Modulation Optimization under Energy Constraints

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***Abstract*— We consider radio applications where the nodes operate on batteries so that energy consumption must be minimized while satisfying given throughput and delay requirements. In this context, we analyze the best modulation strategy to minimize the total energy consumption required to send a given number of bits. The total energy consumption includes both the transmission energy and the circuit energy consumption. We show that for both MQAM and MFSK the transmission energy decreases with the BT_{on} product while the circuit energy consumption increases with T_{on}, where B is the modulation bandwidth and T_{on} is the transmission time. Thus, in short-range applications where the circuit energy consumption is nonnegligible compared with the transmission energy, the total energy consumption is minimized by using the maximum system bandwidth along with an optimized transmission time T_{on}. We derive this optimal T_{on} for MQAM and MFSK modulation in both AWGN channels and Rayleigh fading channels. Our optimization considers both delay and peak-power constraints. Numerical examples are given, where we exhibit up to 68% energy savings over modulation strategies that minimize the transmission energy alone.**

I. Introduction

Recent hardware advances allow more signal processing functionality to be integrated into a single chip. It is believed that soon it will be possible to integrate an RF transceiver, A/D and D/A converters, baseband processors, and other application interfaces into one device that is as small as a piece of grain and can be used as a fully-functional wireless node. Such wireless nodes typically operate with small batteries for which replacement, when possible, is very difficult and expensive. Thus, in many scenarios, the wireless nodes must operate without battery replacement for many years. Consequently, minimizing the energy consumption is a very important design consideration. In [1], the authors show that the hardware, the link layer, the MAC layer, and all other higher layers should be jointly designed to minimize the total energy consumption for energy-constrained wireless networks. The μAMPs project [2] at MIT, the WINS project [3] at UCLA and the PicoRadio project [4] at Berkeley are investigating energy-constrained radios and their impact on overall network design.

Achieving an optimal joint design across all layers of the network protocol stack is quite challenging. We therefore consider pair-wise optimization of the hardware and link layer designs. We investigate the energy consumption associated with both the transmitting path and the receiving path: namely the total energy required to convey a given number of bits to the receiver for reliable detection. We assume that the traffic between two nodes is approximately symmetric. Thus, minimizing the total energy consumption along both the transmitting path and the receiving path is equivalent to minimizing the total energy consumption inside a given node.

The issue of energy saving is significant since in a wireless node, the battery energy is finite and hence a node can only transmit a finite number of bits. The maximum number of of bits that can be sent is defined by the total battery energy divided by the required energy per bit. Most of the pioneering research in the area of energy-constrained communication has focused on transmission schemes to minimize the transmission energy per bit. In [5] the authors discuss some optimal strategies that minimize the energy per bit required for reliable transmission in the wide-band regime. In [6] the authors propose an optimal scheduling algorithm to minimize transmission energy by maximizing the transmission time for buffered packets. The emphasis on minimizing transmission energy is reasonable in the traditional wireless link where the transmission distance is large ($\geq$ 10 m), so that the transmission energy is dominant in the total energy consumption. However, in many recently-proposed wireless ad hoc networks the nodes are densely distributed, and the average distance between nodes is usually below 10 m. In this scenario, the circuit energy consumption along the signal path becomes comparable to or even dominates the transmission energy in the total energy consumption. Thus, in order to find the optimal transmission scheme, the overall energy consumption including both transmission and circuit energy consumption needs to be considered. In [7], some insightful observations are drawn for choosing energy-efficient modulation schemes and multi-access protocols when both transmission energy and circuit energy consumption are considered. It is shown that M-ary modulation may enable energy saving over binary modulation for some short-range applications by decreasing the transmission time. In [8], MQAM modulation is analyzed in detail, and optimal strategies to minimize the total energy consumption are proposed for AWGN channels. We extended these ideas to a detailed tradeoff analysis of the transmission energy, the circuit energy consumption, the modulation bandwidth, the transmission time, and the constellation size for MQAM and MFSK in both AWGN and Rayleigh fading channels. This analysis also takes peak-power and delay constraints into account.

For both MQAM and MFSK we minimize the total energy consumption required to meet a given BER requirement by optimizing two system parameters: the modulation bandwidth and the transmission time. The transmission time is bounded above by the delay requirement and bounded below by the peak-power constraint. The transmission energy is analyzed via probability of error bound approximations and the circuit energy consumption is approximated as a linear function of the transmission time. We show that the total energy function has nice properties such that an optimal bandwidth-time pair can be found numerically. From this optimization, we also find the optimal constellation size for MQAM and MFSK.

The remainder of this paper is organized as follows. Section II describes the system model in detail. Section III and IV solve the energy-constrained modulation problem for MQAM and MFSK respectively, in both an AWGN channel and a Rayleigh fading channel. Section V makes some comments on the optimization algorithms. Section VI summarizes our conclusions.

II. System Model

We consider a communication link connecting two wireless nodes. In order to minimize the total energy consumption, all signal processing blocks at the transmitter and the receiver

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need to be considered in the optimization model. However, at this stage we neglect the energy consumption of baseband signal processing blocks (*e.g.*, source coding, pulse-shaping, and digital modulation). We also assume that the system is uncoded. In order to clearly illustrate the tradeoff between the transmission energy and the circuit energy consumption, the power consumption of the A/D and D/A blocks is not included in the model. Otherwise, the introduced quantization noise will complicate the analysis. The methodology used here will be extended to include the A/D, D/A as well as other baseband signal processing blocks in our future research. The resulting signal paths on the transmitter and receiver sides are shown in Fig. 1 and Fig. 2, respectively. Although this model is based on a generic Low-IF transceiver structure, our framework can be easily modified to analyze other architectures as well.

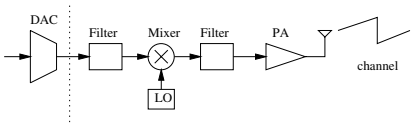

Fig. 1. Transmitter Circuit Blocks (Analog)

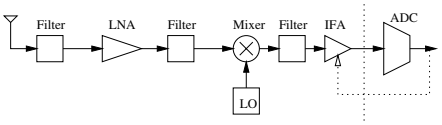

Fig. 2. Receiver Circuit Blocks (Analog)

We assume that the transceiver circuitry works on a multi-mode basis: when there is a signal to transmit all circuits work in active mode, when there is no signal to transmit they work in sleep mode, and when switching from sleep mode to active mode there is a transient mode. The multi-mode operation provides a significant saving of energy when the sleep mode is deployed. We also assume that the power consumption of the mixer, the frequency synthesizer, and the Low Noise Amplifier (LNA) can be approximated to be independent of the modulation bandwidth B, which is true when $B \ll f_c$ with f_c the carrier frequency. For the active analog filters and the Intermediate-Frequency Amplifier (IFA), their power consumption is dependent on the signal bandwidth. However, since their power consumption values are much less than that of the frequency synthesizer, the LNA or the power amplifier, they are also approximated as independent of B in our model for simplicity. Hence, as a first-order model, the circuit energy consumption can be expressed as a linear function of active time , since energy is the product of power and time.

We assume a node has L bits to transmit with a deadline T. The transceiver spends time $T_{on} \leq T$ to communicate these bits, where T_{on} is a parameter to optimize, and then returns to the sleep mode where all the circuits in the signal path are shut down for energy saving. Although the transient duration from active mode to sleep mode is short enough to be negligible, the start-up process from sleep mode to active mode may be slow due to the finite Phase Lock Loop (PLL) settling time in the frequency synthesizer. Thus, the transmission period T is given by $T = T_{tr} + T_{on} + T_{sp}$, where T_{tr} is the transient mode duration which is equal to the frequency synthesizer settling time (the start-up process of the mixer and power amplifier is fast enough to be neglected). Correspondingly, the total energy consumption E required to send L bits also consists of three components:

$$\begin{aligned} E &= P_{on}T_{on} + P_{sp}T_{sp} + P_{tr}T_{tr} \\ &= (P_t + P_{c0})T_{on} + P_{sp}T_{sp} + P_{tr}T_{tr}, \end{aligned} \quad (1)$$

where P_{on}, P_{sp} and P_{tr} are power consumption values for the active mode, the sleep mode, and the transient mode, respectively. The active mode power P_{on} comprises the transmission signal power P_t and the circuit power consumption P_{c0} in the whole signal path. Specifically, P_{c0} consists of the power amplifier power consumption P_{amp}, the mixer power consumption P_{mix}, the frequency synthesizer power consumption P_{syn}, the LNA power consumption P_{LNA}, the active filter power consumption P_{fil} (including all filters in the signal path), and the IFA power consumption P_{IFA}, where $P_{amp} = \alpha P_t$ and $\eta = \frac{1}{1+\alpha}$ is the drain efficiency [10] of the RF power amplifier. Although strictly speaking P_t should be part of the total amplifier power consumption, here we define P_{amp} as the value excluding the transmission signal power for convenience.

Since batteries are not only energy-limited but also peak-power-limited, the total power consumption of the wireless node can never exceed the maximum battery output power. The maximum power available for transmission and the related circuits, denoted as P_{max}, is equal to the maximum battery output power minus the total power consumption in all other unaccounted blocks. Since $P_{on} = \max\{P_{on}, P_{tr}, P_{sp}\}$, the peak-power constraint is given by

$$\begin{aligned} P_{on} &= P_t + P_{amp} + P_c \\ &= (1+\alpha)P_t + P_c \\ &\leq P_{max}, \end{aligned} \quad (2)$$

where $P_c = 2P_{mix} + 2P_{syn} + P_{LNA} + P_{fil} + P_{IFA}$ is used to denote the circuit power consumption (excluding the power amplifier power consumption) in the active mode and P_cT_{on} will be used to denote the corresponding circuit energy consumption in the following sections.

The start-up time for other circuit blocks is negligible compared to that of the frequency synthesizers. Hence, the optimal strategy for the start-up process is to turn on the frequency synthesizers first, and once they settle down, turn on the rest of the circuits. As a result, there is no unnecessary energy-wasting while the transceiver waits for the frequency synthesizers to settle down. Hence, P_{tr} merely needs to include the power consumption of the frequency synthesizers.

In the sleep mode, the power consumption is dominated by the leaking current I_l of the switching transistors if the circuitry is properly designed. Since CMOS technology is exclusively used in our analysis, the leaking current $I_l \approx 0$ [11] compared with the active mode. Thus, we set $P_{sp} = 0$. Our analysis can be easily modified to incorporate $P_{sp} \neq 0$.

Given Eq. (1) and Eq. (2), and the fact $P_{sp} = 0$ and $P_{tr} \approx 2P_{syn}$, the energy consumption per information bit $E_a = E/L$ is given by

$$\begin{aligned} E_a &= ((1+\alpha)P_t + P_c)T_{on} + P_{tr}T_{tr})/L \\ &\approx ((1+\alpha)E_t + P_cT_{on} + 2P_{syn}T_{tr})/L, \end{aligned} \quad (3)$$

where $E_t = P_tT_{on}$, and P_c, P_{syn} and T_{tr} can be treated as constants defined by the particular transceiver structure in use. As shown in the following sections, the transmission energy

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E_t is a monotonically increasing function of the bandwidth efficiency defined as $B_e = L/(BT_{on})$ (in bits/s/Hz). In other words, E_t is a monotonically decreasing function of the BT_{on} product for any fixed packet size L.

One thing we need to point out is that since the model shown in Fig. 1 and Fig. 2 is a generic model, it may need some modifications for specific systems. For example, the mixer at the transmitter side needs to be deleted for MFSK systems since frequency modulation is usually implemented digitally inside the frequency synthesizer. As a result, the corresponding expression for the P_c term in all the energy consumption formulas needs to be revised.

Finally, the energy-constrained modulation problem can be modeled as

$$\begin{array}{ll} \text{minimize} & E_a \\ \text{subject to} & 0 \le T_{on} \le T - T_{tr} \\ & 0 \le B \le B_{max} \\ & 0 \le (1+\alpha)P_t + P_c \le P_{max} \end{array} \tag{4}$$

where we can see that our task is to find the most efficient way to use the available bandwidth and transmission time under the given system constraints so that the total energy consumption is minimized. From the resulting optimal (B, T_{on}) pair, the optimal constellation size for a particular modulation scheme can be obtained. In the following sections, the optimization problem is solved for both MQAM and MFSK.

III. Energy-Constrained MQAM

We first take MQAM as a design example. Analysis is done over an AWGN channel and a Rayleigh fading channel, respectively.

A. AWGN Channels

For MQAM, the number of bits per symbol is defined as $b = \log_2 M$. The number of MQAM symbols needed to send L bits is denoted as $L_s = \frac{L}{b}$. If the symbol period is denoted as T_s, we can also represent L_s as $L_s = \frac{T_{on}}{T_s}$. Thus, $\frac{L}{b} = \frac{T_{on}}{T_s}$, *i.e.*,

$$b = \frac{LT_s}{T_{on}}. \tag{5}$$

If square pulses are used, $T_s \approx 1/B$. Hence,

$$b \approx \frac{L}{BT_{on}}. \tag{6}$$

Since the bandwidth efficiency is defined as $B_e = \frac{L}{BT_{on}}$, we can see that $b \approx B_e$ for MQAM.

The probability of error bound for MQAM is given by [12]

$$P_e \le 4(1-\frac{1}{2^b})Q\Big(\sqrt{\frac{3}{2^b-1}\gamma}\Big) \le 4(1-\frac{1}{2^b})e^{-\frac{3}{2^b-1}\frac{\gamma}{2}}, \tag{7}$$

where $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{u^2}{2}} du$. The Signal to Noise Ratio (SNR) γ is defined as $\gamma = \frac{P_r}{2B\sigma^2 N_f}$, where P_r is the received signal power, σ^2 is the power spectral density of the AWGN and N_f is the receiver noise figure defined as $N_f = \frac{N_{total}}{2B\sigma^2}$, where N_{total} is the total noise power which combines the channel noise and the noise introduced by all receiver circuits.

Hence, by approximating the bound as equality we obtain

$$P_r \approx \frac{4}{3} N_f B\sigma^2 (2^b - 1) \ln \frac{4(1-\frac{1}{2^b})}{P_e}. \tag{8}$$

Assuming free space propagation at distance d (meters), the transmission power is equal to

$$P_t = P_r G_d, \tag{9}$$

with $G_d \triangleq \frac{(4\pi d)^2}{G\lambda^2}$ the power gain factor, λ the carrier wavelength, and G a constant defined by the antenna gain and other system parameters. According to Eq. (6), Eq. (8) and Eq. (9), we obtain the transmission energy as

$$\begin{aligned} E_t &= P_t T_{on} \\ &\approx \frac{4}{3} N_f \sigma^2 (2^{\frac{L}{BT_{on}}} - 1) \ln \frac{4(1-2^{-\frac{L}{BT_{on}}})}{P_e} G_d B T_{on}. \end{aligned} \tag{10}$$

It is easily shown that E_t is a monotonically decreasing function over the product BT_{on} when MQAM is well defined, *i.e.*, when $b = \frac{L}{BT_{on}} \ge 2$. Thus, when the packet size L is fixed, there are two ways to decrease the transmission energy: increase the bandwidth B or increase the time duration T_{on}. Since the value of E_t is only dependent on the product of B and T_{on}, the optimal bandwidth-time pair to minimize the transmission energy will always be the maximum B together with the maximum T_{on}.

However, when we include the circuit energy consumption in the model, the situation may change. According to Eq. (3), the expression for the total energy consumption per information bit in term of T_{on} is given by

$$\begin{aligned} E_a &= \big((1+\alpha)\frac{4}{3} N_f \sigma^2 (2^{\frac{L}{BT_{on}}} - 1) \ln \frac{4(1-2^{-\frac{L}{BT_{on}}})}{P_e} \\ &\quad \times G_d B T_{on} + P_c T_{on} + 2P_{syn} T_{tr}\big)/L, \end{aligned} \tag{11}$$

where we see that in order to minimize the total energy consumption we must use the maximum bandwidth since the circuit energy consumption is independent of B and the transmission energy decreases with B. However, the value for T_{on} needs to be optimized under the delay and peak-power constraints. The peak-power constraint in Eq. (4) can be rewritten as

$$\begin{aligned} &(1+\alpha)\frac{4}{3} N_f \sigma^2 (2^{\frac{L}{BT_{on}}} - 1) \ln \frac{4(1-2^{-\frac{L}{BT_{on}}})}{P_e} G_d B \\ &\le P_{max} - P_c. \end{aligned} \tag{12}$$

For $B = B_{max}$, this inequality is equivalent to

$$T_{on} \ge T_{min}, \tag{13}$$

where T_{min} is the solution for T_{on} for which the equality in Eq. (12) holds. Thus, for MQAM the optimization model in Eq. (4) can be rewritten as

$$\begin{array}{ll} \text{minimize} & E_a \\ \text{subject to} & T_{min} \le T_{on} \le T - T_{tr} \\ & B = B_{max} \end{array} . \tag{14}$$

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$f_c = 2.5$ GHz	$\alpha = 1.9$
$G = 1$	$\sigma^2 = \frac{N_0}{2} = 10^{-16}$ W/Hz
$B_{max} = 1$ MHz	$L = 200$ kb
$P_{mix} = 30.3$ mW	$P_{syn} = 50$ mW
$P_{LNA} = 20$ mW	$P_{IFA} = 3$ mW
$P_{max} = 250$ mW	$P_{fil} = 5$ mW
$T_{tr} = 5$ μs	$T_s = \frac{1}{B}$
$T = 100$ ms	$P_e = 10^{-3}$
$N_f = 10$ dB	

TABLE I
MQAM PARAMETERS

For a specific numerical example, the circuit-related parameters need to be defined first. Here, the associated circuitry is composed of several blocks quoted from [10], [13], [14], and [15]. The corresponding parameters are summarized in Table I, where $\alpha = 1.9$ corresponds to the drain efficiency $\eta = 0.35$, which is a practical value for class-A RF power amplifiers [10] (Due to the linearity requirement for amplifying MQAM signals, class-A power amplifiers are usually used.). The values for B_{max}, L, and T are set up in such a way that $b_{min} = \frac{L}{B_{max}T} = 2$. Thus, the constellation size for MQAM is well defined inside the feasible region.

The plot of E_a over T_{on} for a maximum bandwidth $B = 1$ MHz is shown in Fig. 3. The vertical axis is the energy consumption per information bit (in terms of dB relative to a millijoule: $\log_{10}\frac{E_a}{0.001}$ dBmJ). The horizontal axis is the normalized transmission time. We see that the total energy consumption is no longer a monotonically-decreasing function over T_{on} when the transmission distance d is small. For example, when $d = 1$ m, E_a at the optimal $T^\star_{on} \approx 0.28T$ is about 5 dB lower than the non-optimized case where $T_{on} = T - T_{tr}$. Thus, T_{on} optimization results in an 68% energy saving. To guarantee that the peak-power constraint is satisfied, we need to verify that $T^\star_{on}$ is larger than T_{min}. From Eq. (12) we can numerically verify that the peak-power constraints are satisfied when $d \leq 10$ m. If $T^\star_{on} < T_{min}$ does occur, $T_{on} = T_{min}$ is chosen as the final solution. For example, when P_{max} is decreased from 250 mW to 189 mW, $T_{min} = 0.41T$ when $d = 1$ m. Thus, $T_{on} = 0.41T$ is used instead of $T_{on} = 0.28T$ for $d = 1$ m.

The transmission energy is dependent on the transmission distance d while obviously the circuit energy consumption is independent of d. Thus, we can save energy by optimizing T_{on} only when the circuit energy consumption is nontrivial relative to the transmission energy. Since the transmission energy increases with d, there exists a threshold for the value of d above which there is no energy savings possible. For the above example, $d = 10$ m is the threshold, where the derivative of E_a relative to T_{on} is approximately zero at the point $T_{on}/T \approx 1$. In general, to find the threshold we just need to find the value of d that makes the derivative of E_a relative to T_{on} at the maximum transmission time equal to zero.

According to the relationship defined in Eq. (6), we can find the optimal constellation size from the optimal values of B and T_{on}. We redraw E_a over b for the $d = 1$ m case in Fig. 4. We see from the figure that $b_{opt} \approx 7$ if the total energy consumption is considered versus $b_{opt} = 2$, its minimum value, when only transmission energy is considered.

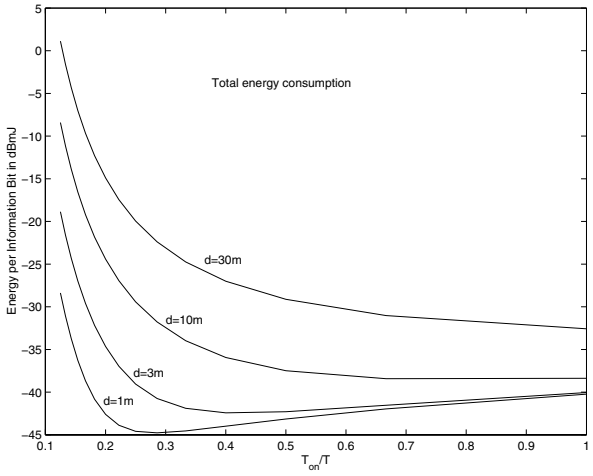

Fig. 3. Total Energy Consumption, MQAM, (AWGN)

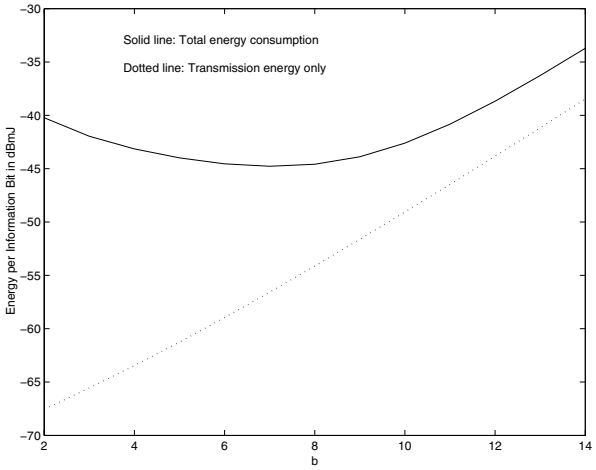

Fig. 4. Total energy consumption versus constellation size, MQAM (AWGN)

B. Rayleigh Fading Channels

In a flat Rayleigh fading channel, the average probability of error is given by (see [16])

$$P_e \approx \frac{1}{2}(1 - \sqrt{\frac{g\bar{\gamma}}{1+g\bar{\gamma}}}), \tag{15}$$

where $g = \frac{3}{2(M-1)}$ for MQAM, and the average SNR $\bar{\gamma}$ is defined as $\bar{\gamma} = \int \gamma p(\gamma) d\gamma$, where $p(\gamma) = \frac{1}{\bar{\gamma}} e^{-\gamma/\bar{\gamma}}$ is the SNR distribution in a Rayleigh fading channel.

From Eq.(15), we derive

$$\bar{\gamma} \approx \frac{(1-2P_e)^2}{g(1-(1-2P_e)^2)} \approx \frac{1}{4gP_e} \approx \frac{1}{4\frac{3}{2(M-1)}P_e} = \frac{2^b - 1}{6P_e}, \tag{16}$$

where we used the fact that $P_e \ll 1$. Considering $\bar{\gamma} = \frac{P_r}{2B\sigma^2 N_f}$, the required average received power for the target average

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probability of error P_e is given by

$$P_r \approx N_f B\sigma^2 \frac{2^b-1}{3P_e} = N_f B\sigma^2 \frac{2^{L/(BT_{on})}-1}{3P_e}. \quad (17)$$

We still assume that the average signal power is attenuated according to the square-law. Thus, the required transmission power for the target average probability of error P_e is given by

$$P_t = P_r G_d = N_f B\sigma^2 \frac{2^{L/(BT_{on})}-1}{3P_e} G_d. \quad (18)$$

The energy consumption per information bit at the transmitter is expressed as

$$\begin{aligned} E_a &= \big((1+\alpha)N_f\sigma^2 \frac{2^{L/(BT_{on})}-1}{3P_e} G_d BT_{on} \\ &\quad + P_c T_{on} + 2P_{syn}T_{tr}\big)/L. \end{aligned} \quad (19)$$

The optimization model can also be simplified into the form of Eq. (14), where the value of T_{min} is calculated in the same way as in AWGN channels. For numerical examples, we use the same setup as described in Table I. The energy consumption over T_{on} is plotted in Fig.5. Since in a fading channel the transmission energy requirement is much higher than that in an AWGN channel with the same BER requirement, the transmission energy consumption becomes dominant more quickly when we decrease T_{on}. Hence, the energy we can save by choosing the optimal T_{on} is less than that in an AWGN channel at the same distance. Non-trivial energy savings only occurs when the transmission distance is very small (*e.g.*, $d = 0.1$m).

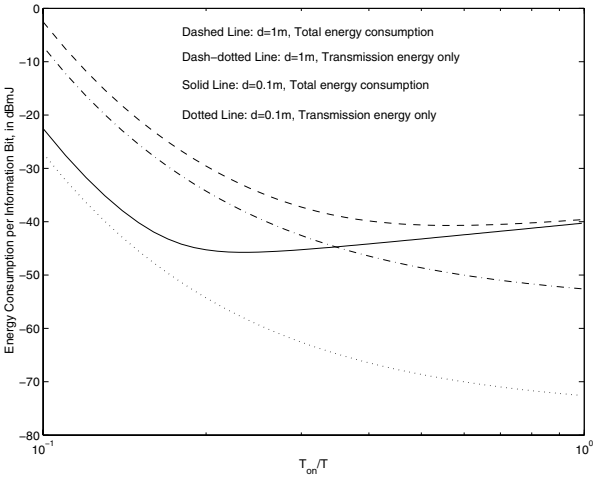

Fig. 5. Total energy consumption versus T_{on}, MQAM (Rayleigh fading)

IV. Energy-Constrained MFSK

For MFSK, the number of orthogonal carriers is $M = 2^b$. We assume the carrier separation is equal to $\frac{1}{2T_s}$, where T_s is the symbol period. Thus, the data rate $R = \frac{b}{T_s}$ and the total bandwidth can be approximated as $B \approx \frac{2^b}{2T_s}$ (see [12]). As a result, the bandwidth efficiency for MFSK is given by

$$B_e \triangleq 2b/2^b \ \ (b/s/Hz). \quad (20)$$

Since in general the bandwidth efficiency can also be represented as $B_e = \frac{L}{BT_{on}}$ regardless of modulation schemes, the relationship between the constellation size and the bandwidth-time product for MFSK is given by

$$2b/2^b = L/(BT_{on}), \quad (21)$$

which is different from the MQAM case where $b = L/(BT_{on})$. However, there still exists a one-to-one relationship between b and the BT_{on} product for any fixed value of L, except for $b = 1$ and $b = 2$, which correspond to the same BT_{on} product. We will discuss this interesting phenomena at the end of this section. For simplicity, all the following transmission energy functions for MFSK will be represented in term of b.

A. AWGN Channel

Since most practical MFSK receivers use non-coherent detectors, the probability of error bound for non-coherent MFSK detection is used in our derivation:

$$P_e \le \frac{2^b-1}{2} e^{-\frac{\gamma}{2}}. \quad (22)$$

Approximating the bound as an equality, we obtain $\gamma = \frac{bE_b}{N_0 N_f} \approx 2\ln\frac{2^b-1}{2P_e}$, where E_b is the energy per information bit at the receiver and $N_0 = 2\sigma^2$. Hence, $\frac{E_b}{2\sigma^2 N_f} = \frac{2}{b}\ln\frac{2^b-1}{2P_e}$. Following the same way as in the MQAM case, the transmission power and the transmission energy are given by

$$P_t = 4N_f\sigma^2 \ln\frac{2^b-1}{2P_e} G_d \frac{2B}{2^b} \quad (23)$$

and

$$E_t = P_t T_{on} = 4N_f\sigma^2 \ln\frac{2^b-1}{2P_e} G_d \frac{L}{b} \quad (24)$$

respectively, where we used the fact $T_{on} = \frac{2^b}{2b}\frac{L}{B}$ derived from Eq. (21).

One necessary modification in the hardware configuration compared to the MQAM system is that the mixer at the transmitter side should be deleted as we discussed in Section II. Correspondingly we redefine $P_c = 2P_{syn} + P_{mix} + P_{LNA} + P_{fil} + P_{IFA}$. Thus, the total energy consumption per information bit is given by

$$\begin{aligned} E_a &= \big((1+\alpha)4N_f\sigma^2 \ln\frac{2^b-1}{2P_e} G_d \frac{L}{b} \\ &\quad + P_c T_{on} + 2P_{syn}T_{tr}\big)/L. \end{aligned} \quad (25)$$

From Eq. (21) we see that the product of B and T_{on} defines the value of b when the packet size L is fixed. Hence, the value of E_t is dependent on the BT_{on} product. It can be proved that E_t is a monotonically decreasing function over b (when $b \ge 1$) unless P_e is unreasonably large (on the order of 0.1). Due to

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the relationship between b and BT_{on} as described in Eq. (21), E_t is also a monotonically decreasing function over the BT_{on} product which is similar to the MQAM case. Hence, increasing B always decreases the total energy consumption, but the optimal T_{on} may not be the maximum allowable transmission time. The optimization model is easily described in term of b. When $B = B_{max}$, it turns out that Eq. (4) can be rewritten as

$$\begin{array}{ll} \text{minimize} & E_a \\ \text{subject to} & b_{min} \le b \le b_{max} \\ & B = B_{max} \end{array} . \quad (26)$$

where b_{min} is calculated based the peak-power constraint, specifically, $(1+\alpha)P_t(b_{min}) = P_{max} - P_c$, and b_{max} is defined by the delay requirement in such a way that $\frac{2b_{max}}{2^{b_{max}}} = \frac{L}{B_{max}T}$.

To give a numerical example, we first assume the power consumption of corresponding circuit blocks is roughly the same as in the MQAM case. Since there is no longer a strict linearity requirement on the RF power amplifier, the value of α in Table I is changed to 0.33, *i.e.*, the drain efficiency $\eta = .75$, which corresponds to a class-B or a higher-class (C,D or E) power amplifier. The maximum bandwidth B_{max} and the packet size L are kept as 1 MHz and 200 kb, respectively. The maximum delay T is changed to 1.07 s, such that $b_{max} = 6$. Compared with the MQAM case, the increment of T is due to the fact that MFSK is less bandwidth-efficient than MQAM.

Hence, by fixing $B = B_{max} = 1$ MHz, we draw E_t and E_a directly over b as shown in Fig. 6. Not surprisingly, the

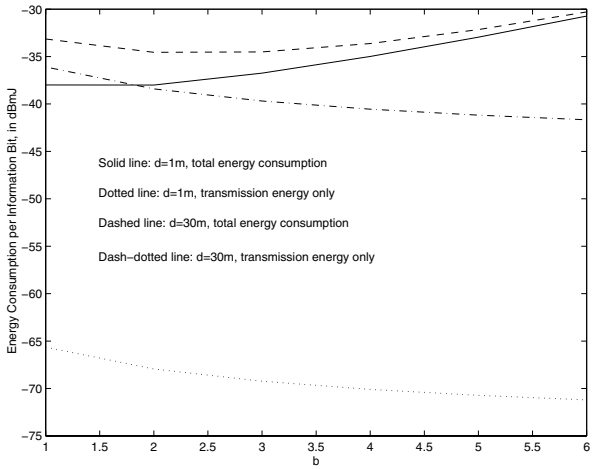

Fig. 6. Total energy consumption versus b, MFSK (AWGN)

transmission energy E_t goes down when b increases, since it is well known that the larger M is, the more energy efficient MFSK is, in an AWGN channel. In other words, $M = \infty$ is optimal in the sense of minimizing the energy consumption per information bit ([12]). When the circuit energy consumption is considered as shown in Fig. 6, 4-FSK turns out to be the best choice for both $d = 1$ m and $d = 30$ m if we do not consider the peak-power constraint. To take the peak-power constraint into account, we can numerically obtain $b_{min} = 1$ and $b_{min} = 4$ for $d = 1$ m and $d = 30$ m respectively. Thus, the final optimal values for b are $b_{opt} = 2$ for $d = 1$ m and $b_{opt} = 4$ for $d = 30$ m, respectively.

B. Rayleigh Fading Channel

Using the tight bounds derived in Chapter 7 of [12] for the P_e of MFSK in AWGN:

$$P_e \le \begin{cases} 2e^{-b(\frac{\gamma}{b} - 2\ln 2)/2} & (\ln M \le \frac{\gamma}{4}) \\ 2e^{-b(\sqrt{\frac{\gamma}{b}} - \sqrt{\ln 2})^2} & (\frac{\gamma}{4} \le \ln M \le \gamma) \end{cases} , \quad (27)$$

and taking the average over the distribution of the received power, we can numerically derive a new bound for the average probability of error in a Rayleigh fading channel. From this new bound we can numerically calculate the relationship between E_b and b for any given average P_e. Then the total energy consumption is calculated as

$$E_a = (1+\alpha)N_f E_b G_d + \big(P_c T_{on} + 2P_{syn}T_{tr}\big)/L, \quad (28)$$

where $T_{on} = \frac{2^b}{2b}\frac{L}{B}$. For a numerical example, we use the same setup as in the AWGN channel case. The transmission energy and the total energy consumption are drawn in Fig. 7. We see that $b_{opt} = 4$ and $b_{opt} = 2$ for $d = 5$ m and $d = 1$ m, respectively, if the total transmission energy is considered. We can numerically check that the peak-power constraint is satisfied when $P_{max} = 250$ mW.

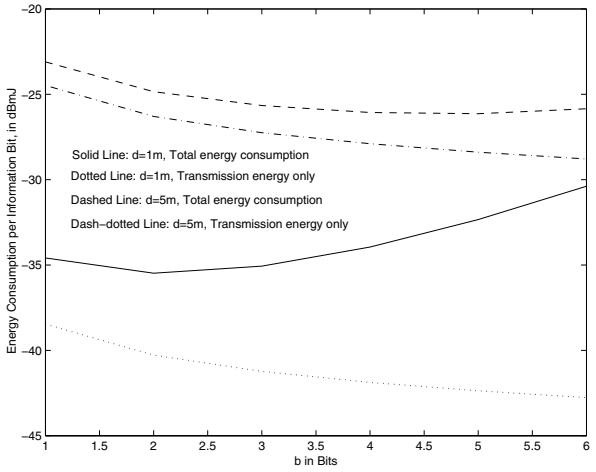

Fig. 7. Total energy consumption versus b, MFSK (Rayleigh fading)

One interesting observation is that for both AWGN and Rayleigh fading channels, 4-FSK is always more energy-efficient than BFSK. This is because the transmission energy is monotonically decreasing over b, while the circuit energy consumption is the same for the two cases since $T_{on} = \frac{2^b}{2b}\frac{L}{B}$ is the same for both $b = 1$ and $b = 2$. This result is based on the assumption that both BFSK and 4-FSK use the same transceiver architecture.

Another interesting observation is that for MFSK, there are two ways to increase b in order to decrease the transmission energy. According to the relationship $\frac{2b}{2^b} = \frac{L}{BT_{on}}$, to increase b, we can either increase B or increase T_{on} for a fixed L. The first approach is achieved by exponentially expanding the bandwidth ($B = \frac{2^b}{2T_s}$) while keeping the carrier separation

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$\frac{1}{2T_s}$ constant, and the second approach is achieved by packing a larger number of orthogonal carriers inside the fixed bandwidth as a result of exponentially decreasing the carrier separation (then the T_{on} is increased accordingly since $T_{on} = \frac{2^b}{2b}\frac{L}{B}$). The two strategies work equivalently well since the product $BT_{on} = \frac{2^b}{2b}L$ (according to Eq. (21)) is the same when the value of b is the same for these two approaches. Thus, the wide-band optimality (see [12]) of MFSK in the sense of saving transmission energy can be achieved by utilizing either infinite bandwidth or infinite transmission time.

V. Comments on the Optimization Algorithms

For MQAM, the transmission energy E_t can be shown to be monotonically decreasing over the BT_{on} product inside the feasible region ($b \geq 2$) in both AWGN and Rayleigh fading channels. Since $b = \frac{L}{BT_{on}}$ can only take on discrete values for an uncoded system, it is not useful to talk about convexity. Simple searching algorithms can be used to find the optimal solution due to the monotonicity of E_t and the fact that the feasible region is finite in practical systems.

For MFSK, monotonicity of E_t over b can be shown numerically unless the probability of error P_e takes extremely large values (on the order of 0.1). This dependence on P_e is due to the looseness of the probability of error bounds we use. As in the MQAM case, simple searching algorithms can be used to find the optimal solution.

VI. Conclusions

We have shown that for transmitting a given number of bits, the traditional belief that a longer transmission duration lowers energy consumption may be misleading if the circuit energy consumption is included, especially for short-range applications. For both MQAM and MFSK, we show that the transmission energy is completely dependent on the product of B and T_{on}. To minimize the transmission energy, both maximum bandwidth and maximum transmission time are desired. To minimize the total energy consumption, the maximum bandwidth is still desired and the transmission time needs to be optimized under the delay and peak-power constraints. The optimization is done for both AWGN and Rayleigh fading channels with up to 80% energy savings. We show that at the same transmission distance, the possible energy saving by optimizing the transmission time in a Rayleigh fading channel is less than that in an AWGN channel, since the transmission energy is more dominant in the former channel.

The energy-constrained modulation results can be applied to the optimal transmission adaptation problem to minimize the energy consumption. We assume that the transmitter works in a periodic manner, where the period T is defined by the delay requirement. At the beginning of each period T, the energy-constrained modulation problem is solved according to the number of bits in the buffer to be transmitted. In order to inform the receiver of the constellation size update, a short signaling header is transmitted to the receiver coded with a predefined system setup. Thus, an energy-minimizing adaptation is achieved.

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