Research Article
Energy Efficient Video Transmission over Fast Fading Channels

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With the explosive development of new generation wireless communication technique, the bandwidth is no longer the bottleneck of the wireless video transmission. Energy consumption is the biggest concern now. In this paper, an energy-efficient variable-rate and variable-power modulation method is proposed, which is the optimization of the power and rate of M-QAM signal constellations. Then an adaptive scheme on energy-efficient video transmission over fading channels is proposed. In this scheme, in order to satisfy the requirement with energy efficiency and usage of client/receiver buffer, we implement adaptive selection of modulation level for every video frame, and adaptive power control to compensate the effect by fading channels for every packet. Simulation results show this scheme has good performance on energy saving.

1. Introduction

Wireless multimedia services, which are growing in popularity, pose several challenges, including overcoming bandwidth variations and limited battery lifetime. While the next-generation wireless technologies promise more reliable communication and higher bandwidth, the problem of high energy consumption during video transmission is largely unresolved. For the design of energy-efficient wireless video transmission schemes, the cause of the energy consumption needs to be better understood. According to [1], about 75% of the total power is dissipated in the RF front-end circuit. In order to accurately evaluate the effects of different communication system parameters on RF front-end energy consumption, we build on our RF front-end energy model work [2] and tie the physical layer (PHY) parameters, such as bit error rate (BER), modulation level, bandwidth, bit rate, and multiple access interference (MAI), to the RF circuit energy consumption. The energy-efficient wireless video transmission schemes must also consider the video streaming QoS constraints, such as the client/receiver buffer status and the video frame playout deadlines to ensure the timely delivery of the video frames. Besides, wireless channel variation is one of main causes to QoS of video transmission.

Until now, there has not been much work on low power video transmission over fading channels. Lu et al. [3] present a Reed-Solomon (RS) channel encoder power model, a block-based H.263 encoder power model, and a distortion model. Chan and Mathiopoulos [4] propose a modified version of the H.263 video codec incorporating a forward error correction (FEC) coding scheme combined with a forced intraframe update mechanism for IS-95 CDMA systems. Zhang et al. [5] propose a power-minimized bit-allocation scheme jointly considering the processing power for source coding and channel coding, as well as the transmission power. The total bits are allocated between source and channel coders to minimize the total power consumption, according to the wireless channel conditions and video quality requirement. For high-quality video stream transmission, the peak data rate may exceed the nominal bandwidth over wireless links. In [6], Galluccio et al. define an analytical framework for the evaluation of the performance of real-time MPEG video transmission over a wireless link that applies adaptive FEC. Li et al. [7] propose a rate control algorithm for real-time video transmission, which allocates more power as well as more bits to the regions of interest of a video frame and less power and fewer bits to the rest regions. In [8], Luna et al. propose a joint source

coding and data rate adaptation method to minimize the transmission power under delay and quality constraints. In [9], Li et al. propose an energy-efficient video transmission scheme that considers QoS of video transmission, and RF circuit and energy-efficient adaptive modulation, but this scheme only considers slow fading channels and does not mention power adaptation policy.

In this paper, we propose a new video transmission scheme for fading channels, while [9] only considers AWGN channels. With the consideration of switching power in status change, so we implement adaptive selection of modulation level for every video frame, and adaptive power control to compensate the effect by fading channels for every packet in this scheme. Moreover, when deep fading happens, a power adaptation policy will turn off power amplifier (PA) in terms of energy efficiency. In addition, though [9] proposes a way to find optimal modulation level for adaptive modulation, it is difficult to find roots of a high-degree polynomial equation. Therefore, in this paper, we give a lookup table to determine the optimal modulation for energy-efficient adaptive modulation quickly.

The paper is organized as follows. In Section 2, we discuss the system model for energy consumption in RF front-end. Section 3 describes energy-efficient variable-rate variable-power modulation method using M-QAM signal constellations over fading channels. An adaptive video transmission scheme based on energy-efficient variable-rate variable-power M-QAM is proposed in Section 4. Simulation results are presented in Section 5. Finally, conclusions are drawn in Section 6.

2. System Model

We assume a full-duplex transceiver for wireless communication system, in which the receiver and the transmitter work independently. During communication, the transmitter delivers a video stream to the base station via the uplink while the receiver gets the feedback and state information from base station via the downlink. Uplink and downlink work at different data rates and at different modulation levels. In order to minimize the total energy consumption for video transmission, it is essential to consider the energy consumption of the RF front-end. We use the standard wireless transmitter and receiver model from [10] as described in Figure 1. The main components of the analog signal chain of the transmitter are DAC, reconstruction filter, mixer, PA, and RF filter. Similarly, the main components of the receiver signal chain are RF band select filter, LNA, downconversion mixers, baseband amplifier, baseband and anti-aliasing filter, ADC, and RF synthesizer.

2.1. PA Model. Energy consumption for PA is dominant in all components of RF front-end. The PA increases the signal power so that the antenna can radiate sufficient power for a reliable communication. The Class A linear PAs are utilized in this model, since they are commonly used in QAM-based point-to-point systems. The high linearity of

this amplifier preserves communication accuracy and limits spectral regrowth.

The efficiency η of Class A PA is proportional to the value of the transmission signal power P_{sig} [2]

$$\eta = \frac{P_{\text{sig}}}{P_{\text{PA}}} = \frac{K}{\text{PAR}}, \tag{1}$$

where K is a proportionality constant, and PAR is the peak-to-average ratio. We choose $K = 0.5$ in this model and simulation.

Therefore

$$P_{\text{PA}} = \frac{P_{\text{sig}}}{K} \cdot \text{PAR}. \tag{2}$$

According to [2], symbol error rate (SER) at receiver can be expressed as

$$\text{SER} = 4\left(1 - \frac{1}{\sqrt{M}}\right) \cdot Q\left(\sqrt{\frac{3 \cdot P_{\text{detected}}}{(M-1) \cdot N}}\right), \tag{3}$$

where N is the noise power and M is the constellation size, P_{detected} denotes the detected signal power at the receiver, and Q denotes the function

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy. \tag{4}$$

Therefore,

$$P_{\text{detected}} = \frac{1}{3}\left(2^b - 1\right) \cdot N \cdot \left(Q^{-1}\left(\frac{1}{4}\left(1 - \frac{1}{2^{b/2}}\right)^{-1} \cdot \text{SER}\right)\right)^2, \tag{5}$$

where b is modulation level. If over fading channels, assuming free space propagation at distance d (meter), and the amplitude of channel gain is h, the transmission signal power P_{sig} is given by [2]

$$P_{\text{sig}} = \frac{P_{\text{detected}} \cdot (4\pi)^2 \cdot d^2 \cdot L}{G_t G_r \lambda^2 h^2}, \tag{6}$$

where G_t and G_r are the transmitter and receiver antenna gain, L is the system loss factor not related to propagation, λ is the carrier wavelength. Let P_0 denote the transmission signal power when $h = 1$, which is

$$P_0 = \frac{P_{\text{detected}} \cdot (4\pi)^2 \cdot d^2 \cdot L}{G_t G_r \lambda^2}. \tag{7}$$

The power consumption of the PA over fading channels is thus given by

$$P_{\text{PA}} = \frac{P_{\text{sig}}}{K} \cdot \text{PAR} = \frac{16\pi^2 \cdot d^2 \cdot L}{3 G_r G_t \lambda^2 h^2 K}\left(2^b - 1\right) \cdot N$$

$$\cdot \left(Q^{-1}\left(\frac{1}{4}\left(1 - \frac{1}{2^{b/2}}\right)^{-1} \text{SER}\right)\right)^2 \text{PAR}. \tag{8}$$
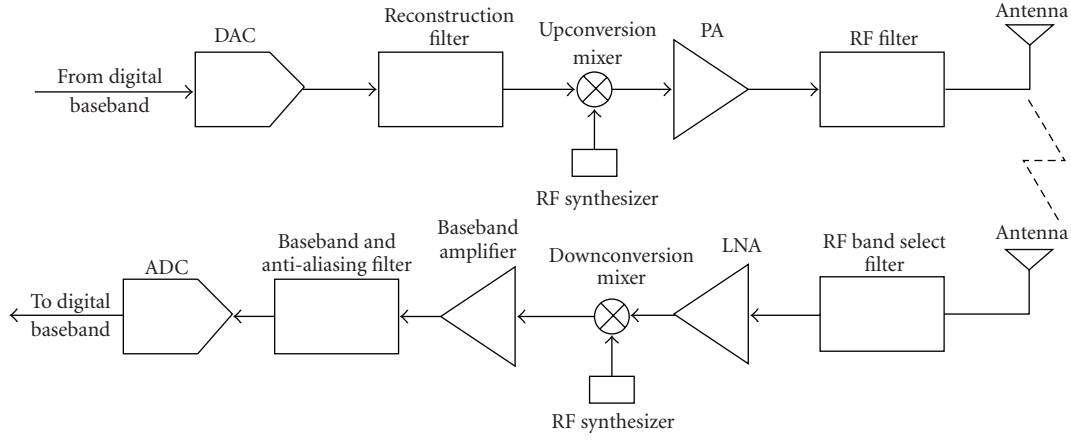
FIGURE 1: Block diagram of the transceiver analog signal chain.

2.2. Energy Consumption for RF Front-End. According to [9], the total energy consumption in the RF front end is the sum of the transmission energy consumption E_{trans} and the receive energy consumption E_{rec}, which can be expressed as

$$E_{\text{total}} = E_{\text{trans}} + E_{\text{rec}}. \qquad (9)$$

As illustrated in [9], the transmission power consumption of all blocks except PA for RF front-end can be considered to be fixed at 107 mW. Consider M-QAM modulation and denote $T_{\text{bit}} = 1/(b \cdot R_s)$, where R_s is the symbol rate in Hz. Then, the transmission energy consumption per bit for the RF front-end over fading channels is given by

$$E_{\text{trans}} = \frac{107 \times 10^{-3}}{b \cdot R_s} + \frac{16\pi^2 d^2 L}{3 G_r G_t \lambda^2 K \cdot h^2} \left(2^b - 1\right) N_0 \frac{1}{b}$$
$$\cdot \left(Q^{-1}\left(\frac{1}{4}\left(1 - \frac{1}{2^{b/2}}\right)^{-1} b \cdot \text{BER}\right)\right)^2 \text{PAR}(b, \alpha), \tag{10}$$

where $N_0 = N/R_s$, BER denotes the bit error rate, and *PAR* is the function

$$\text{PAR}(b, \alpha) = \sqrt{\frac{3 \cdot \left(2^{b/2} - 1\right)}{2^{b/2} - 1}} \cdot \text{PAR}_C \cdot \text{PAR}_{\text{roll-off}}(\alpha). \tag{11}$$

Here, let

$$C_1 = \frac{107 \times 10^{-3}}{R_s}, \tag{12}$$

$$C_2 = \frac{16\pi^2 L N_0 \text{PAR}_C \cdot \text{PAR}_{\text{roll-off}}}{3 G_r G_t \lambda^2 K}, \tag{13}$$

$$F(b) = \frac{2^b - 1}{b}\left(Q^{-1}\left(\frac{1}{4}\left(1 - \frac{1}{2^{b/2}}\right)^{-1} \cdot b \cdot \text{BER}\right)\right)^2$$
$$\cdot \sqrt{\frac{3\left(2^{b/2} - 1\right)}{2^{b/2} + 1}}, \tag{14}$$

thus,

$$E_{\text{trans}} = \frac{C_1}{b} + C_2 \left(\frac{d}{h}\right)^2 \cdot F(b). \tag{15}$$

As to analysis results in [9], the receive power consumption for RF front-end can be considered to be fixed at 122.35 mW

$$P_{\text{rec}} = 122.35 \times 10^{-3}. \tag{16}$$

Then the receive energy consumption per bit is

$$\tilde{E}_{\text{rec}} = P_{\text{rec}} \cdot \frac{1}{R_s} \cdot \frac{1}{b} = \frac{122.35 \times 10^{-3}}{b \cdot R_s}. \tag{17}$$

If let

$$C_3 = \frac{122.35 \times 10^{-3}}{R_s}, \tag{18}$$

then,

$$\tilde{E}_{\text{rec}} = \frac{C_3}{b}. \tag{19}$$

3. Energy-Efficient Variable-Rate Variable-Power M-QAM for Fading Channels

In this section, we consider an energy-efficient variable-rate and variable-power modulation method using M-QAM signal constellations. We will present the optimization of power and rate using the power model of RF front-end mentioned in Section 2 for minimizing the energy consumption. Considering a family of M-QAM signal constellations with a fixed symbol rate R_s, if transmission distance d and the amplitude of channel gain h are known, then the optimal modulation level b_{opt} and the "cutoff" value h_0 for power adaptation will be adaptively selected.

3.1. Optimal Modulation Level. In this subsection, we determine the optimal modulation level that minimizes the transmission energy consumption per bit for fixed bandwidth systems over fading channels. Figure 2 describes the effect of the modulation level b on E_{trans} for different values of d/h, there is a modulation level b for which E_{trans} is minimal, that is, b_{opt}. For instance, for $d/h = 1$, $b_{\text{opt}} = 8$, and for $d/h = 6$, $b_{\text{opt}} = 5$. When b is less than b_{opt}, the RF
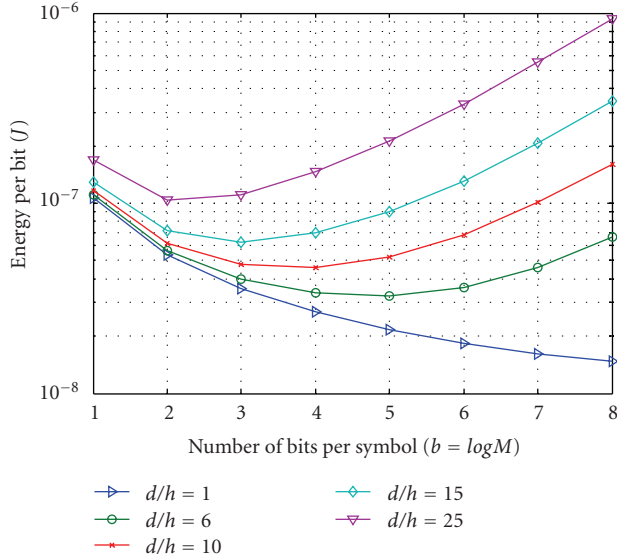
FIGURE 2: RF front-end transmission energy per bit versus modulation level b with different d/h (PAR = 5 dB, and BER = 10–3).

front-end transmission energy consumption reduces with the increase in b, because, for small b, the transmission energy consumption of other RF front-end components, except for the PA (i.e., the first term in (10)), are dominant. For b larger than b_{opt}, the energy that is consumed in the PA (i.e., the second term in (10)) is dominant, and the RF front-end transmission energy increases with b. For larger b, the signal is more susceptible to interference, and higher PA radiated power is necessary to maintain the BER. In typical wireless environments, modulation levels b of 8 or higher are impractical; therefore, we focus on the energy performance in the range from 1 to 8.

Intuitively, solving (15) for b will give the optimal modulation level b_{opt} which is a function of d and h. While the optimal modulation level b_{opt} is also affected by the parameters R_s, N_0, λ, α, G_r and G_t, these are typically fixed or have negligible effect on b, and are considered constant in this analysis, which is to say that C_1 and C_2 can be considered as constant. Let $\tilde{d} = d/h$, thus E_{trans} is a function of $\tilde{d}$ and b

$$E_{trans} = f\left(\tilde{d}, b\right) \qquad (20)$$

b_{opt} is the b that minimize E_{trans}, and then it can be expressed as

$$b_{opt} = \min_{b \in S_b} f\left(\tilde{d}, b\right) \qquad (21)$$

Subsequently, the set of $\tilde{d}$ that satisfies $b_{opt} = i$, denotes $D(i)$,

$$D(i) = \left\{\tilde{d} \in (0, +\infty) : f\left(\tilde{d}, i\right) < f\left(\tilde{d}, j\right), \forall j \neq i\right\}$$
$$= \bigcap_{\substack{j \in S_b \\ j \neq i}} \left\{f\left(\tilde{d}, i\right) - f\left(\tilde{d}, j\right) < 0\right\} \bigcap \{d > 0\}. \qquad (22)$$

The number of elements in the set S_b is practically finite, for instance $S_b = \{2, 3, 4, 5, 6, 7, 8\}$ in M-QAM systems, so we can directly obtain the solution to $D(i)$.

TABLE 1: System parameter values for Wi-Fi application considered in determining the optimal modulation level b.

R_s = 1 MHz	$G_r = 1$
$G_t = 1$	$L = 0.8$
f_c = 2.5 GHz	$\lambda = 0.12$ m
$\alpha = 0.25$	$K = 0.5$
$N_0/2 = 10^{-16}$ W/Hz	BER = 10^{-3}
$I_{0\_DAC} = 10\,\mu$A	$SQNR_{ADC}$ = 50 dB
$SQNR_{DAC}$ = 60 dB	OSR_{DAC} = 4

In the next, we will explain it by one instance of $D(4)$. We set the BER and the other system parameters as listed in Table 1.

$$D(4) = \left\{\tilde{d} > 0\right\} \bigcap \left\{f\left(\tilde{d}, 4\right) < f\left(\tilde{d}, 2\right)\right\}$$
$$\bigcap \left\{f\left(\tilde{d}, 4\right) < f\left(\tilde{d}, 3\right)\right\}$$
$$\bigcap \left\{f\left(\tilde{d}, 4\right) < f\left(\tilde{d}, 5\right)\right\} \bigcap \left\{f\left(\tilde{d}, 4\right) < f\left(\tilde{d}, 6\right)\right\}$$
$$\bigcap \left\{f\left(\tilde{d}, 4\right) < f\left(\tilde{d}, 7\right)\right\} \bigcap \left\{f\left(\tilde{d}, 4\right) < f\left(\tilde{d}, 8\right)\right\}$$
$$= \left\{\tilde{d} > 0\right\} \bigcap \left\{-16.2288 < \tilde{d} < 16.2288\right\}$$
$$\bigcap \left\{-11.8321 < \tilde{d} < 11.8321\right\}$$
$$\bigcap \left\{\tilde{d} > 6.9881, \tilde{d} < -6.9881\right\}$$
$$\bigcap \left\{\tilde{d} > 5.4460, \tilde{d} < -5.4460\right\}$$
$$\bigcap \left\{\tilde{d} > 4.2410, \tilde{d} < -4.2410\right\}$$
$$\bigcap \left\{\tilde{d} > 3.2894, \tilde{d} < -3.2894\right\}$$
$$= \{6.9881 < d < 11.8321\}.$$
$$(23)$$

Similar to $D(4)$, we can obtain

$$D(i) = \begin{cases} [21.6988, +\infty), & i = 2, \\ [11.8321, 21.6988), & i = 3, \\ [6.9881, 11.8321), & i = 4, \\ [4.3204, 6.9881), & i = 5, \\ [2.7504, 4.3204), & i = 6, \\ [1.7865, 2.7504), & i = 7, \\ (0, 1.7865), & i = 8. \end{cases} \qquad (24)$$

Thus, if $\tilde{d}$ is known, we just need to look for (24), and then the optimal modulation level b_{opt} is decided.

3.2. Power Adaptation.
In this paper, a fixed-bandwidth system is considered, and the power spectral density of noise is

assumed to be fixed, thus noise power deems to be constant. So, we can let $S(h)$ denote the transmission signal power (P_{sig}) adaptation policy relative to an instantaneous value of h. The expectation of the total energy consumption per bit of RF front-end can be derived as

$$
\begin{aligned}
\overline{E}_{\text{total}} &= \int_0^{+\infty} [E_{\text{trans}}(h) + E_{\text{rec}}(h)] p(h) dh \\
&= \int_0^{+\infty} \left[\frac{C_1}{b} + \frac{S(h)}{K} \cdot \text{PAR} \cdot \frac{1}{b \cdot R_s} + E_{\text{rec}}(h) \right] p(h) dh,
\end{aligned}
\tag{25}
$$

where $p(h)$ denotes the distribution of the amplitude of channel gain, and Rayleigh fading channel model is adopted in the following analysis, so

$$
p(h) = \frac{2h}{\Omega} \cdot e^{-h^2/\Omega}, \tag{26}
$$

where $\Omega = E(h^2)$ that denotes the average power of channel gain. Generally, we can assume $\Omega = 1$. So,

$$
p(h) = 2h \cdot e^{-h^2}. \tag{27}
$$

The power adaptation which minimize (25) is

$$
S(h) = \begin{cases} P_{\text{sig}} = \dfrac{P_0}{h^2}, & h \geq h_0, \\ 0, & h < h_0. \end{cases} \tag{28}
$$

for a certain "cutoff" value h_0. If $h[i] < h_0$ at time i, then no power is allocated to the ith data transmission, which means the transmitter will shut down at that time. Then, the probability that the transmitter will temporarily stop is

$$
p = \int_0^{h_0} 2h \cdot e^{-h^2} dh = 1 - e^{-h_0^2}. \tag{29}
$$

In the next, in order to minimize (25), the transmission and receive energy consumption will be analyzed, respectively. Substituting (28) into (25), the expectation of the transmission energy consumption per bit for RF front-end can be derived as

$$
\begin{aligned}
\overline{E}_{\text{trans}} &= \int_{h_0}^{+\infty} \left(\frac{C_1}{b} + \frac{C_2 \cdot d^2 F(b)}{b \cdot h^2} \right) \cdot 2h \cdot e^{-h^2} dh \\
&= -\frac{C_1}{b} \cdot e^{-h^2} \bigg|_{h_0}^{+\infty} + \frac{C_2 \cdot d^2 F(b)}{b} \int_{h_0}^{+\infty} \frac{2}{h} \cdot e^{-h^2} dh \\
&= \frac{C_1}{b} \cdot e^{-h_0^2} + \frac{C_2 \cdot d^2 F(b)}{b} \int_{h_0}^{+\infty} \frac{2}{h} \cdot e^{-h^2} dh.
\end{aligned}
\tag{30}
$$

In the receiver, according to (16), the receiver power consumption can be thought as constant, and then the receiver energy consumption only depends on time. Usually, when transmitter turns on, receiver will also be on, but when transmitter is temporarily off, receiver will still turn on to receive the feedback information. Then, as to transmitting one symbol, if channel condition is good enough to transmit,

then the receiver will be on for the duration of one symbol. But, if channel is so poor that transmitter will turn off, then the receiver will always be on for the duration of transmitting one or more symbols until the symbol succeeds to be transmitted. For this reason, the receiver energy consumption will be one or more times higher. The probability that the receiver is on for n symbol duration time so as to transmit only one symbol is

$$
P_n = p^{n-1}(1 - p). \tag{31}
$$

According to (17) and (19), the expectation of the receiver energy consumption per bit for RF front-end can be derived as

$$
\begin{aligned}
\overline{E}_{\text{rec}} &= \tilde{E}_{\text{rec}}(1 - p) + 2\tilde{E}_{\text{rec}}p(1 - p) + 3\tilde{E}_{\text{rec}}p^2(1 - p) \\
&\quad + \cdots + n\tilde{E}_{\text{rec}}p^{n-1}(1 - p) + \cdots \\
&= \frac{C_3}{b}(1 - p) + 2\frac{C_3}{b}p(1 - p) + 3\frac{C_3}{b}p^2(1 - p) \\
&\quad + \cdots + n\frac{C_3}{b}p^{n-1}(1 - p) + \cdots \\
&= \frac{C_3}{b}\big[(1 - p) + 2p(1 - p) + 3p^2(1 - p) \\
&\quad + \cdots + np^{n-1}(1 - p) + \cdots\big] \\
&= \frac{C_3}{b}(1 + p + p^2 + \cdots + p^{n-1} + \cdots) \\
&= \frac{C_3}{b} \lim_{n \to \infty} \frac{1 - p^n}{1 - p} \\
&= \frac{C_3}{b(1 - p)} \\
&= \frac{C_3}{b} e^{h_0^2}.
\end{aligned}
\tag{32}
$$

Then, the expectation of the total energy consumption per bit for RF front-end $\overline{E}_{\text{total}}$ can be derived as

$$
\begin{aligned}
\overline{E}_{\text{total}} &= \overline{E}_{\text{trans}} + \overline{E}_{\text{rec}} \\
&= \frac{C_1}{b} \cdot e^{-h_0^2} + \frac{C_2 \cdot d^2 F(b)}{b} \int_{h_0}^{+\infty} \frac{2}{h} \cdot e^{-h^2} dh + \frac{C_3}{b} e^{h_0^2}.
\end{aligned}
\tag{33}
$$

In order to find the optimal cutoff value h_0 for the transmission signal power adaptation policy, we need to find the value of h_0 for which $\partial \overline{E}_{\text{total}}/\partial h_0 = 0$. Then,

$$
\frac{\partial \overline{E}_{\text{total}}}{\partial h_0} = 0,
$$

$$
\frac{-2C_1 h_0}{b} \cdot e^{-h_0^2} - \frac{C_2 d^2 F(b)}{b} \cdot \frac{2}{h_0} e^{-h_0^2} + \frac{2C_3 h_0}{b} e^{h_0^2} = 0,
$$

$$
-2C_1 h_0^2 - 2C_2 d^2 F(b) + 2C_3 h_0^2 e^{2h_0^2} = 0.
\tag{34}
$$

Denote $x = 2h_0^2 > 0$, then,

$$
C_3 x e^x - C_1 x - 2C_2 d^2 F(b) = 0. \tag{35}
$$

Theorem 1. *For a fixed $b_0 \in S_b$ and d_0 ($d_0 > 0$), (35) has only one root in the field $[0, +\infty)$.*

Proof. Define

$$y = f(x) = C_3 x e^x - C_1 x - 2C_2 d_0^2 F(b_0). \tag{36}$$

Then, for $x \in [0, +\infty)$

$$\begin{aligned}
\frac{dy}{dx} &= C_3 x e^x + C_3 e^x - C_1 \\
&= C_3 x e^x + (C_3 - C_1)e^x + C_1(e^x - 1) \\
&= C_3 x e^x + \frac{122.35 \times 10^{-3} - 107 \times 10^{-3}}{R_s} e^x + C_1(e^x - 1) \\
&= C_3 x e^x + \frac{115.35 \times 10^{-3}}{R_s} e^x + C_1(e^x - 1) > 0.
\end{aligned} \tag{37}$$

It is obvious that $f(x)$ is continuous in the field $[0, +\infty)$. In other word, $f(x)$ is a continuous and monotonically increasing function in the field $[0, +\infty)$. Then,

$$f(0) = C_3 \cdot 0e^0 - C_1 \cdot 0 - 2C_2 d_0^2 F(b_0) = -2C_2 d_0^2 F(b_0). \tag{38}$$

According to (14), obviously, for any $b_0 \in S_b$, $F(b_0)$ will always be positive. Therefore, $f(0) < 0$. Denote

$$x_0 = \frac{2C_2 d_0^2 F(b_0)}{C_3 - C_1} > 0. \tag{39}$$

Then,

$$\begin{aligned}
f(x_0) &= C_3 x_0 e^{x_0} - C_1 x_0 - 2C_2 d_0^2 F(b_0) \\
&= (C_3 - C_1)x_0 e^{x_0} + C_1(e^{x_0} - 1) - 2C_2 d_0^2 F(b_0) \\
&= (C_3 - C_1) \cdot \frac{2C_2 d_0^2 F(b_0)}{C_3 - C_1} e^{x_0} + C_1(e^{x_0} - 1) \\
&\quad - 2C_2 d_0^2 F(b_0) \\
&= 2C_2 d_0^2 F(b_0)(e^{x_0} - 1) + C_1(e^{x_0} - 1) > 0.
\end{aligned} \tag{40}$$

According to Bolzano's Theorem [11], there exists a number $\tilde{x} \in [0, x_0]$ with $f(\tilde{x}) = 0$. In other word, (35) has at least one root in the field $[0, +\infty)$. Moreover, $f(x)$ is a continuous and monotonically increasing function in the field $[0, +\infty)$, so we can conclude that (35) has only one root in the field $[0, +\infty)$. □

Corollary 1. *If let x_0 denote the only one root in $[0, +\infty)$ of (35), then $\sqrt{x_0/2}$ would be the optimal cutoff value for the transmission signal power adaptation policy.*

Proof. The first derivative of $\overline{E}_{\text{total}}$ is

$$\frac{\partial \overline{E}_{\text{total}}}{\partial h_0} = -2C_1 h_0^2 - 2C_2 d^2 F(b) + 2C_3 h_0^2 e^{2h_0^2},$$

$$\left.\frac{\partial \overline{E}_{\text{total}}}{\partial h_0}\right|_{h_0 = \sqrt{x_0/2}} = -C_1 x_0 - 2C_2 d^2 F(b) + C_3 x_0 e^{x_0} = 0. \tag{41}$$

The second derivative of $\overline{E}_{\text{total}}$ is

$$\frac{\partial^2 \overline{E}_{\text{total}}}{\partial h_0^2} = -4C_1 h_0 + 4C_3 h_0 e^{2h_0^2} + 8C_3 h_0^3 e^{2h_0^2},$$

$$\begin{aligned}
\left.\frac{\partial^2 \overline{E}_{\text{total}}}{\partial h_0^2}\right|_{h_0 = \sqrt{x_0/2}} &= -4C_1 \sqrt{\frac{x_0}{2}} + 4C_3 \sqrt{\frac{x_0}{2}} e^{x_0} \\
&\quad + 8C_3 \left(\sqrt{\frac{x_0}{2}}\right)^3 e^{x_0}.
\end{aligned} \tag{42}$$

As to $C_3 > C_1$ and $e^{x_0} > 0$, it is obvious that

$$\left.\frac{\partial^2 \overline{E}_{\text{total}}}{\partial h_0^2}\right|_{h_0 = \sqrt{x_0/2}} > 0. \tag{43}$$

Then the function $\overline{E}_{\text{total}}(h_0)$ will get the minimum value in the field $[0, +\infty)$ at $h_0 = \sqrt{x_0/2}$. In other word, $\sqrt{x_0/2}$ would be the optimal cutoff value for the transmission signal power adaptation policy.

But (35) is a transcendental equation, which is hard to obtain the analytical root. So a numerical computing software, for example, Matlab, is used to solve (35). The numerical results are show in Table 2. □

4. Video Transmission Using Energy-Efficient Variable-Rate Variable-Power M-QAM

We consider VBR-encoded video streams, where the frame size (in bits) is variable, and the frame period of 33 ms. We propose two adaptive video transmission schemes based on energy-efficient variable-rate variable-power M-QAM: (1) frame-by-frame transmission; and (2) channel and client buffer related energy-efficient video transmission (CCEVT). We consider a fast fading channel in which the channel gain is varying over the duration of a frame. In principle, our algorithms require that the parameters that affect the optimal modulation level and power level, including the distance and channel conditions, are frequently updated such that the currently valid optimal modulation level and power level are available when our transmission schemes make decisions on the modulation level and power level that is used for the transmission of a video frame, that is, every video frame period. Practically, every video frame needs to be divided into several packets and then transmits in networks. In order to compensate the effect by fast fading channels, the basic idea of our adaptive transmission schemes is to adjust the modulation level b (and, correspondingly, the data transmission rate) for every video frame, and the transmission signal power level for every packet to save energy. The reasons for adaptive modulation for every frame transmission time are (1) modulation level cannot be switched too frequently because switching time required and thus switching power consumed, which is also mentioned by the reviewer; (2) if switching modulation level frequently, energy consumption by switching will arise and cannot be neglected any more. In the existing standards, for example WIFI, the power level is assigned for every packet. So, we can change the power level only at the packet level. In addition, if consider channel conditions may change very

(1) $T_{\text{frame}} = 33 \times 10^{-3}$ sec; temp = constant; /* temp $\geqslant 0$
(2) T_{packet} = constant /* the duration of one packet
(3) $M = T_{\text{frame}} / T_{\text{packet}}$ /* the number of packet in a frame
(4) BER = constant /* the predefined bit error rate (BER)
(5) $k = 0$
(6) $h_{\text{est}}(1)$ = channel_prediction $(h(0))$ /* function for channel prediction
(7) Repeat /* video transmission begins
(8) $k = k + 1$
(9) b_{opt} = optimal_mod (d, h_{est}) /* b_{opt} is selected with respect to d and h_{est}
(10) $C_{\text{opt}} = b_{\text{opt}} \times R_s$
(11)   IF $\sum_{i=1}^{k+1} L(i) \leq \text{Buffer} + \sum_{i=1}^{k} L(i) < \sum_{i=1}^{k-1} a(i) + C_{\text{opt}} \times T_{\text{frame}}$ /* buffer overflow
(12)   IF $\sum_{i=1}^{k-1} a(i) - \sum_{i=1}^{k+1} L(i) \geq$ temp
(13) $a(k) = 0$; $b(k) = 0$
(14)   ELSE
(15) $b(k) = \dfrac{\text{Buffer} + \sum_{i=1}^{k} L(i) - \sum_{i=1}^{k-1} a(i)}{T_{\text{frame}} \times R_s}$; $a(k) = b(k) \times R_s \times T_{\text{frame}}$
(16)   END IF
(17) h_0 = optimal_cutoff $(b(k), d)$ /* find the optimal cutoff value for power adaptation
(18) $m = k \times M$; Num_suspend $= 0$
(19)   Repeat
(20) $m = m + 1$
(21) $P_{\text{PA}}(m)$ = PA$(b(k), \text{BER}, h_{\text{est}}(m))$ /* transmission signal power adaptation
(22)   IF $h(m) < h_0$
(23) $P_{\text{PA}}(m) = 0$ /* transmitter suspends when channel gain is less than cutoff value
(24)   Num_suspend = Num_suspend + 1
(25)   END IF
(26) $h_{\text{est}}(m+1)$ = channel_prediction $(h(m))$ /* Channel prediction for next packet
(27)   UNTIL $m = (k+1) \times M$
(28) $a(k) = a(k) - b_{\text{opt}} \times R_s \times T_{\text{packet}} \times$ Num_suspend
(29)   ELSEIF $\sum_{i=1}^{k+1} L(i) \leq \sum_{i=1}^{k-1} a(i) + C_{\text{opt}} \times T_{\text{frame}} < Buffer + \sum_{i=1}^{k} L(i)$ /* optimal transmission
(30) $a(k) = C_{\text{opt}} \times T_{\text{frame}}$; $b(k) = b_{\text{opt}}$
(31)   Num $= 0$
(32)   IF $\sum_{i=1}^{k+1} L(i) > \sum_{i=1}^{k-1} a(i)$ /* the $(k+1)$th frame data has not finished to be transmitted
(33)   Num = ceil$\left\lceil \dfrac{\sum_{i=1}^{k+1} L(i) - \sum_{i=1}^{k-1} a(i)}{b_{\text{opt}} \times R_s \times T_{\text{packet}}} \right\rceil$ /* number of packet left to be transmitted
(34)   END IF
(35) h_0 = optimal_cutoff $(b(k), d)$ /* find the optimal cutoff value for power adaptation
(36) $m = k \times M$; Num_suspend $= 0$
(37)   Repeat
(38) $m = m + 1$
(39) $P_{\text{PA}}(m)$ = PA$(b(k), \text{BER}, h_{\text{est}}(m))$ /* transmission signal power adaptation
(40)   IF $m > k \times M + \text{Num}$ AND $h(m) < h_0$ /* make sure if the $(k+1)$th frame data has been transmitted
(41) $P_{\text{PA}}(m) = 0$ /* transmitter suspends when channel gain is less than cutoff value
(42) $Num\_suspend = Num\_suspend + 1$
(43)   END IF
(44) $h_{\text{est}}(m+1)$ = channel_prediction $(h(m))$ /* Channel prediction for next packet
(45)   UNTIL $m = (k+1) \times M$
(46) $a(k) = a(k) - b_{\text{opt}} \times R_s \times T_{\text{packet}} \times$ Num_suspend
(47)   ELSEIF $\sum_{i=1}^{k-1} a(i) + C_{\text{opt}} \times T_{\text{frame}} < \sum_{i=1}^{k+1} L(i)$ /* buffer starvation
(48) $b(k) = $ ceil$\left\lceil \dfrac{\sum_{i=1}^{k+1} L(i) - \sum_{i=1}^{k-1} a(i)}{T_{\text{frame}} \times R_s} \right\rceil$; $a(k) = b(k) \times R_s \times T_{\text{frame}}$
(49) $m = k \times M$
(50) h_0 = optimal_cutoff $(b(k), d)$ /* find the optimal cutoff value for power adaptation
(51)   Repeat
(52) $m = m + 1$
(53) $P_{\text{PA}}(m)$ = PA$(b(k), \text{BER}, h_{\text{est}}(m))$ /* transmission signal power adaptation
(54) $h_{\text{est}}(m+1)$ = channel_prediction $(h(m))$ /* Channel prediction for next packet
(55)   UNTIL $m = (k+1) \times M$
(56)   END IF
(57) UNTIL $k = N$
(58) END Function

ALGORITHM 1: CCEVT Function: find optimal schedule.

Table 2: Cutoff value h_0 for different distance $d(m)$ and modulation level b.

h_0	$b = 1$	$b = 2$	$b = 3$	$b = 4$	$b = 5$	$b = 6$	$b = 7$	$b = 8$
$d = 1$	0.038	0.054	0.071	0.092	0.117	0.147	0.182	0.222
$d = 2$	0.074	0.102	0.131	0.164	0.201	0.242	0.289	0.341
$d = 3$	0.107	0.143	0.180	0.219	0.263	0.312	0.366	0.426
$d = 4$	0.136	0.179	0.221	0.265	0.314	0.367	0.427	0.492
$d = 5$	0.162	0.210	0.256	0.304	0.356	0.414	0.478	0.547
$d = 6$	0.186	0.237	0.286	0.338	0.394	0.455	0.522	0.594
$d = 7$	0.207	0.262	0.314	0.369	0.427	0.491	0.561	0.636
$d = 8$	0.227	0.285	0.339	0.396	0.457	0.524	0.596	0.673
$d = 9$	0.245	0.306	0.363	0.422	0.485	0.553	0.627	0.706
$d = 10$	0.263	0.325	0.384	0.445	0.510	0.581	0.656	0.737
$d = 11$	0.279	0.344	0.404	0.467	0.534	0.606	0.683	0.764
$d = 12$	0.294	0.361	0.423	0.488	0.556	0.629	0.708	0.790
$d = 13$	0.308	0.377	0.441	0.507	0.577	0.651	0.731	0.814
$d = 14$	0.322	0.393	0.458	0.525	0.596	0.672	0.752	0.836
$d = 15$	0.335	0.407	0.474	0.543	0.615	0.691	0.772	0.857
$d = 16$	0.348	0.421	0.489	0.559	0.632	0.710	0.791	0.876
$d = 17$	0.360	0.435	0.504	0.575	0.649	0.727	0.809	0.895
$d = 18$	0.371	0.448	0.518	0.590	0.665	0.744	0.827	0.912
$d = 19$	0.383	0.460	0.531	0.604	0.680	0.760	0.843	0.929
$d = 20$	0.393	0.472	0.544	0.618	0.694	0.775	0.858	0.944
$d = 21$	0.404	0.484	0.557	0.631	0.708	0.789	0.873	0.959
$d = 22$	0.414	0.495	0.569	0.644	0.722	0.803	0.887	0.973
$d = 23$	0.423	0.505	0.580	0.656	0.735	0.816	0.901	0.987
$d = 24$	0.433	0.516	0.592	0.668	0.747	0.829	0.914	1.000
$d = 25$	0.442	0.526	0.602	0.679	0.759	0.841	0.926	1.013
$d = 26$	0.451	0.536	0.613	0.690	0.770	0.853	0.938	1.025
$d = 27$	0.460	0.545	0.623	0.701	0.781	0.864	0.949	1.036
$d = 28$	0.468	0.555	0.633	0.712	0.792	0.875	0.961	1.047
$d = 29$	0.476	0.564	0.643	0.722	0.803	0.886	0.971	1.058
$d = 30$	0.484	0.572	0.652	0.731	0.813	0.896	0.982	1.068

Table 3: Characteristics of the videos used in the simulation.

	Stream 1	Stream 2	Stream 3
Peak-to-mean ratio	8.42	14.22	11.7
Mean bit rate (Mbps)	0.0588	0.1231	0.2696
Peak bit rate (Mbps)	0.4951	1.7489	3.156

fast, because of the time delay of feedback transmission, so the channel information feedback by receivers may be outdated. In our scheme, channel prediction algorithm [12] is introduced, which can predict the current channel information by previous channel information.

We compare the performance of our adaptive transmission schemes with respect to a baseline transmission scheme, which transmits the video frames without any adjustment. Baseline transmission uses 16-QAM and transmits each frame with the fixed modulation level $b = 4$, which is large enough to transmit the largest video frame within one video frame period of 33 ms (for smaller frames, the transmitter finishes the transmission before the end of the video frame

period and, then, becomes idle until the end of the video frame period). We evaluate the performance of our schemes for different data rates and client (receiver) buffer sizes.

We set the BER to 10^{-3} and suppose that nonadaptive forward error control (FEC) can correct this level of bit error such that there is no frame loss. (Note that the FEC is only one of the many functions that are carried out in the digital baseband processor, which consumes significantly less power than the RF front end. Hence, the power consumption for the FEC can be considered a small constant and is ignored in this work.)

Knowing the client buffer capacity, the transmitter keeps track of the client buffer occupancy by tracking its transmissions and the size of the video frames that were retrieved from the buffer for playout according to the fixed known playout schedule of the preencoded video. In a system with frame loss on the wireless link, an acknowledgment/negative acknowledgment mechanism would be necessary so that the transmitter can track the successfully received video frames. In addition, note that in a system with frame loss, for a fixed BER, which we achieve by adjusting the modulation level and

TABLE 4: Performance comparison for different buffer sizes for Stream 1 ($d = 15$ m).

Buffer size	Scheme	Peak to Mean Ratio	Std Dev	Rec. Energy per Bit (J)	Trans. Energy per Bit (J)	Total Energy per Bit (J)
	Baseline	8.42	0.70	$1.98e-6$	$2.55e-7$	$2.24e-6$
	Frame by Frame	97.37	55.15	$1.98e-6$	$1.97e-7$	$2.18e-6$
128 KB	Proposed	64.32	6.04	$1.97e-6$	$6.65e-8$	$2.04e-6$
512 KB	Proposed	78.06	5.97	$1.91e-6$	$6.62e-8$	$1.98e-6$
2 MB	Proposed	68.80	5.85	$1.68e-6$	$6.51e-8$	$1.75e-6$
4 MB	Proposed	56.37	5.55	$1.38e-6$	$6.35e-8$	$1.44e-6$
16 MB	Proposed	2.08	0.61	$0.04e-6$	$5.62e-8$	$0.10e-6$
32 MB	Proposed	2.08	0.61	$0.04e-6$	$5.62e-8$	$0.10e-6$
64 MB	Proposed	2.08	0.61	$0.04e-6$	$5.62e-8$	$0.10e-6$

TABLE 5: Performance comparison for different buffer sizes for Stream 2 ($d = 15$ m).

Buffer size	Scheme	Peak to mean ratio	Std Dev	Rec. Energy per Bit (J)	Trans. Energy per Bit (J)	Total Energy per Bit (J)
	Baseline	14.22	1.33	$9.13e-7$	$2.44e-7$	$1.16e-6$
	Frame by Frame	44.75	25.33	$9.13e-7$	$1.90e-7$	$1.10e-6$
128 KB	Proposed	29.70	4.30	$9.08e-7$	$6.38e-8$	$9.72e-7$
512 KB	Proposed	36.63	4.17	$8.96e-7$	$6.42e-8$	$9.60e-7$
2 MB	Proposed	34.63	4.13	$8.47e-7$	$6.37e-8$	$9.11e-7$
4 MB	Proposed	32.06	4.05	$7.84e-7$	$6.31e-8$	$8.47e-7$
16 MB	Proposed	19.49	3.14	$3.97e-7$	$5.96e-8$	$4.57e-7$
32 MB	Proposed	2.07	0.61	$0.42e-7$	$5.62e-8$	$0.98e-7$
64 MB	Proposed	2.07	0.61	$0.42e-7$	$5.62e-8$	$0.98e-7$

the transmission power, the frame loss and retransmission rates are constant for different modulation levels, which allows us to ignore the retransmission energy consumption.

4.1. Frame-by-Frame Transmission.

A given frame is transmitted within one frame period. Let b_{req} be the required modulation level to transmit the frame in one frame period. If b_{req} is smaller than b_{opt}, we choose b_{opt} as the modulation level; if b_{req} is larger than b_{opt}, we use b_{req}. When b_{opt} is chosen for low-power transmission, the data rate increases, and the frame is transmitted in a shorter time, that is, within less than the 33-ms frame period. After the transmission, the transmitter goes to the idle mode for the remainder of the frame period, and only the receiver is in operation. In addition, the signal power adaptation policy is also applied in the transmission.

4.2. CCEVT Algorithm.

Frame-by-frame transmission does not consider the effect of the client (receiver) buffer size and client buffer occupancy. However, in practical systems, the client buffer occupancy is one of the most important factors to help ensure good communication quality. For example, if the client buffer overflows, the lost frames have to be unnecessarily retransmitted, thus increasing the network load. On the other hand, in case of buffer starvation, frames are lost for uninterrupted playback, and the video must be suspended. In this section, we present the CCEVT scheme to avoid the client buffer from overflowing or starving while saving energy.

Algorithm Parameter Definition.

N: Number of frames in the video.

Buffer: Client buffer capacity for storing unplayed video frames.

$L(t)$: Size of frame in time slot t in bits ($t = 1, 2, \ldots, N$).

$D(t)$: Cumulative amount of data (in bits) that the client consumed over $[1, t]$: $\sum_{i=1}^{t} L(i)$.

$a(t)$: Amount of data (in bits) that the transmitter transmitted during time slot t.

$A(t)$: Cumulative amount of data that was transmitted over $[1, t]$: $\sum_{i=1}^{t} a(i)$.

$B(t)$: Maximum cumulative data that can be received over $[1, t]$ without any buffer overflow

C_{opt}: Transmission rate that minimizes the RF energy per bit, $b_{opt} \times R_s$, where R_s is the symbol rate.

In this algorithm, firstly, channel prediction algorithm is used to predict the current channel gain based on previous channel gains. Then, the optimal modulation level b_{opt} is selected with respect to distance d and the estimated current channel gain h_{est} according to (24). Subsequently, we will judge how is the status of client buffer occupancy if b_{opt} is decided to be the modulation level in the current time slot, which includes three cases: overflow, normal, and starvation (frames are lost for uninterrupted). If overflow, the modulation level b will decrease, and then the optimal cutoff value h_0 is determined according to Table 2 for power

TABLE 6: Performance comparison for different buffer sizes for Stream 3 ($d = 15$ m).

Buffer size	Scheme	Peak to mean ratio	Std Dev	Rec. Energy per Bit (J)	Trans. Energy per bit (J)	Total Energy per Bit (J)
	Baseline	11.7	0.95	$4.11e-7$	$2.51e-7$	$6.62e-7$
	Frame by Frame	20.15	11.37	$4.11e-7$	$1.94e-7$	$6.05e-7$
512 KB	Proposed	16.68	2.88	$4.07e-7$	$6.14e-8$	$5.02e-7$
2 MB	Proposed	16.29	2.87	$3.98e-7$	$6.13e-8$	$4.59e-7$
4 MB	Proposed	15.71	2.83	$3.84e-7$	$6.11e-8$	$4.45e-7$
16 MB	Proposed	15.02	2.61	$3.06e-7$	$6.00e-8$	$3.66e-7$
32 MB	Proposed	9.91	2.17	$2.02e-7$	$5.85e-8$	$2.61e-7$
64 MB	Proposed	2.07	0.61	$0.42e-7$	$5.62e-8$	$0.98e-7$

TABLE 7: Performance comparison for different distances for Stream 1.

Buffer Size	Scheme	Rec. Energy per Bit (J)			Trans. Energy per Bit (J)			Total Energy per Bit (J)		
		$d = 15$ m	$d = 30$ m	$d = 100$ m	$d = 15$ m	$d = 30$ m	$d = 100$ m	$d = 15$ m	$d = 30$ m	$d = 100$ m
	Baseline	$1.98e-6$	$1.99e-6$	$1.99e-6$	$2.55e-7$	$9.39e-7$	$102e-7$	$2.24e-6$	$2.92e-6$	$12.1e-6$
	Frame by Frame	$1.98e-6$	$1.99e-6$	$1.99e-6$	$1.97e-7$	$4.38e-7$	$35.9e-7$	$2.18e-6$	$2.42e-6$	$5.58e-6$
128 KB	Proposed	$1.97e-6$	$1.97e-6$	$1.97e-6$	$6.65e-8$	$9.05e-8$	$29.2e-8$	$2.04e-6$	$2.06e-6$	$2.26e-6$
512 KB	Proposed	$1.91e-6$	$1.91e-6$	$1.91e-6$	$6.62e-8$	$9.04e-8$	$29.2e-8$	$1.98e-6$	$2.00e-6$	$2.20e-6$
2 MB	Proposed	$1.68e-6$	$1.68e-6$	$1.86e-6$	$6.51e-8$	$9.02e-8$	$29.2e-8$	$1.75e-6$	$1.77e-6$	$2.15e-6$
4 MB	Proposed	$1.38e-6$	$1.38e-6$	$1.38e-6$	$6.35e-8$	$8.99e-8$	$29.2e-8$	$1.44e-6$	$1.47e-6$	$1.67e-6$
16 MB	Proposed	$0.04e-6$	$0.06e-6$	$0.09e-6$	$5.62e-8$	$8.91e-8$	$29.2e-8$	$0.10e-6$	$0.15e-6$	$0.38e-6$
32 MB	Proposed	$0.04e-6$	$0.06e-6$	$0.09e-6$	$5.62e-8$	$8.91e-8$	$29.2e-8$	$0.10e-6$	$0.15e-6$	$0.38e-6$
64 MB	Proposed	$0.04e-6$	$0.06e-6$	$0.09e-6$	$5.62e-8$	$8.91e-8$	$29.2e-8$	$0.10e-6$	$0.15e-6$	$0.38e-6$

adaptation policy in (28). If normal, $b = b_{opt}$ and h_0 is determined. But if data of the next frame have not finished being transmitted in the last time slot and need to be transmitted in the current time slot, then the packets that transmit data of the next frame will not be controlled by power adaptation policy in order that data can succeed to be received. If starvation, b will increase, and all packets will not be controlled by power adaptation policy (see Algorithm 1).

5. Simulation Results

In the section, we compare baseline transmission and the proposed algorithm with respect to the data rate peak-to-mean ratio, standard deviation of the data rate, receiving energy per bit, transmission energy per bit, and total energy consumption per bit. We simulate the transmission schemes with three 30-minute VBR MPEG-4 QCIF format encodings from the movie Terminator 1. The video streams with a range of bit rates are available at http://trace.eas.asu.edu/ and their properties are summarized in Table 3. We run many independent replications of each simulation with random start points in the video streams until the 99% confidence level is less than 10% of the corresponding sample mean. In order to simulate a fading channel, we suppose that, carrier frequency f_c = 2 GHz, and speed of user v = 50 Km/h, and thus max Doppler frequency offset f_{max} = 92.6 Hz. In addition, without loss of generality, the transmission distance d is fixed for the sake of convenience to performance comparisons, and the duration of a packet is assumed to be 3 ms.

In the simulations reported in Tables 4, 5, and 6, we compare the performance for Stream 1, 2, and 3 for different buffer sizes, d = 15 m and QR-RLS algorithm mentioned in [12] is adopted as channel prediction algorithm. Table 4 shows that the proposed algorithm achieves the better performance with energy savings of up to 96% compared to the baseline transmission for Stream 1 when the buffer size is 16 MB, and from Tables 5 and 6 we observe energy savings up to 91% for Stream 2 with a buffer size of 32 MB and 85% for Stream 3 with a buffer size of 64 MB. We also see that energy performance of the proposed scheme improves with increasing buffer size. More specifically, we observe that for a stream with a low bit rate, for a small buffer, the energy saving comes mainly from the transmission energy component, while for large buffer sizes, the savings comes mainly from the receiving energy component. For instance, in Table 4, when the buffer size is 128 KB, 95% of the energy saving comes from the transmission component and only 5% from the receiving component. When the buffer size increases to 16 MB, the energy saving comes from the transmission component, which numerically stays constant for growing buffer sizes, is 9% and the receiving component is 91%. These observations can be explained by two main facts. First, the considered common client buffers are sufficiently large to allow the transmission of essentially all video frames of the low bit rate stream at the optimal data rate C_{opt}. Second, since C_{opt} is larger than the average bit rate of Stream 2, transmission at C_{opt} prefetches video frames into the receiver buffer until it is completely filled. The larger the receiver buffer capacity, the sooner all frames of the 30-min video stream can be prefetched, that is, the shorter the active time.

TABLE 8: Performance comparison for different channel prediction algorithms for Stream 1 ($d = 15$ m).

Buffer size	Scheme	Rec. Energy per Bit (J)		Trans. Energy per Bit (J)		Total energy per Bit (J)	
		QR-RLS	Burg	QR-RLS	Burg	QR-RLS	Burg
128 KB	Proposed	$1.97e - 6$	$1.97e - 6$	$6.65e - 8$	$6.64e - 8$	$2.04e - 6$	$2.04e - 6$
512 KB	Proposed	$1.91e - 6$	$1.91e - 6$	$6.62e - 8$	$6.61e - 8$	$1.98e - 6$	$1.98e - 6$
2 MB	Proposed	$1.68e - 6$	$1.68e - 6$	$6.51e - 8$	$6.49e - 8$	$1.75e - 6$	$1.75e - 6$
4 MB	Proposed	$1.38e - 6$	$1.38e - 6$	$6.35e - 8$	$6.34e - 8$	$1.44e - 6$	$1.44e - 6$
16 MB	Proposed	$0.04e - 6$	$0.04e - 6$	$5.62e - 8$	$5.63e - 8$	$0.10e - 6$	$0.10e - 6$
32 MB	Proposed	$0.04e - 6$	$0.04e - 6$	$5.62e - 8$	$5.63e - 8$	$0.10e - 6$	$0.10e - 6$
64 MB	Proposed	$0.04e - 6$	$0.04e - 6$	$5.62e - 8$	$5.63e - 8$	$0.10e - 6$	$0.10e - 6$

Hence, a large buffer reduces the receive energy consumption in the transceiver by completing the transmission of the entire video in less time. Further increases in the buffer size will further reduce the receive energy consumption. When the receive buffer can hold essentially the entire video, then no further receiving energy reductions are achieved by further increasing the receiver buffer.

In the simulations reported in Table 7, we compare the performance for Stream 1 for different transmission distances. As transmission distance d increases, the variation range of modulation levels will shrink, which is caused by (24). For example, if transmission distance $d = 100$ m, the modulation will mostly be fixed to 4QAM according to (24), that is to say the modulation will be nonadaptive, which is in accord with simulation results of transmission energy. But at this time the proposed power adaptation algorithm still brings the benefit to the performance. Though the energy consumption increases as transmission distance d increases, but both transmission and receiving energy when the proposed scheme is adopted are still much less than baseline and frame by frame schemes.

Moreover, Burg algorithm mentioned in [12] is adopted as channel prediction algorithm to evaluate the effect on performance by different channel prediction algorithms. According to analysis results in [12], prediction performance for QR-RLS algorithm is much better than Burg algorithm. However, it is seen from simulation results in Table ?? that performances for QR-RLS and Burg algorithm are nearly close. So we can deduce that the error caused by channel prediction algorithms has little impact on the performance of CCEVT algorithm.

According to analysis results in [13] written by an engineer in Infineon Technologies, Mobile RAM that is used in mobile device, generally works in Standby mode for about 93% time and in Active mode for 5%. And [13] gives the expression of energy consumption for Mobile RAM as follows:

$$E_{\text{RAM}} = V_c \cdot I_{\text{active}} \cdot t_{\text{active}} + V_c \cdot I_{\text{stdby}} \cdot t_{\text{stdby}}. \quad (44)$$

Then, according to the 4MB (or 32Mbit) Mobile RAM datasheet made by NEC [14], we can estimate the energy

consumption by memory during the video plays, which is 30 minutes in our simulation,

$$\begin{aligned} E_{\text{RAM}} &= V_c \cdot I_{\text{active}} \cdot t_{\text{active}} + V_c \cdot I_{\text{stdby}} \cdot t_{\text{stdby}} \\ &= 2.7 \times 45 \times 10^{-3} \times 30 \times 60 \times 5\% \\ &\quad + 2.7 \times 100 \times 10^{-6} \times 30 \times 60 \times 93\% \\ &= 11.39 \, (\text{J}). \end{aligned} \quad (45)$$

Then, as to Stream 1 with 4 MB buffer, the energy consumption by memory per bit is

$$E_{\text{bit}}^{\text{RAM}} = \frac{E_{\text{RAM}}}{\text{Total\_bit}} = \frac{11.39}{1.1 \times 10^8} = 1.04 \times 10^{-7} (\text{J}). \quad (46)$$

Similarly, as to Stream 1 with 16 MB buffer that consists of four 4 MB Mobile RAM chips, the energy consumption by memory per bit is

$$E_{\text{bit}}^{\text{RAM}} = \frac{E_{\text{RAM}}}{\text{Total\_bit}} = \frac{4 \times 11.39}{1.1 \times 10^8} = 4.16 \times 10^{-7} (\text{J}). \quad (47)$$

According to Table 4 (transmission distance $d = 15$ m) in P.15, the total energy of RF with 4 MB and 16 MB are $1.44e - 6$ and $0.10e - 6$, respectively. Then the total energy of RF and memory with 4 MB and 16 MB are $1.54e - 6$ and $0.52e - 6$, respectively. So our conclusion is still in effect with the consideration of both RF and memory energy consumption. Similarly, when transmission distance d is equal to 30 m or 100 m, the total energy of RF and memory with 16 MB is also much less than 4 MB.

6. Conclusion

In this paper, an energy-efficient variable-rate and variable-power modulation method is proposed, which is the optimization of the power and rate of M-QAM signal constellations. Then an adaptive scheme on energy-efficient video transmission over fading channels is proposed, which is called as CCEVT. In CCEVT scheme, in order to satisfy the requirement with energy efficiency and usage of client/receiver buffer, we implement adaptive selection of modulation level for every video frame, and adaptive power control to compensate the effect by fading channels for every packet. Simulation results show this scheme has good performance on energy saving.

Acknowledgments

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