POWER EFFICIENT ADAPTIVE M-QAM DESIGN USING ADAPTIVE PIPELINED ANALOG-TO-DIGITAL CONVERTER

Byung-tae Kang[*], *Vijaykrishnan Narayanan*[**], *Mary Jane Irwin*[**], *R. Chandramouli*[***]

{bkang, vijay, mji}@cse.psu.edu, rchandr1@stevens-tech.edu
* Electrical Engineering Department
** Computer Science and Engineering Department, Pennsylvania State University
*** Department of Electrical and Computer Engineering, Stevens Institute of Technology

ABSTRACT

In broadband wireless applications, power consumption is one of the critical system parameters. It is important to achieve high spectral efficiency and power saving at the same time. For high spectral efficiency, adaptive M-QAM systems have been previously proposed, but the impact of the additional hardware components required to implement such systems have not been well studied. In this paper, we study the effect of adaptive M-QAM modems on hardware power consumption. This is followed by the description of a new architecture for low power ADC.

1. INTRODUCTION

Mobile devices such as laptops and personal digital assistants have limited battery life. The re-chargeable battery technology has resulted in only a small increase in battery efficiency. It is important to optimize network protocols for minimum power to ensure the continued growth of wireless based multimedia communication. Physical layer is an especially important factor of power consumption because it is closely related to the hardware components. The physical layer consists of a transmit power amplifier, filters, frequency synthesizer, VCO, analog-to-digital converter (ADC), digital-to-analog converter (DAC) and discrete analog components.

Traditional wireless system designs strive to achieve high spectral efficiencies. Many solutions have been proposed to achieve spectral efficiency. Among these the channel-adaptive modulation and demodulation technique has been observed to perform well for mobile wireless applications. A number of parameters such as the constellation size, transmission power, and/or rate can be adapted based on the estimated or predicted state of the wireless channel. Different adaptation procedures have been studied to ensure that a constant quality of service (QoS) is maintained.

In most implementations, providing adaptation involves additional hardware complexity. The impact of these additional components on computational power consumption is not yet clear. The goal of this paper is to explore this tradeoff and provide a power-efficient solution for providing adaptation.

We choose an adaptive M-ary Quadrature Amplitude Modulation (M-QAM) system in this study. To implement a M-QAM system, ADC and DAC are important components. ADC is especially important as it is a dominant source of power consumption. The resolution of the ADC has a significant impact on the power consumption as well as the received signal quality. When the symbol rate of M-QAM becomes higher, the resolution of ADC needs to be more. More resolution bits translate into more power consumption as well as reduced bit error rates (hence, better quality) during detection. Therefore, by varying the resolution of the ADC, we explore the relationship between quality and power consumption of M-QAM systems.

In Section 2, the physical layer power model is defined and the relative importance of the ADC power consumption in both indoor and outdoor applications is presented. In Section 3, the adaptive M-QAM system is introduced and is followed by the description of system parameters used for experimentation. In Section 4, the power characteristics of the pipelined ADC used in a M-QAM system are reviewed and are followed by the description of the newly proposed adaptive pipelined ADC. In section 5, an energy-aware adaptation mechanism that changes the modulation scheme and ADC resolution in conjunction is proposed and is followed by simulation and experimental results for our adaptation scheme.

2. SYSTEM STRUCTURE OF WIRELESS PHYSICAL LAYER

Fig-1 shows the typical block diagram of a wireless physical layer. The major sources of power consumption are the power amplifier, the ADC/DAC and the analog circuits (RF/IF/PLL) and the overall energy consumption can be defined by Eq-1 as in [1].

$$E_{PHY} = E_{AMP} + E_{ANALOG} + E_{ADC/DAC}$$
$$= (P_{AMP}+P_{ADC/DAC}+P_{ANALOG})*T_{ON}+P_{ANALOG}*T_{PLL} \quad (Eq\text{-}1)$$

0-7803-7402-9/02/$17.00 ©2002 IEEE

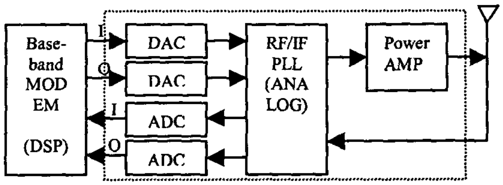


Fig-1 The block diagram of wireless physical layer

In Eq-1, T_{ON} is the actual communication time of one packet and T_{PLL} is the synchronization time of the transceiver. Therefore, T_{ON} is factored for all components, while only the analog components are active for the duration of T_{PLL}. Note that T_{ON} is inversely proportional to $\log_2(M)$, where M is the symbol rate

Wireless broadband applications can be divided into two types, indoor and outdoor. Indoor applications such as wireless LAN uses a low power transmit amplifier. So among other components, ADC is the dominant factor of power consumption. On the other hand, outdoor applications such as W-CDMA use high power transmit amplifiers. The M-ary systems energy consumption can be normalized with respect to a system that uses BPSK modulation (whose symbol rate is one) for comparison purposes and can be expressed as:

$$\frac{P_{ADC\,DAC\text{-}M}\cdot\left(\frac{T_{ON}}{n}\right)+P_{AMP}\cdot\left(\frac{T_{ON}}{n}\right)+P_{ANALOG}\cdot\left(\frac{T_{ON}}{n}\right)+P_{ANALOG}\cdot T_{PLL}}{P_{ADC\,DAC\text{-}bpsk}\cdot T_{ON}+P_{AMP}\cdot T_{ON}+P_{ANALOG}\cdot T_{ON}+P_{ANALOG}\cdot T_{PLL}}$$

(Eq-2), where n is $\log_2(M)$.

Fig-2 shows the energy benefits of using an adaptive M-ary modulation scheme with varying symbol rate for both indoor and outdoor applications. Outdoor applications are more efficient than indoor applications when a higher symbol rate is used. This happens due to the larger energy savings obtained from the more power-consuming amplifier used for outdoor applications.

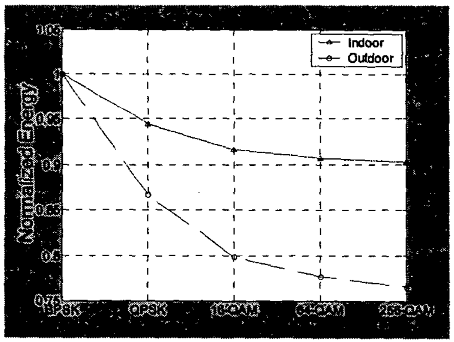


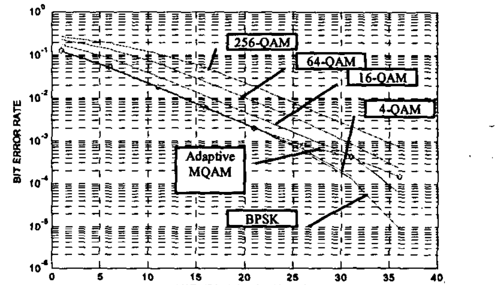
Fig-2 The energy impact of M-ary modulator

3. ADAPTIVE M-QAM SYSTEM

In high-speed wireless applications, robust and spectrally efficient techniques are needed. A variant of the variable-rate, variable-power adaptive MQAM technique proposed in [2] serves as the basis of our adaptive system. This system optimizes both the transmission rate and power in order to maximize spectral efficiency, while at the same time satisfying average power and BER (Bit Error Rate) constraints. In a QAM system, constellation is an important factor influencing quality. To focus more on the influence of ADC resolution, we use only rectangular constellations in our analysis. In contrast to [2], where symbol power levels were controlled by channel condition, the symbol power level is fixed in our experimentation for simplicity.

Fig-3 shows the performance of proposed adaptive M-QAM system. Target BER (Bit Error Rate) is 10^{-3}. X-axis is the received power when the channel is modeled using slow Rayleigh fading. From Fig-3(b), adaptive M-QAM's spectral efficiency is close to that of Shannon's (Note that the Shannon's spectral efficiency is the ideal case). When the received power increases (as channel becomes more reliable), spectral efficiency saturates at eight bps/Hz. This is because the maximum symbol rate is 256 bps/Hz. Also from Figure 3(a), we observe that the target bit error rate is met by the proposed adaptive system.

(a) *Bit Error Rate*



(b) *Spectral Efficiency*

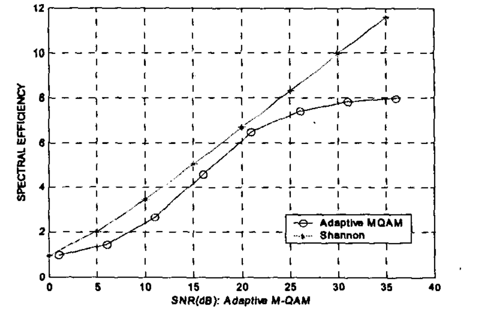


Fig-3 Performance of proposed adaptive M-QAM system

4. PIPELINED ADC

Now we focus on the structure and the power consumption of pipelined ADC used in traditional communication systems. The power consumed by the pipelined ADC can be described in terms of the power consumed by a comparator and can be given as follows [3].

$$\frac{P_T}{P_C} \approx \left(\frac{N-x}{n-x}\right)\left(R_p - 1 + 2^n\right), \quad R_p = \frac{P_{SHA}}{P_C}$$

(P_T: total power, P_C: comparator power, P_{SHA}: SHA power, N: total resolution, n: sub resolution, x: residual resolution) *(Eq-3)*

In an ideal ADC, quantization error is the only source of error. Approximating quantization error as common white noise, ENOB (Effective Number of Bits) of the ADC can be defined by Eq-4 [4].

$$ENOB = \frac{(SNR - 1.76)}{6.02} \qquad (Eq\text{-}4)$$

Also Eq-5 shows the relationship between the error probability of M-QAM and DAC's SNR. To guarantee the system's performance, we set the ADC's resolution to be larger than DAC's resolution (ENOB obtained using Eqs 4 and 5) as suggested in [4].

$$SNR_{DAC} = 20\log\left\{Q^{-1}\left[\frac{1}{4\left(1-\frac{1}{\sqrt{M}}\right)}P_{QAM}\right]\right\} + 10\log\left\{\frac{(M-1)\left(\sqrt{M}-1\right)}{\left(\sqrt{M}+1\right)}\right\}$$
$$+ 20\log(\beta) - 10\log(OSR)$$

(M: Symbol Rate, P_{QAM}: the error probability, β: excess bandwidth, OSR: Over-sampling ratio) *(Eq-5)*

4.1. Proposed Adaptive pipelined ADC

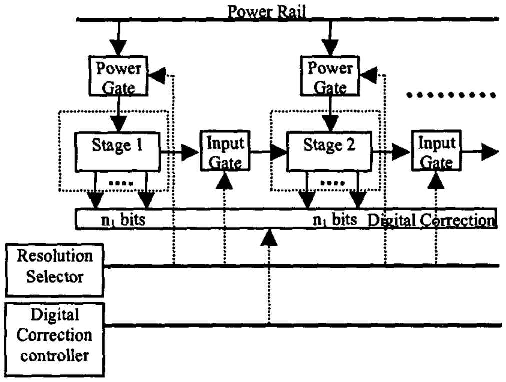


Fig-4 Block diagram of proposed adaptive pipelined ADC

The architecture of the pipelined ADC can be easily modified for providing the required resolution. Each stage has the same function and its input is only correlated to the previous stage's output. The MSB (Most Significant Bit) is defined by left most stage of the ADC. Similarly, the LSB (Least Significant Bit) is defined by right most stage of the ADC. If unused stages could be shut down, significant power saving can be expected. Supply gating is used as the mechanism for reducing power consumption in the unused segments. There is no leakage current or static power consumption in the supply gated units. However, a recovery latency of 350ns is incurred for activating a shutdown segment.

Based on the required resolution, supply gating is applied to selected units in our adaptive system shown in Figure 4. Further, the input gates of the unused stages are disabled. Also, in our implementation the Digital corrector is redesigned to account for the variation in number of bits that are input to it.

5. DESIGN OF ADAPTIVE MODULATOR AND ADAPTIVE ADC BASED ON QOS

In our adaptive system, we use the adaptive M-QAM described in section 3 and the adaptive pipelined ADC proposed in section 4. An adaptive M-QAM system should meet the required bit error rate of the application. Further, the performance of our adaptive system is measured by its spectral efficiency. As illustrated by Fig-3, higher symbol rates guarantee higher spectral efficiency. However, higher symbol rates are possible only when channel conditions are good and when the ADC supports higher resolution to detect the symbol correctly. In this case, the ADC consumes more power to support the higher resolution. Thus, it is important to choose the modulation scheme and the ADC resolution based on the bit error rate, required spectral efficiency and available power on the system (See Figure 5).

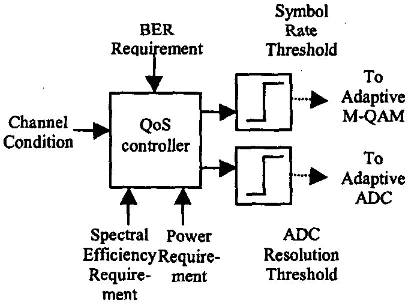


Fig-5 The block diagram of QoS controller

Two experiments are performed to show the effectiveness of the proposed system. The first experiment compares the power consumption of a system that uses our adaptive pipelined ADC system compared to that using a traditional fixed pipelined ADC. The second experiment involves speculating the relationship between performance and power consumption. This provides a means of determining the threshold for the QoS controller shown in Figure 5.

In these experiments, the wireless channel is modeled as a low Rayleigh fading channel. It is known that adaptive M-QAM is not feasible on fast fading channels. Each component's power value of Fig-1 is referenced using typical W-CDMA system examples of

RF micro device, Inc. [5]. The power consumption of adaptive pipelined ADC is obtained using Eq-3 and data sheets of Analog Devices' AD6644. Packet length is assumed to be 1500 bits/packet as nominal Ethernet packet. A raw data of 2Mbps and a T_{PLL} time of 1us are used as per W-CDMA specification.

The objective of the first simulation is to speculate the power savings when using adaptive pipelined ADC. To do this, the first step is the calculation of BER along with channel conditions. The channel condition is determined by the receiving power. The adaptive M-QAM's symbol rate is then determined based on the channel condition. The symbol rate threshold was determined by pre-simulated result to ensure required bit error rate (using Figure 3). The second step is to determine the ENOB of adaptive pipelined ADC. ENOB was calculated using Eq-4 and Eq-5. Based on the ENOB, the number of stages of the ADC pipeline that can be supply gated are determined to calculate the ADC's power consumption. Using Eq-1, parameters from RF micro device's W-CDMA model and the power consumed by the ADC, total energy is calculated. Finally, the energy values are normalized as given in Eq-2.

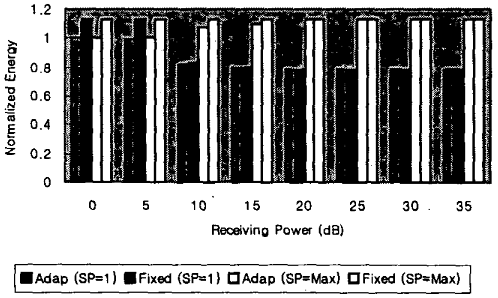
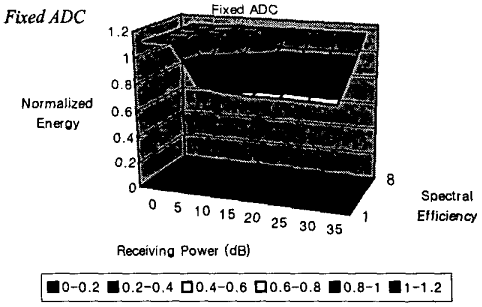


Fig-6 The energy impact of Adaptive ADC

In figure 6, energy consumption is calculated for two cases. The first two bars show the energy consumption for the minimum spectral efficiency case. The third and fourth bars are for the maximum (Shannon's) spectral efficiency. We observe that adaptive pipelined ADC can provide up to 17% energy saving on noisy channels.

The goal of the second experiment was to examine the relationship between power consumption and performance. In figures 7(a) and 7(b), energy value is calculated by varying the spectral efficiency when using fixed and adaptive ADC architectures. When fixed ADC is used, maximum energy is required to get maximum performance regardless of the channel conditions. But in the case of adaptive ADC, energy is optimized based on channel condition, especially in the case of noisy channel conditions. This means that the proposed ADC saves energy without any degradation of performance. Also using the above results, a decision rule can be defined in Fig-5, QoS controller.

(a) *Fixed ADC*



(b) *Adaptive ADC*

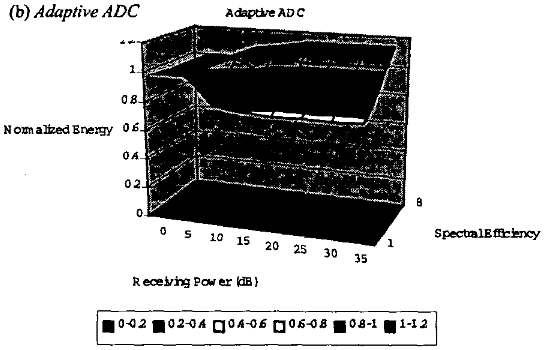


Fig-7 The energy comparison with different channel condition and spectral efficiency

6. CONCLUSION

An channel-adaptive pipelined ADC has been proposed. When it is used in a slow Rayleigh fading channel, up to 17% energy is saved when the cannel is noisy. An adaptive M-QAM system can be optimized with the respect to power using the proposed ADC.

7. REFERENCES

[1] E. Shih, et al, "Physical layer driven algorithm and protocol design for energy-efficient wireless sensor networks," *Mobicom 2001*, ACM, July 2001.

[2] A.J.Goldsmith, "Variable-Rate Variable-Power MQAM for Fading Channels", *IEEE Trans. on Comm.*, Vol.45. pp.1218~1230, October 1997

[3] S.H.Lewis, "Optimizing the stage resolution in pipelined, multistage, analog-to-digital converter for video-rate applications", *IEEE Trans. Circuits Sys. II*, pp.516~523, Aug. 1992.

[4] Mikael Custavsson, et al., *CMOS Data Converters for Communications*, Kluwer Academic Publishers, 2000

[5] http://www.rfmd.com