ENERGY-AWARE ADAPTIVE OFDM SYSTEMS*

Y. Emre and C. Chakrabarti

School of Electrical, Computer and Energy Engineering
Arizona State University, Tempe, AZ 85287
{yemre,chaitali}@asu.edu

ABSTRACT

An effective way of reducing the energy consumption without affecting the quality of service is by adapting to the channel conditions. In this paper we describe one such scheme for an OFDM system using space division multiplexing technology. We consider tuning parameters such as modulation level and number of antennas that are considered by WiMax and LTE, as well as number of sub-carriers, peak to average power ratio, interpolation, pilot length and cyclic prefix. We describe a two-phase procedure for determining the parameter settings for minimizing energy consumption given the transmission rate, error performance and channel conditions for frequency selective fading channels. Our results show that we can reduce energy by an additional 5%-30% compared to systems that can only adapt modulation order and number of antennas.

***Keywords*:** OFDM, parameter tuning, QoS, energy optimization

1. INTRODUCTION

Wireless devices have proliferated in the last couple of years, and the number of applications supported by these devices has increased significantly. Each additional application comes at a cost of increased bandwidth requirement and larger energy consumption. Since the wireless devices are battery powered, it is important that every effort be made to reduce the energy consumption. The challenge is to achieve this without affecting the quality of service (QoS) requirement. This is a very important problem and has applications in cognitive radio, and protocols such as IEEE 802.16 (WiMax), IEEE 802.22, 3GPP Long Term Evolution (LTE) etc. [1-4].

Several researchers have tackled this problem by exploiting the variation in channel conditions to switch to lower complexity algorithms [5-7]. Examples include [5], where MAC and physical layer interaction is investigated for OFDM networks. Data rate adaptation over each subcarrier, dynamic subcarrier assignment and dynamic power allocation are considered. In [6], a SmartMIMO system has been proposed which adaptively switches between space-division multiplexing (SDM), space-time coding, and single-antenna scheme depending on channel characteristic. A cross layer approach that spans physical layer, MAC layer and link layer have been proposed in [7]. Parameters such as modulation, code rate, power amplifier (PA) consumption and linearity factor have been considered along with the mode of operation.

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Standards such as IEEE 802.16, 3GPP LTE support multiple combinations of modulation order and coding rate [2-4]. Transmission rate (TR) is adjusted using QoS and channel quality information (CQI). In addition, they support adaptive antenna selection with MIMO technology. In addition to modulation and multiple antennas, we also consider parameters such as number of subcarriers, peak to average power ratio (PAPR), interpolation and pilot length. These also affect the performance metrics, such as TR, error performance and energy consumption. We observe that using these additional parameters, our system can save up to 30% of digital energy above that saved by systems that control only modulation order and antenna number for fading and frequency selective channels at BER=10^{-2}.

Our methodology consists of two phases. In the characterization phase or off-line phase, we derive look up tables (LUT) based on extensive simulations for error performance and energy consumption, for different channel conditions. At run time, we first find the settings that satisfy the TR constraint. Then, we check the error performance using the LUTs, compare the surviving ones with respect to energy consumption and choose the one with the smallest value. Since the impact of the parameters also changes with the channel conditions, separate tables are maintained for each of the representative channels. In our analysis, energy consumption consists of two components: digital energy consumption which is proportional to the number of computation cycles taken by the TI TMS32C6713 processor, and analog energy consumption which is dominated by PA energy consumption.

The rest of the paper is organized as follows. In Section 2, we describe the OFDM system model. Section 3 presents effects of each parameter on system performance. In Section 4, we present a way of configuring the system under QoS constraints. Section 5 concludes the paper.

2. SYSTEM DESCRIPTION

In this paper we consider a general OFDM system, the block diagram of which is given in Figure 1. A brief description of the main blocks is given below.

Digital Modulator: It maps the information bits to symbols. The choices are BPSK-QPSK-8PSK. Higher modulation orders can also be supported.

IFFT (inverse FFT): It maps the PSK symbols onto multiple orthogonal frequencies: 512, 1024, and 2048.

Tx-Front-end: The PA is the dominant energy consuming component. Its energy is proportional to the PAPR.

Rx-Front-end: Consists of analog components that convert electromagnetic waves to digital signal.

FFT: It converts the signal from time domain to frequency domain.

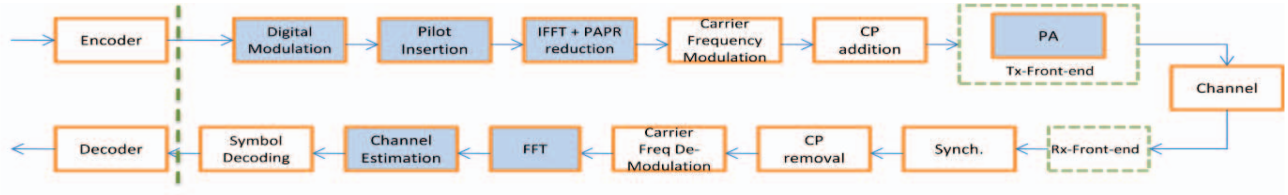


Figure 1. General block diagram of an OFDM system; the shaded blocks have the control knobs.

2.1. Simulation Environment

The system is simulated using Matlab. The BER of the system is calculated by keeping the following parameters constant $F_s(sampling) = 96MHz, BW = 8MHz$, $Fc(center) = 12MHz$. The settings of the other parameters are changed using QoS and BER. The data size is set to 25000 information bits. Error correction has not been considered as is the case for systems where the transmission range is small [8].

The channel is characterized using tap delay line model with Rayleigh distribution coefficients and exponential decay of power with a time constant. Noise is assumed to be an independent, zero mean Gaussian process. Results are presented for three different channels. Channel A is a typical Rayleigh fading channel with no-ISI and 20 dB of SNR, while Channels B and C are representative of frequency selective fading channels. Channel B has 8 non-zero tap with 6us delay spread and 20 dB SNR. Channel C has same frequency response with Channel B under 15 dB SNR. In addition, we assume an error free channel between the transmitter and the receiver to send the channel estimates from transmitter to receiver and system configurations from receiver to transmitter.

The computation time, measured in terms of number of cycles, is obtained from the TI TMS320C6713 Floating point DSP simulator. TMS320C6713 is Very Long Instruction Word (VLIW) processor with a clock rate of 225 MHz. We assume that the energy consumption of the digital part is proportional to the number of cycles. For analog power consumption, we only consider PA energy consumption which is related to modulation order and PAPR ratio.

3. EFFECT OF PARAMETER SETTINGS ON THE PERFORMANCE METRICS

In this section, we consider three performance metrics: error rate (BER), TR and energy consumption. We investigate the effect of different settings of each of the parameters on these metrics. We include the results of configuring only one parameter at a time in this section. The default setting is for a 128 us *OFDM* word with SISO, BPSK, 1024 subcarriers, quarter of symbols as pilots, 1920 samples for CP (which corresponds to 20 us of OFDM word), full-interpolation, and tone reservation (to reduce PAPR).

3.1. Digital Modulator

The choice of the modulation scheme (BPSK, QPSK, 8-PSK) affects all three performance metrics. Figure 2-a illustrates the BER results of the three schemes for three types of channels. In each case, the error rate increases as the modulation order increases as expected. Table 1 shows the transmission rates and number of clock cycles for these cases. We see that higher modulation reduces number of cycles and active time duration, resulting in reduced digital energy consumption.

3.2. Multiple Antennas

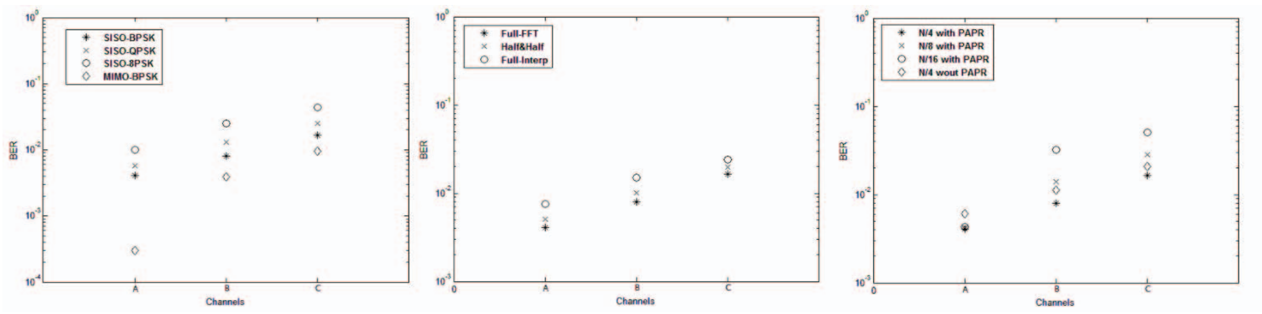
MIMO systems can increase transmission rate linearly with the number of antennas. We compare SDM scheme which consists of 2 transmit and 2 receive antennas with SISO. The computational cost and memory requirements increase more than two times with a SDM scheme because each channel estimation requires two dimensional matrix manipulations instead of scalar computations. Pilot symbol based ML decoding algorithm is employed in channel estimation and decoding. Since there are two channels per symbol in this configuration, the complexity of ML decoding increases significantly especially for higher modulation. Table 1 shows the number of clock cycles for SISO and MIMO schemes with different modulation order. Increase in computational cost is not linear with the modulation and antenna number. Figure 2-a shows the BER results of both systems. The spread reduces when SNR is lower and/or frequency selectivity increase. The performance degradation in frequency selective channels for MIMO is due to suboptimal channel estimation.

3.3. Interpolation

In dynamic spectrum utilization systems such as cognitive radio, the transmission band switches between available spectrum holes. If static digital to analog converter (DAC) is employed in the front-end, the number of samples required by the DAC changes. This can be provided by oversampling the signal in digital domain by a factor of $OS = \frac{F_s}{BW}$. Unlike LTE and WiMax that employ fixed oversampling, we employ three oversampled systems: (a) information bits are zero-padded and IFFT is applied on $OS * N$ points, (b) IFFT is applied on $\frac{OS}{2} * N$ points, and (c) IFFT is applied on N points followed by linear interpolation. Up/down-sampling reduces the computational cost of the digital system significantly. Figure 2-b illustrates the BER performance of full-FFT and interpolated versions. Although BER performance degrades, the number of cycles can be reduced significantly as shown in Table 2.

3.4. Number of Subcarriers

The number of subcarriers affects the TR but has a small effect on the BER when Doppler spread and carrier frequency offset is low. Both LTE and WiMax have fixed subcarrier separation (15 KHz and 11.2 KHz). However, if the channel in the given BW is better, more subcarriers can fit in and higher TR can be achieved by lowering CP redundancy ratio (CPRR) expressed as $CPRR = \frac{CP}{CP+Ts}$, where Ts is OFDM word length. Increasing the number of subcarriers in a given bandwidth improves transmission rate if the CP is fixed. Table 3 shows the number of clock cycles and transmission rates for the three cases (N =512, 1024 and 2048).



(a) **(b)** **(c)**

Figure 2. BER performances for a)Digital modulation and SDM schemes, b) Interpolation vs FFT, c) Pilot length and PAPR

When Doppler spread is high, then increasing the number of subcarriers increases inter-carrier interference (ICI) which results in higher BER for higher number of subcarriers [9].

3.5. Channel Estimation

We use pilot based frequency domain channel estimation where we embed pilot signals into the information block periodically. Increasing the number of pilots reduces transmission rate but improves the performance by reducing estimation error. WiMax and LTE use fixed pilot ratio: 1/7 and 1/32 respectively [2-4]. In contrast, we consider three different length pilot sequences $N/4, N/8$ and $N/16$. We generate look-up table for pilots and pick pseudo random symbols for each location to keep the PAPR low. Otherwise same information symbol is inserted periodically, and the signal envelope contains high peaks. Figure 2-c illustrates the BER results for the three pilot sequences. For Channel A, BER is the same for all three lengths because of flat fading, thus the smallest length sequence ($N/16$) is favorable. For Channels B and C, the spread in BER is quite large because of the inability of the pilot based interpolator to estimate the channel between pilot locations and so pilot sequence of size $N/4$ is the preferred choice.

3.6. Peak to Average Power Ratio

PAPR is the ratio of signal peak power to its rms value, $PAPR = 10\log(P_{peak}/P_{rms})$. In OFDM systems, peak power reduction is important since subcarriers with different phases and frequencies get added up. High PAPR forces OFDM to operate in non-linear region of PA which results in undesirable harmonics. Tone reservation is one of the digital domain techniques that reduce PAPR iteratively [10]. Figure 2-c illustrates BERs of two methods with and without tone reservation for three channels. Although tone reservation results in superior performance, it implements gradient search algorithm iteratively which increase the overhead in digital domain. However, reduction of PAR results in lower energy consumption of the PA and is favored in our system.

3.7. Analog Power Consumption

The PA and data converters in a typical OFDM system consume significant amount of power. The power consumption depends on parameters that are controllable in the digital domain [11]. We investigate the effects of the control knobs on power consumption in the analog front-end here. For instance, Class A, PA power consumption can be expressed as $P_{PA} = \frac{\frac{PAPR}{K}(4\pi)^2 d^2 L N_0}{G_t G_r \lambda^2\, 2(\log_2 M \sin(\frac{\pi}{M}))^2 BER}$ where M is the constellation size, K is proportionality constant, d is the transmission distance, G_t and G_r are antenna gains, L is the system loss, λ is the carrier wavelength, and BER is the bit error rate. We advocate the use of tone reservation algorithm since it reduces the PAPR approximately 21% on average in our system, causing a similar reduction in the PA power. The DAC and ADC power consumption can also be reduced using tone reservation algorithm since their energy consumption is proportional to PAPR and SQNR [12]. We see that for the same BER and PAPR, QPSK has the best analog energy per bit performance. However, 8PSK has lower BER and smaller digital energy consumption and cannot be easily dismissed.

Mod. Order	TR (Mbps)	# of Cycles
BPSK	5.19	768,835,558
QPSK	10.38	394,891,486
8PSK	15.57	268,430,528
MIMO-BPSK	10.38	927,689,087
MIMO-QPSK	20.76	1,375,541,780
MIMO-8PSK	31.14	2,137,489,500

Table 1 TR and computational cost (CC) for digital modulation and MIMO Schemes

	TR (Mbps)	# of Cycles
Full-Interpolation (c)	5.19	192,348,657
FFT & Interpolation (b)	5.19	493,199,471
Full-FFT (a)	5.19	768,835,558

Table 2 TR and CC of interpolation based methods

#of Subcarriers	TR (Mbps)	# of Cycles
512	4.58	722,375,452
1024	5.19	768,835,558
2048	5.57	802,221,468

Table 3 TR and CC for different number of subcarriers

4. SYSTEM DESIGN

In the previous section we described the effect of each parameter on the system performance separately. In this section we describe how that information can be used to choose the settings of each parameter such that energy consumption is minimum given the constraints of TR and BER.

Our procedure consists of two phases. In the characterization phase, we run extensive simulations to characterize the effects of each parameter for each representative channel condition, and generate LUTs for BER -Energy consumption relation. Size of this LUT depends on the number of combinations which is 162 (3x2x3x3x3) for each channel which corresponds to 8 bits of configuration overhead. Note that we always choose tone reservation to reduce PAPR. We do not need to store the results for TR since these can be derived very easily. At run time, we first find the closest channel model using features such as delay spread, frequency selectivity etc., and then the match that satisfies the TR and BER constraints with the lowest energy consumption.

We start by identifying the candidates that satisfy the TR constraint. The smallest TR rate is 4.58 Mbps corresponding to SISO-BPSK-N/4-512. Since each of parameters has a multiplicative effect on overall TR, it is easy to calculate TR. The search engine then eliminates the configurations that do not satisfy the BER constraint using BER-energy LUTs. It then picks the one from surviving configurations that has the lowest digital energy consumption.

Example: In this example, we compare two schemes: System-1 can only adjust modulation, antenna selection and interpolation features similar to LTE and WiMax, System-2 (our system) has full configuration ability. The BER is set to 10^{-2} which is a practical error rate for an uncoded system. Let us elaborate the procedure for Channel A at 20 Mbps TR. System-1 can only pick MIMO-QPSK and MIMO-8PSK to satisfy TR (See Table 1), while System-2 can add more options such as SISO-8PSK-N/16-2048 to the candidate set. System-1 picks MIMO-QPSK-N/4-1024-PAPR-interpolated and System-2 picks SISO-8PSK-N/16-2048-PAPR-no-interpolation as the lowest energy configuration. For these configurations, the digital energy consumption of System-2 is ~30% lower than that of System-1. On the other hand, due to modulation order, PA energy consumption is higher for the second system; however the difference is less than 8%.

In Figure 3, we provide the relative digital energy savings of System-2 wrt System-1 under three different channel scenarios for 6 different TR constraints. The highest gain is observed for Channel A. This is because most of the combinations can satisfy this BER limitation, giving more opportunities to pick the one with the lowest energy. The highest gain is at 25 Mbps since System-1 is forced to operate at MIMO-8PSK which has significantly high energy while System-2 can operate at MIMO-QPSK. At 30 Mbps both systems have to operate at MIMO-8PSK, the 15% additional energy reduction of System-2 is due to settings of parameters such as pilot length, and number of subcarriers. The energy gain is lower for Channel B and almost disappears for Channel C. This is because at BER of 10^{-2} the number of possible candidates for Channels B and C is very small.

Finally, the quality of the solution depends on the number of channels that have been pre-characterized. If an exact match is not found, we choose the closest channel model corresponding to a more conservative match. For instance, for a channel with parameters 18 dB SNR, 4 non-zero taps of 3 us delay spread we choose Channel B. We find that for $TR = 15\ Mbps$, the energy saving would be 13 due to Channel B settings but could have been 18 if the channel had been pre-characterized.

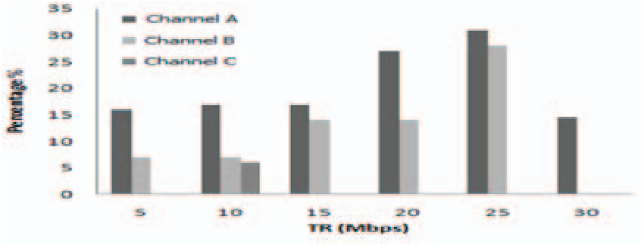


Figure 3 Digital Energy for different TRs.

5. CONCLUSION

In this paper, we showed the effects of different physical layer parameters on the performance of an uncoded OFDM based wireless system measured in terms of transmission rate, bit error rate and digital energy consumption. The parameters that we consider are digital modulation, antenna number that have been considered by other standards as well as number of subcarriers, interpolation, pilot length, and PAPR. The digital energy saving is 5-30% compared to a system that has modulation and antenna number configurability at BER=10^{-2} for a representative set of channel conditions.

Although new standards embed highly complex ECC such as LDPC, Turbo coding that significantly increase the computational complexity, use of additional control knobs helps reduce the BER which in turn results in fewer iteration and thus lower the total energy consumption. One of our future goals is to analyze these effects and develop an adaptation procedure for coded systems.

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