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Abstract:

Single carrier frequency division multiple access (SC-FDMA), a modified form of Orthogonal FDMA (OFDMA), is a promising technique for high data rate uplink communications in future cellular systems. SC-FDMA has similar throughput performance and essentially the same overall complexity as OFDMA. A principal advantage of SC-FDMA is the peak-to-average power ratio (PAPR), which is lower than that of OFDMA. SC-FDMA is currently a strong candidate for the uplink multiple access scheme in the Long Term Evolution of cellular systems under consideration by the Third Generation Partnership Project (3GPP). In this paper, we give an overview of SC-FDMA. We also analyze the effects of subcarrier mapping on throughput and PAPR. Among the possible subcarrier mapping approaches, we find that localized FDMA (LFDMA) with channel-dependent scheduling (CDS) results in higher throughput than interleaved FDMA (IFDMA). However, the PAPR performance of IFDMA is better than that of LFDMA. As in other communications systems there are complex tradeoffs between design parameters and performance in an SC-FDMA system.

Single Carrier FDMA for Uplink Wireless Transmission

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Over the past fifteen years, the bit rates achieved in cellular and local area wireless communications systems have increased steadily. The earliest digital cellular systems, North American TDMA and GSM employed time division multiple access. Second generation CDMA systems and the two third generation cellular systems all use direct sequence spread spectrum for multiplexing and multiple access [1]. The highest bit rates in commercially deployed wireless systems are achieved by means of Orthogonal Frequency Division Multiplexing (OFDM) in wireless LANs based on the IEEE 802.11a and IEEE 802.11g standards. The next advance in cellular systems, under investigation by the Third Generation Partnership Project (3GPP), also anticipates the adoption of OFDMA to achieve higher bit rates.

1.1 Frequency Division Multiple Access

In cellular applications, a big advantage of OFDMA is its robustness in the presence of multipath signal propagation [2]. The immunity to multipath derives from the fact that an OFDMA system transmits information on M orthogonal frequency carriers, each operating at $1/M$ times the bit rate of the information signal. On the other hand, the OFDMA waveform exhibits very pronounced envelope fluctuations resulting in a high peak-to-average power ratio (PAPR). Signals with a high PAPR require highly linear power amplifiers to avoid excessive intermodulation distortion. To achieve this linearity, the amplifiers have to operate with a large backoff from their peak power. The result is low power efficiency (measured by the ratio of transmitted power to dc power dissipated),

which places a significant burden on portable wireless terminals. Another problem with OFDMA in cellular uplink transmissions derives from the inevitable offset in frequency references among the different terminals that transmit simultaneously. Frequency offset destroys the orthogonality of the transmissions, thus introducing multiple access interference.

To overcome these disadvantages, 3GPP is investigating a modified form of OFDMA for uplink transmissions in the “long-term evolution (LTE)” of cellular systems [3]–[5]. The modified version of OFDMA, referred to as single carrier FDMA (SC-FDMA), is the subject of this paper. As in OFDMA, the transmitters in an SC-FDMA system use different orthogonal frequencies (subcarriers) to transmit information symbols. However, they transmit the subcarriers sequentially, rather than in parallel. Relative to OFDMA, this arrangement reduces considerably the envelope fluctuations in the transmitted waveform. Therefore, SC-FDMA signals have inherently lower PAPR than OFDMA signals. However, in cellular systems with severe multipath propagation, the SC-FDMA signals arrive at a base station with substantial intersymbol interference. The base station employs adaptive frequency domain equalization to cancel this interference. This arrangement makes sense in a cellular system because it reduces the burden of linear amplification in portable terminals at the cost of complex signal processing (frequency domain equalization) at the base station.

1.2 Performance Measures

While PAPR is a major concern in portable terminals, information throughput is an even more important indicator of system performance. As in OFDMA, throughput in SC-FDMA depends on the way in which information symbols are applied to subcarriers. There are two approaches to apportioning subcarriers among terminals. In localized SC-FDMA (LFDMA), each terminal uses a set of adjacent subcarriers to transmit its symbols. Thus the bandwidth of an LFDMA transmission is confined to a fraction of the system bandwidth. The alternative to LFDMA is distributed SC-FDMA in which the subcarriers used by a terminal are spread over the entire signal band. One realization of distributed SC-FDMA is interleaved FDMA (IFDMA) where occupied subcarriers are equidistant from each other [6]. Figure 1 shows the two arrangements in the frequency domain. There are three terminals, each transmitting symbols on four subcarriers in a system with a total of 12 subcarriers. In the distributed arrangement, terminal 1 uses subcarriers 0, 3, 6, and 9; with LFDMA it uses subcarriers 0, 1, 2, and 3.

With respect to immunity to transmission errors (which determines throughput), distributed SC-FDMA is robust

against frequency selective fading because its information is spread across the entire signal band. Therefore it offers the advantage of frequency diversity. On the other hand, LFDMA can potentially achieve multi-user diversity in the presence of frequency selective fading if it assigns each user to subcarriers in a portion of the signal band where that user has favorable transmission characteristics (high channel gain). Multi-user diversity relies on independent fading among dispersed transmitters. It also requires *channel-dependent scheduling* (CDS) of subcarriers. CDS requires the system to monitor the channel quality as a function of frequency for each terminal, and adapt subcarrier assignments to changes in the channel frequency responses of all the terminals.

In this paper, we present the results of our studies of some of the important issues in the design of a SC-FDMA system. In particular, we compare LFDMA and IFDMA with respect to the two major performance indicators, system throughput and PAPR. For each configuration, we present throughput measures with static subcarrier assignments and with channel dependent scheduling. We find that as in other engineering systems there are complex tradeoffs between design parameters and performance. Configurations with the lowest PAPR tend to have lower throughput. Therefore equipment designers and system operators can use their judgment to find the best tradeoff to meet their specific needs. For example, we find that a system with many users each transmitting at a moderate bit rate is better off with IFDMA, while LFDMA works better in a system with a few high-bit-rate users.

This article is organized as follows. We describe the signal processing operations in SC-FDMA and OFDMA systems in the next section. The third section contains the results of our analysis of PAPR. We show that IFDMA has inherently lower PAPR than LFDMA and that both of them are better than OFDMA with respect to PAPR. However, much of the advantage of IFDMA is eroded by the pulse shaping that is necessary to curtail out-of-band spectrum components prior to radio transmission. The fourth section analyzes system throughput, with respect to two performance measures: an upper bound on achievable bit rate given by Shannon’s capacity formula, and outage defined as the probability that the signal-to-interference ratio falls below a certain threshold. The

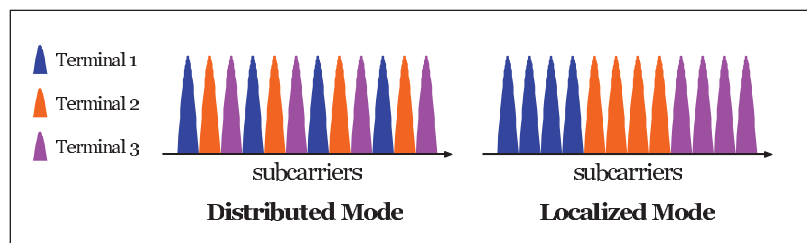


FIGURE 1 Subcarrier allocation methods for multiple users (3 users, 12 subcarriers, and 4 subcarriers allocated per user).

analysis considers static subcarrier assignments and channel dependent scheduling for LFDMA and IFDMA. It demonstrates that LFDMA with channel-dependent scheduling has the potential for considerably higher capacity in terms of number of users than IFDMA. The final section summarizes our major findings and describes work in progress.

2. System Configuration of Single Carrier FDMA

The transmitter of an SC-FDMA system converts a binary input signal to a sequence of modulated subcarriers. To do so, it performs the signal processing operations shown in Figure 2. Signal processing is repetitive in a few different time intervals. Resource assignment takes place in transmit time intervals (TTIs). In 3GPP LTE, a typical TTI is 0.5 ms. The TTI is further divided into time intervals referred to as *blocks*. A block is the time used to transmit all of subcarriers once. At the input to the transmitter, a baseband modulator transforms the binary input to a multilevel sequence of complex numbers x_n in one of several possible modulation formats including binary phase shift keying (BPSK), quaternary PSK (QPSK), 16 level quadrature amplitude modulation (16-QAM) and 64-QAM. The system adapts the modulation format, and thereby the transmission bit rate, to match the current channel conditions of each terminal.

The transmitter next groups the modulation symbols, x_n into blocks each containing N symbols. The first step in modulating the SC-FDMA subcarriers is to perform an N -point discrete Fourier transform (DFT), to produce a

frequency domain representation X_k of the input symbols. It then maps each of the N DFT outputs to one of the $M(> N)$ orthogonal subcarriers that can be transmitted. As in OFDMA, a typical value of M is 256 subcarriers and $N = M/Q$ is an integer submultiple of M . Q is the bandwidth expansion factor of the symbol sequence. If all terminals transmit N symbols per block, the system can handle Q simultaneous transmissions without co-channel interference. The result of the subcarrier mapping is the set $\tilde{X}_l (l = 0, 1, 2, \dots, M - 1)$ of complex subcarrier amplitudes, where N of the amplitudes are non-zero. As in OFDMA, an M -point inverse DFT (IDFT) transforms the subcarrier amplitudes to a complex time domain signal \tilde{x}_m . Each \tilde{x}_m then modulates a single frequency carrier and all the modulated symbols are transmitted sequentially.

The transmitter performs two other signal processing operations prior to transmission. It inserts a set of symbols referred to as a *cyclic prefix* (CP) in order to provide a guard time to prevent inter-block interference (IBI) due to multipath propagation. The transmitter also performs a linear filtering operation referred to as pulse shaping in order to reduce out-of-band signal energy. In general, CP is a copy of the last part of the block, which is added at the start of each block for a couple of reasons. First, CP acts as a guard time between successive blocks. If the length of the CP is longer than the maximum delay spread of the channel, or roughly, the length of the channel impulse response, then, there is no IBI. Second, since CP is a copy of the last part of the block, it converts a discrete time linear convolution into a discrete time circular convolution. Thus transmitted data propagating through the channel can be modeled as a circular convolution between the channel impulse response and the transmitted data block, which in the frequency domain is a point-wise multiplication of the DFT frequency samples. Then, to remove the channel distortion, the DFT of the received signal can simply be divided by the DFT of the channel impulse response point-wise or a more sophisticated frequency domain equalization technique can be implemented, as described at the end of this section.

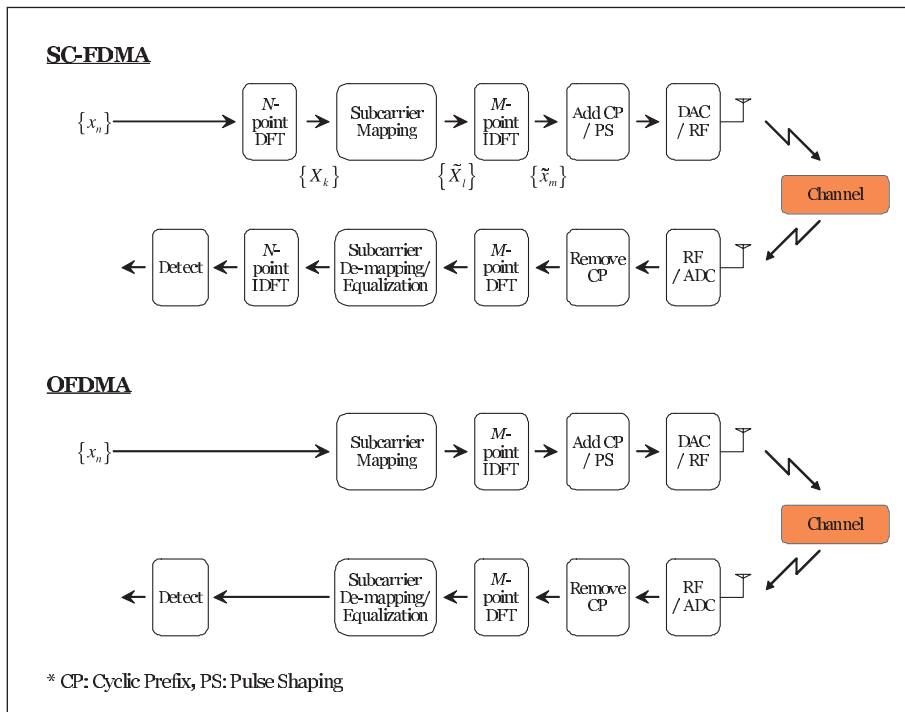


FIGURE 2 Transmitter and receiver structure of SC-FDMA and OFDMA systems.

Figure 2 includes a block diagram of an OFDMA transmitter and receiver. It has much in common with SC-FDMA. The only difference is the presence

of the DFT in the SC-FDMA transmitter and the IDFT in the SC-FDMA receiver. For this reason SC-FDMA is sometimes referred to as *DFT-spread* OFDMA.

Several approaches to mapping transmission symbols X_k to SC-FDMA subcarriers are currently under consideration. They are divided into two categories; *distributed* and *localized* as shown in Figure 1. In the distributed subcarrier mapping mode, DFT outputs of the input data are allocated over the entire bandwidth with zeros occupying the unused subcarriers resulting in a non-continuous comb-shaped spectrum. As mentioned earlier, *interleaved* SC-FDMA (IFDMA) is an important special case of distributed SC-FDMA. In contrast with IFDMA, consecutive subcarriers are occupied by the DFT outputs of the input data in the localized subcarrier mapping mode resulting in a continuous spectrum that occupies a fraction of the total available bandwidth. Subcarrier mapping methods are further divided into static and channel dependent scheduling (CDS) methods. CDS assigns subcarriers to users according to the channel frequency response of each user. For both scheduling methods, distributed subcarrier mapping provides frequency diversity because the transmitted signal is spread over the entire bandwidth. With distributed mapping, CDS incrementally improves performance. By contrast CDS is of great benefit with localized subcarrier mapping because it provides significant multi-user diversity as discussed in the first section of this paper.

Until now, we have referred in general to mappings of the N symbols in each block onto the $M > N$ transmission subcarriers. However, with $M = 256$ in a practical system the number of possible mappings is far too large for practical scheduling algorithms to consider. To reduce the complexity of the mapping, subcarriers are grouped into *chunks* and all of the subcarriers in a chunk are assigned together. In our research we have studied 256 subcarriers grouped in 32 chunks of 8 subcarriers per chunk or 16 chunks with 16 subcarriers per chunk. Figure 3 shows an example of SC-FDMA transmit symbols in the frequency domain for $N = 4$, $Q = 3$ and $M = 12$. After subcarrier mapping, the frequency data is transformed back to the time domain by applying M -point inverse DFT (IDFT). As in Figure 1, different users occupy different orthogonal subcarriers.

For IFDMA, time symbols are simply a repetition of the original input symbols with a systematic phase rotation applied to each symbol in the time domain [6]. Therefore, the PAPR of IFDMA signal is the same as in the case of a conventional single carrier signal. In the case of LFDMA, the time signal has exact copies of input time symbols in N sample positions. The other $M-N$ time samples are weighted sums of all the symbols in the input block [7]. Figure 4 shows an example of IFDMA and LFDMA signals that occupy the chunk that includes subcarrier zero.

The receiver transforms the received signal into the frequency domain via DFT, de-maps the subcarriers, and then performs frequency domain equalization. Because SC-FDMA uses single carrier modulation, it suffers from intersymbol interference (ISI) and thus equalization is necessary to combat the ISI. Practical considerations favor minimum mean square error (MMSE) frequency domain equalization. MMSE is generally preferred over zero forcing (ZF) due to the robustness against noise. The equalized symbols are transformed back to the time domain via IDFT, and detection and decoding take place in the time domain.

Relative to OFDMA, there is a fundamental difference in the SC-FDMA receiver equalization and detection processes. Since each data symbol is conveyed on individual subcarriers in OFDMA, channel equalization or

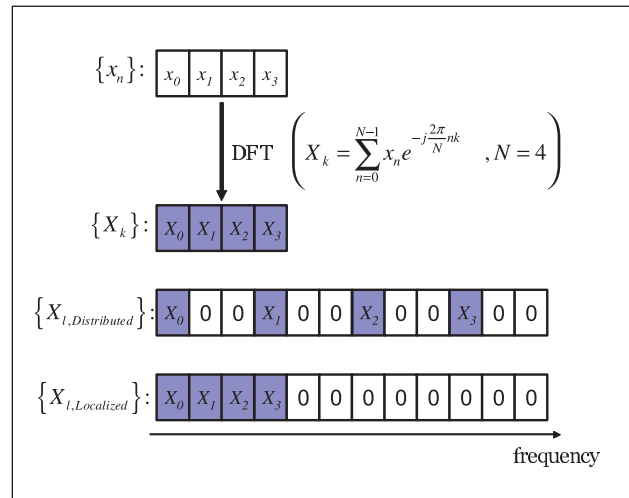


FIGURE 3 An example of SC-FDMA transmit symbols in the frequency domain for $N = 4$ subcarriers per user, $Q = 3$ users, and $M = 12$ subcarriers in the system. $\tilde{X}_{l,Distributed}$ denotes transmit symbols for distributed subcarrier mapping scheme and $\tilde{X}_{l,Localized}$ denotes transmit symbols for localized subcarrier mapping scheme.

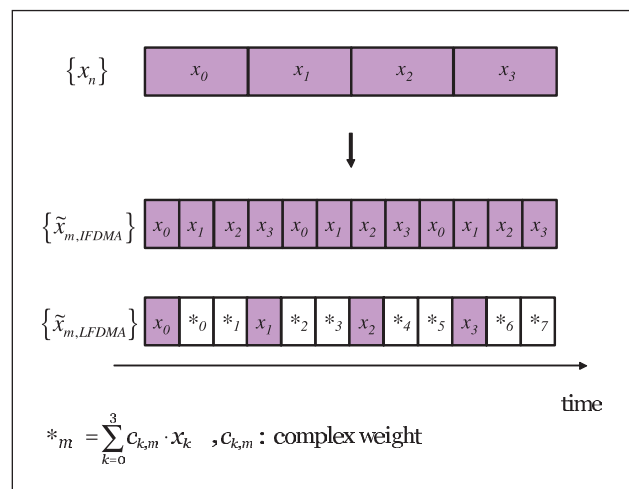


FIGURE 4 An example of SC-FDMA transmit symbols in the time domain for $N = 4$, $Q = 3$, and $M = 12$.

inversion is performed individually on each subcarrier and data detection is also carried out on each subcarrier. Thus, a null in the channel spectrum severely degrades the system performance since there is essentially no way to recover the data that is affected by the null. To protect individual subcarriers from frequency nulls in the channel, channel coding or power/rate adaptation is required for OFDMA. In the case of SC-FDMA, channel equalization is done similarly in the frequency domain but data detection is performed after the frequency domain equalized data is reverted back to time domain by IDFT. Hence, it is more robust to spectral nulls compared to OFDMA since the noise is averaged out over the entire bandwidth. Additional disadvantages of OFDMA compared to SC-FDMA are the strong sensitivity to carrier frequency offset and strong sensitivity to nonlinear distortion in the power amplifier due to the high PAPR, both properties of the multicarrier nature of OFDMA [8], [9].

The next two sections of this paper demonstrate that the details of the subcarrier mapping have a strong effect on the two main performance measures: PAPR and throughput. We also describe how the pulse shaping influences PAPR.

3. PAPR analysis of SC-FDMA

In this section, we analyze the PAPR of the SC-FDMA signal. We use the notation in Figure 3 and assume that the total number of subcarriers is $M = Q \cdot N$, where N is the number of subcarriers per block. The integer Q is the maximum number of terminals that can transmit simultaneously. For distributed subcarrier mapping, we consider the case of IFDMA with subcarriers equally spaced over the system bandwidth.

The PAPR is defined as the ratio of peak power to average power of the transmitted signal in a given transmission block. Without pulse shaping, that is, using rectangular pulse shaping, symbol rate sampling will give the same PAPR as the continuous time domain case since an SC-FDMA signal is modulated over a single carrier.

To evaluate PAPR of individual system configurations, we have simulated the transmission of 10^5 blocks of symbols. After calculating PAPR for each block, we present the data as an empirical CCDF (Complementary Cumulative Distribution Function). The CCDF is the probability that PAPR is higher than a certain PAPR value PAPR_0 ($\Pr\{\text{PAPR} > \text{PAPR}_0\}$). Our simulations apply to 256 subcarriers in a transmission bandwidth of 5 MHz. The data block size is $N = 64$ and the spreading factor is $Q = M/N = 4$. We used 8 times oversampling to calculate PAPR for each block when pulse shaping is considered. To evaluate the effects of pulse shaping on SC-FDMA, we convolved each transmitted symbol waveform with a raised cosine pulse truncated from $-6T$ to $+6T$, where T seconds is the symbol duration. No pulse shaping was applied in the case OFDMA. The impulse response of a raised cosine filter is,

$$r(t) = \text{sinc}\left(\pi \frac{t}{T}\right) \frac{\cos\left(\frac{\pi \alpha t}{T}\right)}{1 - \frac{4\alpha^2 t^2}{T^2}} \quad (1)$$

where the parameter α ($0 \leq \alpha \leq 1$) is referred to as the rolloff factor. Lower values of α introduce more pulse shaping and more suppression of out-of-band-signal components.

Figure 5 contains plots of the distribution (CCDF) of PAPR for IFDMA, LFDMA, and OFDMA. For each example,

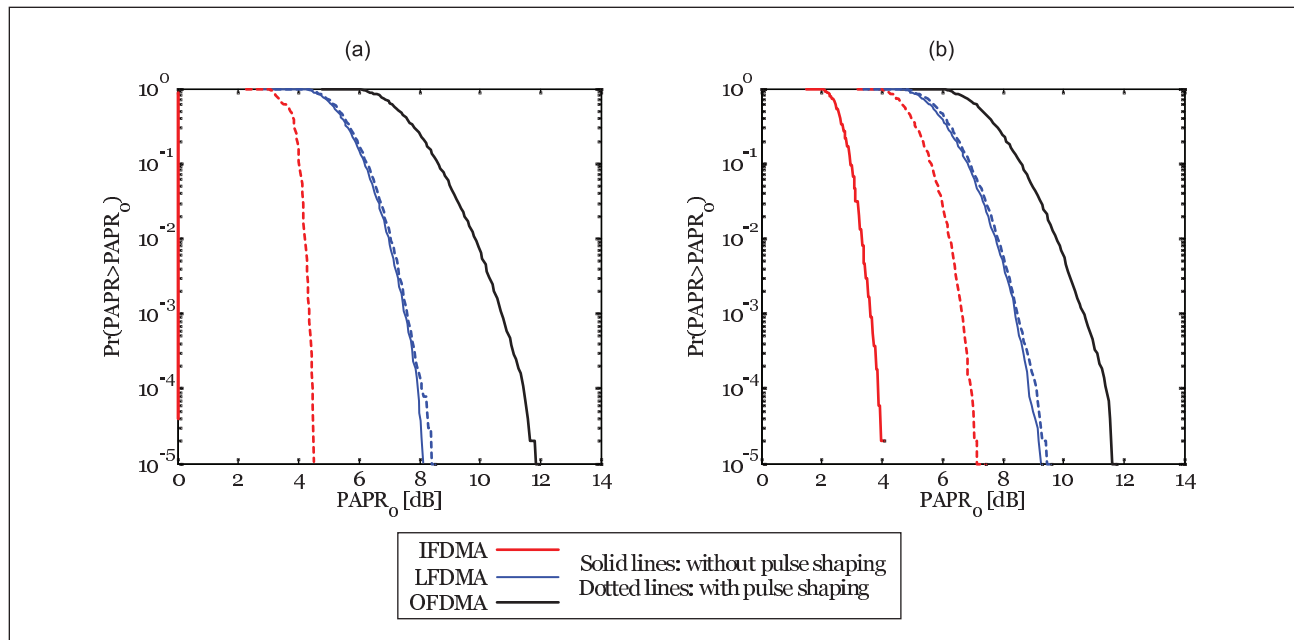


FIGURE 5 Comparison of CCDF of PAPR for IFDMA, LFDMA, and OFDMA with $M = 256$ system subcarriers, $N = 64$ subcarriers per user, and a $\alpha = 0.5$ rolloff factor; (a) QPSK; (b) 16-QAM.

we observe the $PAPR_0$ value that is exceeded with probability less than 0.1% ($\Pr\{PAPR > PAPR_0\} = 10^{-3}$), or 99.9-percentile PAPR. First, in the case of no pulse shaping, the PAPR of IFDMA is 10.5 dB lower than the PAPR of OFDMA for QPSK modulation. The difference is 7 dB for 16-QAM. The PAPR of LFDMA is lower than the PAPR of OFDMA by 3 dB for QPSK. The difference is 2 dB for 16-QAM. Therefore LFDMA has 7.5 dB higher PAPR than IFDMA with QPSK and 5 dB higher PAPR for 16-QAM. With raised-cosine pulse shaping with rolloff factor of 0.5, PAPR increases significantly for IFDMA whereas PAPR of LFDMA hardly increases.

Figure 6 also shows that raised-cosine pulse shaping is more harmful in terms of PAPR for IFDMA than it is for LFDMA. As the rolloff factor α increases from 0 to 1 (progressively less rolloff), PAPR decreases significantly for IFDMA. This implies that there is a tradeoff between PAPR performance and out-of-band radiation since out-of-band radiation increases with increasing rolloff factor.

We also relate the PAPR to RF transmit power amplifier efficiency. In an ideal linear power amplifier where linear amplification is achieved up to the saturation point, maximum power efficiency is achieved when the amplifier is operating at the saturation point. To prevent distortion in the presence of PAPR, transmit power backoff is needed to operate the power amplifier in the linear region.

Together, Figures 5 and 6 show that SC-FDMA signals indeed have lower PAPR than OFDMA signals. Also, LFDMA incurs higher PAPR compared to IFDMA but, compared to OFDMA, it is lower, though not significantly. Another noticeable fact is that pulse shaping significantly increases the PAPR of IFDMA. A pulse shaping filter should be designed carefully in order to limit the

A KEY QUESTION OF CHANNEL DEPENDENT SCHEDULING IS HOW WE SHOULD ALLOCATE TIME AND FREQUENCY RESOURCES FAIRLY AMONG USERS WHILE ACHIEVING MULTI-USER DIVERSITY AND FREQUENCY SELECTIVE DIVERSITY.

PAPR without degrading the system performance. In general, IFDMA is more desirable than LFDMA in terms of PAPR and power efficiency. However, in terms of system throughput, we will show in the next section that LFDMA is clearly superior when channel-dependent scheduling is utilized [10].

4. Channel-Dependent Scheduling (CDS) for Uplink SC-FDMA

In this section, we investigate channel-dependent resource scheduling for an SC-FDMA system in uplink communications. A key question of CDS is how we should allocate time and frequency resources fairly among users while achieving multi-user diversity and frequency selective diversity. To do so, we introduce utility-based scheduling where utility is an economic concept representing level of satisfaction. The choice of a utility measure influences the tradeoff between overall efficiency and fairness among users. In our studies, we consider two different utility functions: aggregate user throughput for maximizing system capacity and aggregate logarithmic user throughput for maximizing proportional fairness [11], [12]. The objective is to find an optimum chunk assignment for all users in order to maximize the sum of user utility at each transmit time interval (TTI). If the user throughput is regarded as the utility function, the

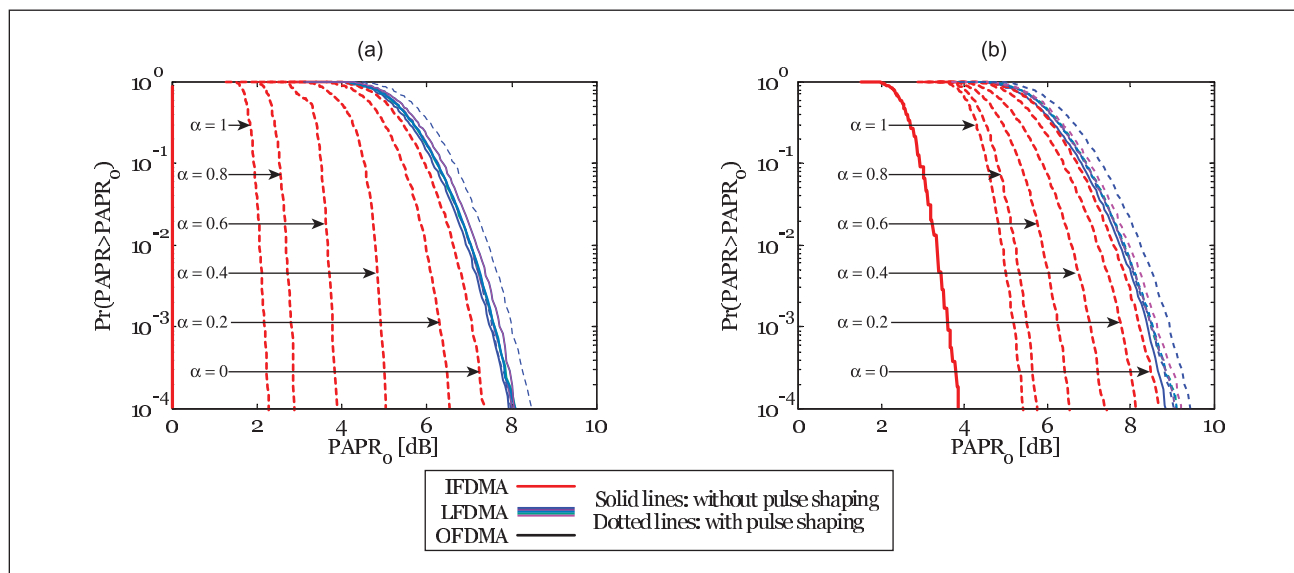


FIGURE 6 Comparison of CCDF of PAPR for IFDMA and LFDMA with $M = 256$ system subcarriers, $N = 64$ subcarriers per user, and rolloff factor α of 0, 0.2, 0.4, 0.6, 0.8, and 1; (a) QPSK; (b) 16-QAM.

resource allocation maximizes rate-sum capacity ignoring fairness among users. Therefore, only the users near the base station who have the best channel conditions occupy most of the resources. On the other hand, setting the logarithmic user data rate as the utility function provides proportional fairness.

In considering the optimization problem of CDS for multicarrier multiple access, it is theoretically possible to assume that the scheduler can assign subcarriers individually. Allocating individual subcarriers is, however, a prohibitively complex combinatorial optimization problem in systems with 256 subcarriers and on the order of ten terminals transmitting simultaneously. Moreover, assigning subcarriers individually would introduce unacceptable control signaling overhead. In practice, the units of resource allocation are chunks, which are disjoint sets of

subcarriers. As a practical matter chunk-based transmission is desirable since the input data symbols are grouped into a block for DFT operation before subcarrier mapping. We will consider only chunk-based scheduling in the remainder of this section. With regards to chunk structure, there is a restriction on chunk selection for IFDMA such that all assigned subcarriers should be equidistant in order to maintain the lowest PAPR [13].

Even with subcarriers assigned in chunks, optimum scheduling is extremely complex for two reasons: 1) The objective function is complicated, consisting of nonlinear and discrete constraints dependent on the combined channel gains of the assigned subcarriers; and 2) there is a total transmit power constraint for each user. Furthermore, the optimum solution entails combinatorial comparisons with high complexity. Instead of directly solving the optimization

problem, a sub-optimal chunk allocation scheme can be used for both IFDMA and LFDMA to obtain most of the benefits of CDS. For LFDMA, a greedy chunk selection method can be applied where each chunk is assigned to the user who can maximize the marginal utility when occupying the specific chunk. For IFDMA, the benefit of multi-user diversity can be achieved by selecting users in order of the estimated marginal utility based on the average channel condition over the entire set of subcarriers. The users with higher channel gains may occupy a larger number of chunks than users with lower channel gains [10].

Our throughput measure in this study is the sum of the upper bound on user throughputs given by Shannon's formula, $C = B \log(1 + SNR)$ where B is the effective bandwidth depending on the number of occupied subcarriers and SNR is signal-to-noise ratio of a block.

Figures 7, 8, and 9 are the results of computer simulations of SC-FDMA with 256 subcarriers spread over

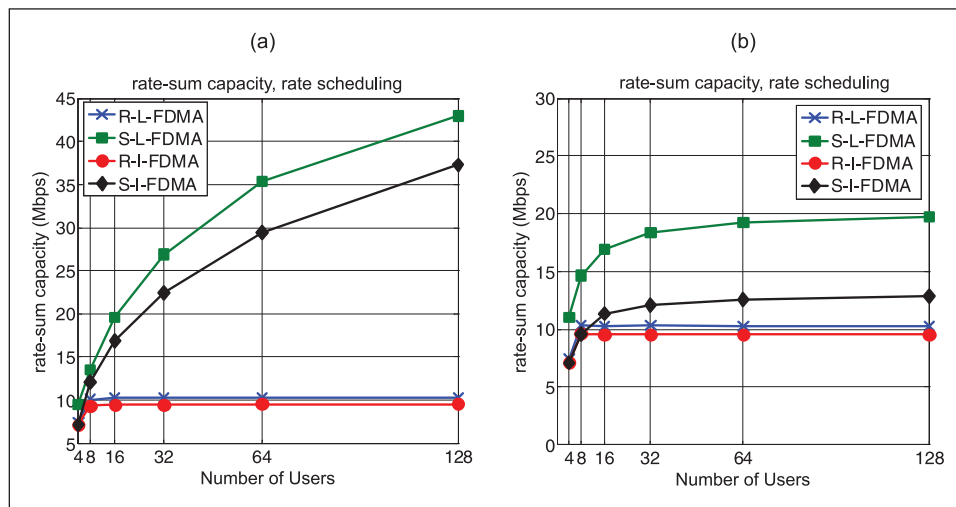


FIGURE 7 Comparison of rate-sum capacity with $M = 256$ system subcarriers, $N = 8$ subcarriers per user, bandwidth = 5 MHz, and noise power per Hz = -160 dBm; (a) utility function: sum of user throughputs; (b) utility function: sum of the logarithm of user throughputs.

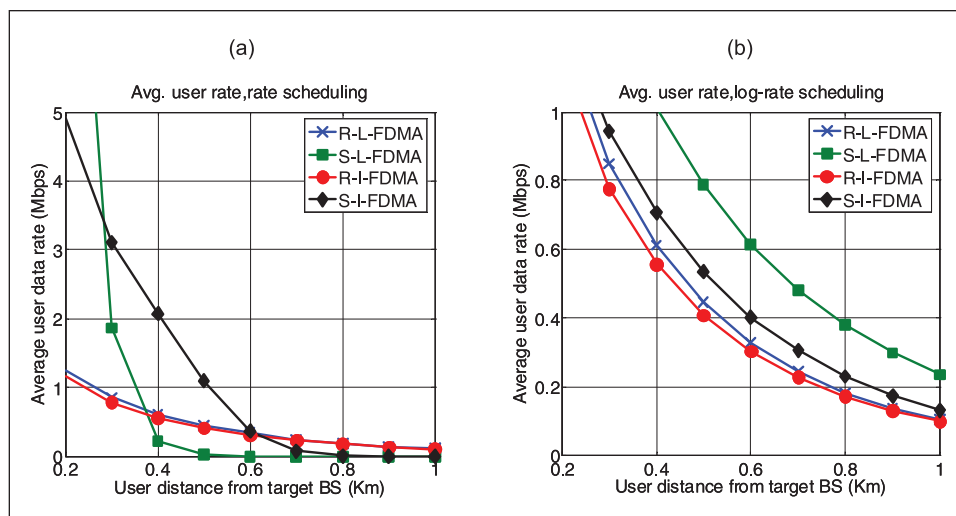


FIGURE 8 Average user data rate as a function of user distances with $M = 256$ system subcarriers, $N = 8$ subcarriers per user, bandwidth = 5 MHz, and noise power per Hz = -60 dBm; (a) utility function: sum of user throughputs; (b) utility function: sum of the logarithm of user throughputs.

a 5 MHz band. They compare the effects of channel dependent subcarrier allocation (S) with static (round-robin) scheduling (R) for localized FDMA (L-FDMA) and interleaved FDMA (I-FDMA). In all of the examples, the scheduling took place with chunks containing 8 subcarriers.

Figure 7 shows two effects of applying different utility functions in the scheduling algorithm. In the two graphs in Figure 7, the utility functions are the sum of user throughputs and the sum of the logarithm of user throughputs, respectively. Each graph shows the aggregate throughput as a function of the number of simultaneous transmissions. Figure 8 shows the expected user throughput at each distance from the base station for the same utility functions. The simulation results in the figures use the following abbreviations: R-LFDMA (static round robin scheduling of LFDMA), S-LFDMA (CDS of LFDMA), R-IFDMA (static round robin scheduling of IFDMA), and S-IFDMA (CDS of IFDMA).

Figure 7 shows that for throughput maximization (utility=bit rate), the advantage of channel dependent scheduling over round robin scheduling increases as the number of users increases. This is because the scheduler selects the closer users who can transmit at higher data rate. If there are more users, the possibility of locating users at closer distance to the base station increases. As a result, the CDS achieves significant improvements for both IFDMA and LFDMA. In the case of logarithmic rate utility, the CDS gain stops increasing beyond approximately 32 users. With 32 users, maximizing logarithmic rate utility can increase system capacity by a factor of 1.8 for LFDMA and 1.26 for IFDMA relative to static scheduling.

Figure 8 shows that the CDS scheme based on the logarithm of user throughput as a utility function provides proportional fairness whose gains are shared among all users, whereas the CDS gains are concentrated to the users near the base station when the user throughput is considered as the utility function.

Figure 9 shows the outage probability which is defined as the probability that the average user throughput is lower than the minimum required data rate after 100 msec. Considering user capacity at 1% outage probability and minimum required rate of 144 Kbps, round robin scheduling supports less than 20 users but CDS schemes can support 24 users for IFDMA and 48 users for LFDMA. Table I compares round robin scheduling and utility-based scheduling with logarithmic user data rate with respect to system capacity and fairness.

For static subcarrier assignment (round robin scheduling), a system with users each transmitting at a moderate data rate is better off with IFDMA while LFDMA works better in

RESULTS SHOW THAT CHANNEL DEPENDENT SCHEDULING INCREASES SYSTEM THROUGHPUT BY UP TO 80% RELATIVE TO STATIC SCHEDULING FOR LOCALISED FDMA BUT THE INCREASE IS ONLY 26% FOR INTERLEAVED FDMA.

a system with a few high data rate users. Due to the advantages of lower outage probability and lower PAPR, IFDMA is an attractive approach to static subcarrier scheduling. For channel-dependent scheduling, LFDMA has the potential for considerably higher data rate. The results show that CDS increases system throughput by up to 80% relative to static scheduling for LFDMA but the increase is only 26% for IFDMA. The scheduling gains in LFDMA can be exploited to reduce power consumption and PAPR by using power control to establish a power margin instead of increasing system capacity.

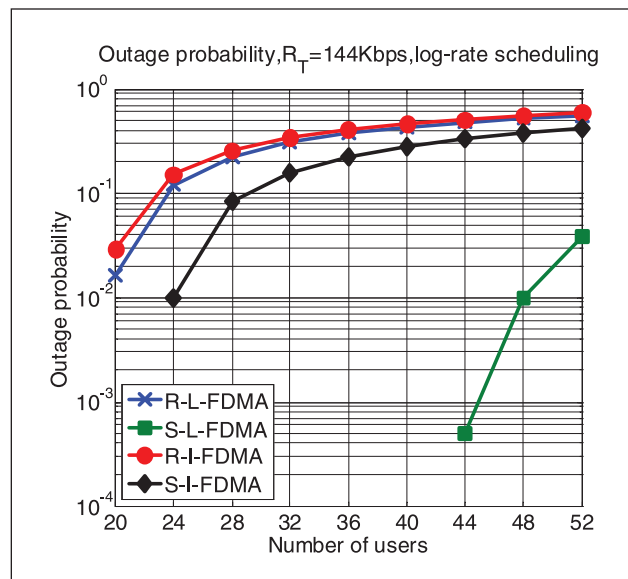


FIGURE 9 Outage probability (utility: logarithmic user data rate, minimum required data rate = 144 Kbps, $M = 256$, system subcarriers, $N = 8$ subcarriers per user, bandwidth = 5 MHz, and noise power per Hz = -160 dBm).

TABLE 1 Comparisons between utility-based scheduling and round-robin scheduling (logarithmic rate utility).

Type	S-LFDMA	R-LFDMA	S-IFDMA	R-IFDMA
Rate-sum capacity (32 users)	18 Mbps	10 Mbps	12 Mbps	9.55 Mbps
Fairness (32 users)	0.417	0.334	0.352	0.334
User capacity	48 users	Less than 20	24 users	Less than 20

Fairness = average user data rate of users at the cell boundary (900 m - 1 km)/average user data rate.
User capacity: Number of users achieving 1% outage probability when the minimum rate equals to 144 Kbps.

RESULTS SHOW THAT SINGLE CARRIER FREQUENCY DIVISION MULTIPLE ACCESS (SCFDMA) IS A PROMISING TECHNIQUE FOR HIGH DATA RATE UPLINK COMMUNICATIONS IN FUTURE CELLULAR SYSTEMS, THOUGH THERE ARE MANY DESIGN AND OPERATIONAL ASPECTS THAT AFFECT PERFORMANCE.

5. Conclusions

SC-FDMA is a promising technique for high data rate uplink communication in future cellular systems. Within a specific SC-FDMA system configuration, there are many design and operational choices that affect performance in a complex manner. In this paper, we have focused on the effects of subcarrier mapping on throughput and peak-to-average power ratio (PAPR). Among the possible subcarrier mapping approaches, we find that localized FDMA (LFDMA) with channel-dependent scheduling (CDS) results in higher throughput than interleaved FDMA (IFDMA). However, the PAPR performance of IFDMA is better by 4 to 7 dB than that of LFDMA. When we consider the pulse shaping necessary to control adjacent channel interference, we find a narrower difference between LFDMA and IFDMA in terms of PAPR performance.

Our work in progress is an investigation of the impact of channel estimation error on the throughput performance of SC-FDMA. Effective scheduling depends on accurate information about the frequency response of the radio channels linking terminals to an SC-FDMA base station. Channel estimation errors are caused by noisy estimation and changes in channel properties. The errors degrade the performance of CDS by causing incorrect adaptation of the modulation technique and incorrect assignment of subcarriers to users. Our research aims to quantify the effects of these errors.

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