Evaluations of a 4G Uplink System Based on Adaptive Single-carrier TDMA

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Abstract

Recent research has shown that a single-carrier system with frequency domain equalization can be a potential alternative to an OFDM-based system in a single user case. In this paper we propose and evaluate an adaptive single-carrier TDMA uplink with scheduling for broadband cellular packet data systems. Frequency division duplex (FDD) is assumed. Multiuser channel estimation and channel prediction are considered. The adaptive modulation scheme is optimized to maximize the throughput including also the ARQ part of the transmission. Frequency domain equalization is employed to combat the inter-symbol-interference (ISI). With the proposed design, the simulation results show that the multiuser diversity gain in spectral efficiency is limited in a wideband system, which indicates that an OFDM based system might be a more favorable candidate.

I. Introduction

OFDM, as a promising approach, in particular for the downlink, has gained strong attention for the future generation radio interface [1], [2], [3], [4]. However, high Peak-to-Average Power Ratio (PAPR) is an inherent drawback of OFDM, which requires highly linear transmitting power amplifiers and more power back-off than single-carrier systems with the same average power output. This will directly translate into higher RF front-end cost and faster battery drain in the uplink mobile terminals. Accurate time and frequency synchronization for different active users in the uplink is also a problematic issue in an OFDM based system.

Recent research [8], [6], [7] has shown that with properly designed frequency-domain equalizers, a single-carrier system can yield a comparable performance to an OFDM system in a single user case. However, there is no evidence showing that an adaptive single-carrier system with scheduling is able to compete with an equivalent OFDM based system.

High data rate services will be a key feature of the future cellular systems. Adaptive modulation and multiuser diversity are beneficial in improving the spectral efficiency. An OFDM based system can explore the diversity effect in both time and frequency, while a single-carrier system has only the time dimension. The loss in spectral efficiency due to limited degrees of freedom has not been evaluated yet.

In this paper we propose an adaptive single-carrier TDMA system with scheduling and also investigate the feasibility of such a system by simulations. In the proposed system, multiple users may then share the total bandwidth by transmitting in different time-slots. A scheduler, which optimizes the resource allocation for multiple active users, plays a key role in such a system. The time-slots are then given to the users who can utilize the channel best. As a result, the spectral efficiency will *increase* with the number of active users, which is denoted as *multiuser diversity*. However, the achievable data rate is subject to each user's throughput requirements and quality of service constraints.

The fading channels are estimated and predicted for all the active users. We implement a pilot-based Least Square (LS) multiuser channel estimator followed by a linear MMSE predictor to predict the channel impulse responses [5]. Severe ISI comes hand in hand with broadband wireless transmission. A frequency-domain MMSE equalizer is utilized at the receiver to mitigate this effect. This Fast Fourier Transform (FFT) based equalization scheme requires lower signal processing complexity than time-domain adaptive equalization in the case of a long channel impulse response, typically 5 to 10 μs.

In Section II, we define the framework of the uplink air interface and give a detailed description of each technical component of our system. We derive the spectral efficiency under some idealized assumptions in Section III. Simulation results are presented in Section IV.

II. The radio Interface of the Uplink

The core design of our approach relies on fast link adaptation and resource allocation, which is distinguishable from conventional single-carrier systems. The scenario, mobile users at high vehicular velocity with rather severe ISI is also taken into consideration. The carrier frequency of the proposed uplink is 1900 MHz and the bandwidth is 5 MHz, which gives a symbol time of $T_s = 0.2\mu s$. The data structure of the proposed uplink is provided in Fig. 1. Each *time block*, which consists of a training period and a payload data period, is 667 μs long with 3335 symbols in total. This provides us with a consistent design as in the downlink [2], [3], which enables the feedback information to flow timely for both directions.

The channel of each user is estimated and predicted during the training period. The data period is finely divided into a number of time-slots, including the cyclic prefix. Each time-slot is allocated to the user who has the most favorable channel condition out of all the active users in the system. In this paper,

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we present two different data structures that are simulated and analyzed in detail in III and IV.

- **Data structure 1**
  - Training period: 409 symbols, in total 81.8 μs long in time, are allocated for the training period.
  - Data period: The payload data period of 585.2 μs consists of 19 time-slots. Each time-slot, translated into 30.8 μs in time, contains 154 symbols of which 128 are the data symbols and the remaining 26 are the cyclic prefix.
- **Data structure 2**
  - Training period: 515 symbols, in total 103 μs long in time, are allocated for the training period.
  - Data period: The payload data period of 564 μs consists of 10 time-slots. Each time-slot, translated into 56.4 μs in time, contains 282 symbols of which 256 are the data symbols and the remaining 26 are the cyclic prefix.

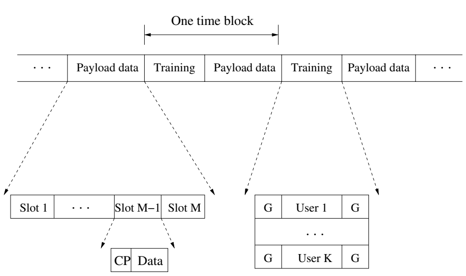

Fig. 1. Data structure of the proposed uplink.

A. Multiuser Channel Estimation

The use of single-carrier TDMA provides us with a quasi synchronized uplink within the training period, which enables us to adopt an overlapping pilots scheme for multiuser channel estimation. As depicted in Fig. 1, a training period is especially dedicated for channel estimation. During the training period, all the users transmit their pilots simultaneously. A guard time period is included both at the beginning and at the end of each training period to take care of the slightly time-shifted pilot symbols from different users and the delay spread of the channel. The following assumptions are made for the multiuser channel estimation:

- The maximum time-shift between different users is about 1 μs, which translates into at most 5 symbols.
- Binary random codes are used as pilot symbols.
- A sparse impulse response is assumed to characterize the channel. The adopted channel power delay profiles are listed in Table I, which are modified according to the symbol time based on ITU-IV vehicular environment.
- The speed of the mobile terminals is 50 km/h.
- The channel varies slowly and is assumed constant over the training period.

Least square channel estimation is performed on the channels in Table I. The number of channel taps would have been

TABLE I

POWER DELAY PROFILES

	ITU-IV Channel A		ITU-IV Channel B	
Tap	Relative delay [ns]	Average power [dB]	Relative delay [ns]	Average power [dB]
1	0	0	0	-2.5
2	400	-1.0	400	0
3	800	-9.0	9000	-12.8
4	1000	-10.0	13000	-10.0
5	1800	-15.0	17200	-25.0
6	2600	-20.0	20000	-16.0

over hundred for channel B in Table I without the assumption of *sparse* channel impulse response. There exists also specialized methods for reducing the estimation complexity in these cases [9]. As a result, we assume we know exactly where the taps are and utilize precisely the right regressors in the LS equations. Therefore, only the non-zero taps are estimated.

Fig. 2 shows the results of LS estimation with the overlapping pilot method that uses random codes as pilot symbols. There are 8 active users in the system. Each tap of the channel impulse responses from all the users are estimated and plotted in Fig. 2. The SNR on the x-axis denotes received SNR at the receiver. The channel signal to estimation error ratio (SER) on the y-axis is evaluated first on each training block and then averaged over the entire channel realization. Each group of the curves represents one estimated channel tap from the 8 users. Some of the taps that have closer power levels lay on top of each other. Taps having lower power are in general difficult to estimate. We can draw the conclusion that LS estimation with overlapping pilots achieves a reasonably good estimation performance in a quasi synchronous environment with limited number of taps.

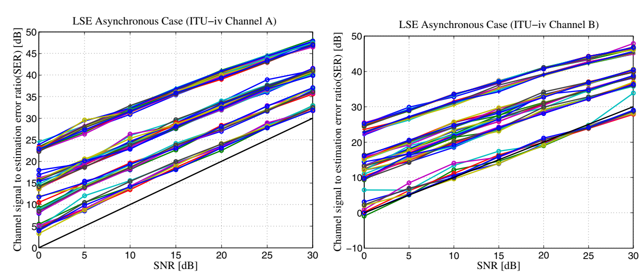

Fig. 2. LS estimation performance with overlapping pilot method in an 8 user case.

B. Channel Prediction

To predict the complex valued channel, we employ a linear FIR predictor which utilizes the regressors vector [5]. The channel is assumed static over each time-slot. For a frequency-selective Rayleigh fading channel, each tap can be seen as a flat Rayleigh fading channel. Assuming independent taps, the complex value of each tap can be predicted separately. Fig. 3 shows the prediction performance versus prediction range of one of the taps of a frequency-selective Rayleigh fading channel. The prediction performance is evaluated both at 16 dB and 20 dB. We need to predict two *time blocks* $(2 \times 667\mu s)$ in future to have enough time for scheduling and feedback delay, which requires a prediction range of 0.12λ at the speed of 50 km/h. The resulting prediction performance is acceptable for scheduling and adaptation [10].

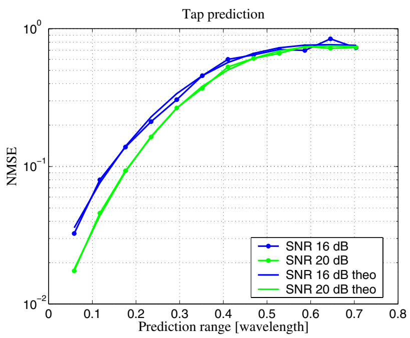

Fig. 3. Prediction performance of one of the taps of a frequency-selective Rayleigh fading channel. The carrier frequency is 1900 MHz. The speed of the terminal is 50 km/h.

C. Frequency Domain Equalization

In broadband wireless communication systems, ISI of the received signal is substantial. FFT based frequency-domain equalizers show a good trade-off between the complexity and the equalization performance. In this paper the performance of both a linear equalizer and a decision-feedback equalizer is evaluated. The optimization of the equalizer coefficients is subject to the MMSE criterion that takes into account the effects of both ISI and the noise [6].

1) Frequency-domain linear equalizer (FD-LE): The frequency-domain equalizer coefficients are given as

$$G_n = \frac{H_n^*}{|H_n|^2 + \sigma_0^2}, n = 0, 1, ..., N-1 \tag{1}$$

where H_n is the channel frequency response and the FFT length is N. The noise variance is σ_0^2.

The equalized SNR at the decision device is defined as

$$\gamma = \frac{\tilde{\sigma_h^2}}{\text{MMSE}_{LE}}, \tag{2}$$

where $\tilde{\sigma_h^2}$ is the filtered signal variance and is calculated as

$$\tilde{\sigma_h^2} = \frac{\sigma_h^2}{N} \sum_{n=0}^{N-1} |G_n \cdot H_n|^2, \tag{3}$$

where σ_h^2 is the transmitted signal variance, which is normalized in the simulations.

The minimum mean square error is expressed as

$$\text{MMSE}_{LE} = \frac{\sigma_0^2}{N} \sum_{l=0}^{N-1} \frac{1}{|H_n|^2 + \sigma_0^2}. \tag{4}$$

2) Frequency-domain decision feedback equalizer (FD-DFE): The FD-DFE employed here is rather a hybrid time-frequency domain equalizer [6]. First the feed-forward part of the filtering is done in the frequency-domain. Then the symbol-by-symbol decisions are made, filtered and fed back in the time-domain to remove the ISI from the subsequent symbols. There are B number of feedback coefficients f_k^*, $k \in F_B$, where F_B is a set of non-zero indexes corresponding to the delays (in symbol time) of the B feedback coefficients. For example, in order to cancel all the echoes in the modified ITU-IV Channel A case, the number of feedback coefficients is $B = 5$, so F_B has 5 indexes. The subscript k of f_k^* takes values from $\{2, 4, 5, 9, 13\}$ if $T_s = 0.2\mu s$ is chosen.

The feed-forward equalizer coefficients can be expressed as

$$G_n = \frac{H_n^*[1 + \sum_{k \in F_B} f_k^* exp(-j2\pi \frac{kn}{N})]}{|H_n|^2 + \sigma_0^2}, n = 0, 1, ..., N-1 \tag{5}$$

where f_k^* is the feedback filter coefficient and calculated as in [6].

The equalized SNR at the decision device is defined as

$$\gamma = \frac{\tilde{\sigma_h^2}}{\text{MMSE}_{DFE}}, \tag{6}$$

where $\tilde{\sigma_h^2}$ is the filtered signal variance and is calculated as

$$\tilde{\sigma_h^2} = \frac{\sigma_h^2}{N} \sum_{n=0}^{N-1} |G_n \cdot H_n|^2 - \sigma_h^2 \sum_{k \in F_B} |f_k|^2. \tag{7}$$

The minimum mean square error is expressed as

$$\text{MMSE}_{DFE} = \frac{\sigma_0^2}{N} \sum_{l=0}^{N-1} \frac{|F_n|^2}{|H_n|^2 + \sigma_0^2}, \tag{8}$$

where $F_n = 1 + \sum_{k \in F_B} f_k^* exp(-j2\pi \frac{kn}{N})$.

III. Analysis on the Spectral Efficiency of the Proposed Uplink

For the analysis we assume that all the users are allocated with equal average received power, and channels to different users fade independently. We also assume the equalized channels are time-invariant within the slots and independent flat Rayleigh fading between the slots. The scheduler selects the user who has the best equalized SNR to transmit in each time-slot. The selected user then chooses the modulation format that maximizes the spectral efficiency in the time-slot. The adaptive modulation scheme is optimized to maximize the throughput including also the ARQ part of the transmission. The employed modulation formats are available in Table II. The spectral efficiency in each time-slot is calculated as follows

$$\eta(\gamma) = G_c \max\{k_i(1 - P_{f,i}(\gamma))\} \quad \text{bits/s/Hz}. \tag{9}$$

Here, k_i is the number of bits per symbol using uncoded 2^{k_i}-ary QAM modulation. G_c is due to the cyclic prefix. Moreover,

TABLE II

SWITCHING LEVELS $\gamma_{i,128}$ AND $\gamma_{i,256}$

i	Modulation	k_i	$\gamma_{i,128}$ (dB)	$\gamma_{i,256}$ (dB)
0	BPSK	1	$-\infty$	$-\infty$
1	4-QAM	2	8.88	9.54
2	8-PSK	3	13.67	14.20
3	16-QAM	4	17.02	17.54
4	32 Cross-QAM	5	20.59	21.07
5	64-QAM	6	23.72	24.19
6	128 Cross-QAM	7	26.97	27.43
7	256-QAM	8	30.05	30.50

$P_{f,i}(\gamma)$ is the frame error rate for the modulation level i. These frame error rates can be calculated as

$$P_{f,i}(\gamma) = 1 - (1 - P_{e,i}(\gamma))^N, \tag{10}$$

where $P_{e,i}(\gamma)$ is the symbol error rate for level i when 2^{k_i}-ary QAM is used in a SNR region $[\gamma_i, \gamma_{i+1})$, $\gamma_L = \infty$. The exponent N represents the number of payload data symbols, which is also the FFT length. These SNR thresholds γ_i, obtained by using the analytical expressions for $P_{e,i}(\gamma)$, are given in Table II for both **data structure 1** and **2**.

For flat Rayleigh fading, the pdf $p(\gamma)$, resulting from the selection diversity of the K active users, is expressed as

$$p(\gamma) = \frac{K}{\bar{\gamma}}(1 - e^{-\gamma/\bar{\gamma}})^{K-1} e^{-\gamma/\bar{\gamma}}, \tag{11}$$

where $\bar{\gamma}$ is the average received SNR of each user. The average spectral efficiency is then calculated as

$$\eta = G_c G_p \sum_{i=0}^{L-1} k_i \int_{\gamma_i}^{\gamma_{i+1}} (1 - P_{f,i}(\gamma)) p(\gamma)\, d\gamma \quad \text{bits/s/Hz} . \tag{12}$$

where G_p is the overhead due to multiuser channel estimation and prediction. In an ideal case, where we assume perfect channel estimation, prediction and equalization, the resulting spectral efficiency is as presented in Fig. 4 at SNR=16 dB. An obvious increase in spectral efficiency can be obtained due to the multiuser diversity effect. One can also notice that the spectral efficiency is higher for the 256 payload data case than the 128 payload data case in the analysis due to a lower overhead ratio. Under relaxed assumptions, the attainable spectral efficiency is a trade-off between the overhead ratio and the channel variations within the time-slot and will be lower than the analytical values given in Fig. 4.

To ease the analysis, we assume the equalized channels to be flat Rayleigh fading. However, there could be a mismatch between the pdf of the equalized channel and the flat Rayleigh fading channel. In addition to this, there will also be estimation and prediction errors. These issues are not taken into account in the analysis.

IV. SIMULATION RESULTS

In the simulations, we investigate the performance of the proposed uplink in a frequency-selective fading channel environment. The modified ITU-IV Channel A channel model is considered, where the delay spread of the impulse response spans 14 symbols in the 5 MHz channel. Perfect estimation and prediction of the impulse responses of each time-slot of each user are assumed. The equalizer assumes that the impulse response is time-invariant within each time-slot. The FD-DFE is designed to cancel all the echoes of the impulse response. The employed modulation formats and the corresponding thresholds are listed in Table II. The speed of the mobile is 50 km/h. We consider both FD-LE and FE-DFE in the simulations.

The spectral efficiency from the simulations are shown in Fig. 4. Comparing to the analytical values, the loss in spectral efficiency is considerable due to less time variations of the equalized single-carrier 5 MHz channel. The FD-DFE yields better results than FD-LE as expected. In a single user case, the spectral efficiency is rather close to the analytical values, which is consistent with the conclusions in [6] and [7]. One interesting observation is that even with a higher overhead ratio, **data structure 1** ($N = 128$) still gives slightly higher spectral efficiency than **data structure 2** ($N = 256$), which is the opposite to the analysis. The discrepancy comes from the time-invariant assumption of the impulse response within each time-slot. In the simulations, the channels are actually time-varying within each time-slot. Therefore the equalizer does a better job in the case of a smaller slot size with less variations within the slots.

We also present simulation results of a 1 MHz channel as comparison. Note that in this case the receiver is not able to separate some of the taps in the modified ITU-IV Channel A power delay profile due to a lower sampling rate. The equivalent power delay profile has 4 taps at 0, 1, 2 and 3 μs with normalized relative power of -0.6 dB, -9.6 dB, -18.1 dB and -23.1 dB. Higher spectral efficiency is achieved since the channels are easier to equalize. The dynamic range of the equalized SNRs in the 1 MHz channel is wider than in the 5 MHz channel, which enables the use of higher modulation. This is illustrated in Fig. 5, which shows the modulation formats used in both the 1 MHz and the 5 MHz case of a single user. It is worth mentioning that the channel varies faster within each time-slot in the 1 MHz case, which leads to a higher symbol error rate.

To compare the performance of the proposed uplink and a traditionally designed single-carrier system, we simulate a round-robin fashion single-carrier system using QPSK without coding, see Fig. 6. The chosen bandwidth is 5 MHz and the terminal speed is 50 km/h. A FD-DFE is implemented in the simulations. In order to make a fair comparison, the same amount of overhead is taken into consideration in the simulations. We also simulate an adaptive round-robin single-carrier system to quantify the adaptation gain. The resulting spectral efficiency in both cases are lower than in the proposed adaptive uplink with scheduling.

It is also interesting to investigate the influence of different terminal speeds on the system performance. The modified ITU-IV Channel A channel model is considered with 5 MHz bandwidth. In Fig. 7, the resulting spectral efficiency at 3 km/h

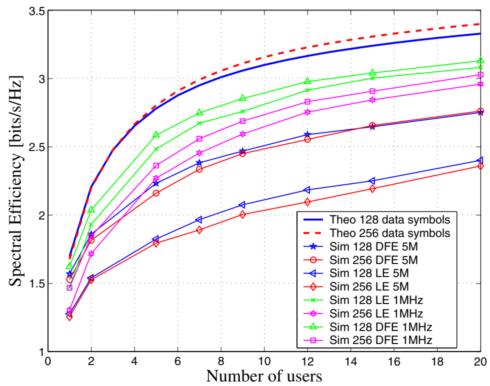

Fig. 4. The two upper curves are the analytical spectral efficiency of **Data structure 1** and **2**. Simulated spectral efficiency of the proposed uplink with 1 MHz and 5 MHz bandwidth when using FD-LE and FD-DFE are also presented. The received SNR is 16 dB.

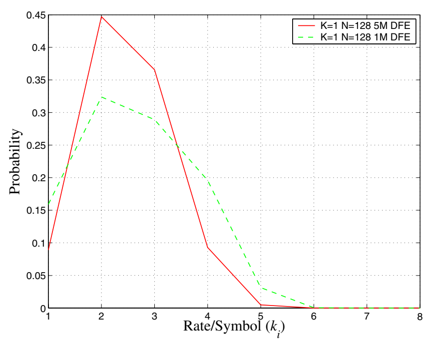

Fig. 5. Probability of using rate k_i in a single user scenario with both 1 MHz and 5 MHz bandwidth. The received SNR is 16 dB. Only **data structure 1** is considered.

and at 120 km/h are presented along with the previous 50 km/h case. Even though the channel changes much slower within a time-slot at 3 km/h compared to 120 km/h, the resulting spectral efficiency almost does not differ.

V. Conclusions

In this paper, we propose and evaluate an uplink single-carrier system based on adaptive modulation and scheduling. Spectral efficiency close to the analytical values can be obtained with a rather narrow bandwidth, e.g., 1 MHz or less. However, as a proposed radio interface for the future cellular network that usually requires wideband transmission, an OFDM based system seems to have more potential when ignoring the non-linearity and the synchronization issues. The drawback of a wideband single-carrier system is the lack of variability of the channel, which weakens the impact of scheduling and therefore gives a relatively limited gain in spectral efficiency.

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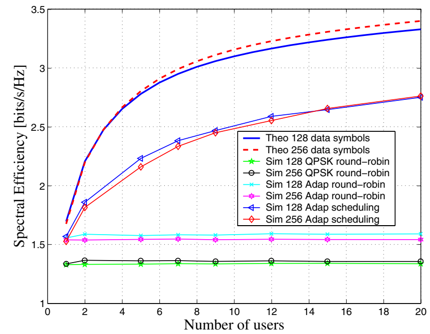

Fig. 6. Spectral efficiency of single-carrier systems without scheduling. One is a round-robin fashion single-carrier system using QPSK without coding and the other is an adaptive round-robin single-carrier system. The received SNR is at 16 dB. The bandwidth is 5 MHz and the terminal speed is 50 km/h.

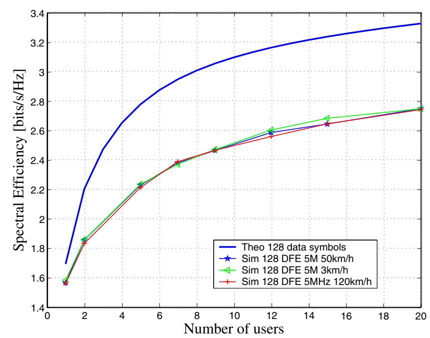

Fig. 7. Spectral efficiency of the proposed uplink at 3 km/h, 50 km/h and 120 km/h. The received SNR is 16 dB and the bandwidth is 5 MHz. The coherence time is larger than one *time block* even at 120 km/h.

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