

Impact of power amplifier configuration on LTE carrier aggregation performance

Chester S. Park¹ and Sungkyung Park^{2a)}

¹ Department of Electronics Engineering, Konkuk University,
120, Neungdong-ro, Gwangjin-gu, Seoul 05029, Republic of Korea

² Department of Electronics Engineering, Pusan National University,
2, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 46241, Republic of Korea

a) fspark@pusan.ac.kr

Abstract: Assuming two non-contiguous carriers, the impact of the power amplifier (PA) configuration is investigated. The mathematical derivations show that the minimum link performance (uplink data rate) occurs when the receive power allocation between carriers amounts to either 3 dB or -3 dB, depending on the bandwidth and path loss allocation. Moreover, it is shown that the link performance can be significantly improved by configuring the PA farther away from the worst-case operating points. The analysis matches well with the experimental results based on the PA measurement campaign.

Keywords: power amplifier backoff, carrier aggregation, 3GPP-LTE

Classification: Microwave and millimeter wave devices, circuits, and systems

References

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1 Introduction

Carrier aggregation is a key feature of the 3GPP Long Term Evolution (LTE), which enables us to achieve higher data rates by transmitting multiple carriers from or to the same terminal [1]. Non-contiguous carrier aggregation is one of the configurations where two carriers are not contiguous in frequency. Because of non-linearity of transmitter, especially the power amplifier (PA), simultaneous transmission of two non-contiguous carriers may cause additional interference to the neighboring channels/bands, which necessitates additional PA backoff so as to keep such interference below an acceptable level (e.g., as low as in single-carrier transmission) [2, 3, 4, 5].

The minimum PA backoff largely determines the link performance (more accurately, the uplink cell coverage) since a cell-edge user equipment (UE) tends to be power-limited, i.e., operate near the maximum transmit power [4]. Therefore a tremendous amount of measurement and simulation effort has been made to determine the minimum PA backoff required to the unwanted emission requirements, in particular, in the 3GPP standardization (e.g., [6, 7, 8]). However, regarding the optimum PA configuration (e.g., in terms of link performance), there has been little report in the literature. In [9] the dependence of the minimum PA backoff on the bandwidth allocation is analyzed and it is shown that the minimum PA backoff is maximized when the bandwidth allocation becomes inversely proportional to the PSD allocation. In this letter, taking a step forward, the relationship between PA configuration and link performance is investigated and verified using the experimental results.

2 Mathematical derivations

2.1 Constraints on link performance

Let P_1 (P_2), B_1 (B_2), L_1 (L_2) denote the transmit power, bandwidth and path loss of Carrier 1 (Carrier 2), respectively. Given the power spectral density (PSD) allocation $R_{PSD} := (P_2/B_2)/(P_1/B_1)$, the link performance (i.e., the uplink data rate) is expressed as $C = \mathbf{C}(P_1, R_{PSD})$ where $\mathbf{C}(P, R)$ is defined as

$$\mathbf{C}(P, R) := B_1 \log_2 \left(1 + \frac{P}{L_1 N_0 B_1} \right) + B_2 \log_2 \left(1 + \frac{RP}{L_2 N_0 B_1} \right). \quad (1)$$

where N_0 is the PSD of the additive white gaussian noise (AWGN).

According to [2], the transmit power is constrained to satisfy the unwanted emission requirements, specifically, the spectrum emission mask (SEM), adjacent channel leakage power ratio (ACLR) and spurious emission requirements. If the two carriers are far apart from each other in frequency, the minimum PA backoff is largely determined by the PSD of the 3rd-order intermodulation (IM3) [9]. In this case, the spurious emission requirements can be seen as the constraints on P_1 , i.e.,

$$P_1 \leq \sqrt[3]{\frac{PSD_{SE}}{\alpha R_{PSD}} \cdot \frac{B_1(2B_1 + B_2)}{B_2}} := P_{max,1} \quad (2)$$

on Carrier 1's side and

$$P_1 \leq \sqrt[3]{\frac{PSD_{SE}}{\alpha R_{PSD}^2} \cdot \frac{B_1^2(B_1 + 2B_2)}{B_2^2}} := P_{max,2} \quad (3)$$

on Carrier 2's side. Here α is a linearity-dependent constant (e.g., determined by the 3rd-order intercept point (IIP3)) and PSD_{SE} is the maximum allowable emission specified by the spurious emission requirements (e.g., -30 dBm/MHz). Since $C(P, R)$ monotonically increases with P , the power constraints in Eq. (2) and Eq. (3) lead to the link performance constraints as

$$C \leq C(P_{max,1}, R_{PSD}) := C_{max,1}, \quad (4)$$

and

$$C \leq C(P_{max,2}, R_{PSD}) := C_{max,2}, \quad (5)$$

respectively, with the overall link performance constraint given as

$$C \leq \min(C_{max,1}, C_{max,2}) := C_{max}. \quad (6)$$

It also follows from Eq. (2) and Eq. (3) that setting $C_{max,1} \leq C_{max,2}$ (or equivalently $P_{max,1} \leq P_{max,2}$) amounts to requiring

$$R_{PSD} \leq \frac{2R_B + 1}{R_B(R_B + 2)} := R_{1,2}, \quad (7)$$

where R_B is the bandwidth allocation defined as $R_B := B_2/B_1$. This implies that the PSD allocation determines which IM3 (i.e., on either Carrier 1's side or Carrier 2's side) constrains the link performance. In other words, the overall link performance constraint in Eq. (6) boils down into Eq. (4) if $R_{PSD} \leq R_{1,2}$ and vice versa.

2.2 Dependence on PSD allocation

Recall that a cell-edge UE typically operates near the maximum transmit power. Therefore, throughout this letter, the received signal-to-noise ratio (SNR) is assumed to be sufficiently low, e.g., $P_1/(L_1 N_0 B_1) \ll 1$ and $P_2/(L_2 N_0 B_2) \ll 1$. Accordingly, $C(P, R)$ in Eq. (1) can be approximated as

$$C(P, R) \approx \frac{\log_2 e}{L_1 N_0} \left(1 + \frac{L_1}{L_2} R_B R \right) P. \quad (8)$$

Then it follows that setting $\partial C_{max,1} / \partial R_{PSD} \leq 0$ amounts to requiring

$$R_{PSD} \geq \frac{R_L}{2R_B} := R_1, \quad (9)$$

where $R_L := L_2/L_1$ is the path loss allocation. Similarly, it also follows from Eq. (8) that setting $\partial C_{max,2} / \partial R_{PSD} \leq 0$ leads to requiring

$$R_{PSD} \geq \frac{2R_L}{R_B} := R_2. \quad (10)$$

It can be summarized that $C_{max,1}$ ($C_{max,2}$) is minimized when R_{PSD} equals R_1 (R_2), or equivalently, when the PSD allocation is set such that the receive power allocation (represented by $R_{PSD}R_B/R_L$) amounts to -3 dB (3 dB).

Note that how the link performance varies with the PSD allocation is determined by $R_{1,2}$, R_1 and R_2 . As shown in Eq. (7), Eq. (9) and Eq. (10) and also in the left side of Fig. 1, the PSD allocation thresholds $R_{1,2}$, R_1 and R_2 are solely determined by the bandwidth allocation (R_B) and the path loss allocation (R_L). For instance, they are independent of the sum bandwidth. In the remainder of this section, we will take a look at how the power allocation of PA should be set in order to maximize the link performance (given the bandwidth allocation and path loss allocation). First, for notational convenience, let us define $\mathbf{R}(R)$ as $\mathbf{R}(R) := (2R + 1)/(R + 2)$. Then, for $R_B > 0$, it follows that

$$0.5 < \mathbf{R}(R_B) < 2, \tag{11}$$

as shown in the right side of Fig. 1.

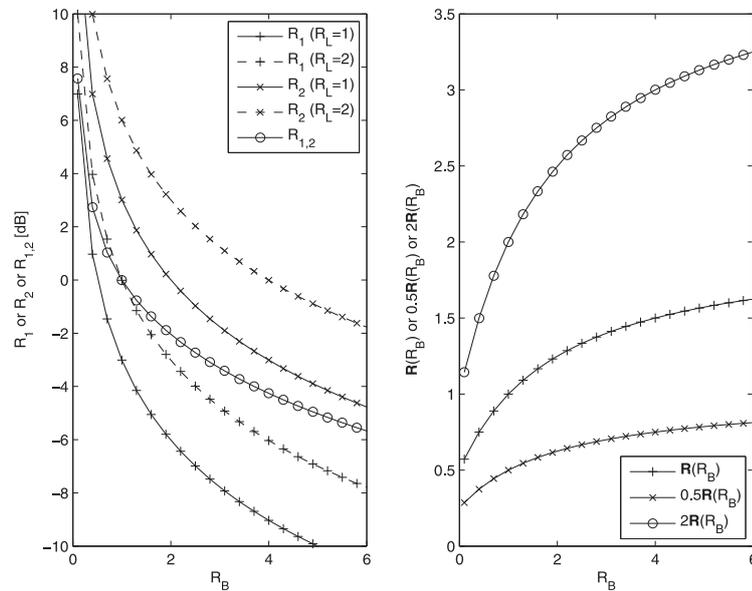


Fig. 1. Dependence of the PSD allocation thresholds (left) and the path loss allocation threshold (right) on the bandwidth allocation.

If $R_L < 0.5\mathbf{R}(R_B)$, then it follows that the link performance C_{max} is minimized when $R_{PSD} = R_1$ since $R_1 < R_2 < R_{1,2}$. Furthermore it is possible to improve the link performance by simply keeping R_{PSD} farther apart from R_1 . It also follows from Eq. (11) that this is always the case, regardless of R_B , as long as $R_L \leq 0.25$. More generally, if the path loss difference exceeds 6 dB, the link performance is minimized when the receive power of the carrier with larger path loss is 3 dB larger and, more importantly, it is possible to improve the link performance by simply moving the PA operating point farther away from the worst-case operating point.

Otherwise, if $0.5\mathbf{R}(R_B) \leq R_L < 2\mathbf{R}(R_B)$, then it readily follows that $R_1 < R_{1,2} \leq R_2$, as exemplified in Fig. 1. In this case, $\partial C_{max}/\partial R_{PSD}$ is given as

$$\frac{\partial C_{max}}{\partial R_{PSD}} < 0, \quad R_{PSD} < R_1, R_{1,2} < R_{PSD} < R_2 \quad (12)$$

$$\frac{\partial C_{max}}{\partial R_{PSD}} = 0, \quad R_{PSD} = R_1, R_{PSD} = R_2 \quad (13)$$

$$\frac{\partial C_{max}}{\partial R_{PSD}} > 0, \quad R_1 < R_{PSD} < R_{1,2}, R_2 < R_{PSD}. \quad (14)$$

Therefore, if $R_{PSD} < R_{1,2}$, the link performance improves as R_{PSD} moves farther away from R_1 and, otherwise, i.e., if $R_{PSD} > R_{1,2}$, it does as R_{PSD} moves farther away from R_2 . In addition, it is easy to show that setting $C(P_{max,1}, R_1) \leq C(P_{max,2}, R_2)$ amounts to requiring

$$R_L \leq \mathbf{R}(R_B). \quad (15)$$

Consequently, if $R_L < \mathbf{R}(R_B)$, C_{max} is minimized when $R_{PSD} = R_1$. Otherwise, if $R_L > \mathbf{R}(R_B)$, C_{max} is minimized when $R_{PSD} = R_2$. (If $R_L = \mathbf{R}(R_B)$, C_{max} is minimized when $R_{PSD} = R_1$ and $R_{PSD} = R_2$.) For example, if $R_L \geq 2$, then the condition in Eq. (15) is never satisfied, regardless of R_B , as clearly shown in Fig. 1, and thus C_{max} is minimized when $R_{PSD} = R_2$. More generally, if the path loss difference is no less than 3 dB, the link performance is minimized, regardless of the bandwidth allocation, when the PA is configured such that the carrier with larger path loss is given 3 dB larger receive power.

Finally, if $2\mathbf{R}(R_B) \leq R_L$, then it follows that C_{max} monotonically increases as R_{PSD} moves farther apart from R_2 since $R_{1,2} \leq R_1 < R_2$.

Before concluding this section, it is worth reiterating that whether the link performance is minimized at the power allocation of 3 dB or -3 dB generally depends on the allocation of bandwidth and path loss.

3 Experimental results

In this section, the mathematical derivations of the previous sections are verified using the experimental results. The extensive PA measurement campaign was carried out to obtain the amplitude-to-amplitude modulation (AM/AM) and amplitude-to-phase modulation (AM/PM) behavior of commercially available PAs [10]. The operating point was set to satisfy the UTRA ACLR1 requirements [2] at the output power of 22 dBm with a fully allocated 20 MHz carrier modulated by quadrature phase shift keying (QPSK), as assumed in [6, 7, 8]. This is a well-developed and proven approach to determine the minimum PA back-off required to satisfy the unwanted emission requirements in the 3GPP standardization.

Given the allocation of bandwidth and power, the total transmit power of carriers is swept over the entire range (i.e., up to 23 dBm) and the minimum PA backoff required to satisfy the unwanted emission requirements (the SEM, ACLR and spurious emission requirements [2]) is measured together with the corresponding link performance, as shown in Fig. 2. Two 20 MHz non-contiguous carriers with 60 MHz gap are assumed so that the IM3 always falls into the spurious emission region where the PSD shall be kept lower than -30 dBm/MHz [3]. The

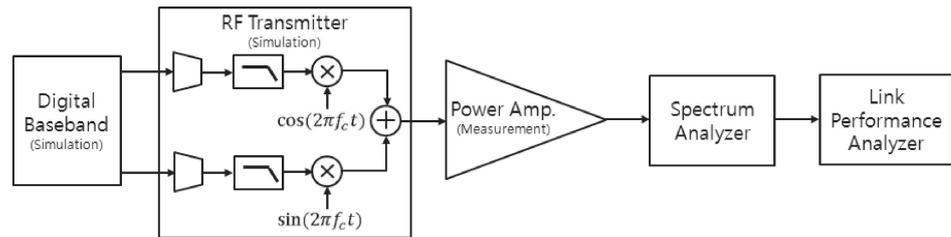


Fig. 2. Measurement of the minimum required PA backoff and the corresponding link performance.

two carriers are modulated with discrete Fourier transform spread orthogonal frequency division multiplexing (DFTS-OFDM), as specified in [11]. The sum bandwidth of two carriers is set to be either 12 Resource Blocks (RBs) (2.16 MHz) or 24 RBs (4.32 MHz). The number of RBs is assumed to be (2, 10), (3, 9), (6, 6) or (9, 3) for the sum bandwidth of 12 RBs and (4, 20), (6, 18), (12, 12) or (18, 6) for the sum bandwidth of 24 RBs such that the bandwidth allocation is given as $R_B \in \{1/3, 1, 3, 5\}$. (Note that the number of RBs of each carrier always has the prime factors of only 2, 3 or 5 [11].) The radio-frequency (RF) transmitter includes the counter IM3 of 60 dBc, the IQ image of 25 dBc and the carrier leakage of 25 dBc, as assumed in [6, 7, 8].

Assuming equal path loss ($R_L = 1$), Fig. 3 shows the PSD of two non-contiguous carriers measured within a bandwidth of 1 MHz (red) or 30 kHz (blue) together with the unwanted emission requirements (black). It is clearly shown that the minimum PA backoff (or equivalently the maximum transmit power) is indeed determined by the spurious emission requirements, as assumed in the previous section. In each of the sub-figures, the transmit power of individual carriers and the corresponding link performance are displayed. The left-side figure shows that, if $R_L = \mathbf{R}(R_B)$ (i.e., $R_B = 1$), the minimum link performance (i.e., the minimum data rate) occurs when the receive power allocation amounts to either -3 dB or 3 dB (i.e., $R_{PSD} = R_1$ or $R_{PSD} = R_2$, respectively), as analyzed in the previous section. Moreover, it is verified in the right-side figure that, if $0.5\mathbf{R}(R_B) < R_L < \mathbf{R}(R_B)$ (i.e., $R_B = 5$), the minimum link performance occurs when the receive power allocation amounts to -3 dB (i.e., $R_{PSD} = R_1$). Obviously, the experimental results justify the significance of appropriate PA configuration (i.e., the power/PSD allocation between carriers) in terms of link performance.

The experimental results in Fig. 4 show how the link performance depends on the PA configuration for a total bandwidth of 12 RBs (left) and 24 RBs (right). Although the analysis in the previous section is based on several approximations, e.g. two carriers and their IM3 are assumed to have frequency-flat PSD, it is shown to match well with our experimental results. In detail, in each of the sub-figures, it is verified that the link performance is minimized when the PA is configured to satisfy $R_{PSD} \approx R_1$ or $R_{PSD} \approx R_2$. For example, in the left sub-figure, it is shown that, in the case of equal bandwidth ($R_B = 1$) and equal path loss ($R_L = 1$), the link performance is minimized when $R_{PSD} \approx 0.5$ or $R_{PSD} \approx 2$, as depicted in the previous section. The middle sub-figure verifies that, if the path loss allocation is

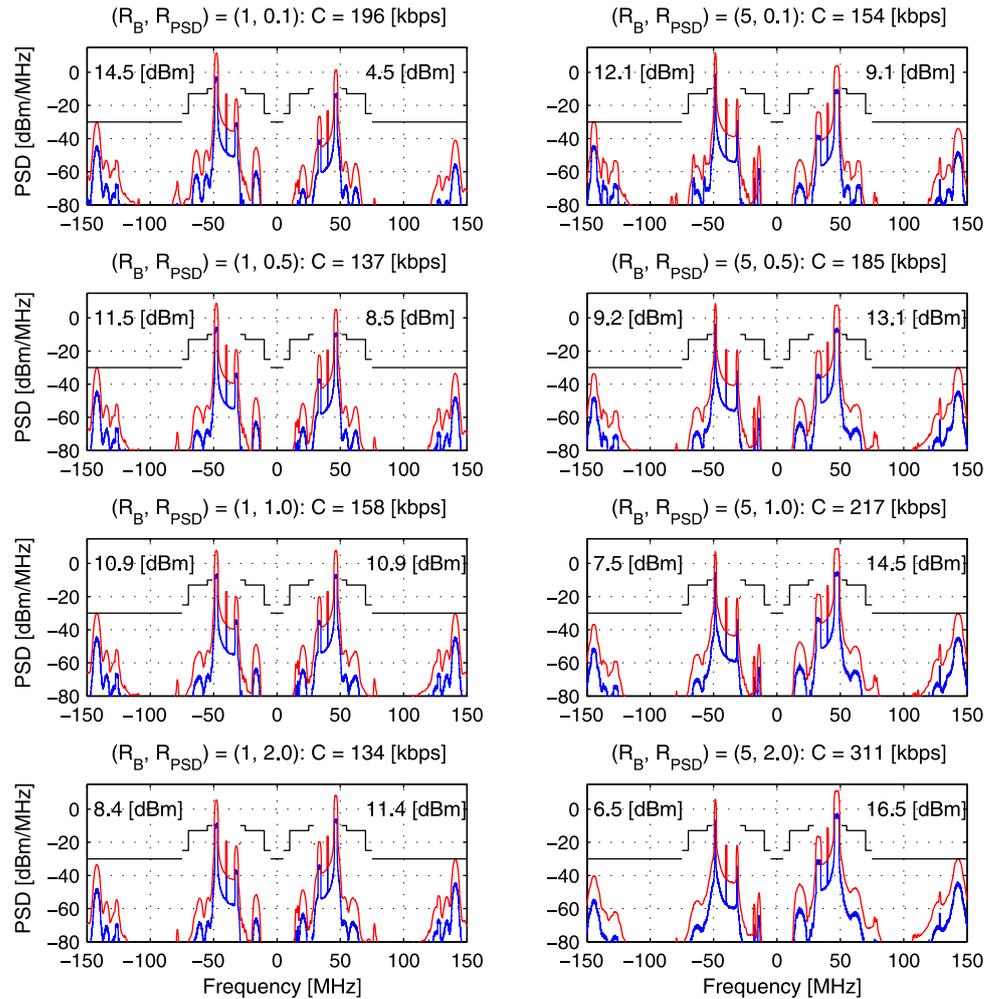


Fig. 3. PSD of two non-contiguous carriers of equal path loss ($R_L = 1$) with the sum bandwidth of 24 RBs.

3 dB ($R_L = 2$), the link performance is minimized when $R_{PSD} \approx R_2$, regardless of R_B , as also mentioned earlier. Moreover, it is clearly shown in the left and middle sub-figures that each of the worst-case operating points (R_1 and R_2) increases by roughly 3 dB, i.e., as much as the path loss allocation increases, as shown in Eq. (9) and Eq. (10). The left and right sub-figures also show that the worst-case operating points are independent of the sum bandwidth. For example, in the case of one-third bandwidth allocation ($R_B = 1/3$) and equal path loss ($R_L = 1$), the link performance is minimized when $R_{PSD} \approx 6$, regardless of the sum bandwidth. Therefore it can be concluded that the analysis in the previous section matches well with the measurement results.

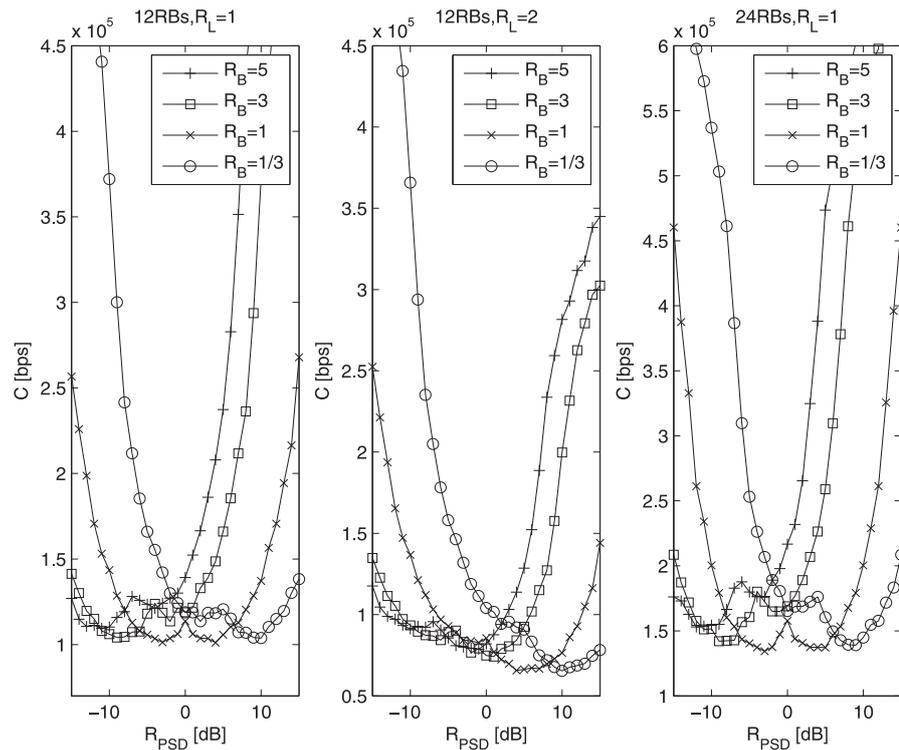


Fig. 4. Dependence of the link performance on the PSD allocation between carriers with the sum bandwidth of 12 RBs (left, middle) and 24 RBs (right) and the path loss allocation of 0 dB (left, right) and 3 dB (middle).

4 Conclusion

In this letter, the dependence of the link performance on the power/PSD allocation between two non-contiguous carriers was analyzed mathematically and verified with the experimental results. It was shown that the link performance is minimized when the power allocation (or equivalently the PSD allocation) of the PA is set such that the receive power allocation amounts to either 3 dB or -3 dB (depending on the bandwidth allocation and the path loss allocation). Recalling that the power control algorithm is based on the explicit or implicit information of path loss, it is possible to significantly improve the uplink cell-edge coverage by simply configuring the PA operating point farther away from the worst-case operating point.

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