Investigation on Rate Matching and Soft Buffer Splitting for LTE-Advanced Carrier Aggregation

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Abstract—**In the LTE-Advanced downlink, carrier aggregation (CA) employing multiple component carriers (CCs) is an essential technique to achieve a target peak data rate of 1 Gbps. 3GPP RAN WG1 meeting decided to adopt one transport block (TB) per CC, where the TB is the unit of channel coding and hybrid automatic repeat request (HARQ). When CA is applied to an LTE-Advanced UE, the soft buffer which is used for HARQ packet combining must be equally split according to the number of CCs, where the soft buffer size is one of the factors to in defining the LTE-Advanced UE categories. When soft buffer splitting is applied to UEs in a lower UE category, the soft buffer size per CC may not be sufficient and the performance of the HARQ packet combining is not ensured. In this paper, we propose a rate-matching scheme for CA and a new receiver suited to this rate matching scheme. Using the proposed scheme, degradation in the HARQ throughput performance due to the soft buffer splitting can be avoided and the same rate-matching scheme can be applied irrespective of the number of CCs. Simulations results show that the proposed scheme always provides better performance than that for equal splitting rate-matching scheme that reuses Rel-8 LTE rate-matching scheme.**

Keywords-component; LTE-Advanced, Carrier aggregation, Rate-matching

I. Introduction

The 3rd Generation Partnership Project (3GPP) finalized the radio interface specifications for the next generation mobile system called Long-Term Evolution (LTE) as LTE Release 8 in 2008. In Japan, the commercial service of LTE was launched in December 2010 [1]. LTE provides full IP packet-based radio access with low latency and adopts an intra-cell orthogonal multiple access scheme such as orthogonal frequency division multiple access (OFDMA) and single-carrier frequency division multiple access (SC-FDMA) in the downlink and uplink, respectively [2],[3]. Meanwhile, in the 3GPP, standardization efforts towards an enhanced LTE radio interface called LTE-Advanced (LTE Release 10 and beyond) are ongoing [4]-[7]. LTE-Advanced supports carrier aggregation (CA) up to 100 MHz by aggregating the maximum of 5 component carriers (CCs), each of which maintains backward compatibility with LTE Release 8. A transport block (TB), which is the unit for channel coding and hybrid automatic repeat request (HARQ), is mapped to each CC [8].

In LTE-Advanced, eight user equipment (UE) categories are specified according to the maximum downlink and uplink data rates, the number of spatial layers for multiple-input multiple-output (MIMO) multiplexing, and the soft buffer size supported by the UE [9]. Here, the term soft buffer size is referred to as the maximum number of received bits to be stored in a buffer used for HARQ packet combining which is defined per UE. The UE categories in LTE-Advanced are summarized in Table I. UE categories 1-5 remain the same as those for Rel-8 LTE while UE categories 6-8 are newly defined for LTE-Advanced UEs in order to meet the higher requirement for LTE-Advanced. When CA is applied to an LTE-Advanced UE, the soft buffer reserved for the UE must be divided by the number of CCs for a given maximum soft buffer size of the UE. Fig. 1 shows the receiver structure for the case of 2 CCs, where the soft buffer before turbo decoding is split and used between two CCs. When soft buffer splitting is applied to a UE in a lower UE category, i.e., UE categories 1-5, the soft buffer size per CC may not be sufficient and the performance of the HARQ packet combining is not ensured. This is because UE categories 1-5 are the same Rel-8 UE categories and are not designed to take into account CA while UE categories 6-8 support a sufficient soft buffer size considering CA. In this paper, we consider that the soft buffer of each UE is equally divided by the number of CCs. In order to achieve efficient HARQ packet combining in CA, the design of the rate matching scheme at an enhanced NodeB (eNodeB) considering the soft buffer size of each CC is an important issue. In [10], equal splitting rate matching is applied so that the number of coded bits is adjusted to the soft buffer size of each CC in the same way as the Rel-8 LTE rate-matching scheme. This way, all the received bits can be stored in the soft buffer of each CC for HARQ packet combining. However, in equal splitting rate matching, the throughput performance may be degraded since the achievable coding gain is reduced by adjusting the coded bits to a smaller soft buffer size. Furthermore, the equal splitting rate-matching scheme depends on the number of CCs. From the viewpoint of eNodeB complexity, it is desirable to use the same rate-matching scheme irrespective of the number of CCs.

In this paper, we propose a rate-matching scheme for CA and the optimum receiver for HARQ packet combining and decoding. In this scheme, rate matching is performed at the

TABLE I. UE CATEGORIES

UE category	DL data rate	Soft buffer size	Maximum number of transmission layers
Category 1	10 Mbps	250368 bit	1
Category 2	50 Mbps	1237248 bit	2
Category 3	100 Mbps	1237248 bit	2
Category 4	150 Mbps	1827072 bit	2
Category 5	300 Mbps	3667200 bit	4
*Category 6	300 Mbps	3654144 bit	2 or 4
*Category 7	300 Mbps	3654144 bit	2 or 4
Category 8	3 Gbps	35982720 bit	8

* Categories 6 and 7 support different UL data rates

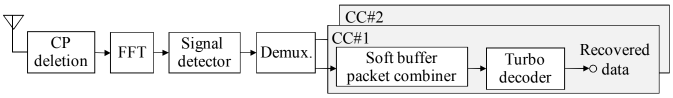


Figure 1. Receiver Structure for CA.

eNbodeB always assuming a single CC and does not depend on the number of CCs. At the proposed UE receiver, all the received bits are once turbo-decoded and only the bits exceeding the soft buffer size of each CC are discarded. The HARQ throughput performance of the proposed rate-matching scheme and receiver is evaluated by computer simulation and compared to that for the equal splitting rate-matching scheme.

In the rest of the paper, Section II describes the procedures for the Rel-8 LTE rate matching and HARQ packet combining. In Section III, after equal splitting rate matching for CA is explained, the proposed rate-matching scheme and receiver are presented. The other receiver types that are applicable to the proposed rate-matching scheme are also investigated in Section IV for comparison. Sections V and VI present the simulation conditions and results of the proposed scheme, followed by our concluding statements.

II. REL-8 LTE RATE-MATCHING SCHEME

Fig. 2 shows the procedures for the Rel-8 rate-matching scheme at the eNodeB and HARQ packet combining at the UE. Although the code block segmentation and interleaving are performed according to the Rel-8 LTE specifications [11], these procedures are omitted in Fig. 2 for simplicity. At the eNodeB transmitter, the systematic bits are turbo encoded with the coding rate of R=1/3 to generate N coded bits. The number of systematic bits is decided based on the number of physical resource blocks (PRBs) and the level of modulation coding scheme (MCS) assigned to each UE. In Rel-8 LTE, two step rate matching is applied. The first-step rate matching is applied so that N coded bits do not exceed the soft buffer size, M, per TB and per HARQ process defined in each UE category. Hence, this rate matching is applied only if

$$N > M \ . \tag{1}$$

When a higher MCS level and a number of PRBs are assigned to a UE, Eq. (1) holds and the rate matching is performed. The second-step rate matching is applied to select consecutive E coded bits to be transmitted out of the M coded bits, where E is the number of bits available for transmission and is decided according to the number of PRBs and MCS level. The starting point of E coded bits is determined by the

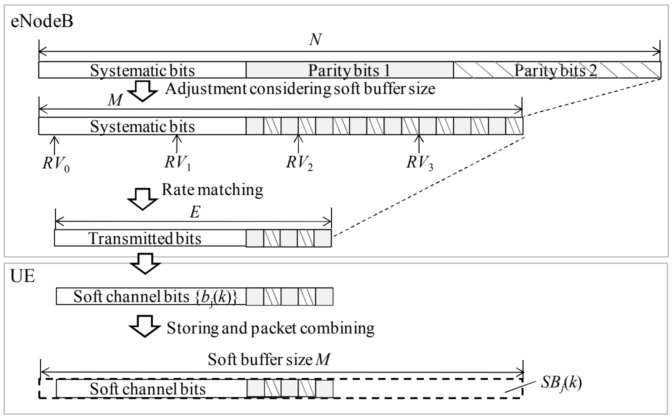


Figure 2. Rel-8 LTE rate matching procedure.

value of RV_i, i=0~3, as shown in Fig. 2. In the event that the retransmission of the same packet is requested, a different RV_i is used to obtain a higher coding gain for an incremental redundancy packet combining scheme [12]. Finally, the E coded bits are transmitted after data modulation, FFT, and cyclic prefix (CP) insertion are performed.

At the UE receiver, after deletion of the CP, IFFT and equalization are performed. The log likelihood ratio (LLRs), $\{b_j(k);\ k = 0\sim E-1\}$, for the jth (re)-transmission, which we call soft channel bits throughout the paper, are calculated. The soft channel bits, $\{b_j(k)\}$, are stored in a soft buffer with the size of M, and soft channel bits $\{SB_j(k);\ k=0\sim M-1\}$ after storing and packet combining are given by

$$SB_j(k) = SB_{j-1}(k) + b_j(k + k'_j) \ , \tag{2}$$

where $\{SB_{-1}(k)=0;\ k=0\sim M-1\}$ and $k'_j \in RV_i$. Finally, turbo decoding is performed for $\{SB_j(k)\}$ to recover the information bits.

III. RATE-MATCHING SCHEME FOR CA

A. Equal Eplitting Rate-Matching Scheme

When CA is configured, the soft buffer with the size of M needs to be split between CCs. In this section, we assume that the soft buffer is equally divided by the number of CCs as

$$M_C = M / C \ , \tag{3}$$

where M_C is the soft buffer size after splitting and C is the number of configured CCs. If soft buffer splitting is applied to a lower UE category supporting a smaller soft buffer size, the HARQ throughput performance is not guaranteed due to an insufficient soft buffer size. Therefore, a rate-matching scheme suitable for soft buffer splitting must be investigated. In [10], equal splitting rate-matching was adopted, where the first-step rate matching is performed so as to adjust the N coded bits to the soft buffer size, M_C, of each CC. Namely, the same rate-matching scheme is employed as that used in Rel-8 LTE. Fig. 3 shows the rate-matching procedure using equal splitting rate matching. In this scheme, the first-step rate matching is performed if

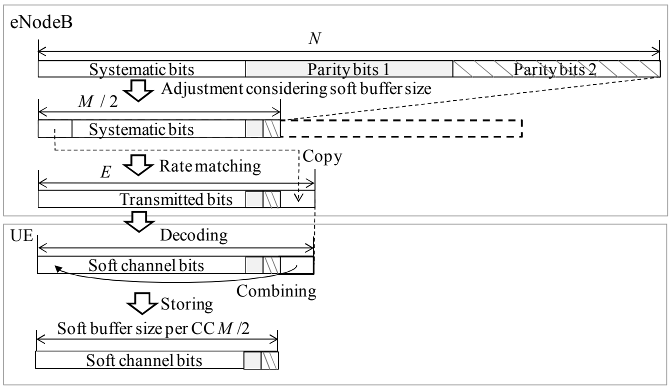


Figure 3. Equal splitting rate-matching procedure.

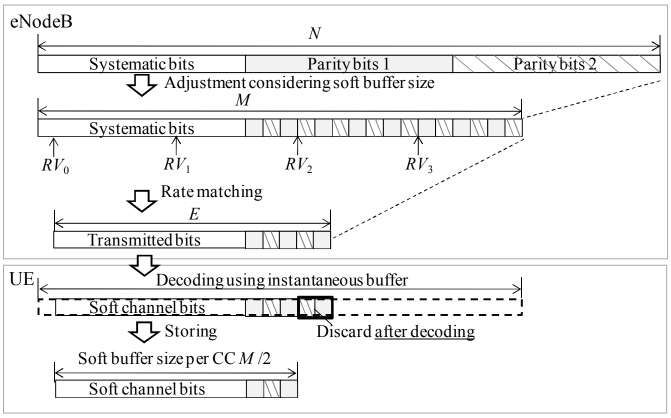


Figure 4. Proposed rate-matching procedure.

$$N > M_C \,. \tag{4}$$

Therefore, only the bits that the UE can store in the soft buffer of each CC are transmitted and no soft channel bits are discarded at the UE receiver. However, in this scheme, many bits will be discarded in the first-step rate matching according to Eq. (4). This may degrade the performance for the initial transmission when $M_C < E$, as shown in Fig. 3. In this case, in the second-step rate matching, parts of the M_C coded bits are copied and appended in order to generate the E coded bits, which limits the achievable coding gain. Furthermore, the equal splitting rate-matching scheme is different according to the number of configured CCs. This is not desired because the complexity at the eNodeB is increased. To overcome these problems, we propose a rate-matching scheme that does not degrade the HARQ throughput performance while retaining the same rate-matching scheme regardless of the number of CCs.

B. Proposed Rate-Matching Scheme

Fig. 4 shows the procedure of the proposed rate-matching scheme. In this scheme, the rate matching is performed at the eNbodeB always assuming a single CC, even though the soft buffer at the UE is split according to the number of configured CCs. More specifically, the first-step rate matching is performed according to Eq. (1), assuming a single CC and the soft buffer size of M irrespective of the number of the configured CCs. On the UE receiver side, all the soft channel bits, $\{b_j(k);\ k = 0 \sim E-1\}$, are input into the turbo decoder using an instantaneous buffer with the size of M as shown in Fig. 5.

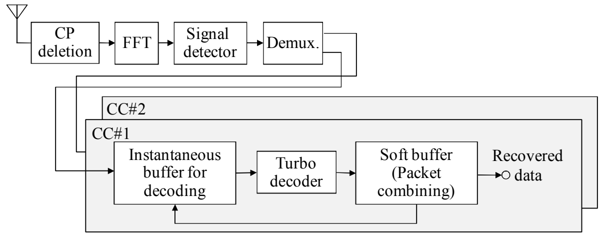


Figure 5. Proposed receiver structure.

Here, we note that a single instantaneous buffer can be shared for all the HARQ processes and that the increase in the complexity due to the introduction of the instantaneous buffer is not significant. After turbo decoding, only M_C bits are stored in a soft buffer with the size of M_C and the remaining $(E-M_C)$ bits are discarded in the case of $E > M_C$. In this scheme, the throughput performance for the initial transmission is ensured owing to the instantaneous buffer while the same rate-matching scheme can be applied at the eNodeB irrespective of the number of configured CCs. On the other hand, there is a disadvantage in that the HARQ throughput performance for retransmission may be deteriorated due to the discarding of the soft channel bits.

IV. Receiver for Proposed Rate Matching

In Section III, we considered that the soft buffer is equally divided by the number of CCs, and a single instantaneous buffer is used for decoding. Below, we simply call this approach the size-limited receiver. In this section, we also investigate another receiver. In [13], the process-limited receiver was proposed. Fig. 6 shows the structure for the size-limited receiver and process-limited receiver when C=2 and the number of HARQ processes, K_{HARQ}, is 8. In [13], the size of the soft buffer at the UE remains the same irrespective of the number of configured CCs, but only K_{HARQ}/C (= 4 in Fig. 6) soft buffers can be reserved per CC. In this scheme, to utilize efficiently the soft buffer, each soft buffer is not reserved for each HARQ process, i.e., each soft buffer is used only when there are decoding errors; otherwise the soft buffer is released for new packet reception. In other words, the UE must discard the soft channel bits if all the soft buffers are already occupied and there are decoding errors in a new packet.

V. Simulation Conditions

We set the number of subcarriers to 600 with a 15-kHz subcarrier spacing assuming the CC-bandwidth of 10 MHz and CA using 2 CCs. The subframe duration, i.e., transmission time interval (TTI), is set to 1 msec, which comprises 14 OFDM symbols. We assume a 2-by-2 MIMO antenna configuration. At the eNB transmitter for LTE-Advanced, binary information data bits are encoded using turbo coding with the channel coding rate of R=1/3 and the constraint length of 4 bits. After channel encoding and interleaving, the rate-matching is performed. Then, adaptive modulation and coding (AMC) is further employed. The modulated symbol sequence is precoded based on the precoding matrix indicator (PMI) associated with the rank indicator (RI), where both PMI and RI are fed back

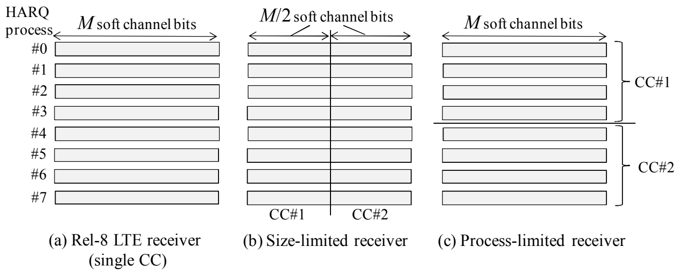


Figure 6. Comparison of receiver types.

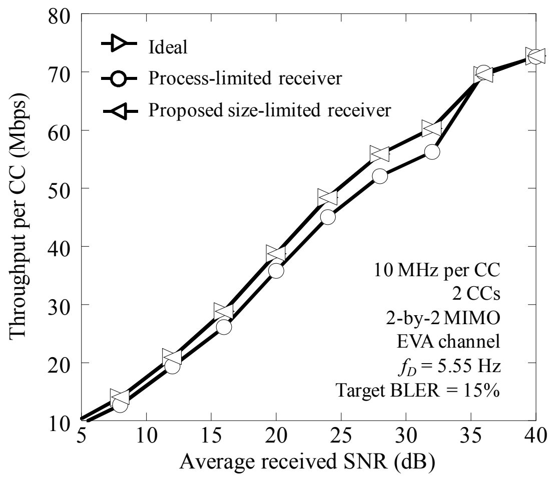
from the UE. After multiplexing the cell-specific reference signal (CRS), the data sequence is converted into OFDM signals by inverse FFT (IFFT) processing followed by the addition of a 4.75-μsec CP. For a multi-path fading channel, the Enhanced Vehicular-A (EVA) channel is assumed [14]. The terminal speed of 3 km/h at the carrier frequency of 2 GHz is also assumed.

At the UE receiver, we assume ideal OFDM symbol timing, i.e., FFT window timing, detection. After the CP is removed, the OFDM signal is decomposed into each subcarrier component by the 2048-point FFT. The CRS is de-multiplexed from the data and channel estimation is performed. The CRSs are used to obtain the channel estimate for demodulation and are also used to calculate the MCS, PMI, and RI that are to be fed back to the eNodeB. Signal detection based on the MMSE criterion is carried out using the channel estimate in order to extract each transmission layer. Finally, turbo decoding is carried out using Max-Log-MAP decoding with eight iterations to recover the transmitted binary data.

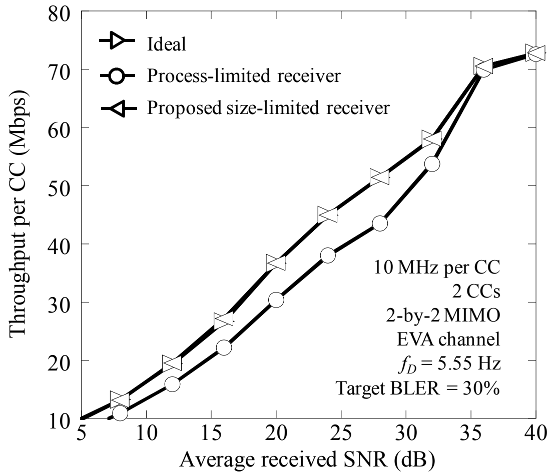
VI. SIMULATION RESULTS

A. Comparison of Receivers Types

The proposed size-limited receiver (including instantaneous buffer) is compared to the process-limited receiver described in Section IV in terms of the HARQ throughput performance. Fig. 7 (a) shows the HARQ throughput performance observed per CC as a function of the average received signal-to-noise power ratio (SNR) per receiver branch when the target BLER for the initial transmission is set to 15%. For reference, we also plotted the HARQ performance when the unlimited buffer size is assumed, i.e., the soft channel bits are not discarded (ideal receiver). With the ideal receiver, there is no performance degradation since all the bits can be used for HARQ packet combining and turbo decoding. Fig. 7 (a) illustrates that the proposed rate matching with the size-limited receiver provides the same performance as that for the ideal receiver. Meanwhile, the HARQ throughput performance of the process-limited receiver is worse than that for the proposed size-limited receiver. When the size-limited receiver is employed, the required SNR for achieving the throughput of 50 Mbps is 25 dB, while that for the process-limited receiver is 27 dB. In the process-limited receiver, the soft channel bits cannot be stored when there is no soft buffer available, i.e., four soft buffers are already occupied. This situation can be observed to some extent since the target BLER error rate is set to 15% and fading in time domain is correlated. Consequently, the number of retransmissions is increased and the HARQ throughput



(a) Target BLER = 15%



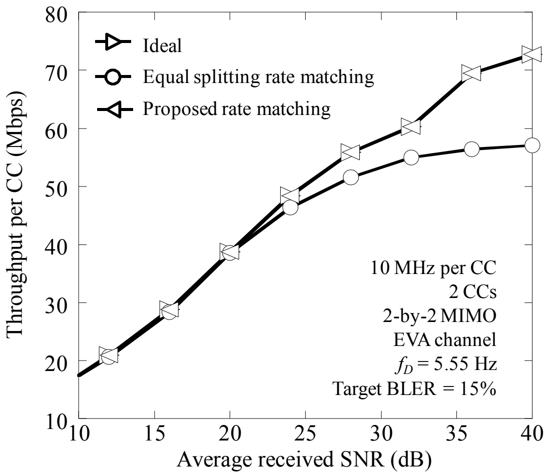
(b) Target BLER = 30%

Figure 7. Performance comparison of receiver types.

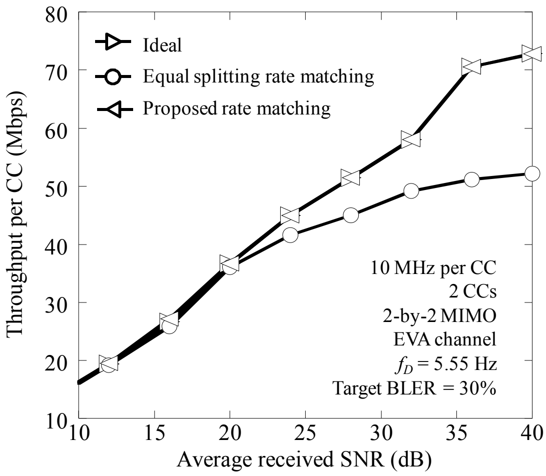
performance is degraded. Fig. 7 (b) shows the HARQ throughput performance when the target BLER = 30%. The figure shows that the performance difference between the size-limited receiver and process-limited receiver becomes larger when a higher BLER is targeted. According to the above evaluation results, we found that the size-limited receiver is more suitable for the proposed rate-matching scheme compared to the process-limited receiver and we used the size-limited receiver for the proposed rate matching in the following evaluations.

B. Comparison of Rate-Matching Schemes

The proposed rate matching is compared to equal splitting rate matching [10] using the HARQ throughput performance. Fig. 8 (a) shows the HARQ throughput performance per CC when the target BLER is set to 15%. For reference, we also plotted the HARQ throughput performance with the ideal receiver. Fig. 8 (a) shows that the proposed rate matching with the size-limited receiver provides higher throughput performance than that for the equal splitting rate-matching scheme in high SNR regions. The reason for this is as follows. In higher SNR regions, a higher MCS is likely to be selected through AMC and the number of bits, E, available for



(a) Target BLER = 15%



(b) Target BLER = 30%

Figure 8. Performance comparison of rate-matching schemes.

transmission increases. When E exceeds the soft buffer size M_C per CC, i.e., $E > M_C$, the achievable coding gain is limited even with the initial transmission as described in Section III. On the other hand, for the proposed rate-matching, no performance loss is observed owing to the instantaneous buffer for decoding. Fig. 8 (b) plots the HARQ throughput performance when the target BLER = 30%. In this case, retransmission is requested more frequently compared to the case of the target BLER = 15% and the HARQ throughput performance is slightly degraded. Nevertheless, no performance degradation compared to the ideal case is observed for the proposed scheme since 70% of the initial transmissions are successfully decoded. Even when the retransmissions are requested, M_C bits can be used for the HARQ packet combining. On the other hand, for the equal splitting rate-matching scheme, we see that the throughput performance is still degraded due to a lower coding gain.

VII. CONCLUSION

In this paper, we first emphasized that the soft buffer size per CC may not be sufficient and the performance of the HARQ packet combining is not ensured when soft buffer splitting is applied to a UE in a lower UE category. To address this problem, we proposed a rate matching scheme for CA and the optimum receiver for efficient HARQ packet combining and decoding. In this scheme, rate matching is performed always assuming a single CC and does not depend on the number of CCs. At the UE receiver, all the received bits are turbo-decoded using a single instantaneous buffer and the bits exceeding the soft buffer size of each CC are discarded. We showed that this proposed receiver, i.e., size-limited receiver, is suitable for CA compared to another receiver, i.e., process-limited receiver. Then, it was shown that the proposed rate-matching scheme and size-limited receiver provide higher throughput performance than that for the equal splitting rate-matching scheme. As a consequence of standardization in the 3GPP RAN WG, the proposed rate-matching scheme with the size-limited receiver is adopted for CA in LTE-Advanced.

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