AN ENERGY-EFFICIENT CROSS-LAYER ADAPTIVE MODULATION AND CODING SCHEME FOR SOFTWARE DEFINED RADIO

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ABSTRACT

In this paper, a simple and novel cross-layer adaptive modulation and coding (AMC) scheme, which increases the energy efficiency of the wireless communication system is proposed. Traditionally, AMC has been used to improve MAC-layer performance in terms of coded bit error rate, packet error rate, and throughput. The modulation and coding scheme is switched according to signal-to-noise ratio thresholds at the PHY layer. We extend the approach, proposing a framework for energy-efficient cross-layer AMC that captures the impact of both MAC layer and PHY layer parameters on the AMC switching criteria. Cross-layer designs are naturally suited to software defined radio applications. Not only are they readily implemented in software, but also they are integral to the radio components. They can optimize performance of the radio either for a given configuration or adaptively. Through an example of CSMA/CA MAC layer and WLAN physical layer, we demonstrate our AMC scheme and verify its effectiveness by simulation.

1. INTRODUCTION

Wireless communication has experienced rapid development in the past several decades seeing its usage extended from personal voice communication to TCP/IP based data communication. Broad applications ranging from low speed sensor networks to broadband internet services challenge existing systems in many ways. One of the key challenges is energy consumption for hand-held or unattended battery-powered user terminals. Users are sensitive to the usage time between battery recharge or replacement. Moreover, for many scenarios, such as a wireless sensor network, the user terminals may be located in areas without easy access for recharging or replacing the battery. For these systems, energy-efficient operation of terminals has become essential.

Adaptive modulation and coding (AMC) has been proposed as a method to push the transmission link closer to the channel capacity by matching the transmission scheme to the channel conditions [1]. The aim is to send high rate data in favorable channel conditions, typically high signal-to-noise-ratio (SNR), yet maintain the link with lower rate transmission in less-favorable conditions. In most cases, the AMC adopts some form of energy constraint. This is either a short-term constraint limiting maximum transmission energy for every time domain symbol, or a long-term constraint limiting other characteristics of the transmission such as the power spectrum. For example, a physical (PHY) layer AMC scheme adapting quadrature amplitude modulation or phase-shift keying modulation to channel conditions was proposed in [2].

Unlike a wired network, a wireless communication system is more vulnerable to environmental interference or distortions. To ensure the quality of wireless data transmission, higher layer quality control measures are widely used. These measures will affect the energy consumption of the whole transmission. Therefore, it is necessary to optimize the energy consumption from a cross-layer point of view. For packet-based networks, the main concern is the rate of packet loss for the medium access control (MAC) layer rather than the bit error rate (BER) implied in channel capacity and data rates at the PHY layer [3]. Taking both the MAC and PHY layers into consideration, cross-layer design enables further improvement of the system performance. For example, in [4], a joint packet retransmission and AMC scheme that is robust to the feedback delay was proposed to maximize throughput under the assumptions of fixed packet length and fixed target BER. In [5], a method to maximize throughput by jointly adapting the packet size and modulation scheme to SNR was proposed. These schemes, like many AMC proposals, target a fixed BER. This additional constraint may not be required to meet the throughput objective.

Although AMC has been studied for some time, applying AMC for the purpose of energy saving is relatively new. In [6], AMC is used to minimize energy consumption at the PHY layer with delay and peak power constraints. In this paper, we consider both PHY and MAC layer. In [7], a cross-layer method for minimizing energy consumption was

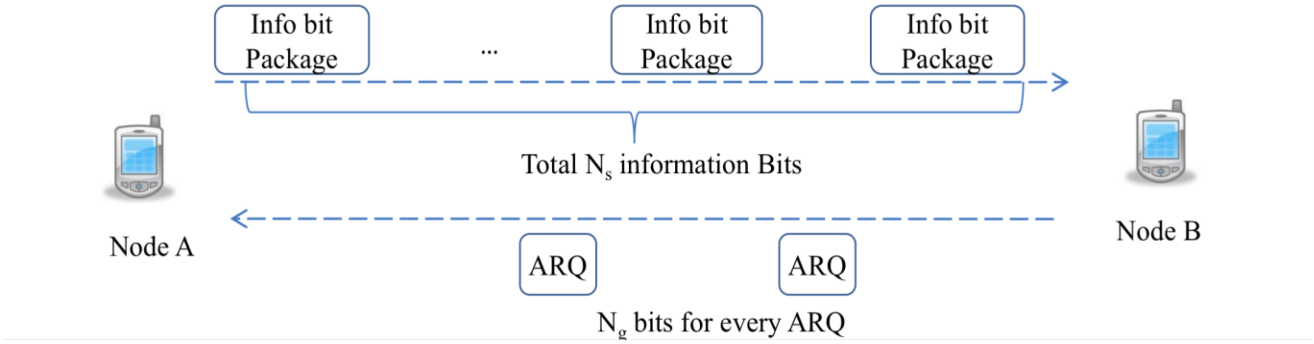

Figure 1. Packet-based transmission system between two battery-powered user terminals, node A and node

proposed. Energy saving was achieved, not by AMC, but rather by adapting the transmission power.

In this paper, we propose an energy-saving cross-layer AMC scheme. Instead of constraining our optimization in terms of packet error rate (PER) or BER performance for SNR, we optimize the system for successful transmission of a given amount of information. We are motivated by application to the most power and energy sensitive networks, that is, those that rely on batteries at both ends of transmission.

Energy-efficient cross-layer designs are particularly suited to software defined radio (SDR) applications. SDR technology is being used more and more widely for mobile and remote user terminals where battery-life is important. At a system level, protocol combinations and processing components can be selected and configured based on user utility, for example interoperability, delay tolerance, spectrum-efficiency, energy-efficiency, quality-of-service or throughput requirements. The very nature of SDR facilitates flexibility in the combination of PHY and MAC layer instantiations.

In terms of energy-efficient SDR, one approach is to have a run-time controller that is energy-aware, selecting processing components, for example within the PHY layer baseband processing, scaled for processing capability and energy consumption [8]. This is a solution with a direct energy and performance or quality-of-service trade-off.

While such high-level energy management may still be applied, when cross-layer design is used, it is integral to the components selected by the SDR. The software controller has the flexibility to reconfigure the complete radio depending on user requirements and application, channel availability and condition. For example, the radio may be configured at the PHY layer as GSM, CDMA or OFDM. The SDR could configure OFDM for a high data rate application in a relative good channel environment and CDMA for low rate application in a low SNR channel with significant fading. Cross-layer designs optimize the system within the particular configuration, and may even adapt to different configurations without intervention of the run-time controller.

With energy-sensitive SDR application in mind, this paper proceeds by considering the total energy consumption of the both transmitter and receiver to transmit certain amount of information from node A to node B in a network. A brief system description is given in section 2. A new framework for the AMC to improve energy efficiency is presented in section 3. We verify our result by simulation of a case study based on WLAN network in section 4. The paper concludes in section 5.

2. SYSTEM DESCRIPTION

In this paper, we consider the scenario that a single link connects two user terminals or nodes in a wireless network. We assume the link quality in terms of SNR, is known to the transmitter, either through a feedback loop or by measuring the reverse channel quality. In some cases, the SNR could vary as the channel conditions change, and accurate estimation of the SNR could be a challenging task for the nodes. To simply our framework, we assume the SNR remains unchanged for the transmission period. We define this transmission period to be the total time that the source, node A, spends transmitting and possibly retransmitting the packet to the destination, node B, in order for node B to successfully receive N_s bits of information. Our target is to minimize the energy used by both node A and B in successfully transmitting and receiving the N_s bits.

As shown in Figure 1, we consider a system with MAC-layer error control based on an acknowledge-repeat-request (ARQ) message sent through a feedback channel from node B to node A. The receiver, node B, calculates a cyclic redundancy check (CRC) from the received and decoded data and compares it to the CRC message attached transmitted data by node A. If the CRCs match, an acknowledgement is sent in the ARQ packet; if there is an error, the ARQ message contains a repeat request.

Typically, when an error occurs, node B will discard the whole packet and await retransmission by node A. We note that more sophisticated ARQ systems are possible, such as incremental redundancy [9] and the framework can easily be extended to accommodate these.

The MAC-layer ARQ mechanism ensures that each packet is correctly received. The total transmission time, including retransmissions, will of course depend on the channel condition. The drawbacks of this ARQ scheme are that is requires an additional time slot (channel resource) and energy from node B to transmit the ARQ message in the feedback channel. In our system, we assume there is an average overhead of N_g bits is transmitted as feedback from node B to node A every time a length N_p packet is transmitted from node A to node B. These N_g bits include the ARQ information and any other overhead generated by control signals, such as request-to-send (RTS) and clear-to-send (CTS) signals in an 802.11wireless local area network (WLAN). To simplify the system, we assume these control signals are sent using BPSK modulation and are always received error-free by node A. We also consider the impact of carrier sense multiple access with collision avoidance (CSMA/CA) on the system performance. In the following section, we will discuss the energy consumed to transmit N_s information bits from node A to node B in this system.

3. ENERGY CONSUMPTION OPTIMIZATION

In this section, we analyze the energy consumption of the system described in Section 2, and propose a method to efficiently adapt the packet length and modulation and coding scheme (MCS) according to both SNR and the number of information bits to be transmitted. Though different modulation and coding schemes yield different power consumption in digital circuits, the difference is insignificant compared with analog or radio frequency (RF) circuit power consumption [6]. Thus, in this paper, we ignore the energy consumed by a digital circuit and focus on the energy consumption as a function of the active time of the transceiver (radio frequency front-end, analog circuits and digital circuits) under different modulation and coding schemes.

Assume there are M possible modulation and coding combinations (i.e. MCSs) for the system and N_m denotes the corresponding number of bits per sample in the baseband system. The parameter N_m accounts for both the coding and mapping of coded bits to modulation symbols. Thus, the total number of time domain samples required to transmit N_s bits from node A to node B is given by

$$N_T = \frac{N_s}{N_m} \tag{1}$$

In a noise free channel, where only N_T samples are required for successful reception, it is straightforward to see that for a given N_s, N_T is inversely proportional to N_m, and the larger N_m is, the more energy-efficient the system is. However, in a noisy channel, a large N_m generally yields larger bit error rate (BER) which will result in a retransmission in a wireless network. The BER is generally a function of SNR and is related to different modulation and coding schemes. Assuming the SNR is γ, then the BER is a function of SNR for each MCS m, and let this be denoted as $p_b = f_m(\gamma)$. As SNR increases, the BER decreases, and the function depends on the MCS. The expected number of bit errors during the transmission of N_s information bits will be $N_e = p_b \cdot N_T$. Clearly, a smaller BER reduces the likelihood that a retransmission is required. For an MCS with small N_m, the number of time domain symbols N_T is larger, and so with fixed transmission energy per symbol, it takes more energy to transmit the same amount of data. However, an MCS with small N_m typically has lower BER for the same SNR, meaning that less energy will possibly be consumed by retransmission. Herein lies the energy trade-off.

In our packet based system, the node B receiver uses only the CRC message to judge whether the received signal is error free, and the whole packet will be discarded and retransmitted if any error occurred. The packet error rate (PER) will be

$$\begin{aligned} p_e &= 1 - (1 - p_b)^{N_p} \\ &= 1 - \alpha^{N_p} \end{aligned} \tag{2}$$

where N_p is the number of bits in one packet. It is obvious that the larger the N_p, the higher the possibility that an error will occur in the packet.

On the other hand, consider the energy consumption of transmitting one packet. We write this here without loss of generality, using a normalized symbol time

$$E_{pt} = \frac{N_p}{N_m} P_t + N_g P_g \tag{3}$$

where as before N_m is the number of bits in one time domain sample, P_t is the energy used to transmit data, N_g is the number of overhead bits associated with packet transmission transmitted in BPSK (1 bit per symbol) using energy P_g.

Another component of the energy consumption is the energy used for retransmission. If we assume the transmission energy does not change for the retransmission, given the packet error rate p_e, expected number of retransmissions is given by

$$N_R = p_e + p_e^2 + \ldots.. \tag{4}$$

Since p_e<1, applying Taylor series and equation (2) to equation (4), we can get

$$N_R = \frac{p_e}{1 - p_e} = \frac{1}{\alpha^{N_p}} - 1 \qquad (5)$$

In addition to the case where bit errors caused by noise or interference make a retransmission necessary, retransmission will also occur when there is a collision in CSMA/CA based access control system or when there is interference from some other transceiver such as a radio using the same band. Denote the number of retransmissions caused by collision or interference as N_r, then the total expected energy consumption for transmission and retransmission of a packet is given by

$$\begin{aligned} E_{ptotal} &= \frac{N_p}{N_m} P_t + N_g P_g \left(1 + N_r + N_R\right) \\ &= \frac{N_p}{N_m} P_t + N_g P_g \left(N_r + \alpha^{N_p}\right) \qquad (6) \end{aligned}$$

To transmit N_s information bits, N_s / N_p packets are required. So the total energy consumed in transmitting these information bits on average is

$$E_{total} = \frac{N_s}{N_p} \frac{N_p}{N_m} P_t + N_g P_g \left(N_r + \alpha^{N_p}\right) \qquad (7)$$

The three multiplication items in equation (7), from left to right, represent the number of packets corresponding to the N_s information bits, the energy consumption per transmission for every packet, and the average number of transmissions (including retransmissions) required for each packet respectively. It is evident that the total energy depends on both PHY layer parameters as well as MAC layer parameters. Equation (7) reveals the dependency between energy consumption and the packet length. When N_p is small, the number of packets N_s / N_p will be large and so will the number of ARQ packets transmitted on the feedback channel. Energy may be wasted on transmitting this ARQ signal. When N_p is large, the number of packets N_s / N_p will be small. However, the other two items in equation (7), being the energy and the number of retransmissions, will be large. It is straightforward to see that the energy consumption in the second term, is linear in N_p. For the third item, since α is smaller than 1, the α^{-Np} will increase with the increasing of N_p, so will the average number of transmissions $N_r + \alpha^{-Np}$. Therefore, it is apparent that making N_p too large may increase the energy used for retransmission by increasing both chance of retransmission and the energy used for every retransmission. Thus, we can efficiently reduce the total energy consumption by optimizing the packet length, N_p.

We can locate the minima of equation (7) by setting the first derivative function of E_{total} to zero. To reduce the complexity, we make some assumptions about the system. To keep the flexibility of the system, we assume the target BER is adaptive to the available SNR and modulation/coding scheme. Instead of separately considering channel errors and access collisions, we assume p_b reflects the collision and other interference errors. So in equation (10), we can remove N_r. Furthermore considering the radio front end circuits and the analog circuits, we find that most of devices have a fixed dynamic range to provide best performance or most energy efficiency. Thus, a fixed transmission energy is more efficient and achievable in practice. We assume a transmitter working at maximum and constant transmission energy given by P_t and as assume that both the node A and node B have the same transmission energy, i.e. $P_g = P_t$. Based on these assumptions, the optimal length is given by

$$N_{p,op} = \frac{N_m}{2} \sqrt{\frac{\ln \alpha N_m N_g^2 - 4 N_g}{N_m \ln \alpha}} - \frac{N_m N_g}{2} \qquad (8)$$

In this section, we studied the total energy consumed during transmission of a certain number of information bits from source node to the target node. By considering the retransmission power, our framework includes the MAC impact in an adaptive modulation and coding scheme. In the next section, we will show an application of this method in a WLAN system.

4. CASE STUDY OF WLAN SYSTEM

In this section, we show how to apply equation (7) and (8) to choose the best modulation and coding scheme (MCS). We can use a BER table rather than a theoretical equation to obtain the parameter α for a given SNR. This table can be obtained by testing the actual hardware so as to include all the physical layer effects on the bit error rate. Such effects include channel fluctuations, channel estimation errors, RF imperfections as well as access collisions. Based on this BER and equation (8), we can calculate the optimal packet length.

In equation (8), we notice that N_m, N_g are pre-defined system parameters, so we can pre-save some items to reduce the real-time computation requirements. After the optimal packet length is obtained, the corresponding energy consumption can be calculated using equation (7).

MCS ***m***	**#1**	**#2**	**#3**	**#4**
link Mbps	6	9	12	18
modu-lation	BPSK	BPSK	QPSK	QPSK
code rate	½	¾	½	¾
N_m	0.5	0.75	1	1.5
SNR	**BER, p_b, measured from WLAN simulation**			
9 dB	0.018	0.0101	0.0178	0.1082
10 dB	0.006	0.008	0.0109	0.0420
11 dB	0.002	0.003	0.0031	0.0122
12 dB	0.0005	0.001	0.002	0.0041
13 dB		4.38e-8	4.125e-7	2.18e-4

Table 1. Parameters for WLAN MCSs used as input to proposed cross-layer AMC scheme in case study.

Comparing the total energy consumption associated with each MCS, the transmitter can choose the most energy efficient scheme for transmission.

For our case study, we consider a single link between node A and node B in an orthogonal frequency division multiplexed (OFDM) WLAN system. WLAN can achieve 6 Mbps to 54 Mbps data rate with BPSK to 64 QAM modulation and rate 1/2, 3/4 and 2/3 convolutional coding. There are a total of 80 time domain symbols per OFDM symbol with 64 data symbols and 16 cyclic prefix symbols. In a typical WLAN system, the MAC layer defines the physical layer packet length based on the number of higher layer data to transmit.

In the simulation, we assume the SNR is in the range of 9dB to 12dB and the possible MCS as listed in Table 1. A multipath-A channel [10] is used in the BER testing and the collision rate is assumed to be once in every 10^7 samples transmitted. Table 1 summarizes the MCS schemes and provides a look-up reference for the number of information bits per time domain symbol, N_m as well as the BER, p_b, measured here during simulation for each MCS and SNR. Note that $\alpha = 1 - p_b$.

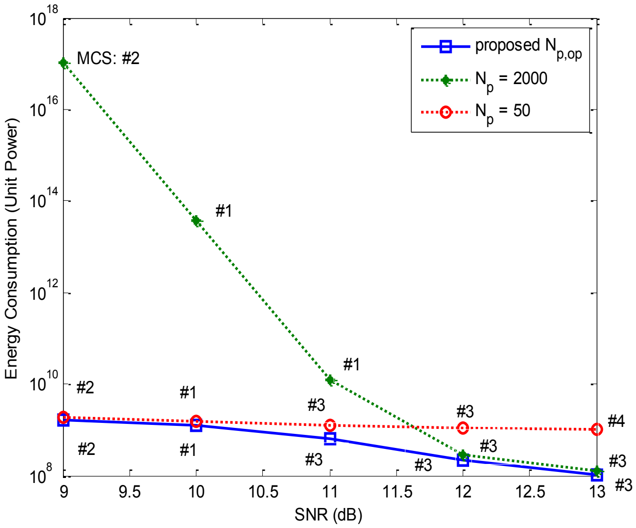

Figure 2. Energy consumption vs SNR for AMC using fixed packet length, N_p, and proposed optimized packet length for energy-efficiency.

Figure 2 shows the average energy consumption for transmitting $N_s = 10^8$ bits from node A to node B through channels with different SNR, calculated using equation (7). We assume the length of the feedback ARQ message, N_g, is 480 bits, equivalent to 6 OFDM symbols. The x-axis is SNR in dB and y-axis is the energy consumption normalized by the symbol period. Equivalently this is the energy consumption per symbol period. Three curves are shown, one with fixed packet length $N_p = 2000$, one with fixed packet length $N_p = 50$, and the third using our proposed AMC scheme which also optimizes packet length to minimize total energy consumption. In all cases, the modulation and coding scheme is switched to achieve the lowest energy consumption.

Figure 2 clearly shows the impact of using different packet lengths, N_p. The curve for $N_p = 2000$ shows that long packets experience large energy consumption when the SNR is low. This comes from the higher packet error in low SNR range. More energy is wasted on the retransmission. For short packets, the packet error rate will stay low but more energy is used on the overheads in the ARQ packets. Figure 2 shows when the packet length is 50 bits and fixed N_g/N_p, the energy consumption is almost flat over SNR, but clearly consumes more energy than the longer packet lengths when the channel condition is good at high SNR. Thus, adapting the packet length as proposed in our scheme, we can significantly reduce the energy consumption in both low and high SNR regimes.

Figure 2 also shows which MCS scheme was used by each of the packet length scenarios to achieve the minimum

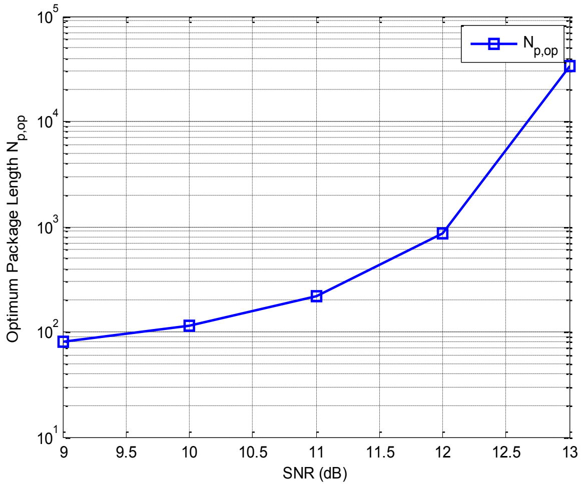

Figure 3. The Optimum Packet Length vs SNR

energy consumption for each SNR. The detailed MCS parameters corresponding to the labels are as given in Table 1. At some SNR values (see for example 11 and 13 dB),

different packet length schemes adopt different MCS. This shows the interaction of packet length and MCS scheme for energy optimization. In the low SNR range, all three schemes use the lowest BER MCS scheme. For example, at 9 dB, they all use #2 MCS scheme because a collision happened in #1 scheme making its effective BER larger than that for #2 (see Table 1). When the SNR increases to 11 dB, the shorter packet length schemes move to an MCS scheme with higher $N_m = 1$. The scheme with longest packet length, $N_p = 2000$, still suffers from a relatively large PER and so stays with smaller $N_m = 0.75$ in order to minimize the number of retransmissions and overall energy consumption. At an SNR of 13 dB, the effect of packet length on PER is again seen, with only the scheme with shortest packet length adopting the MCS with highest $N_m = 1.5$. However, shortest packet length does not correspond to minimum energy consumption at 13 dB. Figure 3 shows the value of the optimum packet length, N_p versus SNR for this case study.

5. CONCLUSION

In this paper, we have analyzed the energy consumption of packet-based transmission when a quality control signal is used in the link. We show that the total energy consumption is related to both PHY layer and MAC layer parameters. In a platform such as a software defined radio, with the help of cross-layer design, the transmitter will be able to adapt packet length and MCS to link quality and different MAC settings as well as PHY layer parameters. The simulation result in section 4 shows that by introducing adaptive packet length, we efficiently reduce the energy consumption for a transmit session.

6. REFERENCES

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