFDM (DFT-s-OFDM).

The most intuitive solution to cope with a multiple component carrier structure is to use a single DFT having dimension equal to the size of the transmit block over the whole used CC set. However, this option (named *clustered* DFT-s-OFDM) has an impact on the Medium Access Control (MAC), since it implies a larger transmit block with respect to a system using a single CC; the logical transport channel needs re-design to cope with the different physical channel capability, thus leading to different specifications between the single and multiple CCs technologies.

The Nx-DFT-s-OFDM solution is therefore preferable due to its full compatibility with a single CC technology. As shown in Fig.2(b), up to 5 transport 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 IFFT can be used to generate the time domain signal. With this solution, the transmissions over multiple CCs can be seen as parallel single CC transmissions, thus allowing link adaptation per CC. The issues related to the link adaptation process per CC will be discussed in Section V. For each CC, non-contiguous allocation of the Resource Blocks (RBs) on which the user data are scheduled has been approved with the aim of enhancing the scheduling flexibility. The RBs are grouped in a certain number of *clusters* before being mapped over disjoint sub-bands belonging to the same CC (see Fig. 2(c)).

IV. CUBIC METRIC PERFORMANCE

As mentioned above, the main selling point of the SC-FDM technology is its low PAPR property. In the technical documentation, the PAPR is likely to be replaced by the cubic metric (CM) which is easily computable with an empirical formula and has been agreed as a more reliable predictor of the power de-rating needed at the transmitter to avoid the incurring of non-linearities [7]. The CM refers to the third power term of the signal, which is known to be the main cause of intermodulation distortions in the amplification process. A low CM property translates to higher power efficiency and therefore longer operation time; furthermore, it can improve coverage since the lower power de-rating compared to the use of OFDM allows users at the cell edge to transmit with relatively higher power.

Unfortunately, the Nx-DFT-s-OFDM leads to multicarrier transmission and therefore breaks the low CM property of the single carrier signal. In order to justify the adoption of Nx-DFT-s-OFDM for the uplink transmission, the gain in terms of CM over OFDM should however be clear.

In this section, we evaluate the CM performance of Nx-DFT-s-OFDM assuming a different number of CCs. Results are obtained through Monte Carlo simulations, assuming the structure in Fig. 2(b) with data encoded with 16QAM. The user RBs are split over 1, 2 or 5 CCs; in each CC, they are further divided in 1, 2 or 5 clusters which are randomly distributed over the bandwidth of a single CC. The CM is calculated according to [7].

In Fig.3, results are shown for the different solutions as well as for OFDM. For the latter, only the single CC case is shown since its performance is not affected by the transmission over multiple CCs. As a general trend, the CM of Nx-DFT-s-OFDM increases with the number of CCs and the number of clusters. This means, a larger power

back-off is required in case of transmission over several CCs to avoid the incurring of non-linearities. However, a slight gain of around 0.2 dB is kept over OFDM even with $N=5$. Furthermore, 5 CCs are likely to be assigned to an UE which is very close to the BS; since such UEs are expected to transmit with relatively low power to reduce their interference contribution in the adjacent cells, preserving a very low CM is not critical. Note that the clustered allocation of RBs over the same CC is highly detrimental for $N=1$ (allocation over 5 clusters performs even worse than 2CCs with 2 clusters), while this effect is considerably reduced when the number of CCs increases. Hence, for users with a single CC, e.g. on the cell edge, contiguous RB allocation should preferably be used.

V. LINK ADAPTATION WITH BUNDLING OF HARQ/MCS FIELDS

The possibility of adapting the modulation and coding scheme (MCS) of the data symbols to the current channel conditions is definitely one of the features enabling efficient transmission for the 4th generation of mobile communication systems. When the UE experiences poor radio link conditions, typically it will transmit data by using a low order MCS (e.g. QPSK with coding rate 1/6) to achieve robustness to the noise and the channel fades. In case of a highly reliable channel it would use instead high order MCSs (e.g. 64QAM with coding rate 5/6), leveraging its throughput. In the BS, the link adaptation module computes the Signal-to-Noise Ratio (SNR) of the user depending on a previously transmitted Reference Signal (RS), and selects the MCS leading to higher expected throughput with respect of a certain Block Error Rate (BLER) target (typically 10 per cent in LTE). The index of the selected MCS is then fed back to the UE through signaling.

Furthermore, Hybrid Automatic Repeat Request (HARQ) is widely recognized as a solution to further boost the robustness of the system [8]. HARQ is basically a physical layer packet retransmission strategy which exploits the error detection capabilities of the modern radio access technologies. For instance, in LTE a cyclic redundancy code (CRC) is appended to the information bits of each codeword (CW) to check if the detection process has been successful. Note that in the LTE terminology the term codeword stands for the a block of bits which are encoded together. In case of correct detection, an ACK message is sent to the UE, otherwise a NACK message is sent and the UE has to retransmit the CW. The fact that this operation is carried out at Layer 1 of the protocol stack reduces the latency between the retransmissions with respect to the traditional MAC ARQ protocols. 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.

The MCS's index and the ACK/NACK (A/N) messages increase however the feedback overhead in the downlink signaling. In single CC technologies, a single MCS's index is fed back for the whole transmission bandwidth of the UE. In multiple CCs technologies the MCS's index might be sent per CC or over the whole used bandwidth. The first solution can make a better use of the frequency selectivity of the channel, but it also increases dramatically

the feedback overhead (up to 5 times in LTE-A). 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 CC set must be retransmitted even only one of them is not correctly decoded.

The usage of MIMO techniques leads to further degrees of freedom in the link adaptation/HARQ design. A single MCS could in fact be used per the whole antenna set over the same CC. Throughout this article, we will assume that each CC carries one CW per antenna. The following alternatives will be therefore considered here:

- 1) *no bundling*: a single MCS field and A/N message per CW (Fig.4(a)). This solution allows to easily cope with the different instantaneous gains of the MIMO links as well as the different channel gains over the CCs, however, it is the most expensive solutions in terms of feedback overhead.
- 2) *bundling per Antenna*: a single MCS field and A/N message per antenna (Fig.4(b)). It only copes efficiently with the instantaneous power gains of the MIMO links. The MCS to be used in the UE is computed as a function of the SNR values of the RSs which are transmitted over multiple CCs. Since the data over multiple CCs are expected to experience uncorrelated fading because of the frequency separation, the selected MCS might not be the one leading to the expected throughput. 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. 4(c). 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 expected throughput.
- 3) *bundling per CC*: a single MCS field and A/N message per CC (Fig.4(d)). It only copes efficiently with the different channel gains over the used CCs, but not with the instantaneously different MIMO links. Similarly to the previous option, the MCS selection can lead to poor performance when the instantaneous SNR of the MIMO links is different. Analogous to alternative 2, we propose to use a *spacial domain (SD) mixing* for equalizing the SNRs of the MIMO links and thus improve the system performance.

Note that, since both *mixing* options are performed on a CW basis, the CM of the signal is not affected. The feedback overhead 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), and a spatial multiplexing system with 2 transmit antennas. While *bundling per CC* allows to halve the feedback overhead, *bundling per Antenna* keeps it constant over different number of CCs. In the next section, we will show that the saving in feedback comes at the expense of lower spectral efficiency performance.

A. Performance evaluation

The link level performance of the multiple component carrier transmission is evaluated by Montecarlo computer simulations. We consider a 2x2 open loop MIMO system, as an expected candidate scheme for LTE-A uplink, and an effective transmission bandwidth of 10 MHz achieved by transmission over different numbers of CCs. A Typical Urban channel model [9] is used in the simulations. A maximum of 3 retransmissions is assumed 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 data streams 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. We use *soft* interference cancellation to avoid the error propagation issue which occurs in the traditional *hard* iterative processing. For further details, we refer to [10]. 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 adaptation parameters, the options described in the previous section are considered.

Fig.5(a) shows the spectral efficiency results assuming the linear receiver, low mobility (3kmph), and transmission over 2 CCs. As expected, *no bundling* is superior to *bundling per CC* by around 1.8 dB. However, the SD mixing allows to improve the performance of the latter of around 1.2 dB, thus dramatically reducing the gap with *no bundling*. Results obtained with *bundling per Antenna* are overlapped with *bundling per CC*, and have not been plotted. It has to be mentioned that no difference of link performance is expected between Channel bonding and Channel aggregation (see Section II), since in both cases the frequency separation between the CCs is much wider than the coherence bandwidth of the Typical Urban channel.

In Fig.5(b), the performance of *bundling per Antenna* is evaluated over multiple CCs. As expected, the spectral efficiency loss increases with the number of CCs being bundled, especially when passing from 3 to 5 CCs. On the other hand, CC mixing has higher impact with 5 CCs. As a result, the performance gap between the different solutions is within 1 dB when CC mixing is applied.

Results obtained with 2 CCs, low mobility and Turbo SIC receiver are shown in Fig.5(c). Again, *no bundling* shows the best spectral efficiency result. *Bundling per Antenna* and *bundling per CC* perform approximately the same, whereas performance with mixing differs. In fact, SD mixing has a detrimental effect on the performance. This can be explained by looking at the particular behaviour of the turbo SIC detector, which benefits from the instantaneous gain imbalance over the antennas. In case of *bundling per CC*, the same MCS is forced over both antennas within each CC; this means, the CWs transmitted over the better channel are more likely to be correctly decoded, and therefore have their interference contribution correctly removed from the CWs sent over the weaker channel. However, SD mixing averages the SNR over the antennas, therefore smoothing the instantaneous gain imbalance over the antennas. This reduces the probability of making the correct interference subtraction, and will therefore lower the spectral efficiency of the UE. In case of *bundling per Antenna* instead, the possibility of equalizing the SNR between the CCs provided by the CCs mixing has still a positive impact on the performance since it will make the interference subtraction more robust. As a consequence, the gap with *no bundling* becomes negligible.

Bundling per CC results to be more robust than both *no bundling* and *bundling per Antenna* for high mobility (50kmph). As shown in Fig.5(d), *bundling per CC* achieves approximately the performance of *no bundling*, while *bundling per Antenna* needs CC mixing to reach the same spectral efficiency values.

VI. CONCLUSIONS AND FUTURE WORK

In this article, we have focused on the transmission over multiple component carriers considering the uplink of LTE-A as a study case. The spectrum configuration as agreed for instance in the 3GPP work item has been presented and Nx-DFT-s-OFDM has been introduced as a suitable modulation and coding scheme which is backward compatible with a single CC technology as LTE. In order to test the validity of this option for the uplink transmission, a cubic metric evaluation of the Nx-DFT-s-OFDM signals has been carried out. The use of Nx-DFT-s-OFDM has been shown to require lower power derating than OFDM for both localized and clustered allocation of the RBs, even for transmission over 5 CCs, thus improving the cell coverage or reducing the power consumption of the UE. Since the transmission over multiple component carriers is expected to dramatically increase the feedback overhead, we foresee the *bundling* of HARQ/MCS parameters over space or frequency. Two mixing techniques over space and frequency have been proposed with the aim of equalizing the SNR in the receiver and thus obtaining a more suitable estimate of the MCS to be used in the transmissions. The link level performance of Nx-DFT-s-OFDM is evaluated in a typical urban scenario for a 2x2 spatial multiplexing MIMO system. Results show that, when a linear receiver is used in the BS, *bundling per Antenna* and *bundling per CC* can improve the spectral efficiency of the UE when combined with CC mixing and SD mixing, respectively, thus reducing the performance gap with *no bundling*. When a turbo SIC receiver is used in the BS, CC mixing combined with *bundling per Antenna* can approximately achieve the performance of *no bundling*, whereas the SNR averaging over the antennas provided by SD mixing is shown to be detrimental. Finally, *bundling per CC* results to be more robust to the UE speed than *bundling per Antenna*, however CC mixing can give *bundling per Antenna* approximately similar performance of *no bundling*.

The sum up, the following main conclusions can be derived:

- mixing techniques over time and frequency can definitely boost the spectral efficiency of the UE when bundling of HARQ/MCS parameters is required to keep a low feedback overhead with linear receiver;
- when *bundling per Antenna* is performed to keep a constant feedback overhead, CC mixing allows approximately the same performance regardless of the number of CCs used for transmission.
- if a turbo SIC receiver is adopted in the base station, *bundling per Antenna* combined with CC mixing is preferred to *bundling per CC* for both low and high speed to achieve approximately the same performance of *no bundling* and with low feedback overhead.

As a future work, the impact of bundling on the closed loop (i.e. precoded) transmission will be also evaluated, considering different precoding options (e.g., per CC, per Antenna). Furthermore, realistic effects for handheld devices, e.g., antenna gain imbalance, will also be included.

VII. ACKNOWLEDGEMENTS

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TABLE I
 FEEDBACK OVERHEAD FOR LINK ADAPTATION (BITS PER FRAME)

	1 CC	2 CCs	3 CCs	4 CCs	5 CCs
<i>no bundling</i>	10	20	30	40	50
<i>bundling per Antenna</i>	10	10	10	10	10
<i>bundling per CC</i>	5	10	15	20	25

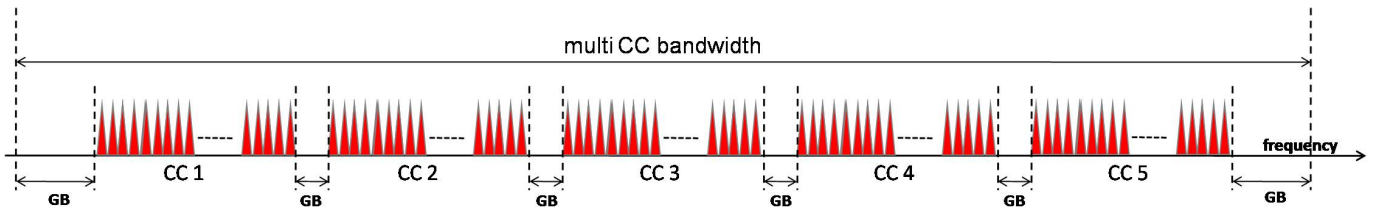


Fig. 1. Multiple CC spectrum structure.

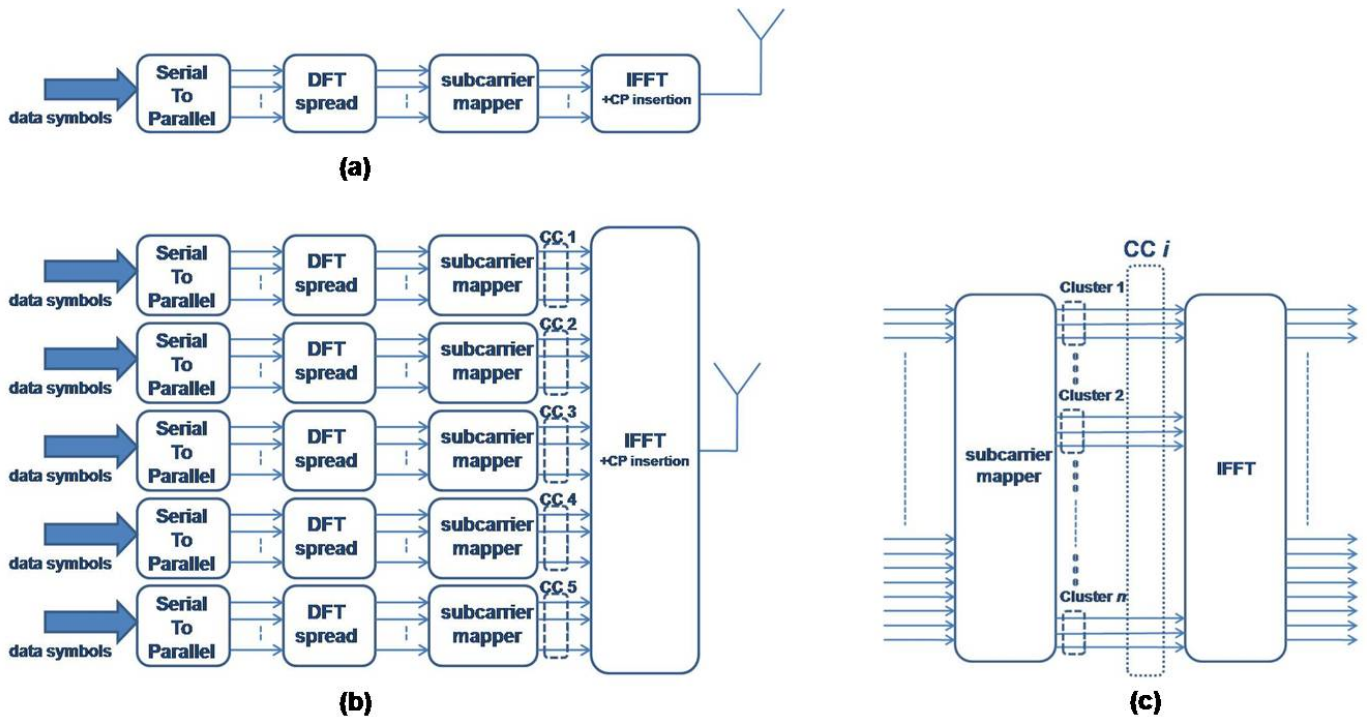


Fig. 2. Signal generation for (a) DFT-s-OFDM, (b) $N \times$ DFT-s-OFDM, with the option of clustered allocation of the RBs (c).

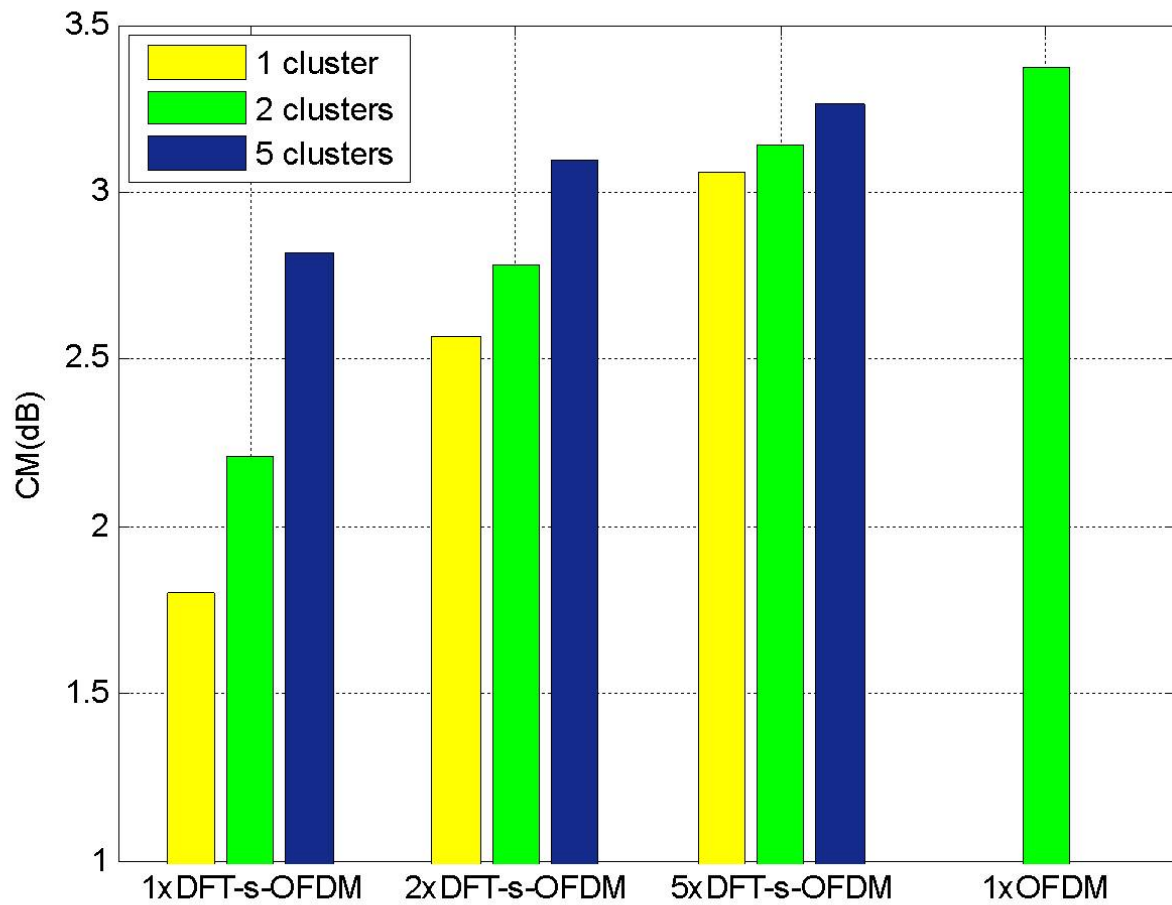


Fig. 3. CM performance of $N \times$ DFT-s-OFDM and OFDM.

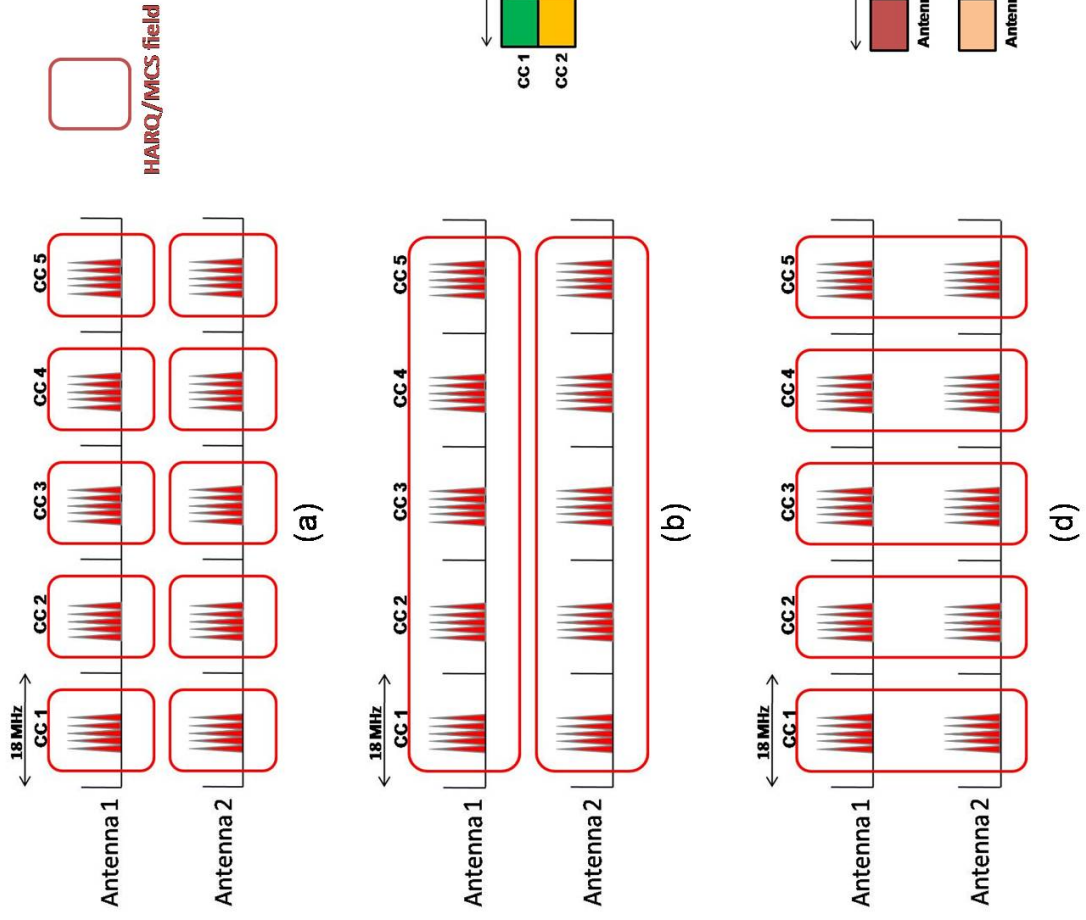
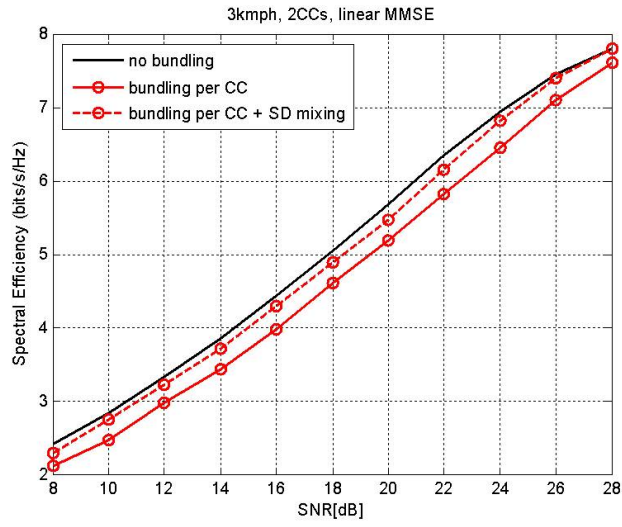
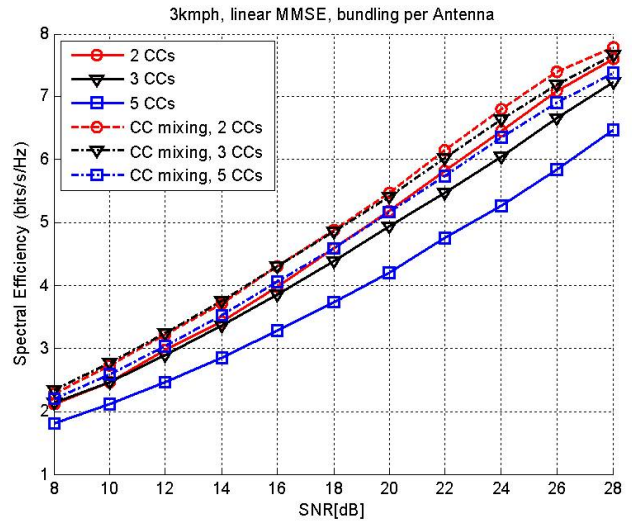


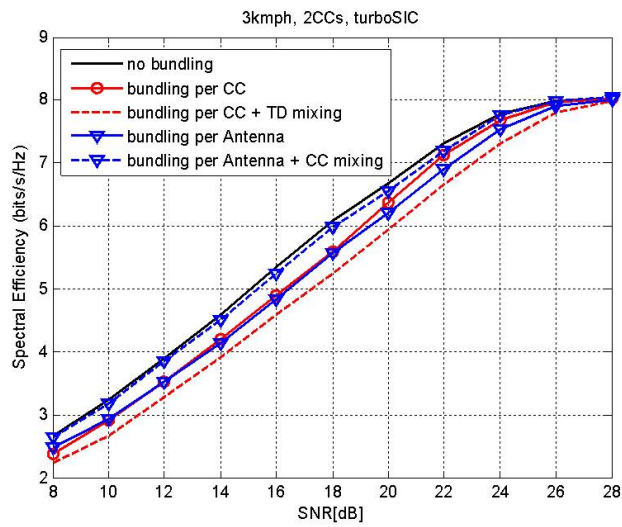
Fig. 4. Link adaptation solutions: (a) no bundling, (b) bundling per Antenna with (c) CC mixing option where only the 2 CCs case is shown for simplicity, (d) bundling per CC with (e) SD mixing option.



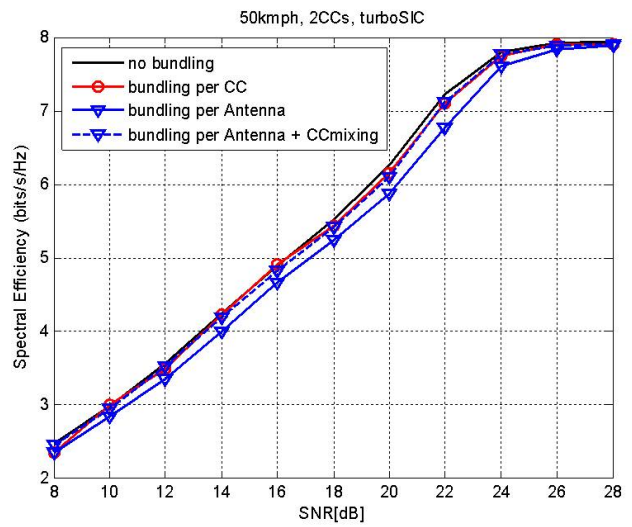
(a)



(b)



(c)



(d)

Fig. 5. Spectral efficiency performance of the *bundling* options with (a) 2 CCs and linear receiver, (b) different number of CCs, turbo SIC receiver with (c) low speed and (d) high speed.