ENERGY-OPTIMISED CODED MODULATION FOR SHORT-RANGE WIRELESS COMMUNICATIONS ON NAKAGAMI-m FADING CHANNELS

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ABSTRACT

When the distance between the transmitter and the receiver of a wireless communication link is sufficiently short, circuit energy consumption and transmission energy consumption become comparable, and substantial energy savings can be achieved by making use of a transmission scheme which takes into account total energy consumption instead of transmission energy alone. In this paper, we consider a trellis coded system operating on a Nakagami-m fading channel, and investigate the manner in which the trade-off between transmission energy and circuit energy consumption is affected by the value of the fading parameter m.

1. INTRODUCTION

When the distance between the transmitter and the receiver of a communication link is sufficiently short, circuit energy consumption and transmission energy consumption become comparable, and substantial energy savings can be achieved by making use of a transmission scheme which takes into account total energy consumption instead of transmission energy alone. This corresponds to joint optimisation of the physical and data link layers, and is a problem which has been considered in [1] for uncoded systems (both for AWGN and Rayleigh fading channels), and in [2] for coded systems (AWGN channels only).

The Nakagami-m fading channel model [3] has received considerable attention due to the fact that it can model a wider range of experimental data than for example the Rayleigh (included as the special case $m = 1$) or Rice fading models. It is also simpler to use than the Rice fading channel model. In this paper, we extend the results of [2] to the case of a coded system operating under Nakagami-m fading. It is our belief that both the Nakagami-m fading model and the joint optimisation of the circuit and transmission energies will play an important part in the design of future short-range wireless communication systems.

2. SYSTEM MODEL

We follow exactly the approach presented in [2] to model circuit power consumption (a summary is also included here for the sake of completeness). The power consumption of baseband signal processing blocks (e.g. source coding, pulse shaping, and digital modulation) is neglected, a generic Low-IF transceiver structure is assumed, and it is assumed that the transceiver circuitry works on a multimode basis: the circuits work in active mode when there is a signal to transmit, in sleep mode when there is no signal to transmit, and in transient mode when switching from sleep mode to active mode. Block diagrams of the transmitter and receiver structures are respectively depicted in Figs. 1 and 2 [2].

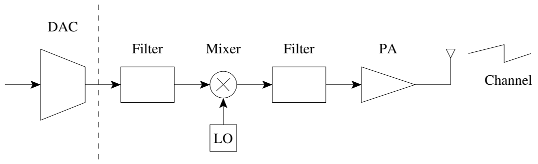

Figure 1: Transmitter Circuit Blocks (Analog)

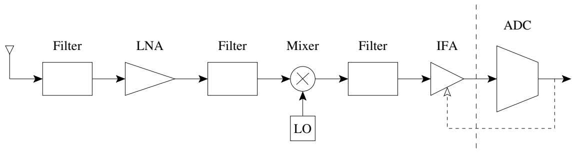

Figure 2: Receiver Circuit Blocks (Analog)

The circuit power consumption at the transmitter P_{ct} is given by $P_{ct} = P_{mix} + P_{syn} + P_{filt} + P_{DAC}$, where P_{mix} denotes the mixer power consumption, P_{syn} the frequency synthesiser power consumption, P_{filt} the active filter power consumption at the transmitter, and P_{DAC} the power consumption of the digital to analog converter. The circuit power consumption at the receiver P_{cr} is given by $P_{cr} = P_{mix} + P_{syn} + P_{LNA} + P_{filr} + P_{IFA} + P_{ADC}$, with identical definitions for P_{mix} and P_{syn}, and where P_{LNA} denotes the low noise amplifier power consumption, P_{filr} the active filter power consumption at the receiver, P_{IFA} the intermediate frequency amplifier power consumption, and P_{ADC} the power consumption of the analog to digital converter. The calculation of P_{ADC} and P_{DAC} is based on the model introduced in [4].

As explained in [2], although the transient duration from active mode to sleep mode is short enough to be neglected, 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 synthesisers. Moreover, the start-up time for other circuit blocks being negligible compared to that of the frequency synthesisers, the optimal start-up process is to turn on the frequency synthesisers first, and to turn on the remaining circuits once these have settled down.

We consider the problem outlined in [2], i.e., minimising the total energy consumption per information bit required to send, within a predefined deadline T, L information bits from the transmitter to the receiver of a communication system. The total energy consumption E required to send L information bits is given by [2]

$$E = P_{on}T_{on} + P_{sp}T_{sp} + P_{tr}T_{tr}, \tag{1}$$

where T_{on}, T_{sp}, and T_{tr} respectively denote the durations of the active, sleep, and transient modes, and P_{on}, P_{sp}, and P_{tr} respectively denote the power consumption during the active, sleep, and transient modes.

The power consumption in sleep mode P_{sp} is neglected because it is much smaller than the power consumption in active mode if the circuitry is properly designed [2]; we set thus $P_{sp} = 0$. The power consumption during the transient mode P_{tr} only needs to include that of the frequency synthesisers, since no power is consumed by the other circuit components while they wait for these to settle down [2]; we hence have $P_{tr} = 2P_{syn}$. Finally, the power consumption during the active mode P_{on} is given by $P_{on} = P_{ont} + P_{onr}$, where P_{ont} and P_{onr} respectively denote the power consumption in active mode at the transmitter and the receiver, and are given by

$$\begin{aligned} P_{ont} &= P_t + P_{amp} + P_{ct} \\ P_{onr} &= P_{cr}, \end{aligned} \tag{2}$$

where P_t denotes the transmission signal power, P_{amp} denotes the power dissipated by the power amplifier (excluding the transmission signal power P_t), and P_{ct} and P_{cr} have been previously defined. The amplifier power consumption is modelled by $P_{amp} = \alpha P_t$, where $\alpha = \frac{\xi}{\rho} - 1$ with ρ the drain inefficiency of the power amplifier and ξ the Peak to Average Ratio (PAR), which is dependent on the modulation scheme and associated constellation size [2].

The total energy consumption per information bit, $E_a = E/L$, is then given by

$$E_a = [((1+\alpha)P_t + P_c)T_{on} + P_{tr}T_{tr}]/L, \tag{3}$$

where $P_c = P_{cr} + P_{ct}$ includes the transmitter and receiver circuit power consumptions.

Batteries being not only energy limited but also peak-power limited [2], the maximum power consumption at the transmitter cannot exceed the maximum available battery power at the transmitter P_{maxt}. Similarly, the maximum power consumption at the receiver must not exceed the maximum available battery power at the receiver P_{maxr}. The maximum power consumption at the (receiver) transmitter being attained in active mode, it is the power consumption during this mode that should be kept lower than (P_{maxr}) P_{maxt}.

Our task will thus be to find the T_{on} (and associated coding scheme among the set of available codes) which minimises E_a, subject to the constraints

$$\begin{cases} 0 \leq T_{on} \leq T - T_{tr} \\ 0 \leq (1+\alpha)P_t + P_{ct} \leq P_{maxt} \\ 0 \leq P_{cr} \leq P_{maxr}. \end{cases} \tag{4}$$

3. TRELLIS CODE PERFORMANCE ANALYSIS

We utilise the set of eight 4-D trellis codes from [5] for our purposes. The nth 4-D trellis code, $n \in \{1, 2, \ldots, 8\}$, utilises an M-QAM constellation containing $M_n = 2^{n+1}$ signal points, has a spectral efficiency $\eta_n = n + \frac{1}{2}$ [bits/s/Hz], and a bit-error rate $P_{e,n}(\gamma)$ on an AWGN channel of signal-to-noise ratio γ which can be approximated by the expression

n	M_n	a_n	b_n
1	4	896.0704	10.7367
2	8	404.4353	6.8043
3	16	996.5492	8.7345
4	32	443.1272	8.2282
5	64	296.6007	7.9270
6	128	327.4874	8.2036
7	256	404.2837	7.8824
8	512	310.5283	8.2425

Table 1: Parameters a_n and b_n

$$P_{e,n}(\gamma) \approx \min\left\{\frac{1}{2}, a_n \exp\left(\frac{-b_n\gamma}{M_n}\right)\right\}, \tag{5}$$

where a_n and b_n are given in Table 1 for $n \in \{1, 2, \ldots, 8\}$ [5]. Now, let

$$p_\gamma(\gamma) = \left(\frac{m}{\bar{\gamma}}\right)^m \frac{\gamma^{m-1}}{\Gamma(m)} \exp\left(-m\frac{\gamma}{\bar{\gamma}}\right), \tag{6}$$

where $\Gamma(\cdot)$ is the Gamma function [6], denote the SNR distribution on a Nakagami-m fading channel with average channel signal-to-noise ratio (CSNR) $\bar{\gamma} = \int_0^\infty \gamma p_\gamma(\gamma)\,\mathrm{d}\gamma$ [7]. An approximative value for the bit-error rate $P_{e,n,\mathrm{nak}}(\bar{\gamma})$ of the 4-D trellis codes from [5] on such a channel can be obtained by evaluating

$$\begin{aligned} P_{e,n,\mathrm{nak}}(\bar{\gamma}) &= \int_0^\infty P_{e,n}(\gamma)p_\gamma(\gamma)\,\mathrm{d}\gamma \\ &\approx \frac{1}{2}\int_0^{\gamma_n} p_\gamma(\gamma)\,\mathrm{d}\gamma + \int_{\gamma_n}^\infty a_n e^{\frac{-b_n\gamma}{M_n}} p_\gamma(\gamma)\,\mathrm{d}\gamma \\ &= I_1 + I_2, \end{aligned} \tag{7}$$

where $\gamma_n = \frac{M_n}{b_n}\log(2a_n)$. It can be found that

$$I_1 = \frac{1}{2\Gamma(m)} \cdot \Gamma_c\left(m, \frac{m}{\bar{\gamma}}\gamma_n\right), \tag{8}$$

and

$$I_2 = \frac{a_n}{\Gamma(m)}\left(\frac{m}{\bar{\gamma}}\right)^m \left(\frac{b_n}{M_n} + \frac{m}{\bar{\gamma}}\right)^{-m} \Gamma\left[m, \left(\frac{b_n}{M_n} + \frac{m}{\bar{\gamma}}\right)\gamma_n\right], \tag{9}$$

where $\Gamma_c(\cdot,\cdot)$, $\Gamma(\cdot,\cdot)$, and $\Gamma(\cdot)$ respectively denote the complementary incomplete gamma function, the incomplete gamma function, and the gamma function [6].

The constant transmission power P_t can be related to the average CSNR by the equation [2]

$$\bar{\gamma} = \frac{P_t}{N_f \cdot N_0 B \cdot G_d}, \tag{10}$$

where N_f is the receiver noise figure, $N_0/2$ is the power spectral density of the AWGN, B is the system bandwidth, and $G_d \triangleq G_1 d^\kappa M_l$ with d the transmission distance, κ the path loss exponent, M_l the link margin compensating the hardware process variations and other additive background noise or interference, and G_1 the gain factor at $d = 1\,\mathrm{m}$.

$\kappa = 3.5$	$N_0/2 = -174$ dBm/Hz
$B = 10$ kHz	$L = 2$ kb
$T = 133.4$ ms	$P_{e,nak} = 10^{-3}$
$T_{tr} = 5$ μs	$\rho = 0.35$
$N_f = 10$ dB	$G_1 = 30$ dB
$M_l = 40$ dB	$P_{maxt} = P_{maxr} = 250$ mW
$P_{mix} = 30.3$ mW	$P_{syn} = 50$ mW
$P_{LNA} = 20$ mW	$P_{IFA} = 3$ mW
$P_{filt} = P_{filr} = 2.5$ mW	$P_{ADC} = 6.7$ mW
$P_{DAC} = 15.4$ mW	

Table 2: System Parameters

Now, for a given target bit-error rate $P_{e,nak}$, the required average CSNR $\bar{\gamma}$ for each of the 4-D trellis codes can be found by using numerical root finding techniques in Eq. (7), where I_1 and I_2 are replaced by their corresponding expressions. Once this value is known, the necessary transmission power P_t can easily be deduced from (10), and subsequently inserted in (3) to compute the corresponding total energy consumption per information bit.

Finally, note that if code n—with spectral efficiency $\eta_n = n + \frac{1}{2}$—is used, the required transmission time T_{on} will satisfy the relation $T_{on} B \eta_n = L$.

4. NUMERICAL EXAMPLE

The set of circuit related parameters we choose for our numerical example is given in Table 2, and is to a large extent inspired by [2]. As explained in Sec. 2, the power amplifier inefficiency of the nth 4-D trellis code, α_n, is computed using the relation [2]

$$\alpha_n = \xi_n/\rho - 1, \tag{11}$$

where ρ is the drain efficiency of the RF power amplifier, and ξ_n is the Peak-to-Average-Ratio of the M-QAM constellation used by the nth 4-D trellis code. If we assume a square M-QAM constellation for all the codes, we obtain $\xi_n = 3\frac{\sqrt{M_n}-1}{\sqrt{M_n}+1}$ [2]. Note that ξ_n depends on $M_n = 2^{n+1}$ and is hence different for each 4-D trellis code.

The total energy consumption per information bit of the 4-D trellis codes from [5], as a function of T_{on}/T, is shown in Fig. 3 for different values of the Nakagami-m fading parameter m and a transmission distance $d = 3$ m. A similar plot is shown in Fig. 4 for a transmission distance $d = 10$ m. In Fig. 5, the transmission energy per information bit alone, $E_{at} = P_t T_{on}/L$, is shown as a function of T_{on}/T for different values of the Nakagami-m fading parameter m and a distance $d = 3$ m. Finally, in Fig. 6, the required transmitter power $(1+\alpha_n)P_t + P_{ct}$ is plotted as a function of T_{on}/T for different values of the Nakagami-m fading parameter m and a transmission distance $d = 10$ m. $P_{maxt} = 250$ mW is also plotted for comparison.

In Figs. 3, 4, 5, and 6, each discrete point computed on the T_{on}/T axis corresponds to one of the eight 4-D trellis codes, following the relation $\frac{T_{on}}{T} = \frac{L}{TB} \cdot \frac{1}{\eta_n}$. Decreasing spectral efficiencies thus correspond to increasing values of T_{on}/T.

Let us now make a few comments based on these figures. First of all, Figs. 3 and 5 show that, designing a communication system to minimise transmission energy alone, or designing it to minimise total energy consumption, can yield completely different results. Indeed, whereas transmission energy is always minimised when using the code with the lowest spectral efficiency (here $\eta_1 = 1.5$ bits/s/Hz) this is not the case for total energy consumption (for example, when $d = 3$ m. under Rayleigh fading ($m = 1$), one should choose the code with spectral efficiency $\eta_5 = 5.5$ bits/s/Hz in order to minimise total energy consumption).

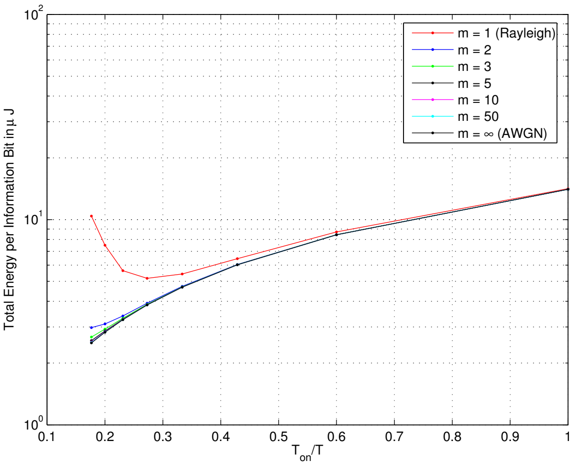

Figure 3: Total energy consumption per information bit of 4-D trellis codes as a function of T_{on}/T for different values of the fading parameter m, assuming a transmitter receiver separation of $d = 3$ m.

By comparing Figs. 3 and 4 we see that, as the transmitter-receiver separation increases, transmission energy consumption becomes more and more dominant compared to circuit energy consumption, and we approach a scenario where it is optimal to transmit using the code with the lowest spectral efficiency (this is already the case for a Rayleigh fading channel at $d = 10$ m). Including circuit energy consumption in the global energy budget in order to design a communication system is therefore only relevant when the transmission distance is sufficiently short.

It is also apparent from the figures that the Ray-

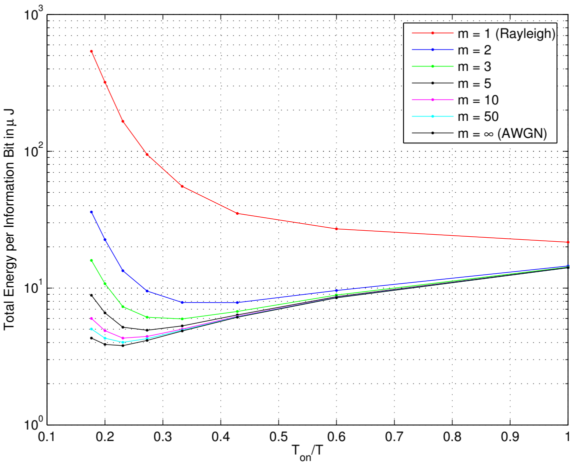

Figure 4: Total energy consumption per information bit of 4-D trellis codes as a function of T_{on}/T for different values of the fading parameter m, assuming a transmitter receiver separation of $d = 10$ m.

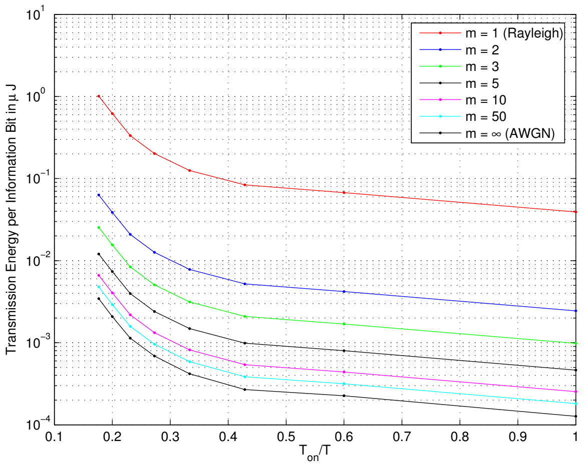

Figure 5: Transmission energy consumption per information bit of 4-D trellis codes as a function of T_{on}/T for different values of the fading parameter m, assuming a transmitter receiver separation of $d = 3\,\text{m}$.

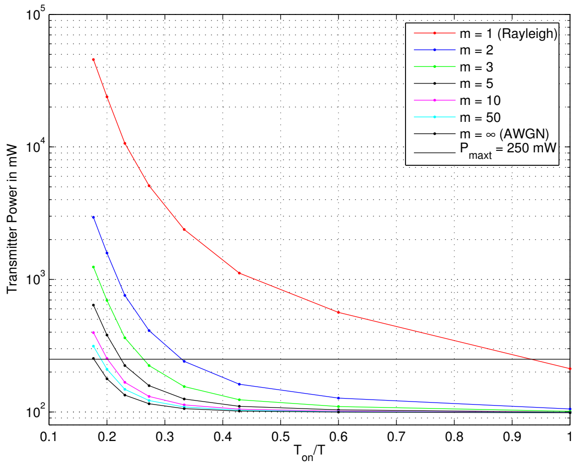

Figure 6: Transmitter power as a function of T_{on}/T for different values of the fading parameter m, assuming a transmitter receiver separation of $d = 10\,\text{m}$. $P_{maxt} = 250$ mW is also plotted for comparison.

leigh fading case ($m = 1$) and the AWGN channel case ($m \to \infty$) exhibit completely different behaviours. Indeed, due to the absence of a line-of-sight component in the Rayleigh fading channel, the required transmission power to achieve the target bit-error rate is larger than in the AWGN case, and this also results in an increased total energy per information bit for all allowed values of T_{on}/T. It is also interesting to see that the total energy consumption curve when $m = 2$ is closer to the case $m = \infty$ than to the case $m = 1$ both when $d = 3\,\text{m}$. and when $d = 10\,\text{m}$. This indicates that, in many cases, significant energy savings can be achieved using the scheme from [2] also when the power of the line-of-sight component is low, even if this might not be possible in the presence of a Rayleigh fading channel with same average CSNR. Our results indicate that for the chosen family of 4-D trellis codes and the simulation parameters from Table 2, energy savings are possible by using the scheme from [2] for distances of up to 18 m. for Nakagami-m fading channels with $m = 2$, whereas in the case of Rayleigh fading, energy savings using this scheme are only possible for distances of up to 8 m. If the circuit energy consumption model were to be augmented by including e.g. baseband signal processing as well, these distances would become even larger.

Finally, note by looking at Fig. 6 that it is possible that the peak power constraint at the transmitter be violated if the code yielding the minimum total energy consumption per information bit is chosen. Although this does not happen when $d = 10\,\text{m}$., it would be straightforward to find, among all the codes satisfying the peak power constraint, the one yielding the minimum total energy consumption per information bit (if such a code exists) in such a case. This can be done by exhaustive search.

5. CONCLUSION

We have suggested a method to compute an approximate expression for the bit-error rate vs. CSNR curve of a set of 4-D trellis codes operating on a Nakagami-m fading channel, and shown how this expression can be used to analyse and optimise the trade-off between transmission and circuit energy consumption in a given framework (transmitting L bits within a deadline T). The results show that, in many cases, the behaviour of Nakagami-m fading channels with $m \geq 2$ in terms of total energy consumption is closer to that of an AWGN channel with the same average CSNR than to that of a Rayleigh channel with the same average CSNR, and that energy savings can hence be achieved for a much wider range of distances for Nakagami-m fading channels with $m \geq 2$ than for Rayleigh fading channels by including circuit energy consumption in the total energy budget.

6. REFERENCES

[1] S. Cui, A. Goldsmith, and A. Bahai, "Modulation optimization under energy constraints," in *Proc. IEEE International Conference on Communications*, May 2003, vol. 4, pp. 2805–2811.

[2] S. Cui, A. Goldsmith, and A. Bahai, "Energy-constrained modulation optimization for coded systems," in *Proc. IEEE Global Telecommunications Conference*, Dec. 2003, vol. 1, pp. 372–376.

[3] M. Nakagami, "The m-distribution: a general formula of intensity distribution of rapid fading," in *Statistical Methods in Radio Wave Propagation*, W. G. Hoffman, Ed. Pergamon, Oxford, U.K., 1960.

[4] S. Cui, A. Goldsmith, and A. Bahai, "Energy-constrained modulation optimization," *to appear in IEEE Trans. Wireless Commun.*

[5] K. J. Hole, H. Holm, and G. E. Øien, "Adaptive multidimensional coded modulation over flat fading channels," *IEEE J. Select. Areas Commun.*, vol. 18, no. 7, pp. 1153–1158, Jul. 2000.

[6] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, Academic Press, 6th edition, 2000.

[7] M. K. Simon and M. S. Alouini, *Digital Communication over Fading Channels: A Unified Approach to Performance Analysis*, John Wiley & Sons, 2000.