ISSN: 2321-2152

IJMECE

International Journal of modern electronics and communication engineering

E-Mail
editor.ijmece@gmail.com
editor@ijmece.com

www.ijmece.com

ISSN2321-2152www.ijmece .com
Vol 6, Issue 3Aug 2018

Modulation Scaling for Energy Aware Communication Systems

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ABSTRACT

In systems that require low energy consumption, voltage scaling isan invaluable circuit technique. It also offers energy awareness,trading off energy and performance. In wireless handheld devices,the communication portion of the system is a major power hog.We introduce a new technique, called modulation scaling, whichexhibits benefits similar to those of voltage scaling. It allows us totrade off energy against transmission delay and as such introducesthe notion of energy awareness in communications. Throughoutour discussion, we emphasize the analogy with voltage scaling. Asanexampleapplication,wepresentanenergyawarewireless

.COMMUNICATIONTHEORY

Sinceweinvestigatetherelationshipbetweenmodulationandtransmissionspeed,wefirstneedtoderivetherelevantexpressions.WefocusonQuadratureAmpitudeModulation(QAM)duetoitseaseofimplementationandanalysis[6].However,ourtechniquesareperfectlyextendabletoothermodulation schemes, only the formulas and curves will changeaccordingly. The performance of QAM in terms of Bit Error Rate(BER) is givenby(1)-(3) [7].

Keywords;energyawareness,adaptivemodulation,scaling

1.INTRODUCTION

Intetherless battery-operateddevices, power consumption is acriticaldesignaspect.Ithasbeenrealizedthatitis**energy awareness**, in addition to low power, that is required for mostapplications [1]. Scaling the supply voltage is the most commoncircuittechniquetoofferbothlowenergyconsumptionandenergyawareness[2].Inoperatingsystemresearch,theclockspeed and supply voltage are dynamically adjusted based on thepredictedworkload[3].Anotherapproach,proposed forself-The constellation size in number of bits per symbol is represented by b. The received Signal to Noise Ratio (SNR) is defined as (2), where PS is the transmit power and A contains all transmission loss components. The noise power Pn is a function of the symbol rate Rs, the noise power spectral density N0 and a factor □ that takes into account all other elements, such as filter non-idealities. [7]. We can manipulate these equations to obtain the following expression for the required transmit power:buffered load to steer the adaptation.

$P_S = C_S$

withawirelesscommunicationsubsystem.Amajorsourceoftheirenergy consumption is the actual data transmission over the air.Despitetheworkonenergyawarenessindigitalelectroniccircuits,ithasbeenoverlookedthatthesametradeoffsare present

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modulationcanbescaledmuchthesamewayasoperatingvoltagecan, reducingtheoverallenergyconsumptionfor transmitting eachbit. Althoughthe basic idea of changing themodulation on the fly has been used to increase the throughput inthepresenceof fading channels [6],ithas never beenexploitedforlow powerpurposes.We have applied this principle towardsan **energy awarewirelessscheduling system**.

Sinceourgoalistoinvestigatetheenergy-delaycharacteristics while varying the communication parameters we want to keep thesystem performance constant for a fair comparison. In practicalscenarios it makes sense to operate at a target BER. Due to theinverse$Q$(.)functionin (6), $C_s$is onlyaweakfunction of$b$.

Anenergy awarecommunicationsystem **adjusts*b*and *R*$_s$**toreducetheoverallenergy.ThetransmitpowerP_S(deliveredmainlybythe power amplifier),however,isnotthe onlysourceof

$P = \lceil C$

The total power consumption is the sum of both the transmit andelectronicspower.Asindigitalcircuitdesign,itmakesmoresenseto

$E_{bit} = (P_S + P_E) \cdot T_{bit}$isthetimeittakestotransmitonebit.The

goal is to minimize the energy per bit by choosing the correctvalues of b and R_s. For typical applications, however, we need toconstrain the total delay a packet may incur, translating to a boundon T_{bit}. Theoptimizationproblemcan besummarized as:

$\min E = \lceil$

$\cdot (2^b - 1) + C$

optiontotradeoffenergyversusdelay.Inpractice,$b$doesnot haveaninfinitesimalgranularitybuttypicallyonlytakesoneveni

PERFORMANCE TRADEOFFS

Our numerical results in this section are based on table 1. Thevalues of C_S,$C_E$and$C_R$are extracted from [8], which describesthe actual implementation of an adaptive QAM system. Figure 1depicts E_{bit}as a function of b and $R_s$as obtained from (10). Thecorrespondingvaluesof $T_{bit}$from (11)areshowninfigure2.Based on these two figures, we can evaluate the performance interms of energy consumption for varying constraints on the delay(i.e. varyingT_{max}).

introducesthetermwithconstantC_R.Sincetheoptimalsymbol rate is always the maximum one, a variable symbol rate provisionis notneededfor energy awareness reasons. In fact, the **systemcan be designed for a fixed symbol rate** instead. The circuitrythat is described by the term with constant $C_R$is still present ofcourse. We therefore cannot simply remove this term. However,we modify equation (10) by setting R_{Smax}equal to R_S, such that theenergyper bitis nowexpressedas:

1

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powerspending.Electroniccircuitryforfiltering,modulating,upconverting, etc. contributes as well. Equation (7) expresses thiscomponent$P_E$forasystemthatcandynamicallychangethesymbol rate [8]. Parts of the circuitry operate at a frequency thatfollows the instantaneous symbol rate, while other parts have afixed frequency proportional to the maximum symbol rate. Theproportionality factors and switching activity are all incorporatedin $C_A$andC_B.

Table1:Simulationsettings

R_{Smax}	1 MHz
BER	10^{-5}

$C_S(b=4)$	10^{-7}
C_E	8.10^{-8}
C_R	10^{-7}

lookattheenergy consumptionratherthanthe totalpower. Wecan expresstheenergyto transmit onebit,E_{bit}, as:

b

Figure2:Delayperbit ***R_S(MHz)***

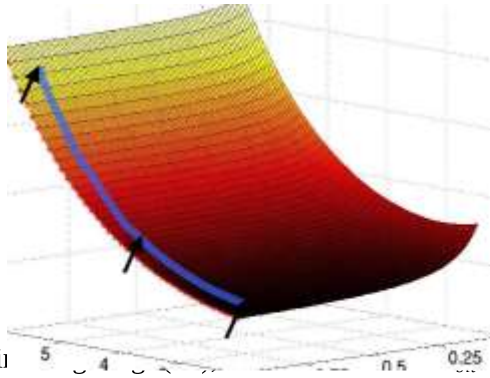
From these figures, it is clear that operating at the maximum $R_S$ispreferable for any b. This is logical as this results in both a lowerT_{bit}anda lower E_{bit}. The symbol rate should therefore be chosenashighaspossible,consideringimplementationissuesandtheir

ntegers, indicated bytheblackarrowsin figures 1 and 2. Notethattheresultsoffigure1areforacommunicationsystemthathasprovisionstovarythesymbolrateonthefly.In(7),this

]

min

E –



Upon i[...] no longer a functionofthesymbolrate.Sinceahigher$R_s$stillresultsin alowerT_{bit},itis still beneficial to operate at the highest symbol rate that can beimplemented efficiently. The reason is that besides the advantageoflowerdelays,thiswouldalsoimprovethecapacityifthewireless medium were shared. We can visualize the energy anddelay curves by taking the intersection of the surface in figures 1and 2withaplaneat R_S=1MHz.

It is clear that energy and delay can be traded off against eachother by varying *b*. In analogy with voltage scaling techniques indigital circuits, we refer to this process as

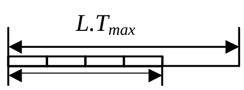
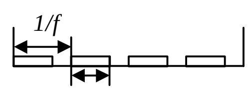
Communications	DigitalCircuits
$P_S=C_S\cdot G_S\cdot R_B\cdot\frac{(2^b-1)}{b}$	$P_S=\alpha\cdot C\cdot f\cdot V_L^2$
$P_E=[C_E+C_R]\cdot\frac{R_B}{b}$	$P_L=V\cdot I_0\cdot e^{\frac{V}{nV_T}}$
$R_B\geq\frac{1}{T_{\max}}\Rightarrow b\geq\frac{1}{R_S T_{\max}}$	$\frac{1}{t_d}\geq f\Rightarrow\frac{(V-V_t)^2}{V}\geq\frac{C_L}{k}\cdot f$
$E=(P_S+P_E)\cdot\frac{1}{R_B}$	$E=(P_S+P_L)\cdot\frac{1}{f}$
	

Figure3:Comparisonbetweenadaptivemodulationandvoltagescaling

3. COMPARISON BETWEEN VOLTAGESCALINGANDMODULATIONSCALING

Theequationsinthepreviousssectionsresemblethoseofvoltage scaling,yettherearesomekeydifferences.Itisimportantto highlightthesedifferences,astheyalsocontributetoaphysical understandingofthetradeoffsofmodulationscaling.Figure3 places both scaling techniques next to each other. In the equationsfor voltage scaling, $P_S$is the switching power and $P_L$the leakagepower [3]. It is clear that **the functionality of supply voltage *V*corresponds to that of the constellation size *b*** (hence the termsvoltage and modulation scaling). In the left column, the energy isonly dependent on *b* and not on R_B.Equivalently in the rightcolumn,theenergytermduetotheswitchingpower(P_S/*f*)depends on *V* and not on *f*.There is however a crucial difference,regardingtheinterpretationoftime.

In the digital circuit case, the total effective delay for an operation$t_d$has to be smaller than *1/f*. Similarly in a communication systemthe total time it takes to transmit a packet (or a bit) has to besmaller than a certain maximum value. **The difference betweenbothsystems,however,istheperiodoverwhichenergyis consumed**.Inacommunicationsystem,thepowerhastobemultipliedbythe**effectivetime**oftheoperation.Indigitalcircuits, on the other hand, the power is multiplied by the cycletime, which is in effect the maximum delay. As such, there is notrue one-to-one mapping between R_B(or$R_S$for that matter) and *f*.However,whenconsidering$R_B$and*f*asconstantsofthesystem,

The average packet arrival rate is denoted by λ. The inverse of theaverage service time is called the service rate, μ, which gives theaverage number of packets that can be sent per unit time. It isexpressed by(13),where*L*istheaveragepacket size.

(13)

L *L*

Because of the statistical properties of inter-arrival and servicetimes, the number of packets in the buffer may vary considerably.Most of the time, the buffer is empty. In those situations, it isbeneficial to scale the modulation down to conserve energy. Whenthe buffer starts to fill up, we can increase *b* to avoid long queuingtimes or buffer overflow. This kind of system therefore is a goodcandidate for modulation scaling. A similar observation has beenmade for digital circuits, where a queue is introduced to averagetherateoverseveral samples inaDSPsystem[5].

Theideaistochoosetheconstellationsizebasedonthenumber of packets in the system (i.e. being transmitted or inthe queue), which we refer to as the system state. For each stateS_n = *n*, we have a particular constellation size b_n, which translatesintoavalueof$\mu_n$throughequation(13).Thecollectionof{b_n}forallthepossiblestatesdeterminestheaverageenergyconsumption and delay of the queuing system. Our goal is to findwhich {b_n} minimizes the energy for a particular delay constraint.We can analyze this problem using queuing theory.In steadystate, theprobabilityofbeingin state$n$ canbeexpressed as[9]:

λ

theyresultinalowerboundon$b$or$V$insimilarways(seethe third lineofequationsin figure3).

n

n

(14)

4. ENERGYAWAREWIRELESSPACKET SCHEDULING

Like energy aware OS scheduling, we can perform energy awarepacketscheduling.Westudy thecommunicationsystem setupdepictedinfigure4,whichconsistsofapoint-to-pointtransmissionlink.Packetsarriveatthesenderandpossiblyneed tobebufferedbeforetransmission.Weassumethatboththepacket sizes and the intervals between packet arrivals, called inter-arrivaltimes,followanexponentialdistribution.Withoutmodulatio nscaling,thissetupcorrespondstothewell-known

In this equation, $P_0$is a constant such that the sum of $P_n$over allstates is equal to 1. We assume an infinite buffer size, which is areasonableapproximationforrealsystems,asmemoryhasbecome rather inexpensive for these applications. For each statetheenergyconsumption per bitisgivenby(12).

The average energy per packet, E_{av}, is the ratio of the averagepower per packet and the packet arrival rate. The average power isthe product of the probability $P_n$of being in a state, the rate $\mu_n$inthatstateand theaverageenergyperpacket ($E_n.L$) in that state:

M/M/1 queuingsystem[9].

λ μ

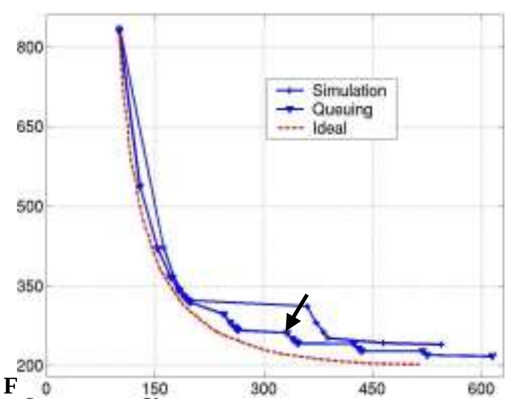
And, according to queuing theory, we can write down the typical packet delay as [9]:

5. We have used the parameters from table 1 for our numerical assessment and subsequent simulations, with some additional parameters from table 2. Figure 5 shows the average performance of the queuing system for a given set of bn as a function of energy and delay. For a given delay requirement, we have only shown the operating positions that provide the lowest energy. The ideal system that permits fractional values of b is shown by the dotted curve. The 'Queuing' curve is the one we really use, and it's the one we get when we choose b from the set of even numbers. The bn values for the arrow's operational point are listed in Table 3.

6. Yet even this approach is challenging to put into reality due to the need of readjusting the modulation whenever the system state changes. This implies that the size of the constellation may shift whenever a packet enters or leaves the queue. However, the constellation size and any changes to it must be conveyed to the receiver for it to be able to decode the signals.

7. In most cases, it is best to adjust the constellation size once, at the start of the packet transmission, rather than repeatedly throughout. The modulation type used for the packet's data, indicated by a header field encoded with a constant modulation. The number of packets in the transmission queue determines the modulation scaling factor. Figure 5 shows the results of such a realistic simulation of the scheme's performance (it includes the overhead due to the indicator). Since the modulation is only adjusted when a packet begins transmission, rather than whenever the number of packets in the system varies, there is a penalty when compared to the theoretical queuing system. We can use the curve in Figure 1 to determine the optimal operating point for this realistic system given a certain delay limit.This operating point defines the values of$\{b_n\}$ that have to bechosen.

E_{av}



F _

delaytradeoffforanenergyawarequeuing system

λ(packets/s)	5000
L(bits)	400
μ_n(packets/s)	$2500 \cdot b_n$

a ble3:Settingsforanexampleoperatingpoint

[11] .".

Settings for the simulation are shown in Table 2.

1 Tav n nPn

n0 (17)

S_n	1	2	3	4	5	≥ 6
b_n	2	4	4	4	6	6

8. CONCLUSIONS

We have presented modulation scaling, which allows us to designenergy aware communication systems. We have highlighted thesimilarities and differences compared to voltage scaling used indigital circuits. A lot of approaches that have been explored in thecontext of voltage scaling can be applied to modulation scaling aswell. We have investigated this for energy aware wireless packetscheduling. However, many other applications can be envisionedthatbenefitfrommodulationscaling.Alsotechniquesthatimprove the system's energy performance canbe incorporatedinto thisframework, suchasparallelism.

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