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Methods for mitigating inter-carrier interference caused by power amplifier transient in LTE modem

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Abstract: Power amplifier transient of LTE modem is discussed. In current LTE specification, the requirement of power amplifier transient period for LTE modem is within 40 µs. Under this requirement, non-negligible inter-carrier interference (ICI) can be observed for both of normal cyclic prefix (CP) (= 4.7 µs) and extended CP (= 16.7 µs). We analyze the ICI in terms of the transient response of power amplifier and propose ICI mitigation schemes: 1) digital pre-distortion at transmitter 2) low complexity multi-tap equalization at receiver based on the ICI analysis.

Keywords: power amplifier, OFDM, inter-carrier interference, pre-distortion, equalization, LTE

Classification: Electron devices, circuits, and systems

References

[1] P. Schniter: IEEE Trans. Signal Process. **52** (2004) 1002. DOI:10.1109/TSP.2004.823503

[2] J. Armstrong: IEEE Trans. Commun. **47** (1999) 365. DOI:10.1109/26.752816

[3] European Telecommunications Standards Institute: 3GPP TS 36.104 V12.5.0, http://www.3gpp.org/DynaReport/36104.htm.

[4] European Telecommunications Standards Institute: 3GPP TS 36.101 V12.5.0, http://www.3gpp.org/DynaReport/36101.htm.

[5] European Telecommunications Standards Institute: 3GPP TS 36.213 V12.3.0, http://www.3gpp.org/DynaReport/36213.htm.

[6] D. R. Morgan, M. Zhengxiang, K. Jaehyeong, M. G. Zierdt and J. Pastalan: IEEE Trans. Signal Process. **54** (2006) 3852. DOI:10.1109/TSP.2006.879264

[7] D. Lei, R. Raich and G. T. Zhou: IEEE Int. Conf. Acoustic, Speech, and Signal Processing (ICASSP) (2002) 2689. DOI:10.1109/ICASSP.2002.5745202

[8] M. Rawat, K. Rawat and F. M. Ghannouchi: IEEE Trans. Microw. Theory Techn. **58** (2010) 95. DOI:10.1109/TMTT.2009.2036334

[9] A. Driss, A. Hadj and M. Elouafi: Appl. Math. Comput. **202** (2008) 441. DOI:10.1016/j.amc.2008.02.026

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[10] Draft new Report ITU-R M.[IMT.EVAL] "Guidelines for evaluation of radio interface technologies for IMT-Advanced," Document 5/69-E.
[11] European Telecommunications Standards Institute: 3GPP TS 36.212 V12.3.0, http://www.3gpp.org/DynaReport/36212.htm.

1 Introduction

Orthogonal frequency division multiplexing (OFDM) system suffers from inter-carrier interference (ICI) due to time varying channel [1] and/or frequency offset [2] between transmitter and receiver. ICI caused by the time varying channel or frequency offset in OFDM system has been widely analyzed and abundant solutions were proposed. However, to our best knowledge, ICI caused by power amplifier (PA) transient has not been studied. In this letter, we analyze ICI caused by transmit power transient due to the imperfect response of PA and propose solutions to mitigate ICI.

Long term evolution (LTE) system is based on OFDM. In LTE system, transmit power and resource allocation can be changed in each sub-frame (= 1 ms duration) that is a notion of OFDM symbol groups for radio resource management. Each sub-frame comprises fourteen OFDM symbols in the case of normal cyclic prefix (CP) or twelve OFDM symbols if extended CP is configured.

In [3, 4], the requirements of PA transient period of LTE base station (BS) and user equipment (UE) are specified. When PA turns on or off, the transient period of LTE BS and UE shall be within 17 µs and 20 µs, respectively. Similar with on-off case, when the transmit power is changed between sub-frames, the transient period of PA shall be within 20 µs. In an uplink sub-frame, sounding reference signal (SRS) can be placed in the last symbol of a sub-frame. SRS is one of the significant signals since it is a pilot symbol for BS to measure UE-to-BS channel. The power offset range between SRS and physical uplink shared channel (PUSCH) can be requested by BS from −3 dB to 12 dB [5]. Therefore, the transmit power can be changed within a sub-frame when SRS is transmitted. The requirement of PA transient when SRS is transmitted in a sub-frame shall be within 40 µs. Fig. 1 illustrates an example of PA transient period placement in LTE uplink. As shown in this figure, one symbol within a sub-frame can be suffered from ICI caused by PA transient period, and this will degrade the link performance. In this letter, we analyze ICI caused by PA transient and propose ICI mitigation schemes. We observe this PA transient phenomenon in a commercial LTE modem. Fig. 2 shows the measured output power at antenna port in a commercial LTE UE when the transmit power is swiftly changed to 10 dB. Since about 10 µs transient period is observed, non-negligible ICI can occur in normal CP case.

Notation: Normal letters represent scalar quantities, boldface and capital letters indicates matrices, boldface and small letters indicates vectors, $[\cdot]^T$ represents a transpose operation, $[\cdot]^H$ represents the conjugate transpose (Hermitian), $\mathbf{A} \circ \mathbf{B}$ represents the element-wise product of $\mathbf{A}$ and $\mathbf{B}$, $\mathbf{0}_{a \times b}$ denotes a $a \times b$ matrix with all zero elements, and $[\mathbf{A}]_{a:b,c:d}$ denotes a sub-matrix selecting entries from the ath row to the bth row and from the cth column to the dth column of $\mathbf{A}$.

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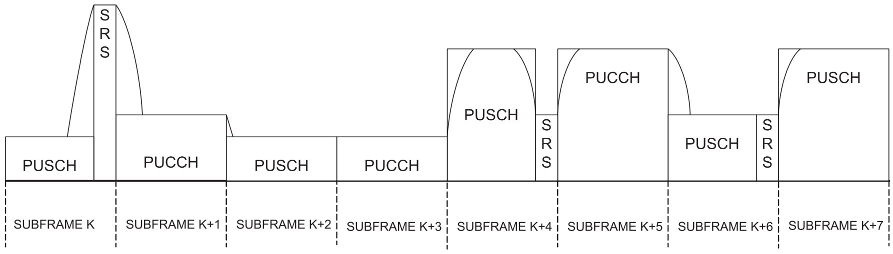

Fig. 1. An example of PA transient period placement in LTE uplink

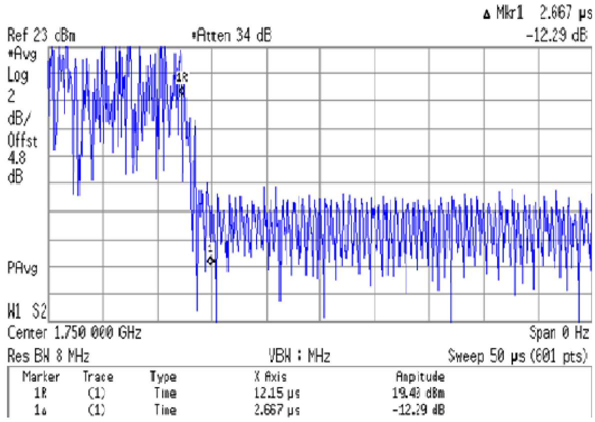

Fig. 2. About 10 µs transient period in a commercial LTE modem when 10 dB power offset is applied

2 ICI analysis caused by the PA transient

We explain the details based on a LTE uplink system. In downlink, PA transient period can occur when the BS change the transmit power for each sub-frame. However, since a BS usually implements better amplifier than that of UE, there may be no issue in downlink. Therefore, we focus on UE's PA transient response in LTE uplink system. In LTE uplink, to reduce PAPR, fast Fourier transform (FFT) spreading before sub-carrier data mapping and contiguous sub-carrier data mapping are adopted. In other words, single carrier frequency division multiple access (SC-FDMA) is used for LTE uplink. The nth time domain sample of ith SC-FDMA transmitting symbol is written as follows,

$$t_n^{(i)} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} s_k^{(i)} e^{j\frac{2\pi}{N}kn}, \quad -N_{CP} \leq n < N, \tag{1}$$

where $s_k^{(i)}$ is the frequency domain uplink signal at the kth subcarrier after M point FFT, N denotes the IFFT size, N_{CP} denotes the number of samples of cyclic prefix (CP). The received signal at BS can be written as follows,

$$r_n^{(i)} = \sum_{l=0}^{L-1} h_l t_{n-l}^{(i)} + v_n^{(i)} \tag{2}$$

where h_l is the time-domain channel gain of the l-th tap, $L(\leq N_{CP})$ denotes the number of taps of the time-domain channel, and $v_n^{(i)}$ denotes additive white Gaussian noise (AWGN) signal with zero mean and σ^2 variance. After receiving the uplink signal, the BS removes CP from the received signal and then performs

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N-point FFT operation. Consequently, the received signal after FFT operation can be written as follows,

$$x_p^{(i)} = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} r_n^{(i)} e^{-j\frac{2\pi}{N}pn} \tag{3}$$

Equation (3) can be re-expressed as a matrix form as follows,

$$\mathbf{x} = \mathbf{F}\mathbf{H}_t\mathbf{t} + \mathbf{F}\boldsymbol{v} = \mathbf{F}\mathbf{H}_t\mathbf{F}^H\mathbf{s} + \mathbf{n}, \tag{4}$$

where $\mathbf{F}$ denotes a N-point FFT matrix, $\mathbf{t} = [t_0^{(i)}, \ldots, t_{N-1}^{(i)}]^T$ is the uplink input signal vector, $\mathbf{r} = [r_0^{(i)}, \ldots, r_{N-1}^{(i)}]^T$ is the received signal vector, $\mathbf{n}$ is a frequency domain AWGN vector, and $\mathbf{H}_t$ denotes a circular convolution matrix expressed by

$$\mathbf{H}_t = \begin{bmatrix} h_0 & 0 & 0 & \cdots & & 0 & h_{L-1} & h_{L-2} & \cdots & h_1 \\ h_1 & h_0 & 0 & 0 & \cdots & & 0 & h_{L-1} & \cdots & h_2 \\ h_2 & h_1 & h_0 & 0 & 0 & \cdots & & 0 & \ddots & \vdots \\ \vdots & \vdots & & \ddots & & & & & 0 & h_{L-1} \\ h_{L-1} & & & & & 0 & 0 & \cdots & & 0 \\ 0 & h_{L-1} & & & & & & & & \\ & 0 & & & & & \ddots & 0 & & \\ \vdots & & \ddots & \ddots & & & & h_0 & 0 & \vdots \\ 0 & \cdots & & 0 & h_{L-1} & & \cdots & h_1 & h_0 & 0 \\ 0 & 0 & \cdots & & 0 & h_{L-1} & \cdots & h_2 & h_1 & h_0 \end{bmatrix}. \tag{5}$$

We assume that the channel is not time varying within a symbol to focus on ICI caused by PA transient period in this letter. We define $\mathbf{H}_C = \mathbf{F}\mathbf{H}_t\mathbf{F}^H$ that is an effective channel matrix after removing CP and FFT operation. The effective channel matrix is diagonal if the time domain channel matrix $\mathbf{H}_t$ is cyclic. However, the PA transient occurs within a symbol, the effective channel matrix is not diagonal since the cyclic property of $\mathbf{H}_t$ is lost.

The PA transient period occurs at four cases in general: the first case is that the previous symbol has lower power (front-rising), the second case is that the previous symbol has higher power (front-falling), the third case is that an next symbol has higher power (end-rising), and the forth case is that a next symbol has lower power (end-falling). Fig. 3 depicts the possible four cases of PA transient period in LTE system. For convenience of explanation, the power of the ith symbol is normalized as one. The transient response of PA is modeled mathematically in (6) and (7) for front transient cases and end transient cases, respectively.

$$\text{Front transient case: } g_n = \begin{cases} \sqrt{f(n)}, & -N_{cp} \le n \le -N_{CP} + N_T - 1 \\ 1, & -N_{CP} + N_T \le n \le N - 1 \end{cases}, \tag{6}$$

$$\text{End transient case: } g_n = \begin{cases} 1, & -N_{cp} \le n \le N - 1 - N_T \\ \sqrt{f(n)}, & N - N_T \le n \le N - 1 \end{cases}, \tag{7}$$

where N_T denotes the number of samples of the transient period, and $f(n)$ denotes the PA response. Fig. 4 illustrates how the PA transient period affects the time

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domain channel matrix. In this figure, the transient gain matrix denoted by $\mathbf{G}$ and illustrated by red box is multiplied to $\mathbf{H}_t$ in element-wise and the transient gain matrix $\mathbf{G}$ is given by

$$\text{For case 1 and 2,}\ \ \mathbf{G} = [\mathbf{A}, \mathbf{B}] = \begin{bmatrix} \underbrace{\begin{matrix} g_{-N_{CP}} & \cdots & g_{-1} \\ \vdots & \vdots & \vdots \\ g_{-N_{CP}} & \cdots & g_{-1} \end{matrix}}_{\mathbf{A}} & \underbrace{\begin{matrix} g_0 & \cdots & g_{N_T-N_{CP}-1} \\ \vdots & \vdots & \vdots \\ g_0 & \cdots & g_{N_T-N_{CP}-1} \end{matrix}}_{\mathbf{B}} \end{bmatrix},$$

$$\text{for case 3 and 4,}\ \ \mathbf{G} = \begin{bmatrix} g_{N-N_T} & \cdots & g_{N-1} \\ \vdots & \vdots & \vdots \\ g_{N-N_T} & \cdots & g_{N-1} \end{bmatrix}. \tag{8}$$

The effective channel matrix $\mathbf{H}_C$ for case 3 and 4 in consideration of PA transient can be written as follows,

$$\mathbf{H}_C = \mathbf{F}(\mathbf{H}_t + \Delta)\mathbf{F}^H = \mathbf{F}\mathbf{H}_t\mathbf{F}^H + \mathbf{F}\Delta\mathbf{F}^H = \mathbf{H}_D + \mathbf{H}_\Delta, \tag{9}$$

where $\Delta = \begin{bmatrix} \mathbf{0}_{(N-N_T)\times(N-N_T)} & \mathbf{0}_{N_T\times N_T} \\ \mathbf{0}_{N_T\times(N-N_T)} & \mathbf{G}\circ[\mathbf{H}_t]_{N-N_T:N-1,N-N_T:N-1} - [\mathbf{H}_t]_{N-N_T:N-1,N-N_T:N-1} \end{bmatrix}.$

Similar analysis can be also applied for case 1 and 2. We note that in (9) $\mathbf{H}_D$ is a diagonal matrix but $\mathbf{H}_\Delta$ has off-diagonal entries.

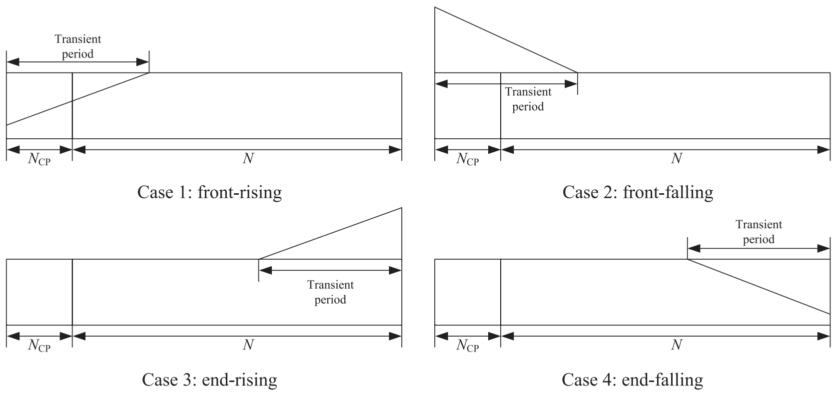
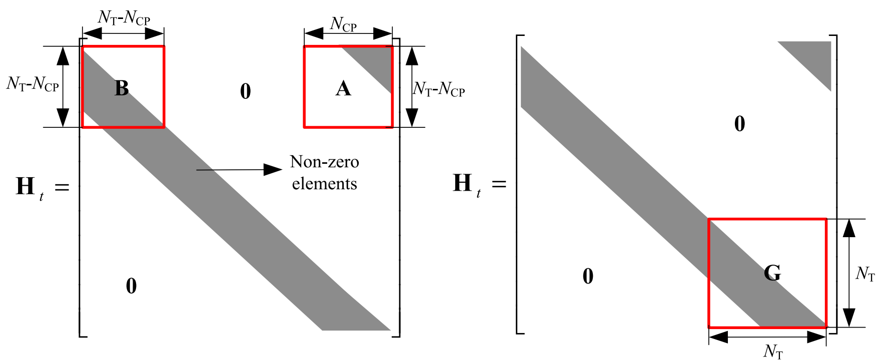


Fig. 3. Possible cases of PA transient period in LTE system



(a) Time domain channel matrix reflected power transient period for transient case 1 and 2

(b) Time domain channel matrix reflected power transient period for transient case 3 and 4

Fig. 4. Time domain channel matrix in consideration of PA transient

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3 ICI mitigation schemes

In this section, we discuss ICI mitigation schemes that can be implemented by either transmitter or receiver.

3.1 Transmitter based ICI mitigation scheme: digital pre-distortion

Baseband digital pre-distortion (DPD) is a widely used for linearity- and efficiency-enhancement technique for radio frequency PAs [6, 7, 8]. This technique can be also applied to mitigate the effect of time domain PA transient. In digital domain, pre-distortion weight can be multiplied to compensate PA transient in analog domain. Fig. 5 illustrates an example of the time-domain pre-distortion to mitigate ICI when power is supposed to ramp up to the next symbol. Fig. 6 depicts the system block diagram of the proposed scheme. The pre-distortion weight in digital domain can be multiplied by the transmit signal as follows,

$$\bar{t}_n^{(i)} = \frac{1}{\hat{g}_n} t_n^{(i)}, \ n = -N_{CP}, \ldots, N-1, \tag{10}$$

where $\bar{t}_n^{(i)}$ denotes in the nth sample, and $\hat{g}_n$ denotes the estimated PA response in digital domain. The PA response can be obtained by feedback loop in Fig. 6 or a look up table for the PA transient response in digital domain can be made. Note that (10) can be applied only in a boundary symbol where the PA transient period exists. This transmitter based solution does not increase the computational complexity but can avoid ICI caused by PA transient. However, every UE may not have such functionality because some UE is old version. In this case, some ICI mitigation scheme at receiver side (i.e. BS) can be devised. In next sub-section, we discuss receiver based ICI mitigation scheme.

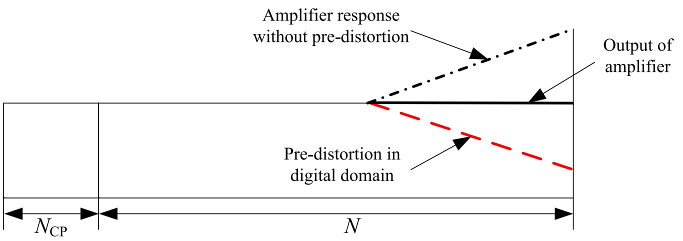

Fig. 5. An example of digital pre-distortion for PA transient

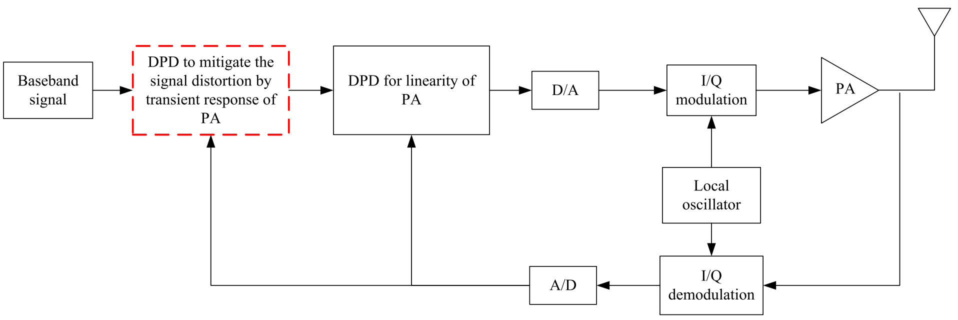

Fig. 6. Digital pre-distortion scheme for PA transient

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Table I. Simulation parameters

Channel model	ITU UMi NLOS clustered delay line model in [10]
Number of subcarriers	128
Coding rate	1/2
Modulation	QPSK
Coding scheme	Turbo code in [11]
Number of resource blocks in a sub-frame	6
CP length	normal CP
Channel estimation	Ideal
Transient period of PA	10 µs
Power difference in transient period	7 dB
Transient cases	Case 3 in Fig. 3
PA Transient response $f(\mathrm{n})$ in (6), (7)	Linear function
PA response estimation method at transmitter and receiver	Perfect

3.2 Receiver based ICI mitigation scheme: multi-tap equalization

The frequency domain equalization output is given by multiplying Hermitian of a weight matrix $\mathbf{W}$ as

$$\mathbf{y} = \mathbf{W}^H \mathbf{x}, \tag{11}$$

where the optimum weight in the minimum mean square error (MMSE) sense is expressed as

$$\mathbf{W} = \left(\mathbf{H}_C \mathbf{H}_C^H + \sigma^2 \mathbf{I}\right)^{-1} \mathbf{H}_C. \tag{12}$$

To calculate (12), $\mathbf{H}_C$ in (9) should be calculated firstly. In (9), $\mathbf{H}_D$ can be obtained by pilot channel estimation phase, but the complexity of calculating $\mathbf{H}_\Delta$ is additionally taken into account. Let us use the relationship of $\mathbf{F}\Delta\mathbf{F}^H = \mathbf{F}(\mathbf{F}\Delta^H)^H$. Here, Δ^H has only N_T non-zero columns, so N_T FFT operations are only necessary. Similarly, $(\mathbf{F}\Delta^H)^H$ has only N_T non-zero columns. Totally, $2N_\mathrm{T}$ FFT operations are required. The computational complexity of N-point FFT operation is known as $\mathrm{O}(N \log N)$. The matrix calculation of (9) is still $\mathrm{O}(N \log N)$ when $N_\mathrm{T} \ll N$.

After obtaining $\mathbf{H}_C$, $\mathrm{O}(N^3)$ complexity is required for the calculation of the matrix inversion in (12), which is much burden to implement it. To reduce the computational complexity, tri-diagonal matrix or penta-diagonal matrix approximation can be considered. Since it is expected that the off-diagonal term rapidly decreases, we propose to approximate $\mathbf{H}_C$ as tri-diagonal or penta-diagonal matrix by forcing $[\mathbf{H}_C]_{p,q} = 0$ for $|p-q| > 1$ or $|p-q| > 2$. For tri- or penta-diagonal matrix, $\mathbf{H}_C\mathbf{H}_C^H$ will not be tri- or penta-diagonal. In this case, we also approximate $\mathbf{H}_C\mathbf{H}_C^H$ as a tri-diagonal or penta-diagonal matrix. Note that the complexity of the matrix inverse of tri- or penta-diagonal matrix is known as $\mathrm{O}(N)$ in [9]. We also note that all of proposed ICI mitigation scheme is applied only in the boundary symbol when the PA transient occurs.

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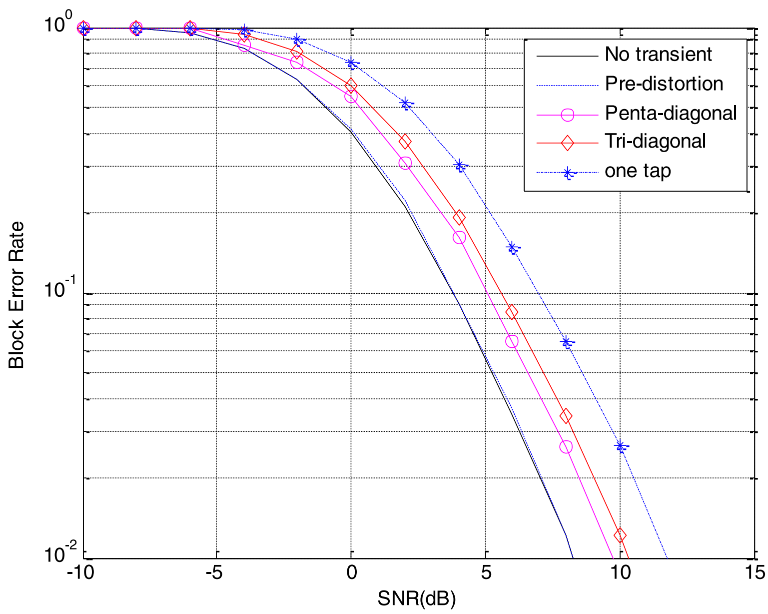

Fig. 7. Block error rate comparison

4 Numerical results

The proposed schemes in previous section are numerically evaluated. The simulation parameters are summarized in Table I. All of parameters and codeword mapping methods are based on LTE uplink sub-frame structure. Fig. 7 shows code block error rate (BLER) performance comparison. We observe that DPD scheme has same performance as no transient period since perfect PA response estimation is assumed in our evaluation. Compared with one tap equalization method, Tri- and penta-diagonal schemes have 1.4 dB and 2 dB performance gain at 10% BLER, respectively.

5 Conclusion

In this letter, implementation schemes to mitigate ICI caused by PA transient have been discussed. When the power offset between two symbols is swiftly changed, the power transient duration is generated due to the response rising and falling time of PA. Such problem causes performance degradation of receiver because it can be a reason of losing orthogonality between subcarriers. We have analyzed the ICI in terms of transient response of PA and proposed two schemes: digital pre-distortion at transmitter and low complexity ($O(N \log N)$) multi-tap equalization at receiver. The evaluation results show that the proposed schemes achieve significant link performance gain.

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