An Energy Efficient Downlink Resource Allocation Strategy for Multiuser CP-OFDM and FBMC Systems

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***Abstract*—We address in this paper the *quality of service* (QoS) constrained radio resource allocation problem at the downlink of multiuser multicarrier systems. Based on the trade-off between energy consumption and transmit power within a cross physical and link layer system model, which jointly considers power allocation, adaptive modulation and coding and ARQ/HARQ retransmission protocols, a transmit power constrained energy minimization problem is formulated. The proposed suboptimal resource allocation algorithm is applied to both cyclic prefix based OFDM (CP-OFDM) and filter bank based multicarrier (FBMC) systems. Due to the absence of CP and the better spectral shaping of subcarriers, the FBMC system can exploit more subcarriers and symbols for data transmission and is less sensitive to *carrier frequency offset* (CFO), as compared to the CP-OFDM system. These advantages further lead to better QoS provisioning and higher energy efficiency of the former, which are demonstrated by simulation results.**

I. Introduction

Energy efficiency is not only a crucial performance metric of mobile devices and sensor networks with limited battery life, but also one of the main design concerns of other types of devices and networks, due to the desire to provide better QoS with the available radio resources and to make wireless communications greener. Depending on the system component or level of abstraction on which one investigates, energy consumption can be defined and minimized in different ways. In [1], the impacts of retransmission protocols on energy and transmit power are studied in a cross-layer fashion. The trade-off between energy efficiency at the link layer and transmit power at the physical layer has been explained, based on which a cross-layer assisted resource allocation problem in multicarrier systems has been mathematically formulated. On the other hand, although CP-OFDM is by far the most popular special case of multicarrier systems due to its efficient implementation and simple equalization, more and more recent researches are focusing on other implementations of multicarrier systems with higher bandwidth efficiency, *e.g.*, FBMC systems as discussed in [2]. By careful design of the prototype filter, FBMC systems provide a better spectral shaping of subcarriers than CP-OFDM systems, which not only simplifies equalization in the absence of CP, but also improves the robustness of the system against CFO [8]. When offset quadrature amplitude modulation (OQAM) is employed, the full capacity of the transmission bandwidth can be achieved in FBMC systems.

In this work, the transmit power constrained energy minimization problem formulated in [1] is solved for both CP-OFDM and FBMC systems. In order to demonstrate the advantage of FBMC systems from a QoS provisioning point of view, on the basis of the resource allocation algorithm proposed in [1], the size of one subchannel is further made adaptive and the interference caused by the residual CFO is accounted. The remainder of the paper is organized as follows: the system model is introduced in Sec. II, followed by a review in Sec. III on the trade-off between energy efficiency and transmit power as well as the problem formulation. Details about the resource allocation algorithm are described in Sec. IV, and simulation results are shown in Sec. V. Finally Sec. VI concludes the paper.

II. System Model

We consider the downlink scenario of an isolated single-cell with K users, each having one data stream to be served. Perfect channel state information at the transmitter (CSIT) is assumed. Resource allocation is done for each *Transmission Time Interval* (TTI), and the consecutive transmissions of data are assumed to be independent from TTI to TTI. Depending on its *throughput* requirement, each data stream may have a number of information bits, in form of *packets*, to be transmitted in each TTI. The other relevant QoS parameter characterizing the data streams, the *latency*, is defined as the delay a packet experiences until received correctly with an outage probability of no more than the predefined value $\pi^{(\mathrm{out})}$. Mathematically, let $f_k[m]$ be the probability that it takes exactly m TTI's to transmit a packet from user k error-free, then the latency of the packet is computed as $\tau_k = (M_k - 1)(T_\mathrm{R} + T_\mathrm{I}) + T_\mathrm{I}$ where T_I and T_R represent the length of a TTI and the *round trip delay*, and

$$M_k = \min_M M \quad \text{s.t.} \quad \sum_{m=1}^{M} f_k[m] \geq 1 - \pi^{(\mathrm{out})}.$$

We derive in the following the mathematical descriptions of the regarded system components stemmed from [3], which lay the basis for cross-layer optimization. A general illustration of the system model is given in Fig. 1.

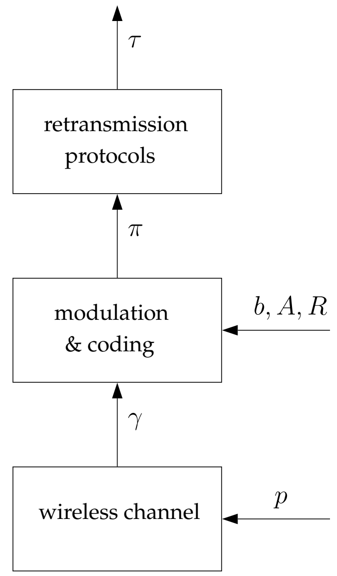


Figure 1. System model over one subchannel

A. Channel Model

The downlink broadcast channel is modeled as frequency-selective fading over the total system bandwidth and frequency-flat fading over each subcarrier. A *subchannel* is defined as a chunk of N_c adjacent subcarriers, where N_c can be adaptive but the bandwidth of one subchannel must be smaller than the channel coherence bandwidth, so that the channel gains over one subchannel can be averaged. Assuming that one TTI contains N_s symbols for data transmission, we define the *minimum allocation unit* (MAU) as an allocation region of one subchannel in the frequency dimension by one TTI in the time dimension, which contains $N_\text{c}N_\text{s}$ symbols. This means that the assignment of one MAU is exclusive to one user, and one channel gain value is used for one MAU.

Let $H_{k,n}$ be the average channel coefficient of user k on subchannel n, and p_n be the power allocated on subchannel n which is equally distributed to each subcarrier in the subchannel. Also we let the white Gaussian noise power on one subcarrier at the receiver of user k be σ_k^2, which leads to a noise power of $N_\text{c}\sigma_k^2$ on one subchannel. When assigned to user k and with *intercarrier interference* (ICI) neglected, the *signal-to-noise-ratio* (SNR) on subchannel n can be computed as

$$\gamma_{k,n} = \frac{|H_{k,n}|^2}{N_\text{c}\sigma_k^2} \cdot p_n.$$

In the next subsections we drop the subscripts k and n for simplicity.

B. FEC coding and modulation

We assume that modulation and coding across the subchannels are done independently, and with reference to the WiMAX standard 8 modulation and coding schemes (MCS) are chosen as candidates. which are listed in Table I.

Table I
MODULATION AND CODING SCHEMES (MCS)

Index	Modulation Type	Alphabet Size A	Code Rate R	$R\log_2 A$
1	BPSK	2	1/2	0.5
2	QPSK	4	1/2	1
3	QPSK	4	3/4	1.5
4	16-QAM	16	1/2	2
5	16-QAM	16	3/4	3
6	64-QAM	64	2/3	4
7	64-QAM	64	3/4	4.5
8	64-QAM	64	5/6	5

Let the modulation alphabet and coding rate on the subchannel under consideration be $\mathcal{A} = \{a_1, \ldots, a_A\}$ and R respectively. Applying the *noisy channel coding theorem* [4], the *cutoff rate* of the subchannel with SNR γ can be expressed as

$$R_0(\gamma, A) = \log_2 A - \log_2 \left[1 + \frac{2}{A}\sum_{m=1}^{A-1}\sum_{l=m+1}^{A} e^{-\frac{1}{4}|a_l - a_m|^2\gamma}\right].$$

The noisy channel coding theorem states that there always exists a block code with block length l and binary code rate $R\log_2 A \leq R_0(\gamma, A)$ in bits per subchannel use, such that with maximum likelihood decoding the error probability $\tilde{\pi}$ of a code word satisfies

$$\tilde{\pi} \leq 2^{-l(R_0(\gamma,A) - R\log_2 A)}.$$

In order to apply this upper bound to the extensively used turbo decoded convolutional code, quantitative investigations have been done in [3] and an expression for the *equivalent block length* is derived based on link level simulations as $n_\text{eq} = \beta \ln L$, where parameter β is used to adapt this model to the specifics of the employed turbo code, and L is the coded packet length. Consequently, the transmission of L bits is equivalent to the sequential transmission of L/n_eq blocks of length n_eq and has an error probability of

$$\pi = 1 - (1 - \tilde{\pi})^{\frac{L}{n_\text{eq}}} \leq 1 - \left(1 - 2^{-n_\text{eq}(R_0(\gamma,A) - R\log_2 A)}\right)^{\frac{L}{n_\text{eq}}}.$$

C. Protocol

At the link layer retransmission protocols are studied. The data sequence transmitted in one MAU, *i.e.*, a *packet*, is used as the retransmission unit.

ARQ: The corrupted packets at the receiver are simply discarded, hence we assume that the *packet error probability* (PEP) of a retransmitted packet is the same as that of its original transmission, *i.e.*, $f[m] = \pi^{m-1}(1-\pi), m \in \mathbb{Z}^+$.

HARQ: The corrupted packets at the receiver are combined and jointly decoded using rate-compatible punctured convolutional codes. For the particular *incremental redundancy* (IR) scheme we employ, the retransmissions contain pure parity bits of the same length as the first transmission, therefore the code rate for the mth transmission can be expressed as $R[m] = \frac{B}{m \cdot L} = \frac{1}{m}R$. Let $\tilde{m}$ denote the maximum number of transmissions determined by the mother code. The equivalent block length n_eq is given by $n_\text{eq} = \beta\ln(\tilde{m}L)$ [3], and the

PEP for the mth transmission can be approximated as

$$\pi[M] = \pi^{(\text{out})}, \pi[m] = 1, m = 1, \ldots, M-1,$$

when $R_0(\gamma)$ satisfies $\frac{1}{M} R \log_2 A < R_0(\gamma) \le \frac{1}{M-1} R \log_2 A$.

The system parameters are summarized in Table II, including some of their notations and the values used for simulations.

Table II
SYSTEM PARAMETERS

Total bandwidth		10 MHz
Center frequency	f_c	2.5 GHz
FFT size	C	1024
Number of data subcarriers	N_d	
Number of subchannels	N	
Number of subcarriers per subchannel	N_c	
Transmission Time Interval (TTI)	T_I	2 ms
Number of data symbols per TTI	N_s	
Round Trip Delay (RTD)	T_R	10 ms
Maximum number of transmissions	$\tilde{m}$	5
Turbo code dependent parameter	β	32
Outage probability	$\pi^{(\text{out})}$	0.01

III. POWER-CONSTRAINED ENERGY MINIMIZATION PROBLEM

The energy consumption for the successful transmission of B information bits loaded on one MAU and the transmit power required for the current transmission are expressed as

$$E = T_\text{s} \cdot \left\lceil \frac{B}{R \log_2 A} \right\rceil \cdot \gamma(B, A, R, M) \cdot \varphi,$$

$$\text{where} \quad \varphi = \sum_{m=1}^{M} f[m] \left(\frac{\sigma^2}{|H|^2} + \frac{(m-1)\sigma^2}{|H|^2_\text{avg}} \right),$$

$$P = \left\lceil \left\lceil \frac{B}{R \log_2 A} \right\rceil / N_s \right\rceil \cdot \gamma(B, A, R, M) \cdot \frac{\sigma^2}{|H|^2},$$

where $\gamma(B, A, R, M)$ is the SNR required to transmit a packet of B information bits successfully within M transmissions using MCS (A, R), $|H|^2$ and $|H|^2_\text{avg}$ are the instantaneous and average channel gains. We refer to the triple (A, R, M) as a *mode of operation* or an *operation mode* from here on. The set of all available modes of operations is denoted by $\mathcal{M}$.

As $\gamma(B, A, R, M)$ monotonically decreases with increasing M when B, A, R are fixed, transmit power P also decreases with more transmission trials. Yet it has been pointed out in [1] based on analysis and simulation results from [5], that to allow for more transmissions is energy inefficient in general. In fact, transmit power and energy consumption as defined are two conflicting, or competing objectives in the QoS-constrained resource allocation problem. As a result, letting the number of information bits to be transmitted to user k be b_k, the maximum latency time for the transmission be $\tau_k^{(\text{rq})}$ and the total available transmit power at the BS be P_tot, we can formulate an energy consumption minimization problem under transmit power and QoS constraints as

$$\begin{aligned} \min_{\boldsymbol{B} \in \mathcal{B}, \boldsymbol{q} \in \mathcal{M}^N} \quad & \sum_{k=1}^{K} \sum_{n=1}^{N} \eta_{k,n}(B_{k,n}, \tau_k^{(\text{rq})}, q_n) \\ \text{s.t.} \quad & \sum_{n=1}^{N} B_{k,n} = b_k, \quad k = 1, \ldots, K, \\ & \sum_{k=1}^{K} \sum_{n=1}^{N} \xi_{k,n}(B_{k,n}, \tau_k^{(\text{rq})}, q_n) \le P_\text{tot}, \end{aligned} \tag{1}$$

where $\eta_{k,n}(B_{k,n}, \tau_k^{(\text{rq})}, q_n)$ and $\xi_{k,n}(B_{k,n}, \tau_k^{(\text{rq})}, q_n)$ are the energy consumption and transmit power required from user k on subchannel n given latency constraint $\tau_k^{(\text{rq})}$ when q_n is chosen as the mode of operation. $\boldsymbol{B} \in \mathbb{Z}_{+,0}^{K \times N}$ represents the bit-loading matrix with its entry $B_{k,n}$ as the number of information bits for the kth user loaded onto the nth subchannel. As the domain of bit-loading matrix $\boldsymbol{B}$, set $\mathcal{B} \subset \mathbb{Z}_{+,0}^{K \times N}$ represents the set of matrices that have only one nonzero entry in each of their columns. Explicitly, there are K bit-loading constraints and one transmit power constraint in (1).

Besides the well known combinatorial natured problem of assigning subchannels to users, (1) adds another degree of difficulty by optimizing the modes of operations on the subchannels at the same time, which is yet another combinatorial problem even with fixed subchannel assignment. We make the simplification that each MAU is fully loaded during the optimization based on observations from simulations [5]. Let the set of MCS transition points, *i.e.*, the turning points in the numbers of information bits that require a higher MCS level, be $\boldsymbol{b}^{(\text{red})}$, and set $\mathcal{B}^{(\text{red})} \subset \mathcal{B}$ have element matrices only taking values from $\boldsymbol{b}^{(\text{red})}$. By restricting $\boldsymbol{B} \in \mathcal{B}^{(\text{red})}$ we simplify (1) to a tightened version of

$$\begin{aligned} \min_{\boldsymbol{B} \in \mathcal{B}^{(\text{red})}, \boldsymbol{q} \in \mathcal{M}^N} \quad & \sum_{k=1}^{K} \sum_{n=1}^{N} \eta_{k,n}(B_{k,n}, \tau_k^{(\text{rq})}, q_n) \\ \text{s.t.} \quad & \sum_{n=1}^{N} B_{k,n} \ge b_k, \quad k = 1, \ldots, K, \\ & \sum_{k=1}^{K} \sum_{n=1}^{N} \xi_{k,n}(B_{k,n}, \tau_k^{(\text{rq})}, q_n) \le P_\text{tot}, \end{aligned} \tag{2}$$

whose optimal value is an upper bound on that of (1).

IV. RESOURCE ALLOCATION ALGORITHM

In this section we first summarize the heuristic algorithm proposed in [1] which gives a suboptimal solution to (2), and then explain the adaptive subchannel size scheme and the compensation for residual CFO.

A. Heuristic Algorithm

The algorithm consists of the following main steps:

1) Feasibility Exam: First of all, the feasibility of (2) is put under test. Let P_min denote the optimal value of the transmit power minimization problem

$$\begin{aligned} \min_{\boldsymbol{B}\in\mathcal{B}^{(\mathrm{red})},\boldsymbol{q}\in\mathcal{M}^N} \quad & \sum_{k=1}^{K}\sum_{n=1}^{N}\xi_{k,n}(B_{k,n},\tau_k^{(\mathrm{rq})},q_n) \\ \text{s.t.} \quad & \sum_{n=1}^{N} B_{k,n} \geq b_k, \quad k=1,\ldots,K. \end{aligned} \tag{3}$$

If $P_{\min} < P_{\mathrm{tot}}$, then (2) is feasible, and the solution obtained with (3) provides an upper bound on the optimal energy consumption. Otherwise we determine that (2) is infeasible. Regarding solving (3), two suboptimal algorithms are proposed in [6] and we employ the heuristic method here due to its lower complexity. By suboptimally taking $P_{\min}$ we tend to be pessimistic about the system performance.

2) Determine the bit-loading matrix $\boldsymbol{B}$: Suboptimally, we replace the objective in (3) with energy times power values, *i.e.*, $\eta \times \xi$, and simply apply the same algorithm to obtain a bit-loading matrix $\boldsymbol{B}$.

3) Choose the modes of operations: As for each $B_{k,n} > 0$, there could be a number of Pareto-efficient modes of operations, the problem of which mode of operation to choose needs to be solved with the obtained $\boldsymbol{B}$. Let $\boldsymbol{V}_{\mathrm{E}}, \boldsymbol{V}_{\mathrm{P}} \in \mathbb{R}_{+}^{\bar{m}\times N}$ be the matrices containing the energy consumption and transmit power of Pareto-efficient operation modes on each of the N subchannels, where $\bar{m}$ is the largest number of efficient modes on one subchannel, and the extra entries for subchannels with less than $\bar{m}$ efficient modes are set to infinity. The optimal selection of operation modes is given by the solution to problem

$$\begin{aligned} \min_{\boldsymbol{X}\in\{0,1\}^{\bar{m}\times N}} \quad & \mathrm{tr}(\boldsymbol{V}_{\mathrm{E}}^T\boldsymbol{X}) \\ \text{s.t.} \quad & \mathrm{tr}(\boldsymbol{V}_{\mathrm{P}}^T\boldsymbol{X}) \;\leq\; P_{\mathrm{tot}}, \\ & \sum_{m=1}^{\bar{m}} X_{mn} \;=\; 1, \quad n=1,\ldots,N, \end{aligned} \tag{4}$$

where $\boldsymbol{X}$ is the selection matrix. In order to turn (4) into a convex problem, we replace the constraint $X_{mn} \in \{0,1\}$ with $X_{mn} \in [0,1]$ which actually makes (4) solvable with linear programming. If rounding up the fractional solution does not give a feasible solution to (4), adjustments on the selection can be done also based on the minimum $\eta \times \xi$ value on each subchannel. Note that due to the replacement performed when determining $\boldsymbol{B}$, (4) does not always have a feasible solution, in which case we would rely on the power-minimizing solution.

We have so far solved (2), and the solution obtained is feasible to (1). By cutting down the additionally loaded bits introduced with the coarse granularity of $B_{k,n}$ the solution can be refined. The whole resource allocation procedure is summarized in Algorithm 1.

Algorithm 1 Resource Allocation Algorithm

Solve the power minimization problem (3);
if $P_{\min} < P_{\mathrm{tot}}$ **then**
  With the optimal bit-loading matrix $\boldsymbol{B}_1$, select modes of operations on each subchannel;
else
  Decide that (2) is infeasible and exit;
end if
Solve the power $\times$ energy minimization problem and determine the bit-loading matrix $\boldsymbol{B}_2$;
Select modes of operations on each subchannel;
Choose from $\boldsymbol{B}_1$ and $\boldsymbol{B}_2$ the one with less energy consumption as the solution to (2);
For each user, cut the extra bits off on the subchannel with the largest energy reduction.

B. Adaptive subchannel size

As one subchannel can be assigned to at most one user, the number of subchannels is practically a hard limit on the number of users that the system could serve. However, the MAU's may be under utilized if the loaded packets are small. In other words, to fix the number of subchannels, or equivalently, to fix the size of each subchannel, is in general inefficient. Therefore, in order to better adapt to diverse traffic situations, we make the number of subcarriers that make up one subchannel, *i.e.*, N_{c}, also an optimization variable.

Beside the possibility to serve more users, the advantages of a small subchannel size also include having a finer frequency granularity and benefiting from multiuser diversity. On the other hand, a large subchannel size leads to more data symbols in one MAU which potentially provides a larger coding gain. Based on these observations, the optimal N_{c} should depend on the frequency selectivity of the channel and the QoS requirements. Note that in addition to the computational effort to find the optimal N_{c}, the performance gain of having N_{c} adaptive comes also at the cost of an extra overhead to inform the receiver the value of N_{c}.

Since the channel should be assumed constant over each MAU, the bandwidth of one subchannel can not exceed the coherence bandwidth of the multipath channel, *i.e.*, $\Delta f \cdot N_{\mathrm{c}} \leq B^{(\mathrm{coh})}$, where Δf and $B^{(\mathrm{coh})}$ denote the subcarrier spacing and the coherence bandwidth of the channel respectively. On the other hand, it is usually unnecessary and impractical to have a very high frequency resolution which requires more iterations to find the optimum N_{c}. As a result, an appropriate interval for two consecutive candidate N_{c} values should be set, which mainly depends on the ratio between pilot subcarriers and data subcarriers. Then for each candidate N_{c}, the heuristic algorithm is executed and the optimal N_{c} can be found by comparing the minimum energy consumption.

C. Compensation for interference induced by CFO

The effects of CFO on CP-OFDM systems have been extensively studied in the literature, *e.g.*, [7]. In our recent work [8], we have analyzed the effects of CFO on FBMC systems, where the *root-raised cosine* (RRC) filter with roll-off factor 1 is chosen to be the prototype filter. We drop user index k in this section and use subscript c to index the subcarriers, which should be distinguished from subchannel index n. For both systems, we denote the normalized CFO as ε which is the CFO between the transmitter and the receiver with respect to the subcarrier spacing. In addition, we assume that there is also a phase offset ϕ between the transmitter and the receiver, and the system is perfectly synchronized in the time domain. Furthermore, we restrict ε to be in the range $(-0.5, 0.5]$, as the integer part of the frequency offset does not affect the *signal-to-interference-plus-noise ratio* (SINR).

For coherent demodulation at the receiver, the phase rotation should be estimated and we assume that it is perfectly compensated. Moreover, we assume that the data symbols transmitted, whether on different subcarriers or at different times, are all statistically independent from each other. Let the power allocated on subcarrier c be p_c. The SINR on subcarrier c in CP-OFDM system can be expressed as

$$\mathrm{SINR}_c(\varepsilon) = \frac{|\nu_C(\varepsilon,0)|^2 |H_c|^2 p_c}{\sum\limits_{\substack{c'=0 \\ c'\neq c}}^{C-1} |\nu_C(\varepsilon, c'-c)|^2 |H_{c'}|^2 p_{c'} + \sigma^2}, \quad (5)$$

where $\nu_C(\varepsilon, c) = \frac{1}{C} \frac{\sin(\pi(\varepsilon-c))}{\sin\frac{\pi(\varepsilon-c)}{C}} e^{j\pi\frac{(\varepsilon-c)(C-1)}{C}}$.

Due to the infinite impulse response of the prototype filter used in the FBMC system, the CFO causes not only ICI but also ISI to the desired signal. The SINR of the lth symbol on subcarrier c in FBMC system is expressed as

$$\mathrm{SINR}_{c,l}(\varepsilon) = \frac{\alpha_c^2(\varepsilon,0,0)p_c}{\sum\limits_{c'=0}^{C-1}\sum\limits_{l'=-\infty}^{+\infty} \alpha_{c'}^2(\varepsilon,\Delta c,\Delta l)p_{c'} - \alpha_c^2(\varepsilon,0,0)p_c + \frac{\sigma^2}{|H_c|^2}}, \quad (6)$$

where $\Delta c = c - c'$, $\Delta l = l - l'$, and

$$\alpha_c(\varepsilon,\Delta c,\Delta l) \triangleq \Re\left\{e^{-j\frac{\pi}{2}(\Delta c+\Delta l)} e^{j\pi\Delta l(c-\varepsilon)} w(\varepsilon,\Delta c,\Delta l)\right\},$$
$$w(\varepsilon,\Delta c,\Delta l) \triangleq \int_{-\infty}^{+\infty} e^{j\pi\Delta l T f} H_{\mathrm{RRC}}(f - \tfrac{\varepsilon-\Delta c}{T}) H_{\mathrm{RRC}}(f)\mathrm{d}f$$

in which H_{RRC} denotes the frequency response of the prototype filter. Here it is assumed that the power allocation stays constant in time, which is reasonable because the weight factor $\alpha(\varepsilon,\Delta c,\Delta l)$ approaches 0 very fast with increasing Δl, which means the influence of symbols that are not close to the one of interest is negligible.

With the aid of pilot symbols, the receiver estimates and compensates for the CFO. However, this compensation could be imperfect even in the downlink, and the system should be able to live with the residual CFO. The bit-loading matrix and the vector of operation modes now give N required SINR values instead of N required SNR, which has a general form of

$$\gamma_c^{(\mathrm{rq})} = \frac{a_{c,c}p_c}{\sum_{c'\neq c} a_{c,c'}p_{c'} + \sigma^2},$$

where $a_{c,c'}$ are nonnegative scalers. Stacking all C equations we have a set of linear equations the solution of which gives the power allocation that is able to achieve all required SINR values on every subcarrier, *i.e.*,

$$\boldsymbol{p} = \sigma^2 \cdot \begin{bmatrix} a_{0,0} & -a_{0,1} & \cdots & -a_{0,C-1} \\ -a_{1,0} & a_{1,1} & \cdots & -a_{1,C-1} \\ \vdots & \vdots & \ddots & \vdots \\ -a_{C-1,0} & -a_{C-1,1} & \cdots & a_{C-1,C-1} \end{bmatrix}^{-1} \begin{bmatrix} \gamma_0^{(\mathrm{rq})} \\ \gamma_1^{(\mathrm{rq})} \\ \vdots \\ \gamma_{C-1}^{(\mathrm{rq})} \end{bmatrix}.$$

Note that the worst case residual CFO is assumed at the transmitter. When determining the bit-loading matrix, the impact of a potential residual CFO is neglected, yet when the modes of operations are selected, the CFO has to be compensated for each obtained mode vector to make sure that the power constraint is not violated.

V. Simulation Results

For simulations, 10 users with their QoS requirements listed in Table III are assumed. Two test scenarios are simulated under 1000 independent channel realizations, where P_{tot} are set to 44 dBm and 50 dBm respectively. Due to the less out-of-band emission and the absence of CP, the FBMC system can employ more subcarriers (5% more than CP-OFDM is assumed) and more symbols per TTI (12.5% more than CP-OFDM is assumed which is a common fraction of CP to the number of data samples) for data transmission. The difference in the two systems are listed in Table IV. We model the wireless channel as a frequency-selective fading channel consisting of 6 independent Rayleigh multipaths with an exponentially decaying power profile where the delay spread is 1 μs. The path loss in dB is computed as $PL(d) = 140.6 + 35.0\log_{10} d$ following the COST-Hata model, where d is the distance between MS and BS in km, and all receiver noise levels are -174 dBm/Hz. The worst case residual CFO is set to 2% of the subcarrier spacing, *i.e.*, $\varepsilon = 0.02$.

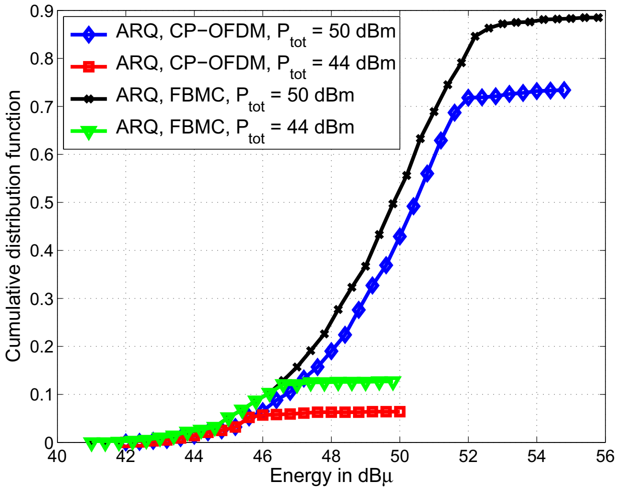
Table III
QoS Requirements of 10 Users for Simulations

User k	b_k / bytes	$\tau_k^{(\mathrm{rq})}$ / ms
$1-5$	64	20
$6-10$	500	50

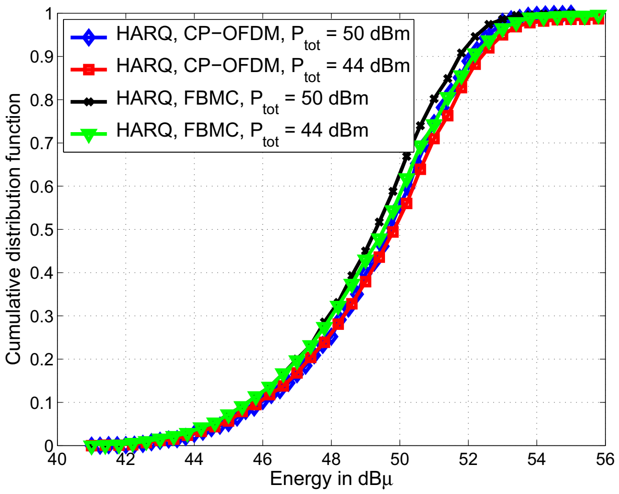
Table IV
Difference in System Parameters

Number of data subcarriers in CP-OFDM	N_{d}	720
Number of data subcarriers in FBMC	N_{d}	756
Number of data symbols per TTI in CP-OFDM	N_{s}	16
Number of data symbols per TTI in FBMC	N_{s}	18

Fig. 2 shows the cumulative distributions of the minimum energy consumption in CP-OFDM and FBMC systems to fulfill the QoS requirements respectively. In Fig. 2(a) where ARQ protocol is employed, the FBMC system has the outage ratio of 12% and 87% corresponding to transmit power constraints of 50 dBm and 44 dBm, whereas the ratios for CP-OFDM system are 27% and 94%. In Fig. 2(b) where HARQ protocol is employed, both systems are able to constantly provide satisfactory QoS with the power constraint $P_{\mathrm{tot}} = 50$ dBm, while the more strict constraint $P_{\mathrm{tot}} = 44$ dBm forces the FBMC and the CP-OFDM system to present an outage ratio of 0.4% and 1.3% respectively. Besides, averaged over all feasible cases, the FBMC system takes the advantage of consuming 7.4% and 6.7% less energy for the two constraints as compared to the CP-OFDM system.

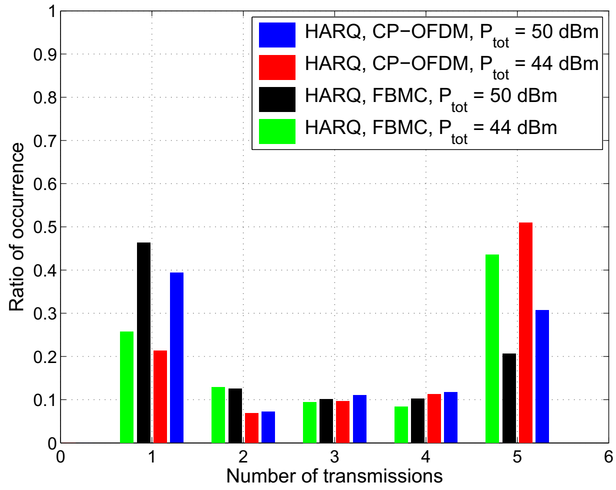


(a) CDF of energy consumption with ARQ protocol

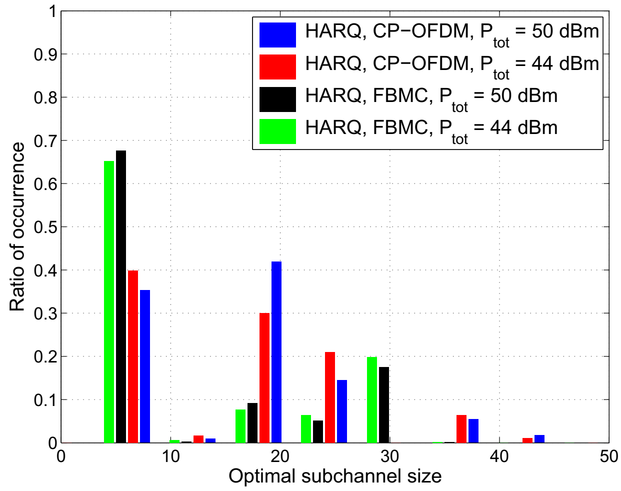


(b) CDF of energy consumption with HARQ protocol

Figure 2. CDF of energy consumption



(a) Distribution of modes of operations chosen for user 10



(b) Distributions of optimum subchannel size

Figure 3. Distributions of optimum modes of operation and subchannel size

The distribution of numbers of transmissions chosen for a user allowing for 5 transmissions are drawn in Fig. 3(a), with HARQ employed. Due to its more efficient usage of resources, the FBMC system chooses more often to operate with few transmission trials, especially when the transmit power constraint is relatively loose. The CP-OFDM system on the other hand, has to go for more transmissions and sacrifice energy efficiency until the transmit power available is sufficient for the current transmission. Fig. 3(b) illustrates the distribution of the optimum subchannel size in both systems, where it can be seen that when the transmit power constraint is crucial to the system, larger subchannel sizes are preferred to small ones, such that the advantage of larger coding gains can be taken.

VI. Conclusion

At the downlink transmitter with a multicarrier infrastructure, a QoS and transmit power constrained energy minimization problem is formulated based on studies on the trade-off between energy consumption and transmit power, which is rooted from optimizing the transmission modes which involve adaptive MCS and retransmission protocols. The resource allocation strategy proposed includes a general algorithm to solve the optimization, as well as an adaptive subchannel size scheme and the compensation for interference induced by residual CFO, which account for different features of various implementations of the multicarrier system. Simulation results of applying the proposed strategy to both CP-OFDM and FBMC systems demonstrate the superior performance of the latter.

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