# PAPR Analysis of the OFDMA and SC-FDMA in the Uplink of a Mobile Communication System

Yingshan Li[1] · Il-Jin Lee[2] · Jangsu Kim[2] · Heung-Gyoon Ryu[2]

## Abstract

In recent years, OFDMA(orthogonal frequency division multiple access) and SC-FDMA(Single Carrier Frequency Division Multiple Access) have been widely studied for the uplink of a mobile communication system. In this paper, PAPR(Peak-to-Average Power Ratio) and BER(Bit Error Rate) performance of the OFDMA and SC-FDMA systems are studied in relation to the uplink of a mobile communication system. Three kinds of sub-carrier allocation methods in the OFDMA system and 2 kinds of sub-carrier allocation methods in SC-FDMA system are suggested to compare and improve system performance. Simulation results show that in the OFDMA system, the first sub-band allocation method has better PAPR reduction performance than the other methods. In the SC-FDMA system, the distributed allocation method offers similar PAPR, compared with the sub-band allocation method. PAPR can be further reduced by adding a spectrum shaping filter with an appropriate roll of factor. Furthermore, it is found that on average, SC-FDMA can reduce the PAPR by more than 5 dB compared to OFDMA, when the total sub-carrier number is 1,024 and the sub-carrier number allocated to each user changes from 8 to 512. Because of the frequency diversity and low PAPR characteristics, SC-FDMA system of the distributed sub-carrier allocation method can achieve better BER performance than the OFDMA system.

***Key words*** : OFDMA, SC-FDMA, PAPR, Sub-Band Allocation.

## Ⅰ. Introduction

The simultaneous transmission of multiple data streams over the same medium can be achieved with different multiplexing schemes. Among these multiple access schemes, frequency division multiplexing is often used in communication systems with FDD(Frequency Division Duplex), for example, in mobile radio systems GSM, IS-95, and UMTS FDD mode. The efficiency of frequency division multiplexing depends on the minimum separation of the sub-bands to avoid adjacent channel interference. OFDM(Orthogonal Frequency Division Multiplexing) is an efficient frequency division multiplexing scheme, which offers minimum spacing of the sub-bands without interference from adjacent channels in synchronous cases. Combining OFDM and FDMA(Frequency Division Multiple Access) for OFDMA(Orthogonal Frequency Division Multiple Access) was proposed for broadband wireless multiple access systems, such as IEEE 802.16 wireless MAN standard and DVB return channel terrestrial(DVB-RCT)[1]~[3].

The evolution of OFDM to OFDMA completely preserves robustness against multi-path propagation and high bandwidth(BW) efficiency. However, the disadvantages associated with OFDM are also inherent in OFDMA. For instance, a high peak-to-average power ratio (PAPR) for the transmitted OFDMA signals is a problem, especially when the allocated sub-carrier number of each user is considerable. In the downlink OFDMA, fully loaded PAPR is equivalent to a single user OFDM signal in terms of its PAPR characterization. On the other hand, in the uplink OFDMA, only a small fraction of sub-carriers are used, so PAPR is different from that of a single user OFDM signal.

Recently, SC-FDMA(Single-Carrier Frequency Division Multiple Access) has received increasing attention for the uplink of the evolved UTRA(EUTRA)[4]~[8]. This single-carrier based radio access scheme has the advantage of low PAPR features so that it can support wide-area coverage in cellular systems. SC-FDMA transmission is divided into two parts. One is time domain processing, IFDMA(Interleaved Frequency Division Multiple Access); the other is frequency domain processing, DFT-SOFDM(DFT Spread Orthogonal Frequency Division Multiplexing). In comparison to other multi-carrier systems, there is no multiple access interference since user discrimination is done by applying an FDMA scheme.

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In this paper, the PAPR and BER performance of the OFDMA and SC-FDMA system are studied in relation to the uplink of a mobile communication system. Three sub-carrier allocation methods for the OFDMA system and two sub-carrier allocation methods for the SC-FDMA system are suggested for comparing and improving system performance. Simulation results show that in the OFDMA system, the first sub-band allocation method has better PAPR reduction performance than the other sub-band allocation methods. In the SC-FDMA system, the distributed allocation method has similar PAPR, compared with the sub-band allocation method. PAPR can be further reduced by adding a spectrum shaping filter with an appropriate roll of factor. Because of frequency diversity and low PAPR characteristics, the SC-FDMA system of the distributed sub-carrier allocation method can achieve better BER performance than the OFDMA system.

## Ⅱ. OFDMA Uplink

OFDMA consists of assigning one or several sub-carrier frequencies to each user(terminal station) with the constraint that the sub-carrier spacing is equal to the OFDM frequency spacing $1/T_s$. That is, in OFDMA, all the available sub-carriers are divided into mutually exclusive sub-channels, each consisting of a distinct set of sub-carriers. Multiple accesses are achieved through the assignment of different sub-channels to different users.

Fig. 1 shows the simplified OFDMA uplink transceiver block diagram. Suppose there are a total of $N$ sub-carriers and $M$ users, thus each sub-channel consists of $S(S=N/M)$ sub-carriers. The uplink the OFDMA transmitted signal for the $m$th user can be written as

$$x_m(n)=\sum_{k\in S_m} X_{m,k}\cdot e^{j\frac{2\pi}{N}kn} \quad \text{for} \quad -N_G \le n < N \tag{1}$$

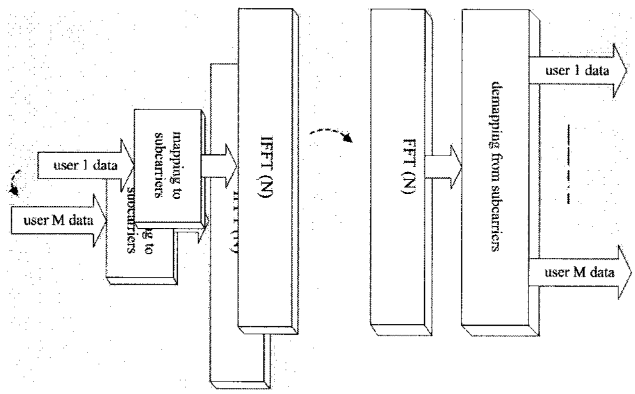



Fig. 1. OFDMA uplink with M users.

where $j=\sqrt{-1}$, $N$ is the total number of sub-carriers, $N_G$ is the length of GI(Guard Interval), $X_{m,k}$ is the $m$th user data symbol in the $k$th sub-carrier, where $k\in S_m$, $S_m$ means the sub-carrier set allocated for the $m$th user.

Through the fading channel, the received signal of all $M$ users at the base station can be expressed as

$$r(n)=\sum_{m=1}^{M} x_m(n)\otimes h_m(n)+v(n), \tag{2}$$

where $x_m(n)$, $h_m(n)$, $\upsilon(n)$, $r(n)$ are the $m$th user's transmitted signal, channel impulse response that corresponds to the $m$th user, complex Gaussian noise, and received signal at the base station, respectively.

After removing cyclic prefix, after FFT, the recovered output for the $m$th user's $l$th sub-carrier is as follows:

$$\begin{aligned} Y_{m,l} &= \frac{1}{N}\sum_{n=0}^{N-1} r[n]\cdot e^{-j\frac{2\pi}{N}nl} \\ &= \frac{1}{N}\sum_{n=0}^{N-1}\sum_{m=1}^{M}\sum_{k\in S_m} H_{m,k}\cdot X_{m,k}\cdot e^{j\frac{2\pi}{N}(k-l)n}+N_l \\ &= X_{m,l}H_{m,l}+N_l \end{aligned} \tag{3}$$

Here, $l\in S_m$, $X_{m,k}$ and $H_{m,k}$ are the frequency domain expressions of $x_m(n)$, $h_m(n)$ corresponding to the $k$th sub-carrier. $N_l$ is the FFT version of AWGN, that is $N_l=\frac{1}{N}\sum_{n=0}^{N-1} v(n)\cdot e^{-j\frac{2\pi}{N}nl}$.

## Ⅲ. SC-FDMA Uplink

DFT-S(Discrete Fourier Transform Spreading) OFDM is a type of SC-FDMA with frequency domain processing[7]. In DFT-SOFDM, suppose user $m(m=1,\cdots,M)$ occupies $S(S=N/M)$ sub-carriers, and each $S$ data symbol $d_{m,s}$, $s=0,\cdots,S-1$ for each user $m$ is used for the construction of one SC-FDMA symbol, they first pass through $S$ point DFT spreading, then after sub-carrier mapping(mapping into $N$ point by the appropriate sub-carrier allocation method), pass through $N$ point IFFT processing.

Suppose $S$ data symbols for user $m$ are

$$c_m=\lfloor d_{m,0}, d_{m,1},\ldots,d_{m,S-1}\rfloor \tag{4}$$

The above data spread onto the $S$ sub-carriers allocated to the user $m$ by the DFT spreading matrix $p_{s,l}$ is as follows,

$$p_{s,l}=\frac{1}{S}e^{-j2\pi sl/S}, \qquad l=0,\ldots,S-1. \tag{5}$$

$$X_{m,s}=\sum_{l=0}^{S-1} d_{m,l}\cdot p_{s,l}=\frac{1}{S}\sum_{l=0}^{S-1} d_{m,l}\cdot e^{-j2\pi sl/S} \tag{6}$$

After sub-carrier mapping, the transmission signal vector $X_m$ of user $m$ passes through $N$ point IFFT processing, suppose the $m$th user sub-carriers are equally spaced over the total bandwidth, so in the IFFT input, the sub-carrier index of user $m$ is $S_m = m,...,m+sM, ..., m+(S-1)M$.

The uplink SC-FDMA(DFT-SOFDM) transmitted signal for the $m$th user is

$$x_m(n) = \sum_{k\in S_m} X'_{m,k} \cdot e^{j\frac{2\pi}{N}kn} = \frac{1}{S}\sum_{k\in S_m}\sum_{l=0}^{S-1} d_{m,l}\cdot p_{s,l}\cdot e^{j\frac{2\pi}{N}kn} \quad (7)$$

where $X'_{m,k} = X_{m,s}$, $k = m+sM$, $S_m$ means the sub-carrier set assigned to user $m$.

The received signal of all $M$ users at the base station is

$$r(n) = \sum_{m=1}^{M} x_m(n)\otimes h_m(n) + v(n), \quad (8)$$

For simplicity of analysis, we suppose $h_m(n)=1$. Then, after removing cyclic prefix, after FFT, the recovered output for the $m$th user's $i$th sub-carrier is as follows:

$$Y_{m,i} = \frac{1}{N}\sum_{n=0}^{N-1} r[n]\cdot e^{-j\frac{2\pi}{N}ni} = \frac{1}{N}\sum_{n=0}^{N-1}\sum_{m=1}^{M}\sum_{k\in S_m} X'_{m,k}\cdot e^{j\frac{2\pi}{N}(k-i)n} + N = \sum_{l=0}^{S-1} d_{m,l}\cdot p_{s,l} + N \quad (9)$$

where, $i\in S_m$, $X'_{m,k}$ is the frequency domain expression of $x_m(n)$.

Finally, after sub-carrier de-mapping, DFT-SOFDM demodulation for the transmitted symbol $d_{m,v}$ of user $s$ is as follows.

$$\hat{d}_{m,v} = \sum_{s=0}^{S-1} Y_{m,i}\cdot e^{j2\pi vs/S} = \sum_{l=0}^{S-1} d_{m,l}\cdot\delta_S(v-l) + N = d_{m,v} + N. \qquad v = 0,\cdots\cdots, S-1 \quad (10)$$

The DFT-SOFDM type uplink transmission system can be described as in Fig. 2.

DFT-SOFDM has similar PAPR performance characteristic. DFT-SOFDM results in more spectral efficiency, provides a greater degree of commonality in design between uplink and downlink, and easily coexists with OFDM on the uplink.

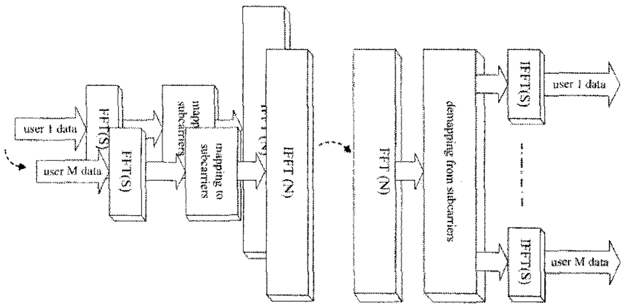



Fig. 2. SC-FDMA uplink with M users.

## Ⅳ. Sub-Carrier Allocation Method

There are several sub-carrier allocation schemes; sub-band allocation; distributed allocation; and random interleaving. As mentioned above, suppose there are a total of $N$ sub-carriers and $M$ users, thus each sub-channel consists of $S$( $S = N/M$ ) sub-carriers. In sub-band allocation, the $N$ sub-carriers are divided into $M$ groups with each group consisting of $S$ contiguous carriers. In the distributed allocation, the total $N$ sub-carriers are partitioned into $S$ groups with each group having $M$ contiguous sub-carriers. Then the $m$th sub-carrier of each group is assigned to the $m$th user. In random interleaving, the sub-carriers are grouped in a similar fashion to distributed allocation; the sub-carrier index of each group assigned to a particular user is a random variable. It is proved that the PAPR of the sub-band allocation method is the same as that of the distributed allocation method and the PAPR of the random interleaving method is inferior to that of the distributed allocation method[1].

In this study, we chose the sub-band allocation method(defined in case 2 below) and the revised sub-band allocation method(defined in cases 1 and 3 below) in the OFDMA system. In case 2, the sub-carrier allocation is the same as in the above sub-band allocation method. So, in case 2, the sub-carrier indices allocated to the $m$th ($0<m<M-1$) user are $S_m = \{mS, mS+1, ..., mS+S-1\}$. Cases 1 and 3 have a small difference compared with case 2. Case 1 and case 3 are the two sub-band allocation methods. For instance, in case 3 and case 1, the $N$ sub-carriers are divided into $2*M$ groups with each group consisting of $S/2$ contiguous sub-carriers. In case 3, two sub groups of one user are located symmetrically, that is, the first and last groups of sub-carriers are assigned to the first user, and the second group and last second group are allocated to the second user and so on. In case 1, the first groups of each user are located orderly in half of the sub-carriers and the second groups of each

user are located orderly in the continuing half of sub-carriers. Therefore, in case 3, the sub-carrier indices allocated to the $m$th user are

$$S_m = \left\{ m\frac{S}{2}, m\frac{S}{2}+1, \ldots, m\frac{S}{2}+\frac{S}{2}-1, \ldots\ldots, \right.$$
$$\left. N-m\frac{S}{2}, N-m\frac{S}{2}-1, \ldots, N-m\frac{S}{2}-\frac{S}{2}+1 \right\}.$$

And in case 1, the sub-carrier indices allocated to the $m$th user are

$$S_m = \left\{ m\frac{S}{2}, m\frac{S}{2}+1, \ldots, m\frac{S}{2}+\frac{S}{2}-1, \ldots\ldots, \right.$$
$$\left. \frac{N}{2}+m\frac{S}{2}, \frac{N}{2}+m\frac{S}{2}+1, \ldots, \frac{N}{2}+m\frac{S}{2}+\frac{S}{2}-1 \right\}.$$

Generally the SC-FDMA distributed allocation method(case 4 is the same as distributed DFT-SOFDM) is applied to each sub-channel. Each user is exclusively assigned a sub-set of sub-carriers and the sub-carriers of the different users are interleaved. So, the sub-carriers of a user are equally spaced over the transmission bandwidth B, so that maximum exploitation of the available frequency diversity gain can be achieved. In case 4, sub-carrier indices allocated to the $m$th user are $S_m = \{m, M+m, \ldots, (S-1)M+m\}$. To compare the PAPR of the other cases with that of case 4, we also consider the sub-band allocation method(case 5 is the same as localized DFT-SOFDM) in the SC-FDMA system. So, in case 5, the sub-carrier indices allocated to the $m$th user are $S_m = \{mS, mS+1, \ldots, mS+S-1\}$.

To compare the PAPR and BER performance in the uplink OFDMA system, one sub-band allocation(case 2) and two sub-band allocation methods(case 3) are considered, and in the SC-FDMA system, the distributed allocation method(case 4) is primarily considered. Another two sub-band allocation methods(case 1) in OFDMA

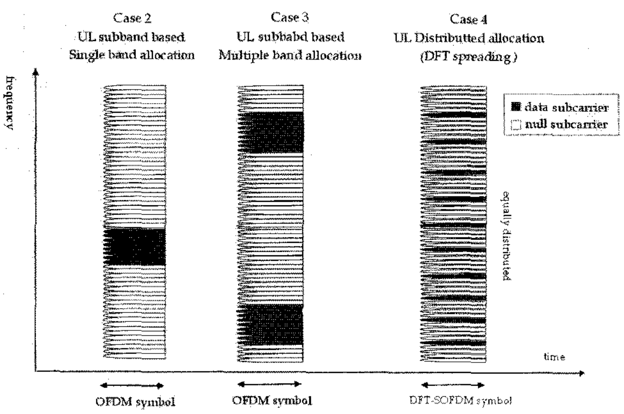



Fig. 3. Sub-carrier allocation method in case 2, case 3, case 4.

and a sub-band allocation method(case 5) in SC-FDMA are considered to compare the PAPR performance for each system.

## V. Simulation Results and Discussion

For OFDMA, case 1, case 2 and case 3 are considered, and for SC-FDMA, case 4, case 5 and case 4 with spectrum shaping filtering("ps" in the figure) are considered. The basic concept of spectrum shaping filtering is depicted in [6], submitted by NTT DoCoMo at the last London meeting. A Square-root Raised Cosine(SRC) filter is used for pulse/spectrum shaping filtering whilst satisfying the zero ISI Nyquist criterion. The $\alpha \times N_{TX}/2$ FFT outputs located at each end of the spectrum are copied to the opposite end and are then multiplied with the filter spectrum samples in the same frequency bins. $\alpha$ is supposed to be 0.1.

As seen from Fig. 4~9 and Table 2, the SC-FDMA (case 5, case 4 and case 4 with spectrum shaping) results in a much smaller PAPR problem compared with that of OFDMA. Furthermore, case 4 using the spectrum shaping filtering method results in the minimum PAPR and the maximum 90 % PAPR reductions are 4.8, 5.0, 5.2, 5.4, 5.5, 6.2, 6.2 and 6.2 when assigned sub-carriers for one user are 8, 16, 24, 32, 64, 128, 256 and 512, respectively. Furthermore, case 1 using the two sub-bands allocation method has similar PAPR properties compared with case 3, and case 5 with sub-band allocation method has similar PAPR properties to case 4. So, below, we only consider cases 2, 3 and 4.

Fig. 10 and Fig. 11 show the BER comparison of case 2, case 3, and case 4 when the FFT size is 1,024 and the assigned sub-carrier for one user is 16. In Fig. 10, when SSPA without backoff is used, at BER=$10^{-3}$, nearly 1.9 dB, 5.3 dB SNR penalties, respectively are caused in cases 2 and 3 when compared with AWGN theory curve. But, only a 0.5 dB SNR penalty is induced in case 4. In Fig. 11, when TWTA without backoff is used, at $BER=10^{-3}$, nearly a 13 dB SNR penalty is generated in case 2 and an error floor occurs in case 3, but, only a 1.7 dB SNR penalty is induced in case 4. This means that case 4, which adopts the SC-FDMA type with a distributed sub-carrier allocation method, can significantly reduce PAPR problems compared with OFDMA, so that lower linearity of HPA can be tolerated.

Fig. 12 and Fig. 13 show the BER comparison of case 2, case 3, and case 4 when doppler frequency is assumed to be 10 and a frequency selective Rayleigh fading channel is used. It is assumed that channel compensation in the receiver is perfect. As seen in Fig. 12

Table 1. System parameters.

| Parameters | Value | Parameters | Value |
|---|---|---|---|
| Basic transmission scheme | OFDMA, SC-FDMA | N_lower guard | 160 |
| Modulation schemes | QPSK, 16QAM | Sub-carrier allocation method | Case 1, Case 2, Case 3, Case 4, Case 5, Case 4+ps |
| Frequency reuse | One-cell frequency reuse | Assigned sub-carrier for one user | 8, 16, 24, 32, 64, 128, 256, 512 (named "para" in the figure) |
| Scalable bandwidth | Same sub-carrier spacing | Guard interval | 8 or 16 |
| IFFT/FFT block size, N_FFT | 1,024 | Symbol rate | 7.2(Msymbol/sec) |
| N_useful | 704(involve 1 DC carrier) | HPA model | SSPA, TWTA |
| N_upper guard | 160 | Channel | AWGN Channel, frequency selective Rayleigh fading channel |

Table 2. PAPR0 Comparison when $\Pr(PAPR > PAPR0) = 10^{-1}$.

| When $\Pr(PAPR > PAPR0) = 10^{-1}$, corresponding to 90 % PAPR [dB] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sub-carrier allocation method | Assigned sub-carriers for one user | | | | | | | |
| | 8 | 16 | 24 | 32 | 64 | 128 | 256 | 512 |
| Case 3 | 9.9 | 10.3 | 10.7 | 11.1 | 11.3 | 12.1 | 12.2 | 12.2 |
| Case 1 | 9.7 | 10.6 | 10.9 | 11.1 | 11.4 | 11.8 | 11.9 | 11.9 |
| Case 2 | 6.9 | 7.6 | 7.9 | 8.0 | 8.6 | 9 | 9.3 | 10.1 |
| Case 5 | 5 | 5.5 | 5.7 | 5.8 | 6.1 | 6.3 | 6.7 | 7 |
| Case 4 | 5.2 | 5.8 | 6.1 | 6.3 | 6.4 | 6.5 | 6.8 | 6.9 |
| Case 4 with spectrum shaping | 5.1 | 5.3 | 5.5 | 5.7 | 5.8 | 5.9 | 6 | 6 |
| Maximum difference of 90 % PAPR 90 % $PAPR_{Case4+ps}$ $-$90 % $PAPR_{Case3}$ | 4.8 | 5.0 | 5.2 | 5.4 | 5.5 | 6.2 | 6.2 | 6.2 |

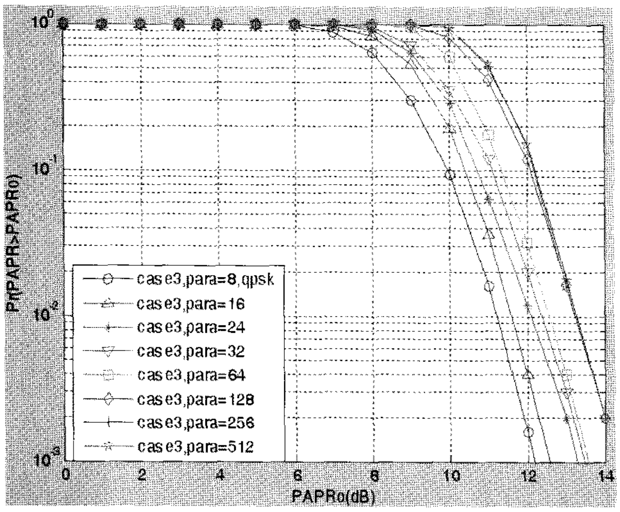



Fig. 4. PAPR of case 3(OFDMA with two sub-band allocation method), 1 user, N=1,024.

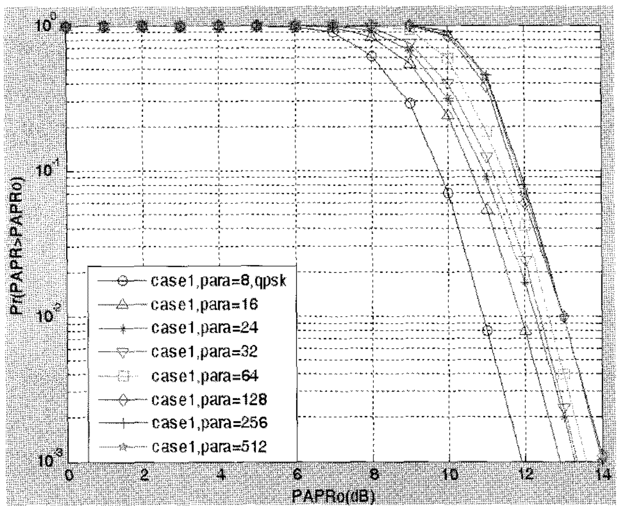



Fig. 5. PAPR of case 1(OFDMA with another two sub-band allocation method), 1 user, N=1,024.

and Fig. 13, when SSPA or TWTA without backoff are considered, the case 4 SC-FDMA type has a slight BER gain compared with OFDMA. This means that case 4-adopting the SC-FDMA type with a distributed sub-

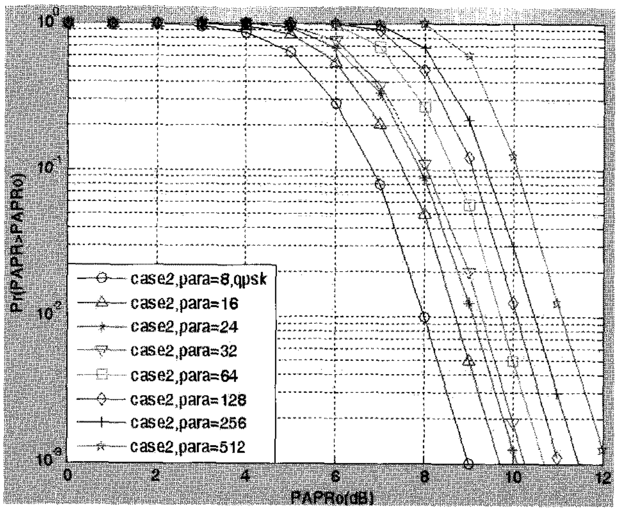



Fig. 6. PAPR of case 2(OFDMA with one sub-band allocation method), 1 user, N=1,024.

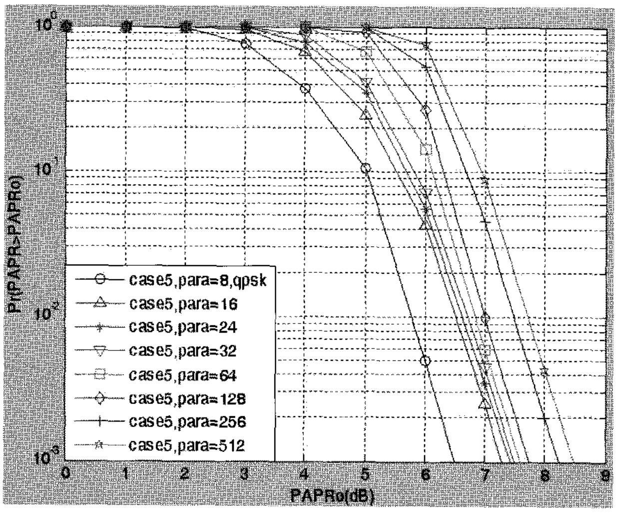



Fig. 7. PAPR of case 5(SC-FDMA with one sub-band allocation method), 1 user, N=1,024.

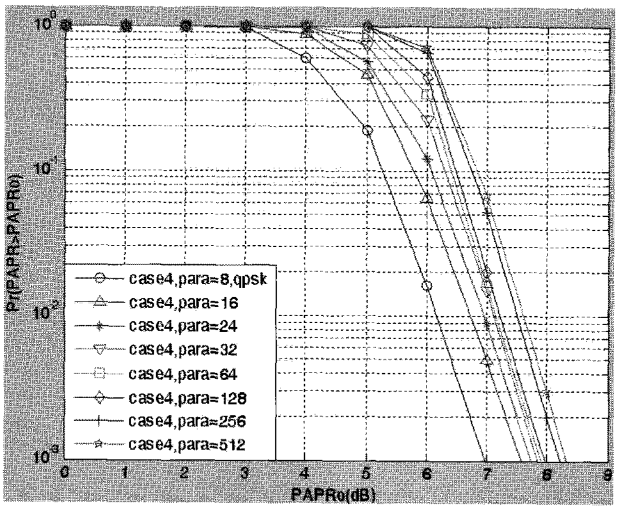



Fig. 8. PAPR of case 4(SC-FDMA with distributed allocation method), 1 user, N=1,024.

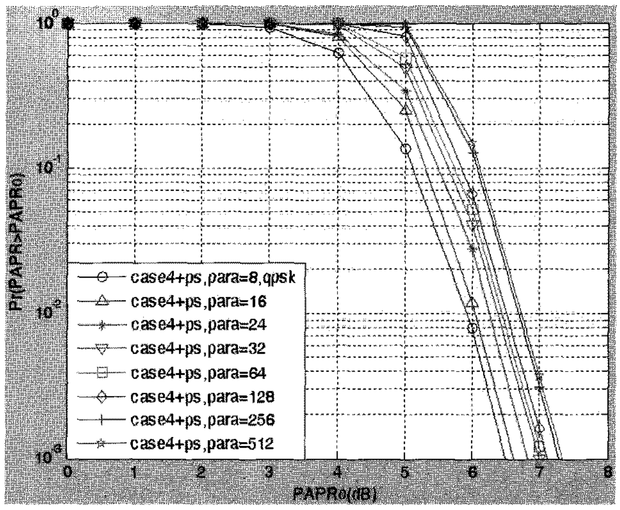



Fig. 9. PAPR of case 4 with spectrum shaping filtering, 1 user, N=1,024.

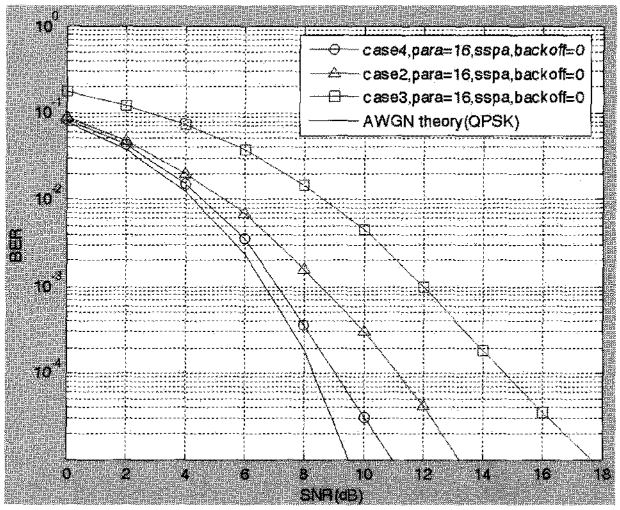



Fig. 10. BER comparison of three cases with SSPA in AWGN channel(N=1,024).

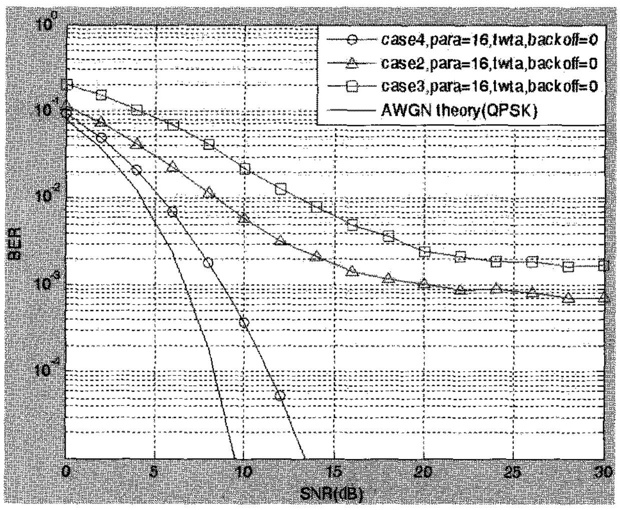



Fig. 11. BER comparison of three cases with TWTA in AWGN channel(N=1,024).

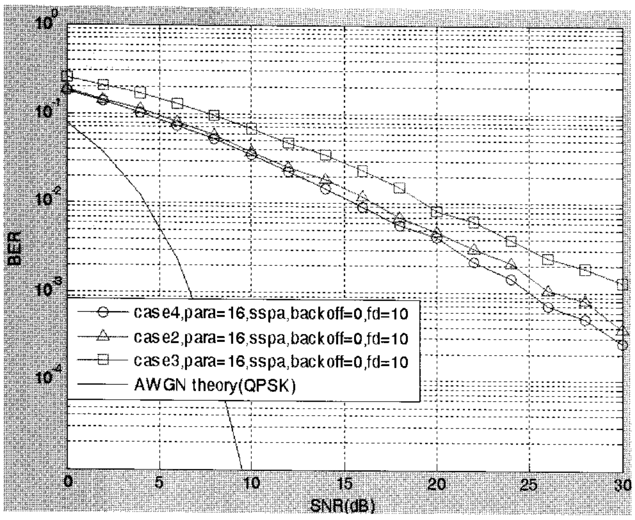



Fig. 12. BER comparison of three cases with SSPA and fd(N=1,024).

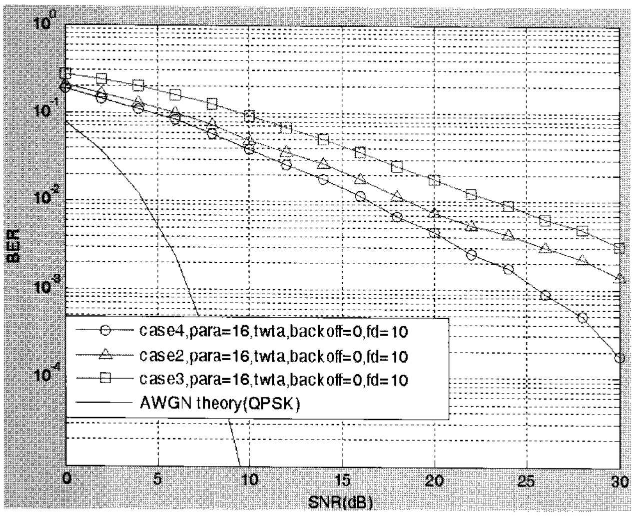



Fig. 13. BER comparison of three cases with TWTA and fd(N=1,024).

carrier allocation method-can improve system performance when nonlinear HPA and Doppler frequency are considered in the frequency selective fading channel. But the performance improvement is not so significant because the SC-FDMA signal results in ISI in the frequency selective channels. If equalization like MMSEC(Minimum Mean-Square Error Combining) is applied to the receiver side, the SC-FDMA may achieve an improved performance. In addition, we find that in the OFDMA, case 2 with one sub-band allocation method offers a slight performance gain compared with case 3 which uses the two sub-bands allocation method.

## Ⅵ. Conclusion

In this paper, OFDMA and SC-FDMA performance are compared from the viewpoint of transmission signal PAPR and BER in the uplink system. Several sub-carrier allocation methods are utilized to improve system performance. In OFDMA, a one sub-band allocation method has better PAPR performance than a two sub-band allocation method. In SC-FDMA, the distributed allocation method offers similar PAPR compared with the sub-band allocation method. And PAPR can be further reduced by adding spectrum shaping filtering with an appropriate roll of factor. Furthermore, on average a more than 5 dB PAPR gain can be achieved by SC-FDMA than OFDMA when the total carrier number is 1,024 and each user allocated sub-carrier number changes from 8 to 512. Because of the frequency diversity and low PAPR characteristics, SC-FDMA with the distributed sub-carrier allocation method can achieve better BER performance than OFDMA.

## References

[1] G. Parsaee, A. Yarali, "OFDMA for the 4/sup th/ generation cellular networks", *Electrical and Computer Engineering, 2004. Canadian Conference on*, vol. 4, pp. 2325-2330, May 2004.

[2] Y. -H. You, W. -G. Jeon, J. W. Wee, Sang-Tae Kim, Intae Hwang, and H. -K. Song, "OFDMA uplink performance for interactive wireless broadcasting", *Broadcasting, IEEE Transactions on*, vol. 51, Issue 3, pp. 383-388, Sep. 2005.

[3] Hao Wang, Biao Chen, "Asymptotic distributions and peak power analysis for uplink OFDMA signals", *Acoustics, Speech, and Signal Processing. Proceedings (ICASSP '04) IEEE International Conference on*, vol. 4, pp. 1085-1088, May 2004.

[4] U. Sorger, I. De Broeck, and M. Schnell, "Interleaved FDMA-a new spread-spectrum multiple-access scheme", *Communications, 1998. ICC 98 Conference Record. 1998 IEEE International Conference on*, vol. 2, pp. 1013-1017, Jun. 1998.

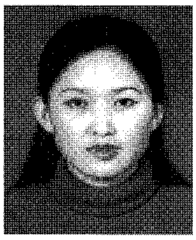
[5] M. Schnell, I. De Broeck, "Application of IFDMA to mobile radio transmission", *Universal Personal Communications, 1998. ICUPC '98. IEEE 1998 International Conference on*, vol. 2, pp. 1267-1272, Oct. 1998.

[6] R1-050702, "DFT-spread OFDM with pulse shaping filter in frequency domain in evolved UTRA uplink", *NTT DoCoMo, NEC, SHARP.*

[7] 3GPP R1-050712, *Single Carrier Uplink Options for E-UTRA: IFDMA/DFT-SOFDM Discussion and Initial Performance Results*, Motorola.

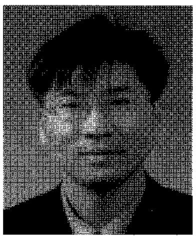
[8] K. Fazel, S. Kaiser, *Multi-Carrier and Spread Spectrum Systems*, John Wiley & Sons Ltd., 2003.

### Yingshan Li



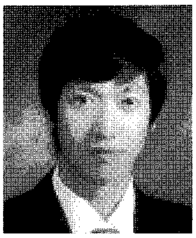
received a B.S. degree in automation engineering from Tsinghua University, Beijing, China, in July 1997. She received an M.S. degree and a Ph.D. degree in electronic engineering from Chungbuk National University, Cheongju, Korea in August 2004 and 2006, respectively. From September 1997 to August 2002, she was a lecturer in the Department of Electronic Engineering, Yanbian University, Yanji, China. From September 2006 to 2008, she was an assistant professor in the Department of Communication Engineering, Nankai University, Tianjin, China. Currently, she is an associate professor in the Department of Communication Engineering, Nankai University, Tianjin, China. Her research interests include digital communication systems, OFDM and CDMA communication systems, PAPR and ICI minimization, and communication circuit design.

### Il-Jin Lee



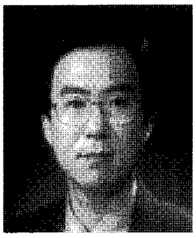
was born in Korea in 1969. He received B.S. and M.S. degrees in electronic engineering from Chungbuk National University, Korea in 1994 and 1996. Currently, he is working towards a Ph.D. in electronic engineering at Chungbuk National University, Cheongju, Korea. From 1996 to 2000, he worked at Samsung Aerospace Co. Since 2000 he has been with the protocol engineering center in ETRI, where he has participated in various research projects, including the development of domestic standards for VoIP, VoIP systems and IMPP systems.

### Jangsu Kim



received a B.S. in electronic engineering from Chungbuk National University, Korea in Feb. 2009. Currently, he is working towards an M.S. degree in electronic engineering at Chungbuk National University, Cheongju, Korea. His research interests include mobile communication systems, OFDM and CDMA communication systems, MIMO, PAPR and ICI minimization.

### Heung-Gyoon Ryu



(M'88) was born in Seoul, Republic of Korea in 1959. He received B.S., M.S. and Ph.D. degrees in electronic engineering from Seoul National University in 1982, 1984 and 1989, respectively. Since Feb. 1988, he has been with Chungbuk National University, Korea, where he is currently Professor in the Department of Electrical, Electronic and Computer Engineering at Chungbuk National University. He worked as Chief of RICIC(research institute of computer, information communication center) in Chungbuk National University from March 2002 to February 2004. His main research interests are digital communication systems, communication circuit design, spread spectrum systems and communication signal processing. Since 1989, he has worked as a reviewer for IEEE transaction papers. He was awarded the '2002 ACADEMIC AWARD' by the Korea Electromagnetic Engineering Society and received the "BEST PAPER AWARD" at the 4th International Conference on Wireless Mobile Communications(ICWMC 2008) Athens, Greece, July 27-Aug.1, 2008.