Exploiting Fading Dynamics along with AMC for Energy-Efficient Transmission over Fading Channels

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***Abstract*—The basic adaptive modulation and coding (AMC) in its lowest mode blindly transmits the frames without payload during outages, which wastes energy. In this letter, we propose to exploit fading dynamics (FD) along with AMC to achieve a higher energy efficiency. In the proposed FD-AMC approach, the frame transmission is suspended judiciously during the outages, thereby saving energy, particularly in harsh channel conditions.**

***Index Terms*—Adaptive modulation and coding (AMC), channel-aware transmission, fading channel, energy saving.**

I. Introduction

To enhance the channel utilization, adaptive modulation and coding (AMC) scheme is widely advocated at the physical layer [1], [2]. In AMC, when the channel offers a high signal-to-noise ratio (SNR), the system switches to a higher constellation, whereas lower modulations are smoothly adopted in unfavorable channel conditions. In bad channel conditions, the AMC scheme results in communication outage, which is more severe when the average SNR of the channel is low. The delay caused by this outage phenomenon makes such adaptive strategies suited for delay-tolerant applications.

Alternatively, for delay-tolerant applications, the effect of channel fading can be mitigated by relying on automatic repeat request (ARQ) protocol at the data link layer. It was shown in [3], [4] that, rather than implementing AMC and ARQ separately, a joint design provides a higher spectral efficiency.

The outage mode zero is an intrinsic part of the systems adopting AMC with or without ARQ. In a slow fading scenario, where deep fade continues over several consecutive frames, the system may remain in mode zero for a long time, blindly transmitting the overhead frames without payload, which causes a significant energy wastage.

In this letter, exploiting fading dynamics (FD), we propose an energy-efficient transmission policy, named FD-AMC, which can track outage durations and postpone the transmission judiciously without significantly affecting the delay performance. Through mathematical analysis and MATLAB simulations, we demonstrate the energy saving performance of the FD-AMC strategy with respect to the basic AMC scheme.

II. System Model

We consider the AMC system as in [5], with M number of transmission modes and 2^m-ary quadrature amplitude modulation (QAM) mapping for mode m, where $m = 1, 2, \cdots, M$ [6]. A physical layer frame may contain multiple upper layer packets for higher transmission modes m. We assume, a frame contains only one packet if the mode is $m = 1$ in that frame. We also assume, the channel state remains constant during a frame transmission period T_f and the transmitter-to-receiver propagation delay is negligibly small. In this study, we take constant power adaptive coded modulation as the basic AMC strategy [5], which is designed to maximize the data rate while maintaining a certain packet error rate (PER) performance. If $\mathcal{P}_0$ is the acceptable upper limit of PER, then the instantaneous PER should not exceed $\mathcal{P}_0$ for any chosen AMC mode. For coded QAM modulation, the mode-dependent approximate PER-SNR relationship is obtained as [3]:

$$\mathcal{P}_m(\gamma) = \begin{cases} 1, & \text{if} \quad 0 < \gamma < \gamma_{pm}, \\ a_m \exp(-g_m \gamma), & \text{if} \quad \gamma \geq \gamma_{pm}, \end{cases} \tag{1}$$

where a_m, g_m, and γ_{pm} are the mode-dependent parameters [5]. A mode index m is selected if the instantaneous received SNR $\gamma \in [\gamma_m, \gamma_{m+1})$, where γ_m are the switching thresholds for rate adaptation and are obtained using (1) as

$$\begin{aligned} \gamma_m &= \frac{1}{g_m} \ln\left(\frac{a_m}{\mathcal{P}_0}\right) \quad \text{for} \quad m = 1, 2, \cdots, M, \\ \gamma_0 &= 0, \quad \gamma_{M+1} = +\infty. \end{aligned} \tag{2}$$

Note that, in deep channel fades, i.e., when $\gamma \in [0, \gamma_1)$, AMC system switches to mode 0 (i.e., it sets $m = 0$) by blocking the payload transmission. But it continues to transmit the frame overhead content blindly after each frame round trip time, which wastes energy until the channel recovers again.

A. The proposed FD-AMC scheme

In FD-AMC, all transmission modes are used as in AMC, and the switching thresholds are obtained from (2). In mode 0, unlike in AMC, FD-AMC stops frame transmission and waits for t_w time, anticipating that the channel would recover within that duration. After waiting for t_w, it resumes transmission.

As we will show in Section III-B, an optimum waiting time $t_w^{(opt)}$ can be chosen that minimizes the total energy consumption in FD-AMC scheme. But, this waiting may reduce the data delivery rate, because waiting up to $t_w^{(opt)}$ time may occasionally result in loss of transmission opportunity when fading recovers before $t_w^{(opt)}$.

Intuitively, the waiting period t_w should be a function of the time varying fading state. To track the fading channel dynamics, t_w should be dependent on the channel characteristics like average SNR $\overline{\gamma}$ and Doppler shift f_d. We have considered different average fading duration (AFD) dependent t_w values other than the optimal one, which offer different trade-offs

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between energy saving and delay. Here, we propose an AFD dependent solution that has the minimum delay trade-off.

For a good estimate of the fading duration, instantaneous received SNR γ is fed back to the transmitter whenever receiver decides to switch to mode 0. For Rayleigh fading channel, the average duration that the received SNR remains below a certain threshold γ_{th} is given by [7]:

$$\text{AFD}(\overline{\gamma}, \gamma_{th}, f_d) = \frac{e^{\rho^2} - 1}{\rho f_d \sqrt{2\pi}}, \tag{3}$$

where $\rho = \sqrt{\frac{\gamma_{th}}{\overline{\gamma}}}$. To achieve a minimum delay trade-off, we suggest the value of t_w as:

$$t_w^{(1)} = \frac{\text{AFD}(\overline{\gamma}, \gamma_1, f_d) - \text{AFD}(\overline{\gamma}, \gamma, f_d)}{2}, \tag{4}$$

Note that, in the fading state (mode 0), $\gamma < \gamma_1$. Thus, $t_w^{(1)}$ depends on γ – which helps track the fading duration faster, and the chosen value of γ_1 – to achieve a desired PER $\mathcal{P}_0$.

III. Energy and Delay Efficiency Analysis

A. Performance indices

We evaluate the performance of the transmission strategies with respect to energy and delay efficiencies. The energy efficiency measure $\mathcal{E}_p$ gives battery the energy consumption (in Joules) per successful (fixed sized) data packet, which accounts for the transmit power e_t, receive power e_r, and idling power e_w. We consider a long time period T during which the transmitter continues to attempt data delivery, and that the node has an unending pool of data packets to send. Let N_s be the number of successfully received data packets, and N_f be the total number of physical layer frames transmitted, out of which N_f^e are without payload. T_f is the data frame duration including the header, where T_h is the time duration of the header. The energy consumption $\mathcal{E}_p$ is given by:

$$\mathcal{E}_p = \frac{1}{N_s}\left[\left(N_f - N_f^e\right)(e_t + e_r) T_f \right. \tag{5}$$
$$\left. + 2e_w\left(T - \left(N_f - N_f^e\right)T_f - N_f^e T_h\right) + N_f^e (e_t + e_r) T_h\right],$$

where, the first term corresponds to the energy consumption in transmissions with data payload, the second term accounts for the total idling energy consumption, and the third term is due to the frame transmissions without payload.

The delay performance is captured by considering effective data rate $\mathcal{R}_p$, defined as the number of successfully transmitted data bits per second, and is obtained as:

$$\mathcal{R}_p = \frac{N_s\ L_p}{T}, \tag{6}$$

where L_p is the number of bits per data packet. The unknowns N_f, N_f^e, N_s, and T in (5) and (6) are analyzed below.

B. Performance analysis of the transmission strategies

We divide the time into slots of duration T_f during which the channel state is assumed to be constant. We define, $p_{11}(x)$ (respectively, $p_{21}(x)$) as the probability that the slot i is not in outage, given that the slot $i-x$ was not in outage (respectively, in outage). Likewise, $p_{22}(x) = 1 - p_{21}(x)$ (respectively, $p_{12}(x) = 1 - p_{11}(x)$) is the probability that the slot i is in outage, given that the slot $i - x$ was in outage (respectively, not in outage). For Rayleigh fading channel, the entities $p_{11}(1)$ and $p_{21}(1)$ are computed in terms of fading margin $F = \frac{\overline{\gamma}}{\gamma_1}$ (γ_1 is the mode 0 switching threshold, given in (2)), Doppler frequency f_d, and time slot unit T_f as [8]:

$$\varepsilon = 1 - e^{-\frac{1}{F}}, \quad p_{11}(1) = 1 - \frac{p_{21(1)}\varepsilon}{1-\varepsilon},$$
$$p_{21}(1) = \frac{Q(\theta, \rho\theta) - Q(\rho\theta, \theta)}{e^{\frac{1}{F}} - 1},$$

where ε is the steady state error probability in a slot, $Q(\cdot, \cdot)$ is the Marcum Q function, $\theta = \sqrt{\frac{2}{F(1-\mu^2)}}$, and $\mu = J_0(2\pi f_d T_f)$ is the Gaussian correlation coefficient of two samples of complex amplitude observed at time interval T_f, $J_0(\cdot)$ is the Bessel function of the first kind and order zero.

In FD-AMC, a frame transmission is postponed for s slots, where $s = \left\lceil \frac{t_w}{T_f} \right\rceil$. Note that, for basic AMC, $s = 1$. The s-step transition probabilities are obtained as:

$$p_{11}(s) = \frac{[p_{21}(1) + \eta^s p_{12}(1)]}{1-\eta},\ p_{21}(s) = \frac{p_{21}(1)\left[1 - \eta^s\right]}{1-\eta},$$

where $\eta = 1 - p_{21}(1) - p_{12}(1)$.

Definition 1: A *cycle* of period T is the duration between the ends of two consecutive frames transmitted in mode 0. Thus, a cycle contains $\mathbf{N_f}$ number of frames with only the last frame transmitted with $m = 0$, followed by a waiting period of s slots. The expected value of the random variable $\mathbf{N_f}$ as a function of s, denoted by N_f, is obtained as:

$$P[\mathbf{N_f} = j] = \begin{cases} p_{22}(s) & \text{for } j = 1, \\ p_{21}(s)[p_{11}(1)]^{j-2} p_{12}(1) & \text{for } j \geq 2, \end{cases}$$

$$N_f \triangleq E\{\mathbf{N_f}\} = \sum_{j=1}^{\infty} j \cdot P[\mathbf{N_f} = j] = \frac{p_{12}(1) + p_{21}(s)}{p_{12}(1)}. \tag{7}$$

For Rayleigh fading channel, the received SNR γ is exponentially distributed with probability density function given by:

$$\text{f}_\gamma(a) = \frac{1}{\overline{\gamma}} \exp\left(-\frac{a}{\overline{\gamma}}\right). \tag{8}$$

To find the expression for N_s, we define the average PER in mode m as $\overline{\mathcal{P}}_m$, which is obtained using (1) and (8) as

$$\begin{aligned} \overline{\mathcal{P}}_m &= \int_{\gamma_m}^{\gamma_{m+1}} a_m \exp\left(-g_m x\right) \text{f}_\gamma(x) dx \\ &= \frac{a_m}{\Pr(m) b_m \overline{\gamma}} \left(e^{-\gamma_m\left(\frac{1}{\overline{\gamma}} + g_m\right)} - e^{-\gamma_{m+1}\left(\frac{1}{\overline{\gamma}} + g_m\right)}\right), \end{aligned} \tag{9}$$

where $\Pr(m)$ is the probability that a transmission mode m is chosen, and it is given by

$$\Pr(m) = \int_{\gamma_m}^{\gamma_{m+1}} \text{f}_\gamma(x) dx. \tag{10}$$

Hence, the average number of successfully received packets in a cycle can be obtained as:

$$N_s = \frac{(N_f - 1)\sum\limits_{m=1}^{M} R_m \Pr(m)\left(1 - \overline{\mathcal{P}}_m\right)}{\sum\limits_{m=1}^{M} \Pr(m)} \triangleq (N_f - 1)\omega, \tag{11}$$

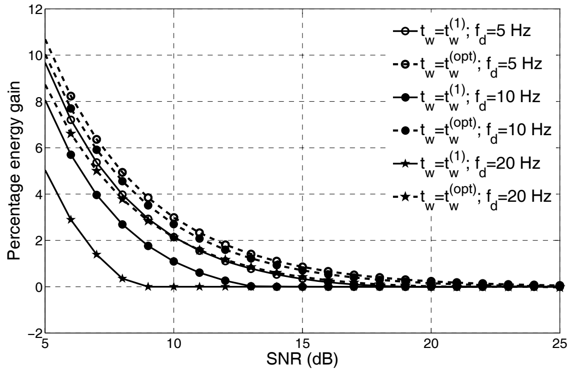

Fig. 1. Energy saving performance in FD-AMC with respect to AMC.

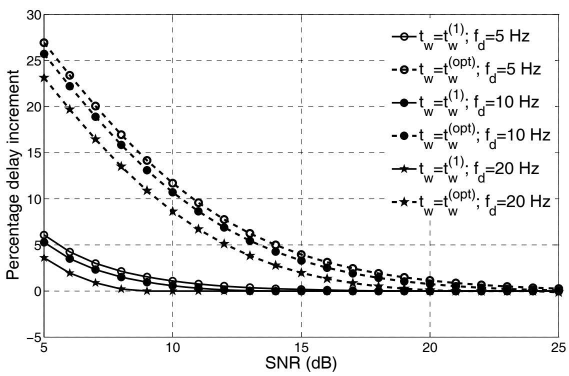

Fig. 2. Relative loss in delay performance of FD-AMC with respect to AMC.

where, R_m is the rate associated with mode m transmission, and the quantity ω is independent of s. By Definition 1, the average value of N_f^e in a cycle is $N_f^e = 1$, and the average cycle length is $T = (s - 1 + N_f)T_f$. Thus, N_f and N_s are known in terms of s from (7) and (11), respectively.

For comparison, we also find an optimum waiting time $t_w^{(opt)}$ (or $s^{(opt)}$ slots) for FD-AMC which provides the maximum energy efficiency by minimizing $\mathcal{E}_p$. From the above analysis, $\mathcal{E}_p$ in (5) can be expressed in terms of s as:

$$\mathcal{E}_p(s) = \frac{1}{\omega}\left[(e_t + e_r)T_f + \frac{(2e_w T_f s + H)(1-\eta)p_{12}(1)}{(1-\eta^s)\,p_{21}(1)}\right], \tag{12}$$

where $H = (e_t + e_r - 2e_w)T_h$. To minimize $\mathcal{E}_p$ in (12), $\frac{d\mathcal{E}_p(s)}{ds}$ is equated to zero. This yields:

$$2e_w T_f\left[1 - \eta^s + s^2\eta^{s-1}\right] + sH\eta^{s-1} = 0, \tag{13}$$

which can be solved by numerical methods to get an optimum $s^{(opt)}$ and hence $t_w^{(opt)} = s^{(opt)}T_f$. (For AMC, $s = 1$.)

IV. Numerical Results and Discussion

We have conducted simulation using MATLAB. Typical system parameters taken are as follows: maximum Doppler shift $f_d = 20$ Hz, frame size $T_f = 2$ ms - which satisfy slow fading scenario, i.e., $f_d T_f < 0.02$, PER limit $\mathcal{P}_0 = 10^{-3}$, packet size $L_p = 1080$ bits, and header size $L_h = 100$ bits (corresponding to T_h). The energy consumption parameters were taken from Chipcon CC1000 data sheet: current consumptions in transmit, receive, and idling (waiting) modes are respectively 17.4 mA, 19.7 mA, and 426 μA.

Energy gain: Fig. 1 presents the percentage energy saving of FD-AMC compared to AMC, which is defined as $\left[\mathcal{E}_p^{AMC} - \mathcal{E}_p^{FD-AMC}\right] \times 100/\mathcal{E}_p^{AMC}$. Particularly at lower values of $\overline{\gamma}$, FD-AMC (for both $t_w^{(1)}$ and $t_w^{(opt)}$) saves energy by waiting for a channel-aware period, which tracks the deep channel fades. It can be observed that, $t_w^{(opt)}$ offers a higher energy saving compared to that with $t_w^{(1)}$. In both schemes, as f_d increases, the energy saving gain with respect to the basic AMC decreases. This is because, a higher f_d implies a reduced AFD, which leads to a reduced scope for exploitation of the fading correlation. *Hence, FD-AMC offers a higher gain in slow fading channels.* Another observation is that, as f_d increases, the decrement in energy gain with $t_w^{(1)}$ occurs at a higher rate than that with $t_w^{(opt)}$, and *as a result, the energy gain with $t_w^{(opt)}$ increases at a higher f_d.* For example, at $f_d = 5$ Hz, $t_w^{(opt)}$ offers only about 1% higher energy gain compared to that with $t_w^{(1)}$, whereas at $f_d = 20$ Hz the additional gain is about 4%. This is because of a high value of $\eta = 1 - P_{12}(1) - P_{21}(1)$ in fading channels, and $t_w^{(opt)} > t_w^{(1)}$ (in number of slots, s). From (12) it is apparent that, the effect of s in the numerator is less pronounced compared to that in the denominator where it appears in the exponent of η. As f_d increases, $s^{(opt)}$ is still appreciably high, but $s^{(1)} \approx 1$. So, $1-\eta^{s^{(1)}}$ decreases at a faster rate than $1-\eta^{s^{(opt)}}$, which causes a sharper increase of $\mathcal{E}_p\left(s^{(1)}\right)$ compared to that of $\mathcal{E}_p\left(s^{(opt)}\right)$.

Delay trade-off: In the proposed FD-AMC scheme, the energy saving is achieved at the cost of an increased delay (reduced frame delivery rate). Fig. 2 presents the percentage increment of delay performance of the FD-AMC scheme as compared to AMC, which is defined as $\left[\mathcal{R}_p^{AMC} - \mathcal{R}_p^{FD-AMC}\right] \times 100/\mathcal{R}_p^{AMC}$. It can be noted that, at a typical operating SNR of 6 dB and $f_d = 10$ Hz, $t_w^{(opt)}$ incurs about 22% additional delay, whereas it is reduced to about 4% with $t_w^{(1)}$. *Thus, the heuristically chosen t_w could be a better choice where the tolerable delay trade-off is limited.*

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