Frequency-Domain Packet Scheduling for Low PAPR in 3GPP LTE Uplink

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Abstract

Single carrier frequency domain multiple access (SC-FDMA) has been adopted for the 3GPP long-term evolution (LTE) uplink multiple access scheme due to the power consumption issue of mobile handsets. Like OFDMA in the downlink, SC-FDMA enables multiple users to be served simultaneously in the uplink. However, all subcarriers allocated to a single user must be contiguous in the frequency domain at each time slot due to its single carrier property. This contiguous allocation constraint makes scheduling difficult. A scheduling scheme in such systems needs to keep this constraint whilst trying to satisfy its own objectives. Therefore, we propose a frequency-domain packet scheduling algorithm to lower the PAPR of the mobile handset under this constraint. In this paper, we perform system level simulation on the 3GPP LTE system model. We compare the proposed scheme and previous one in terms of system throughput, fairness, and PAPR.

Keywords: *LTE, LTE uplink, single carrier frequency domain multiple access, SC-FDMA, FDPS, resource allocation, PAPR*

1. Introduction

Orthogonal frequency division multiple access (OFDMA) has recently been considered as a strong candidate for the mobile broadband air interface. It is robust to multipath fading and has high spectral efficiency and high bandwidth scalability. It has been adopted for 3GPP long-term evolution (LTE) downlink (DL) radio access technology due to these advantages. However, in spite of several advantages, one major disadvantage of OFDMA is that the instantaneous transmitted RF power can vary dynamically in a single OFDM symbol [1]. This means that OFDMA has high peak-to-average power ratio (PAPR). Such a high PAPR is a serious problem for the uplink (UL), since high PAPR leads to large power consumption. Therefore, we have to solve this problem, because power consumption is a key consideration for mobile handsets. Single carrier frequency division multiple access (SC-FDMA) has been selected for the LTE uplink multiple access scheme to solve this problem [2]. SC-FDMA has most advantages of OFDMA, since it has a similar structure to OFDMA. SC-FDMA also has significantly lower PAPR than OFDMA, since the underlying waveform is essentially single carrier [3]. Thus, lower PAPR of SC-FDMA greatly benefits mobile terminals in terms of transmit power efficiency in the uplink transmission.

As in DL OFDMA, multiple access in UL SC-FDMA is performed by assigning different frequency portions of the system bandwidth to individual UEs based on their channel conditions. Such a simultaneous frequency-domain multiplexing of UEs is performed by frequency-domain packet scheduling (FDPS). In LTE UL, the system bandwidth is divided into multiple sub-bands (i.e., group of subcarriers) termed physical resource blocks (RBs). A scheduler needs to know the instantaneous channel condition across all UEs and all RBs to achieve high multi-user diversity gain, so that the scheduler uses it as input for frequency-domain UE-to-RB allocation. Each UE transmits a sounding reference signal (SRS) to the scheduling node (i.e., base station), which is used as channel quality indicator (CQI), to recognize the channel condition [2]. A base station performs RB-to-UE allocation at each time slot (e.g., every 1ms in LTE) according to its scheduling policy using this CQI for access all UEs and all RBs. Therefore, RB is the minimum scheduling unit by adaptive modulation and coding (AMC) in the time-frequency domain.

Most DL FDPS algorithms proposed to date adopt the well-known proportional fair (PF) algorithm as a basic scheduling policy. They apply the PF algorithm directly to each RB, one-by-one independently. However, such a policy cannot be applied in the UL SC-FDMA. All RBs allocated to a single UE must be contiguous in frequency-domain within each time slot (i.e., sub-frame) due to its single carrier property in the SC-FDMA [4, 5]. Therefore, LTE UL FDPS algorithms must respect this constraint whilst achieving their own scheduling objective. In related work, the UL FDPS algorithm has been proposed using the PF algorithm as a metric value. In [6], it allocates RB-to-UE with max PF metric value and expands RB keeping the contiguous constraint [6]. In [7], it sorted PF metric values depending on the channel condition and allocates RB-to-UE in decreasing order. It also proposed a grouping algorithm that forms groups with several RBs and allocates them to the UE. However, most UL FDPS algorithms proposed to date consider system throughput and fairness, not PAPR. If PAPR is high, power efficiency for the mobile terminal is low; this decreases battery life. Thus, PAPR should be considered in UL FDPS algorithms.

In this paper, we propose the UL FDPS algorithm that enhances system throughput and fairness, whilst reducing PAPR of the mobile terminal under contiguous RB allocation constraint. In general, PAPR is reduced if the number of used subcarriers is reduced in SC-FDMA [1]. Therefore, we do not use some RBs in data transmission that have a low channel condition so that we reduce the number of subcarriers used in the mobile terminal. This does not affect throughput much, as reducing PAPR for the mobile terminal is due to not using RBs that have a low channel condition. We perform system level simulation to compare the performance of our proposed scheme and previous studies in terms of throughput, fairness, and PAPR. Our proposed scheme obtains a lower PAPR for the mobile terminal and has similar performance with regard to system throughput and fairness.

The remainder of paper is organized as follows. We introduce related work on FDPS and explain the system model and PF algorithm we have considered in this paper in Section II. Then, we explain our proposed scheme for low PAPR with a figure and pseudo code in Section III. In Section IV, we perform system level simulation and analyze the result in terms of throughput, fairness, and PAPR. Finally, a conclusion is given in Section V.

2. Background

2.1 Related Work

SC-FDMA is used in LTE Uplink as an air interface. SC-FDMA has similar characteristics to OFDMA, while it is a single-carrier transmission scheme. RBs must be allocated to a certain UE contiguously, as opposed to OFDMA to retain the single carrier property. We introduce three SC-FDMA scheduling schemes under the contiguous RB allocation constraint.

In-between RBs. A scheduler performs RBs-to-UE allocation with the largest PF metric value first in the *In-between RBs* scheme. First, the scheduler picks UE *i* and RB *c* that has the largest PF metric value. If the scheduler does not allocate any RBs to UE *i*, it allocates RB *c* to UE *i*. If the scheduler has already allocated any RBs to UE *i*, then it allocates RBs contiguously without violating the contiguous RB constraint. For example, suppose that RB 4 is allocated to UE *i*, and the one with the next largest metric value is RB 5. If, RB 5 is already allocated to other UE, then it violates the contiguous RB constraint allocating RB 6 to UE *i*. Thus, the scheduler allocates all the "in-between" RBs to UE *i* unless it breaks this constraint. Since the length of such "in-between" RBs is arbitrary, this scheme takes advantage of the situation when the channel condition is good across all the RBs.

Riding Peaks. PF metric values between RBs change with frequency at certain time *t*. In a multi-carrier system, the channel condition (i.e., SINR) is correlated in both time and frequency (depending on the Doppler effect and the time delay spread) [8]. That is, if UE *i* has a good channel condition on RB *c*, then the adjacent RBs(c - 1, c + 1) have a high probability of having a high channel condition as well. Therefore, this scheme uses this property. A scheduler allocates the RB with the largest PF metric value first. Next, it allocates adjacent RBs one-by-one in *Riding Peaks*. The important thing is that these RBs must be adjacent to the already allocated RB. Therefore, this scheme takes advantage of the situation when correlation between RBs is high. However, the scheme performs poorly when the channel condition varies dramatically between RBs (i.e., frequency selective fading).

RB Grouping. Channel condition values are indeed correlated in both time and frequency. However, in the general environment, correlation in the frequency domain is not as strong as is the case in the time-domain (frequency selective fading distortion) [8-10]. Such a channel condition, *Riding Peaks*, has a poor result, since it relies on strong channel correlation in the frequency-domain. Thus, grouping PF metric values of RBs help UE-to-RB allocation in frequency selective distortion. That is, we consider frequency selective fading channel to be strongly correlated channel in the frequency-domain as grouping RBs. In this scheme, if there are *m* RBs and *n* UEs in the system, then group size is *floor*(*m*/*n*). Next, the scheduler applies *Riding Peaks* to the grouped PF metric values of the RBs. This scheme has an advantage when there are many active UEs in the system in the frequency selective fading channel.

2.2. System Model and PF Consideration

In this paper, we consider a cellular network in which UL system bandwidth is divided *m* RBs, and we have a base station and *n* active UEs. The base station allocates *m* RBs to *n* UE with the contiguity constraint at each time slot *t*. We use the full buffer model that UE always has data to transmit, so that they can be scheduled at each time slot. Therefore, the base station scheduled *n* UE and *m* RB at each time slot. We define a variable $x_i^c(t)$ that indicates RB *c* is allocated UE *i*. If $x_i^c(t) = 1$, then RB *c* is allocated to UE *i*. We assume that the channel condition depends on UE and RB. We consider the frequency selective fading channel, so that the channel condition changes according to time and frequency. Therefore, each RB has a different channel condition according to UE at each time slot.

In this paper, we use the well-known PF algorithm as the scheduling metric [11]. The PF algorithm aims to maximize the logarithmic utility function $\sum_i \log R_i$, where R_i is the long-term service rate of UE *i*. The PF algorithm makes it possible to achieve high throughput and high fairness simultaneously. $\sum_i r_i(t)/R_i(t)$ should be maximized, where $r_i(t)$ is an instantaneous achievable data rate of UE *i* at time slot *t* to maximize $\sum_i \log R_i$. Therefore, the PF algorithm always schedules the UE with the maximum $r_i(t)/R_i(t)$ value at each time slot *t*. In this paper we define $\rho_i^c(t) = r_i^c(t)/R_i(t)$ as the PF metric value on UE *i* and RB *c*. We aim to maximize the following equation at time slot *t*.

$$\max \sum_i \sum_c x_i^c(t)\rho_i^c(t) \tag{1}$$

A scheduler receives an input matrix *M*, which has PF metric values as elements at each step *t*, as shown in Figure 1 to satisfy Eq. (1), where the size of *M* is [*n* x *m*]. We explain how to perform UE-to-RBs allocation for low PAPR using matrix *M* as an input of the scheduler in the next section.

	RB_1	RB_2	...	RB_m
UE_1	$\rho_1^1(t)$	$\rho_1^2(t)$	...	$\rho_1^m(t)$
UE_2	$\rho_2^1(t)$	$\rho_2^2(t)$		$\rho_2^m(t)$
⋮	⋮			⋮
UE_n	$\rho_n^1(t)$	$\rho_n^2(t)$	...	$\rho_n^m(t)$

Figure 1. Input Matrix of *M*

3. Proposed Scheme: RB Reservation

In this section, we explain a proposed scheduling scheme that achieves high system throughput and fairness and makes a UE has low PAPR. Most of all DL FDPS schemes apply the PF algorithm directly over each RB. Then, the scheduler serves the UE independently that has largest PF metric values, $r_i(t)/R_i(t)$, on RB *c* at each time slot *t*. However, LTE UL cannot apply such a scheme in DL due to the contiguous RB allocation constraint to retain the single carrier property in SC-FDMA. That is, the scheduler cannot allocate RB in a distributed fashion. SC-FDMA also has the property that the PAPR of transmit signal decreases, as the number of subcarriers used in data transmission reduces [1]. Thus, in this paper we exploit the PF metric value, $\rho_i^c(t)$, to achieve high system throughput and fairness and to maximize Eq. (1) under contiguous RB allocation constraint, whilst lowering PAPR of UE.

In general, the channel correlation in the frequency-domain is not as strong as the one in the time-domain. That is, the correlation is strong in the overall frequency, but not in the adjacent RBs (small-scale variation). For example, a certain UE has a good channel condition in the overall frequency, but some channels have a poor channel condition. That is, the overall channel condition is good for a UE, but a sudden drop (poor channel quality) can occur in a small portion of channels. If this sudden drop occurs frequently, then it is difficult to satisfy Eq. (1), whilst following the contiguous RB constraint. We allocate sudden drop RB to maintain the contiguous RB constraint to solve this problem whilst satisfying Eq. (1). We have to use a high order modulation and low coding rate, since this RB has low SINR. That is, we obtain low throughput with this RB, since we must use a low level of AMC. Therefore, we propose the *RB Reservation* scheme that does not use this RB in data transmission to reduce the PAPR of UE.

The basic idea of *RB Reservation* is using the similarity of the channel, such that even if there are many small-scale variations in the frequency selective fading channel, the overall channel condition is similar. (i.e., channel is highly correlated across the overall frequency, but not in a small portion of the frequency.) Therefore, we allocate the sudden drop RB if the one in the middle of the RBs that has good channel quality to follow the contiguous RB allocation constraint and to satisfy Eq. (1). For example, scheduling is not done efficiently to maintain the contiguous RB constraint, if the adjacent RB has low channel quality. (The scheduler cannot satisfy Eq. (1).) Therefore, the scheduler considers not only both the left and the right side RB of the already assigned RBs, but also their adjacent RBs to satisfy Eq. (1) in the frequency selective fading channel. Table 1 details the *RB reservation* algorithm.

Table 1. *RB reservation*

Let S be the sorted list of all the metric values $\rho_i^c(t)$ from input matrix M in decreasing order
Let R be the set of the remained RBs
Let A be the matrix of the already assigned RBs to UEs
Let V be the matrix of the reserved RBs to UEs
m is the number of RBs, *n* is the number of active UEs
Max_dist ← 2
b ← 0
k ← 1
while $R = \emptyset$ **do**
    Pick RB *c* and UE *i* with k^{th} highest metric value $\rho_i^c(t) \in S, c \in R, 1 \leq c \leq m, 1 \leq i \leq n$
    if (*c* is adjacent to A) or ($A = \emptyset$) **then**
        Assign RB *c* to UE *i*
        $S \leftarrow S - \{\rho_i^c(t)\},\ R \leftarrow R - \{c\},\ A \leftarrow A \cup \{c\}$
        k ← 1
    elseif (distance between *c* and A equals *Max_dist*) and (metric value of UE *i* is not the highest one in RB *b* form M) **then**
        if (*c* is on the right side of A) **then**
            b ← *c* – 1
        else
            b ← *c* + 1
        Assign RB *b* and *c* to UE *i*
        $S \leftarrow S - \{\rho_i^b(t), \rho_i^c(t)\},\ R \leftarrow R - \{b, c\},\ A \leftarrow A \cup \{b, c\},\ V \leftarrow V \cup \{b, c\}$
        k ← 1
    else
        k ← *k* + 1

The *RB Reservation* scheme considers not only the adjacent RB, but also each of the two RBs on the left and right sides of the RB with the largest metric value. (i.e., we consider $Max\_dist = 2$ in this paper.) For example, if RB *c* has the largest metric value, then the scheduler considers not only adjacent RBs of RB *c*, *c* – 1 and *c* + 1, but also *c* - 2 and *c* + 2. That is, if RB *c* is the already assigned to UE *i* and RB *c* + 2 is the one with the largest metric value, then RB *c* and *c* + 2 are adjacent to each other in *RB Reservation* scheme. In this case, even if RB *c* + 1 (i.e., The RB is in between the one already assigned to the UE *i* and the candidate RB being allocated to UE *i*.) has very low channel quality, the scheduler allocates those RBs, *c* + 2 and *c* + 1, to preserve the contiguous RB constraint. The reason being because if the previous RBs have good quality, but neighboring RB quality drops very low suddenly, (i.e., sudden drop) then the next RB has good quality with high probability, since channel quality is correlated in the frequency domain.

Figure 2 shows an example of UE-to-RB allocation by the *RB Reservation* scheme in the frequency selective fading channel. First, the scheduler picks UE *i* and RB *c* with the largest metric value from input matrix *M*, if the RB *c* is adjacent to the already assigned RBs to UE *i* or there is no already assigned RB to UE *i*. Otherwise, the scheduler finds the combination of UE and RB with the second largest PF metric value. If the scheduler repeats this procedure until all RBs are allocated, then All UEs are assigned RBs contiguously. For example, if RB *c* – 2 is already assigned to UE *i* and RB *c* is the one with the largest metric value, then RB *c* can be allocated to UE *i*, since it is adjacent to RB *c* -2 in *RB Reservation* scheme. In this case, even if RB *c* – 1, in between RB *c* - 2 and RB *c*, has a very low PF metric value, the scheduler allocates RB *c* and *c* – 1 to UE i together to preserve the contiguous RB allocation constraint. In addition, the sum of the PF metric value of the system is maximized, as every UE achieves the high sum of the PF metric value. Consequentially, system throughput increases as the sum of PF metric values increases.

The *RB Reservation* scheme has the following benefit. First, UE has low PAPR, as it does not use RBs with poor channel quality in data transmission. In the SC-FDMA process, UE's data are spread by the discrete Fourier transform (DFT) operation; then, the spread signal is mapped onto subcarriers based on the result of the scheduling scheme. Then, these subcarriers are used as an input of the inverse discrete Fourier transform (IDFT) operation. In this case, the PAPR of the signal decreases as the size of the DFT decreases [1]. Therefore, the PAPR of UE is reduced, since the size of DFT is reduced by not using the RBs in poor channel conditions in the *RB reservation* scheme. Second, the *RB reservation* scheme enhances system throughput by allocating RBs to UE efficiently. It achieves large multi-user diversity gain by maximizing Eq. (1). We focus on PF metric values $\rho_i^c(t) = r_i^c(t)/R_i(t)$ at time slot *t*. One key observation is that, for each UE *i* for the denominator, $R_i(t)$, is constant for all RBs. Thus, the PF metric value of each RB *c* is determined by the instantaneous channel rate $r_i(t)$. That is, each UE's PF metric values fluctuate exactly as the instantaneous channel rate changes between RB to RB at time slot *t*. Therefore, the *RB reservation* scheme enhances total system throughput, since it maximizes the sum of PF metric values.

4. Performance Evaluation

We have performed system level simulation to measure the performance of *RB Reservation* scheme. We consider a single cell environment with no interferer cells. We generate the frequency selective fading channel based on the Typical Urban channel model, as specified in 3GPP deployment evaluation [12]. Table 2 shows the basic parameters and assumptions used in the simulation.

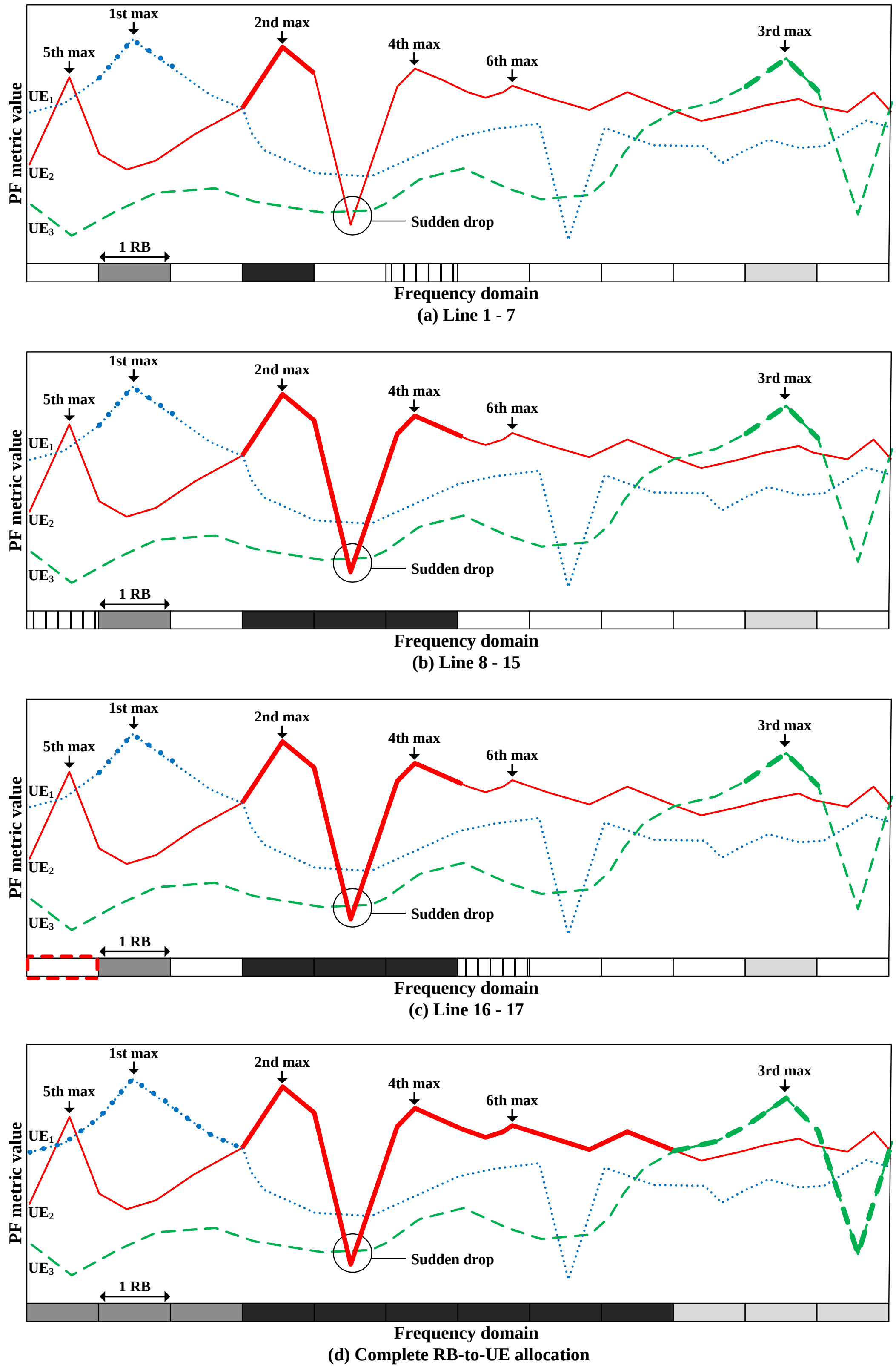

Figure 2. Example of Resource Allocation by RB Reservation

Table 2. Simulation Parameters

Parameter	Setting	Parameter	Setting
System bandwidth	20 MHz	Transmission time interval	1 ms
Number of subcarrier per RB	12	Channel model	Typical Urban
RB bandwidth	180 kHz	UE speed	3 km/h
Number of RBs	100	UE receiver	1x2/MMSE
UE power	23dBm	Modulations and Coding rates	QPSK: 1/3, 1/2, 2/3. 3/4 16QAM: 1/2, 2/3, 3/4 64QAM: 1/2, 2/3, 3/4, 5/6
UE distribution	Uniform		
Number of active UEs in cell	10, 20, 30, 40, 50		
Traffic model	Full buffer		

UEs are uniformly deployed in a cell. We measure system throughput to analyze the performance of the *RB reservation* scheme. We also measure PAPR of UE to examine if the *RB reservation* scheme is working well in the frequency selective fading channel. We also performed system level simulation for the *In-between RBs*, *Riding Peaks*, *RB Grouping*, and *Max-PF* scheme to compare the *RB reservation* scheme in terms of system throughput. The *Max-PF* scheme performs RB-to-UE allocation by assigning the RB with the largest PF metric value to the UE without the contiguity RB allocation constraint. Thus, it offers the upper bound in terms of throughput due to optimizing Eq. (1). We also measure system fairness by the well-known Jain's fairness index.

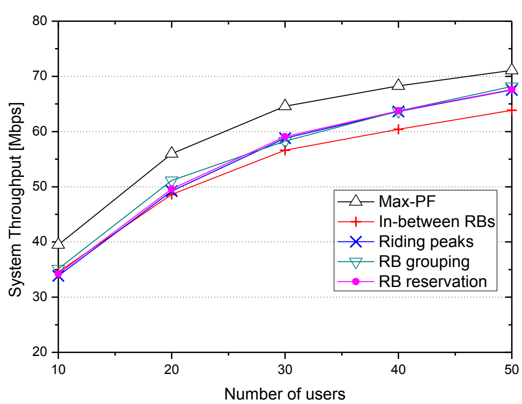

Figure 3. System Throughput

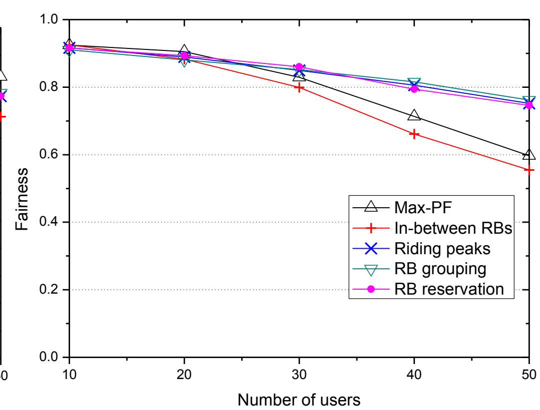

Figure 4. Fairness Index with Varying Number of Users

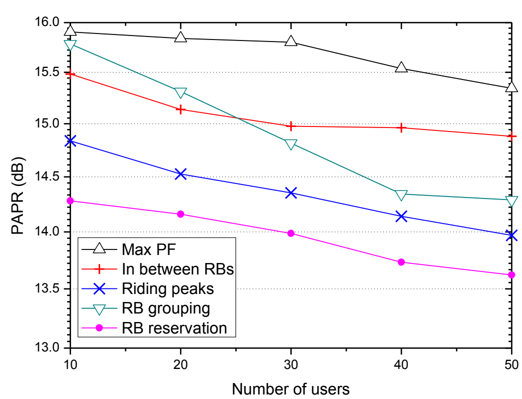

Figure 5. PAPR

Figure 3 shows the system throughput based on the number of UEs. System throughput increases as the number of UE increases, since multi-user diversity gain increases. In the case of the *Max-PF* scheme, it always has maximum throughput compared to other schemes, since it allocates the RBs with the largest PF metric value, without the contiguity RB allocation constraint. Therefore, it optimizes Eq. (1) and offers an upper bound in terms of throughput in the SC-FDMA. In the case of the *In-between RBs* scheme, it has similar performance when the number of UEs is less than 20. However, if the number of UEs exceeds 20, then it has lower performance than other schemes, since it does not exploit multi-user diversity and most RBs are allocated to a certain UE. Our proposed scheme, *RB Reservation*, has similar performance with *Riding Peaks* and *RB Grouping* schemes despite not using some RBs in data transmission. That is, the RB Reservation scheme utilizes small-scale variations in the frequency selective fading channel adoptively. Therefore, the *RB Reservation* scheme is close to optimal performance in terms of system throughput.

Figure 4 shows fairness according to the number of UEs. Fairness decreases as the number of UEs increases, since the number of assigned RBs per UE decreases. *Max-PF* has low fairness compared to the *Riding Peaks*, *RB Grouping*, and *RB Reservation* schemes, since a particular UE with a good channel condition has relatively many RBs. *In-between* RBs also has low fairness for the same reason. Especially, *In-between* RBs has the disadvantage in the frequency fading channel, since it does not adopt small-scale variations well. The *RB Reservation* scheme has similar performance with *Riding peaks* and *RB Grouping* in terms of fairness, as in case of throughput. Each UE has similar fairness between them, since the *RB Reservation* scheme performs RB-to-UE allocation considering the channel condition of each UE and RB. The *RB Reservation* scheme also uses the PF metric value as a scheduling metric, so it enhances system throughput and fairness effectively.

Figure 5 shows the PAPR of UE according to the number of UEs. PAPR of UE decreases as the number of used subcarriers is reduced in data transmission [1, 13]. That is, as long as a lower number of RBs (i.e., group of subcarrier) is assigned to UE, then the PAPR of UE decreases. Therefore, PAPR decreases as the number of UEs increases, since the number of RBs assigned to UE decreases, as shown in Figure 5. Therefore, the *RB Reservation* scheme has the lowest PAPR among other schemes, because each UE uses fewer subcarriers in data transmission, as it is not using an RB with poor channel condition in the *RB Reservation* scheme. In general, as long as the signal PAPR is high, the power amp needs large a back-off to operate in the linear region. It degrades power efficiency and consumes energy rapidly [14, 19]. In addition, as long as PAPR is high, the bit error rate (BER) increases, since in-band and out-of band distortion increases [13]. Our proposed scheme, *RB Reservation*, has 2dB lower PAPR compared to the *Max-PF* scheme. Therefore, the *RB Reservation* scheme improves battery efficiency by over 15 percent [15]. In addition, the *RB reservation* scheme improves the performance tenfold compared to the *Max-PF* scheme, in terms of BER [13]. In conclusion, the RB Reservation scheme improves power efficiency, battery life, and BER performance, reducing the PAPR of UE.

5. Conclusion

The multiple access scheme with low PAPR is required due to the battery life of UE in LTE UL. Therefore, SC-FDMA has been adopted, rather than OFDMA, because OFDMA has high PAPR. SC-FDMA has most of the advantages of OFDMA whilst it has lower PAPR than OFDMA due to its single carrier property. However, all RBs allocated to a single UE must be contiguous in the frequency-domain within each time slot to maintain its single carrier property. Therefore, we proposed the *RB Reservation* scheme to enhance system throughput and fairness, whilst lowering the PAPR of UE under contiguous the RB allocation constraint. The *RB Reservation* scheme uses PF algorithms for the scheduling metric value, so it has high throughput and fairness. In addition, the *RB Reservation* scheme allocates RBs to UE efficiently in the frequency selective fading channel. In this procedure, UE does not use RBs with poor channel conditions, so that it reduces PAPR. Therefore, the RB Reservation scheme improves the battery life of UE and enhances BER performance due to reducing in-band and out-of band distortion.

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