Energy-optimized coded modulation for short-range communications on Nakagami-m fading channels

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Key Point

In short-range applications, the circuit energy consumption is non-negligible compared with the transmission energy

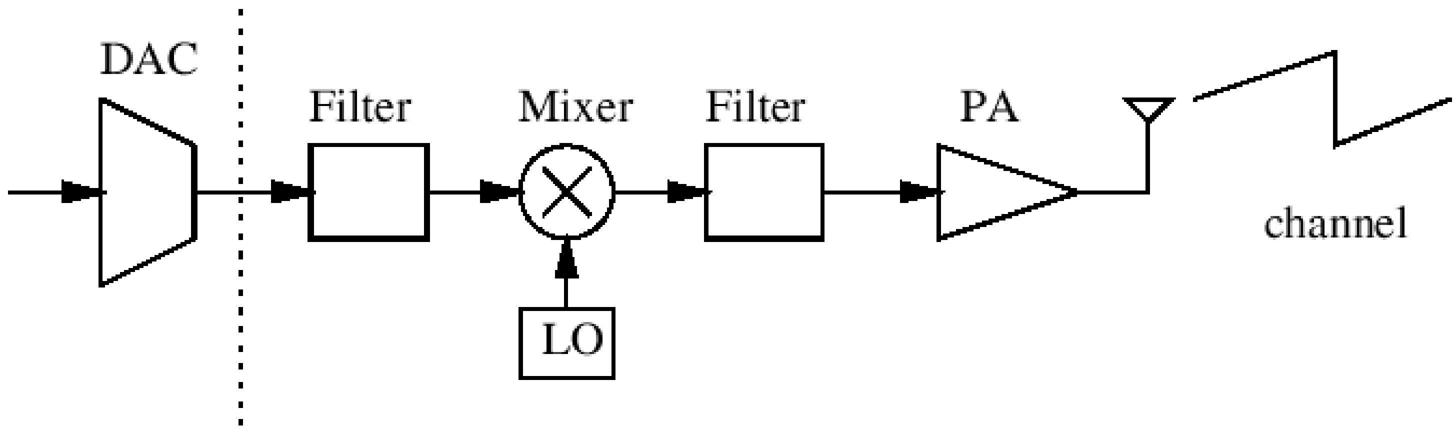
Energy-constrained Modulation Optimization

- Assumption: Both the transmitter and the receiver operate on batteries

- Goal: Find the best modulation strategy to minimize the total energy consumption required to send a given number of bits under a maximum time constraint

Based on: "Energy-constrained Modulation Optimization for Coded Systems", S. Cui, A. Goldsmith and A. Bahai

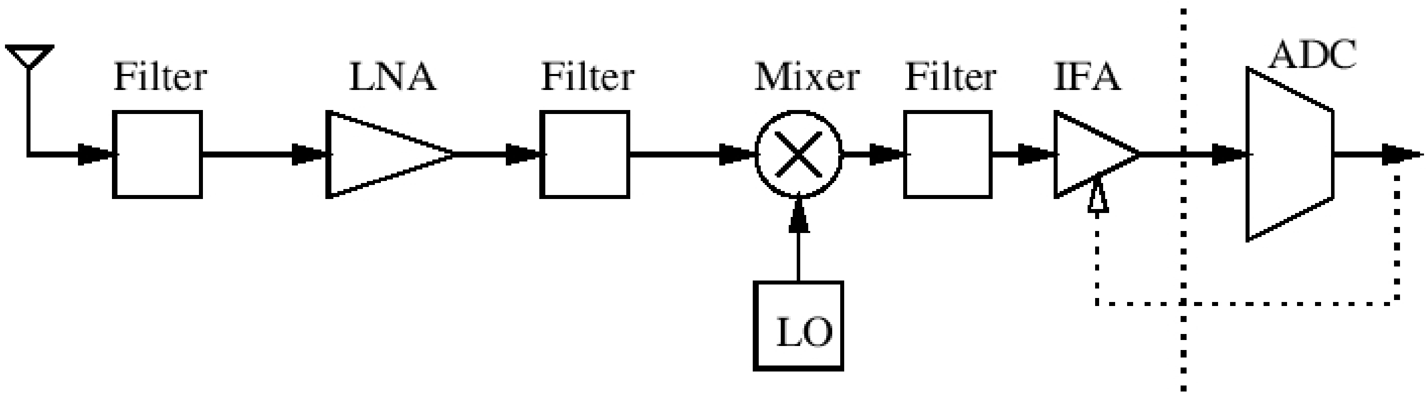
Energy Consumption: Transmitter



$$P_{ct} = P_{mix} + P_{syn} + P_{filt} + P_{DAC}$$

Based on: "Energy-constrained Modulation Optimization for Coded Systems", S. Cui, A. Goldsmith and A. Bahai

Energy Consumption: Receiver



$$P_{cr} = P_{mix} + P_{syn} + P_{LNA} + P_{filr} + P_{IFA} + P_{ADC}$$

Based on: "Energy-constrained Modulation Optimization for Coded Systems", S. Cui, A. Goldsmith and A. Bahai

Total Energy Consumption per Information bit

$$E_a = \frac{(1+\alpha)P_t T_{on} + P_c T_{on} + P_{tr} T_{tr}}{L}$$

α	Losses due to the amplifier
P_t	Transmitted power
T_{on}	Transmission time $(T_{on} \leq T)$
$P_c \triangleq P_{cr} + P_{ct}$	Circuit power consumption
L	Number of transmitted information bits

Based on: "Energy-constrained Modulation Optimization for Coded Systems", S. Cui, A. Goldsmith and A. Bahai

Total Energy Consumption per Information bit

$$E_a = \frac{(1+\alpha)P_t T_{on} + P_c T_{on} + P_{tr} T_{tr}}{L}$$

$$\bar{\gamma} = \frac{P_r}{N_0 B \cdot N_f} = \frac{P_t}{G_d \cdot N_0 B \cdot N_f} = f(P_e, b)$$

$\bar{\gamma}$	Average received SNR
$f(P_e, b)$	$\Longrightarrow$ channel, code, BER, ...
$N_0 B$	AWGN power
N_f	Receiver noise figure
G_d	Free path gain, proportional to $d^{3.5}$

Based on: "Energy-constrained Modulation Optimization for Coded Systems", S. Cui, A. Goldsmith and A. Bahai

Energy-constrained Modulation Optimization

- Analysis for:
  - MQAM modulations
  - AWGN, Rayleigh and Nakagami-m fading channels

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

Nakagami-m fading and Ricean fading

- Nakagami-m fading:

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

- Ricean fading:

$$p_\gamma(\gamma) = \frac{K+1}{\bar{\gamma}} \exp\left[-K - \frac{(K+1)\gamma}{\bar{\gamma}}\right] I_0\left(2\sqrt{\frac{K(K+1)\gamma}{\bar{\gamma}}}\right),$$

where $K \triangleq \dfrac{\text{Line of Sight Power}}{\text{Scattered Power}}$

Nakagami-m fading and Ricean fading

- Nakagami-m fading:

$$\begin{cases} m = 1 & \text{Rayleigh fading} \\ m = \infty & \text{AWGN channel} \\ 1 \leq m < \infty & \text{approximately Ricean fading, with:} \end{cases}$$

$$K = \frac{\sqrt{m^2 - m}}{m - \sqrt{m^2 - m}}$$

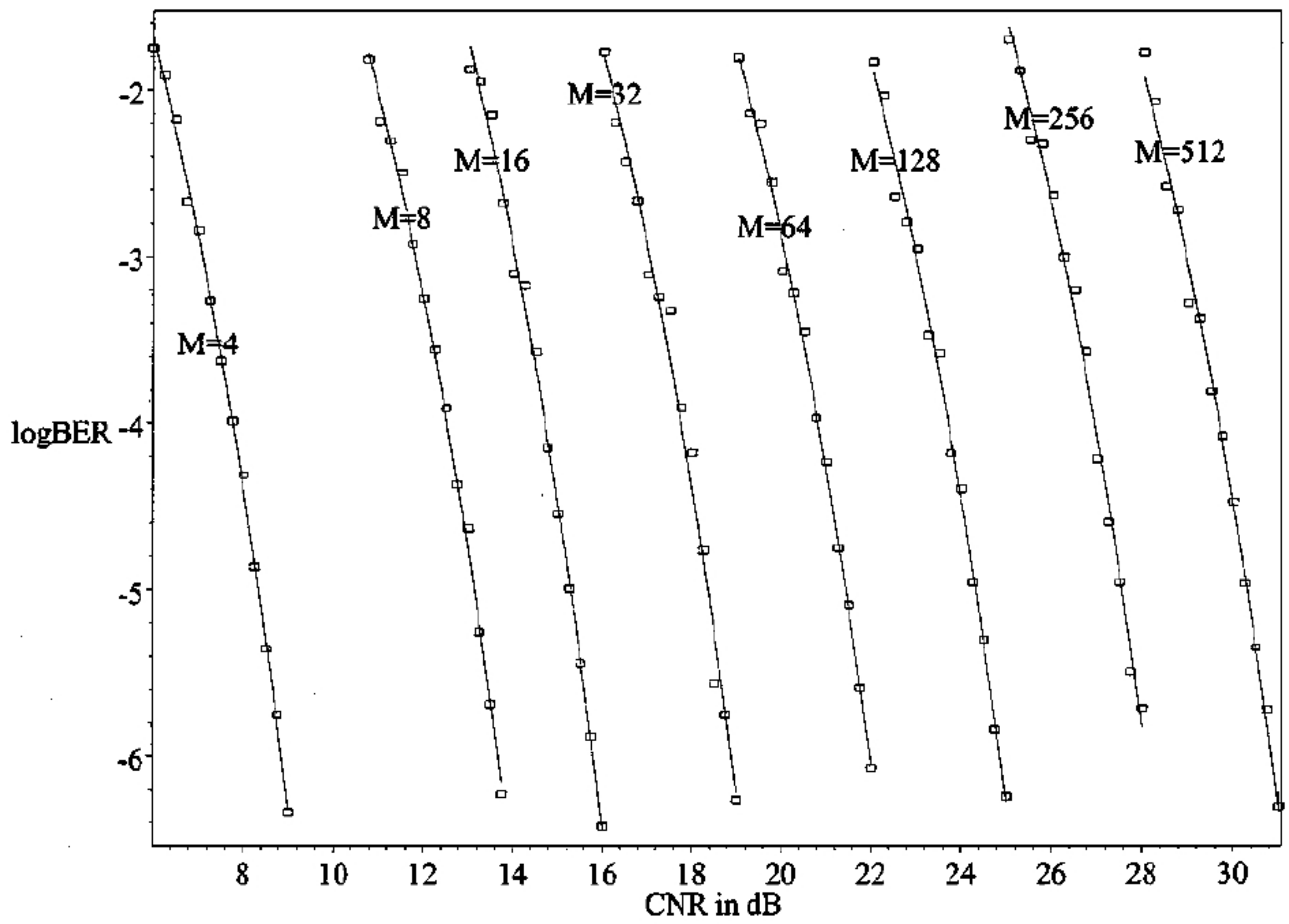
Coding Scheme

- Eight different 4-D Trellis Codes
- $b \in \{1.5, 2.5, \ldots, 8.5\}$ information bits, for a total of $\{2, 3, \ldots, 9\}$ bits per QAM symbol
- BER over AWGN channel for the nth 4-D trellis code approximated by

$$P_e(\gamma) \approx \begin{cases} a_n \exp\left(\frac{-b_n \gamma}{M_n}\right) & \text{if } \gamma \geq \gamma_n^* \\ \frac{1}{2} & \text{if } \gamma < \gamma_n^* \end{cases}$$

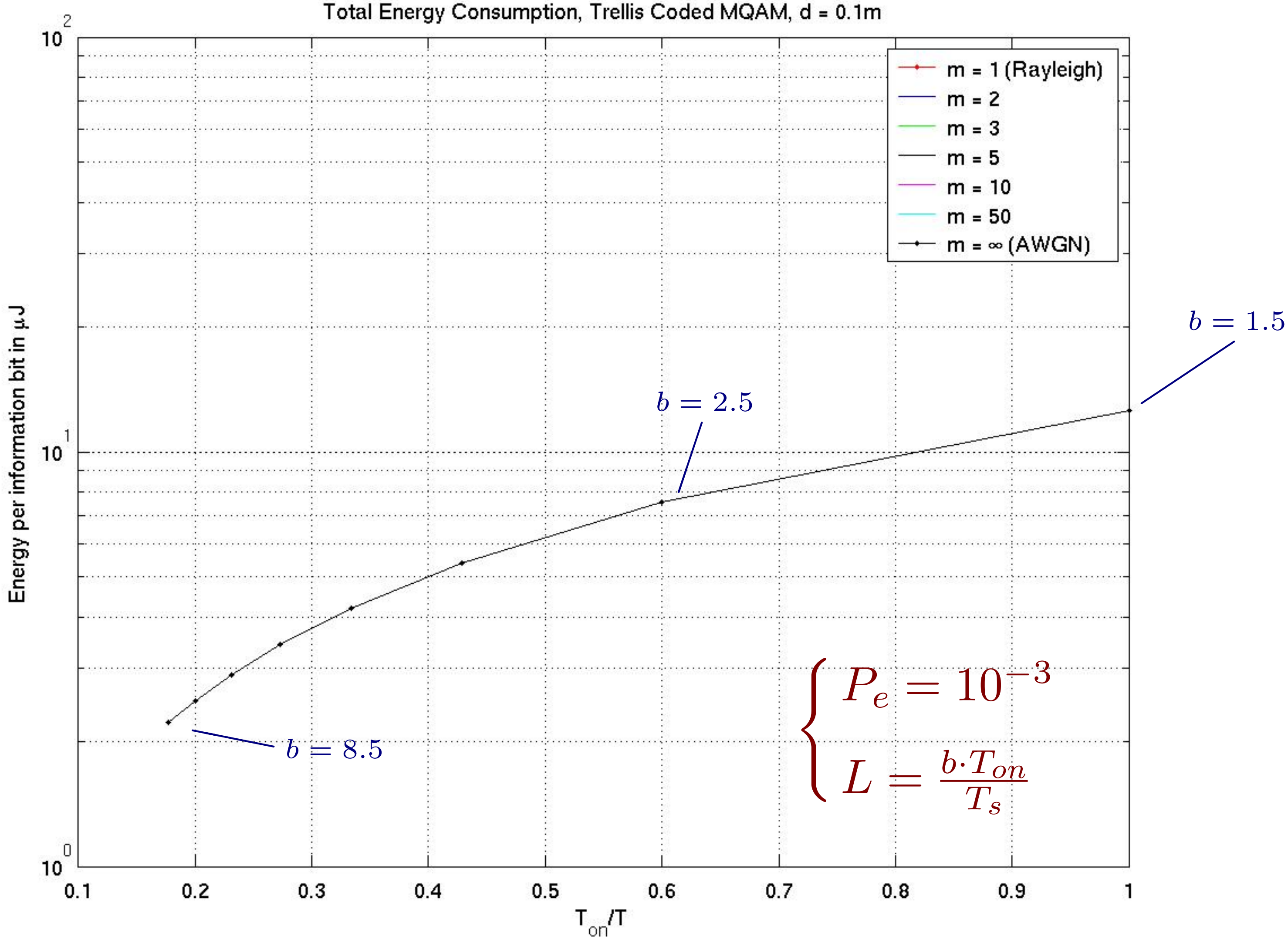
- Nakagami-m fading: $P_e(m, \bar{\gamma}) = \int_0^\infty P_e(\gamma) p_\gamma(\gamma) d\gamma$

BER of the 4-D Trellis Codes over an AWGN channel



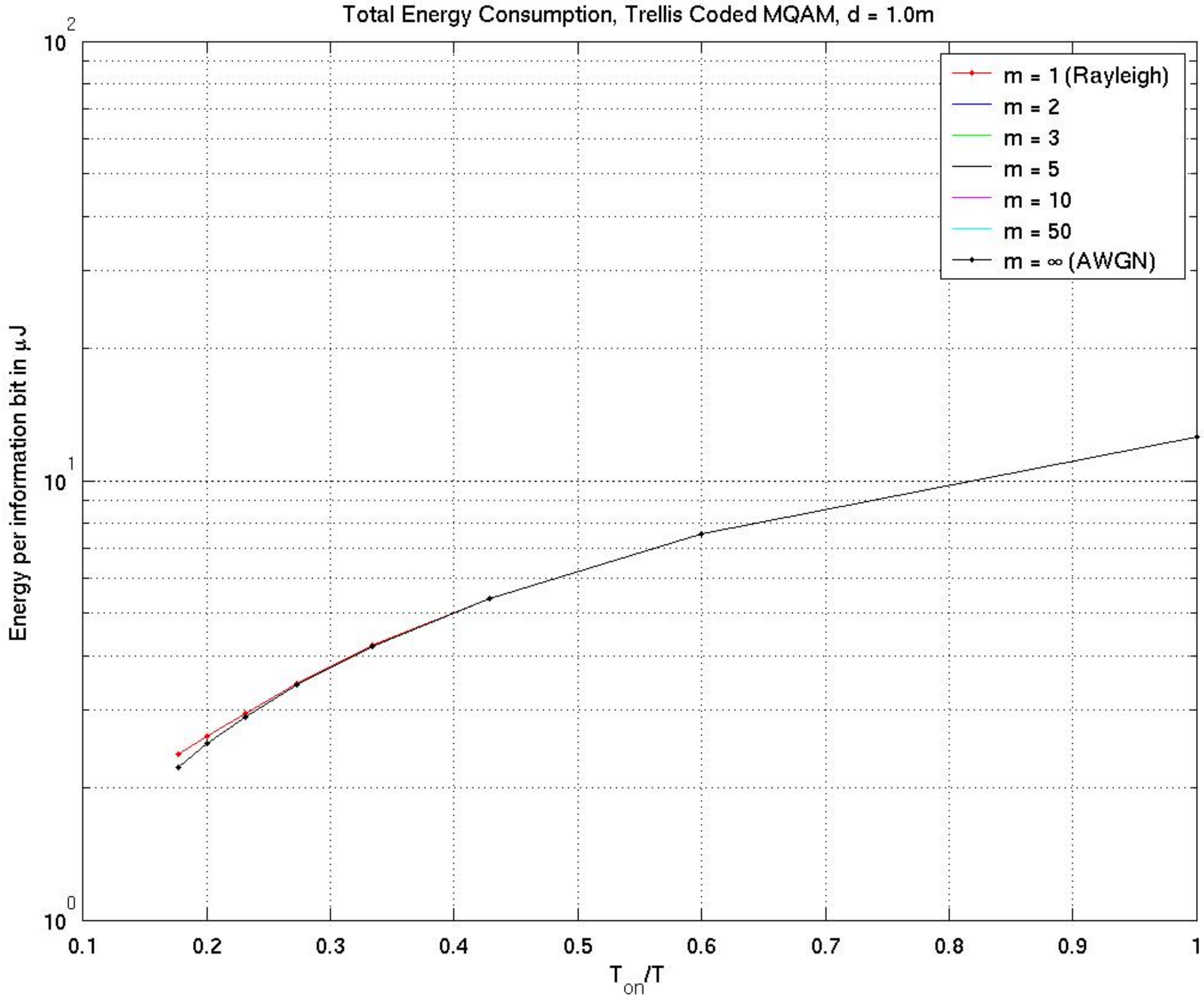
Based on: "Adaptive Multidimensional Coded Modulation Over Flat Fading Channels", K. J. Hole, H. Holm and G. E. Øien

Coded MQAM, $d = 0.1\ m$.

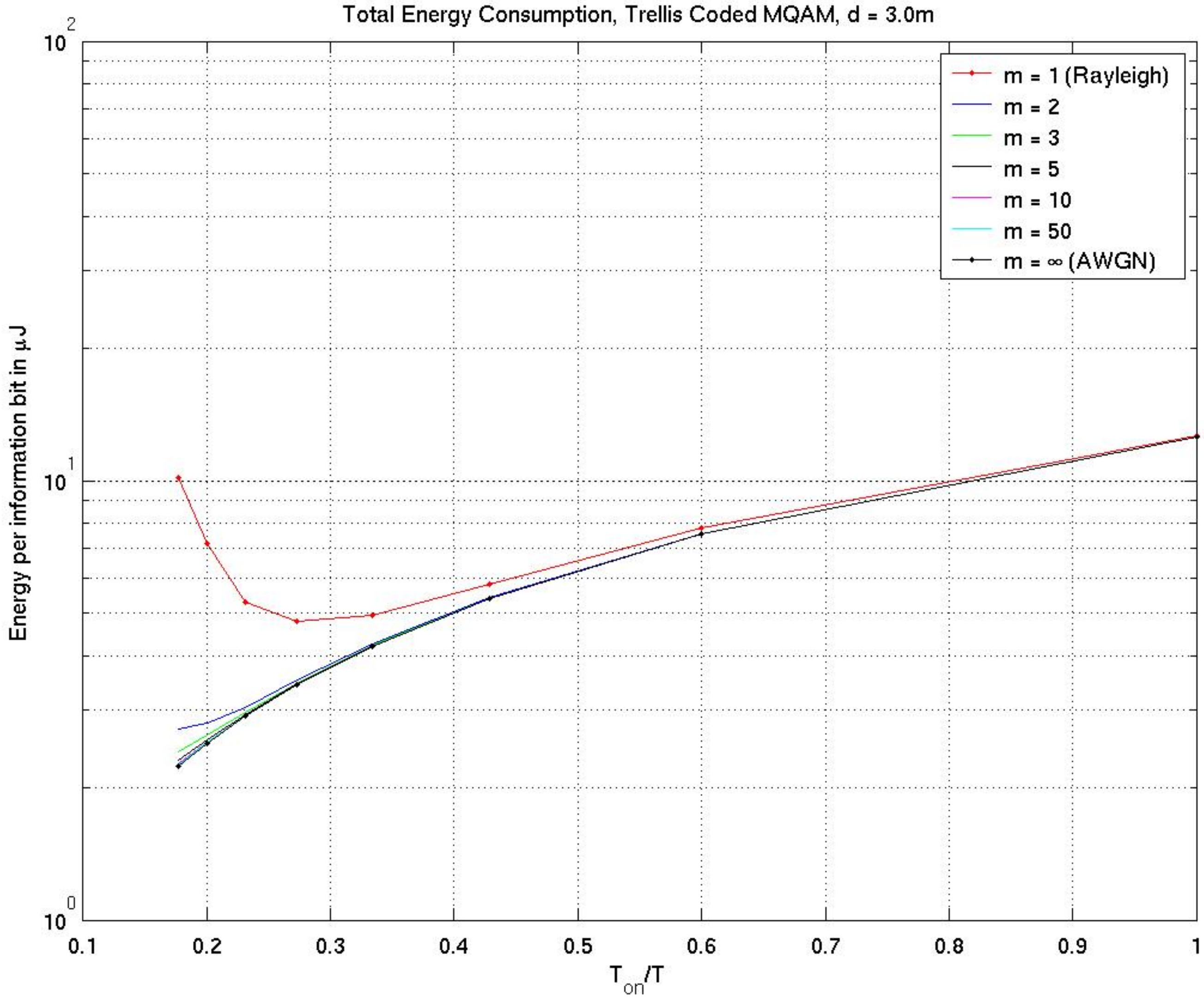


$$\begin{cases} P_e = 10^{-3} \\ L = \frac{b \cdot T_{on}}{T_s} \end{cases}$$

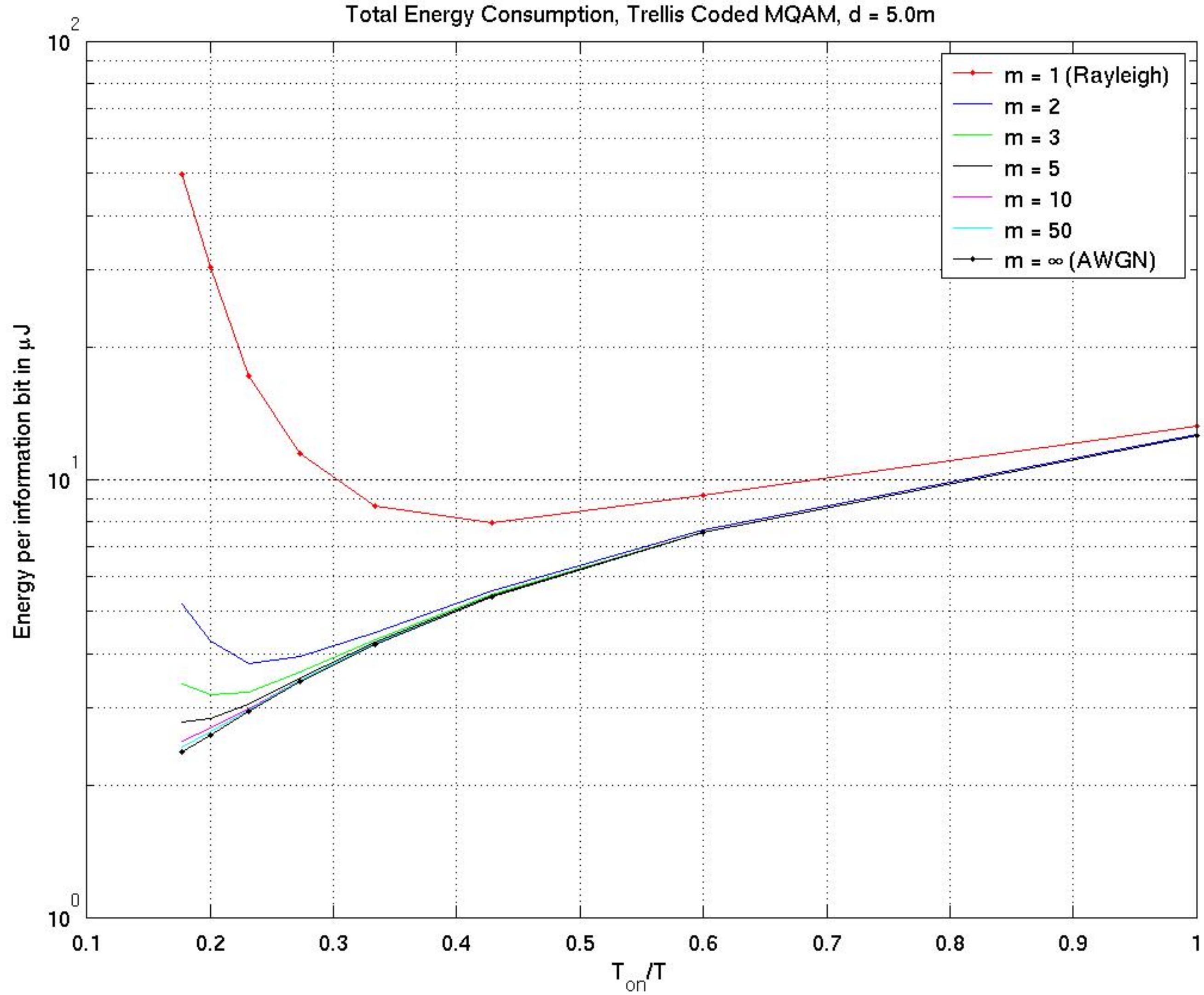
Coded MQAM, $d = 1.0\ m$.



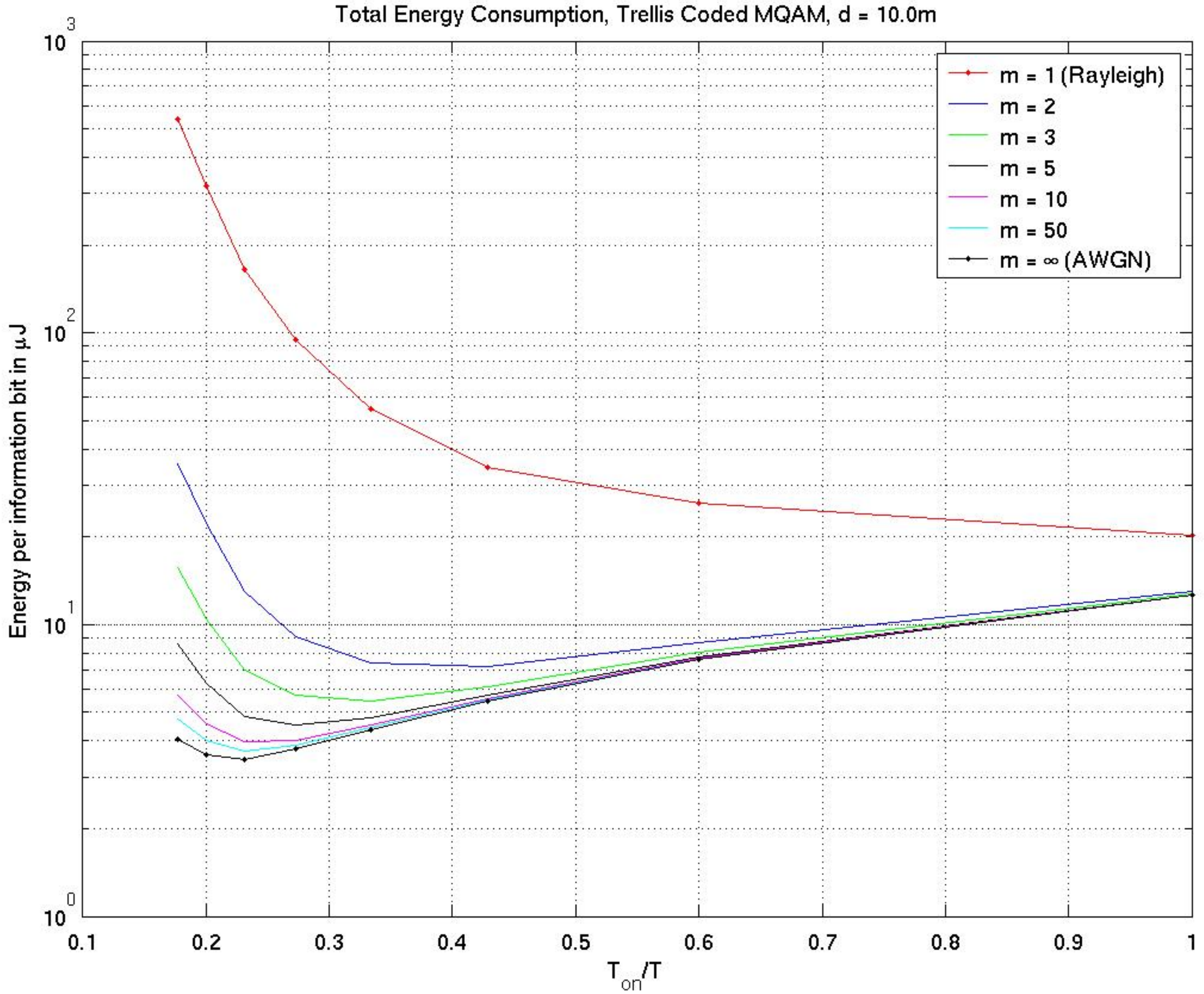
Coded MQAM, $d = 3.0\ m$.



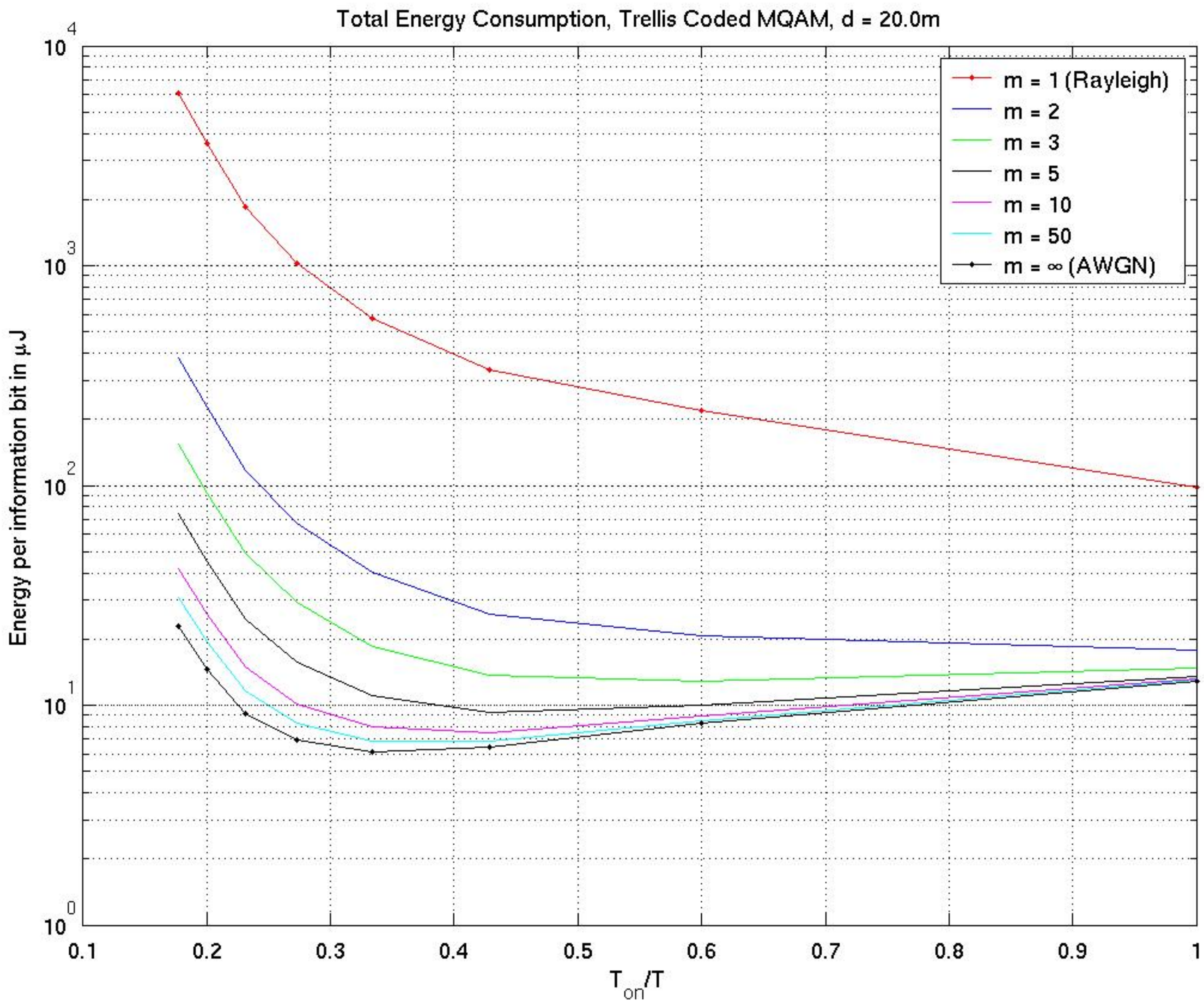
Coded MQAM, $d = 5.0\ m$.



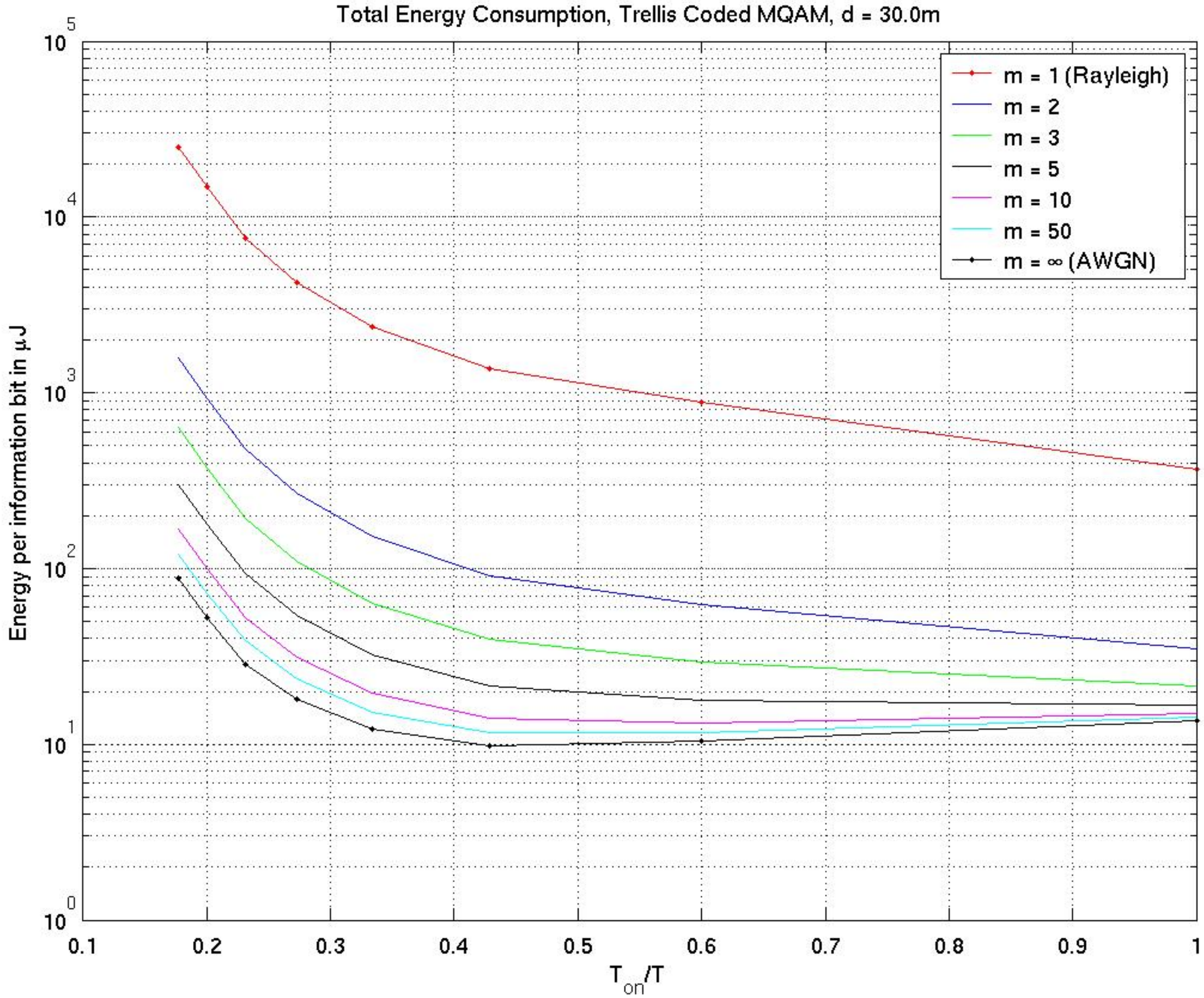
Coded MQAM, $d = 10.0\ m.$



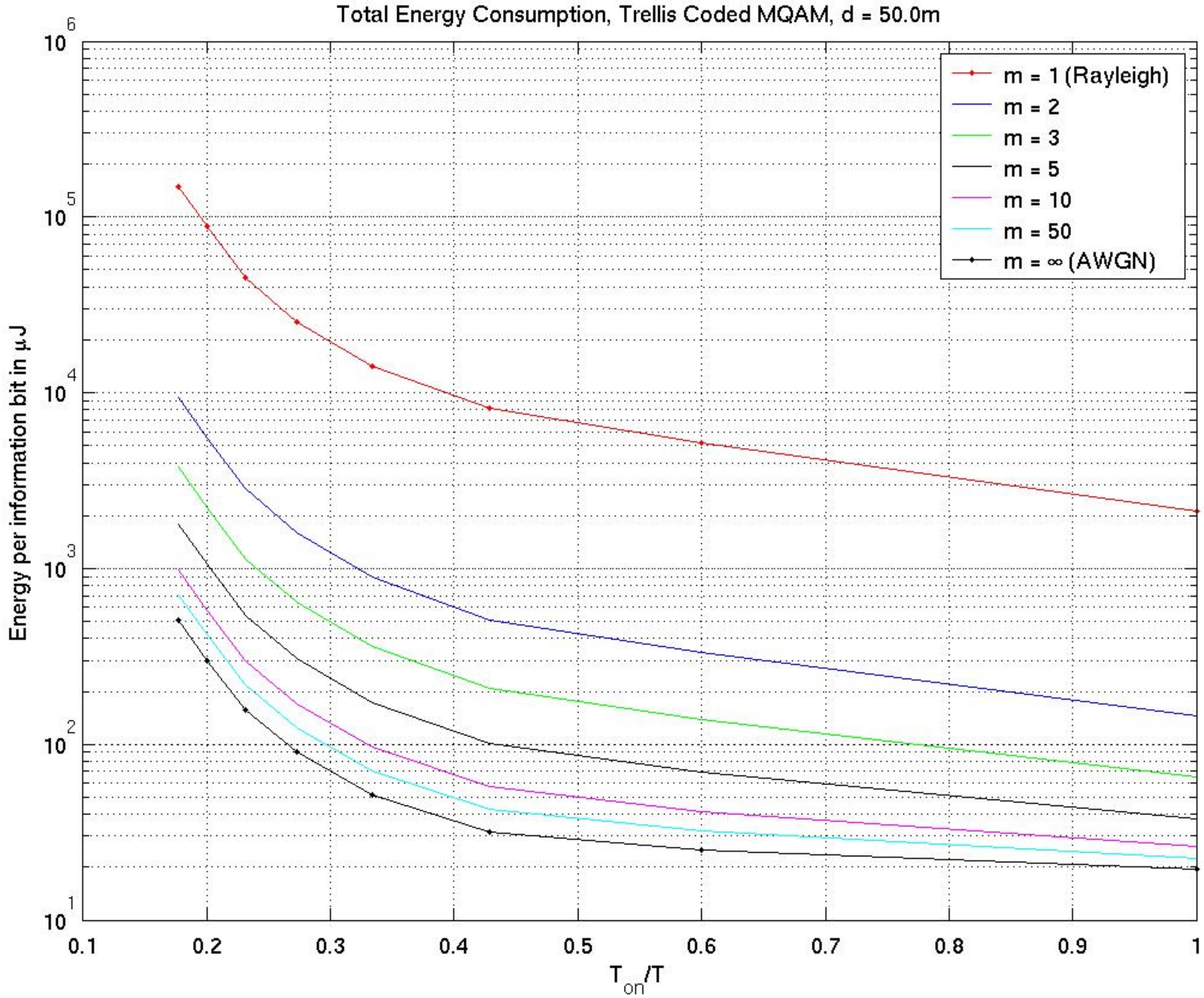
Coded MQAM, $d = 20.0\ m.$



Coded MQAM, $d = 30.0\ m$.



Coded MQAM, $d = 50.0\ m.$



Conclusions

- For short distances ($d < 1 - 2\ m.$), always use the highest spectral efficiency and the shortest transmission time
- For long distances, ($d \approx 50\ m.$) the transmission power dominates
- Rayleigh Fading: Since no LOS (Line of Sight) component is present, more transmission power is required $\longrightarrow$ "early breakoff"
- When a LOS component is present, the results are closer to the AWGN than to the Rayleigh case $\longrightarrow$ short-range optimization is then useful for a wide range of distances

Plans for future research

- Assume variable transmitter-receiver separation (random variable)
- Efficient short-range wireless transmission schemes using adaptive coded modulation
- MIMO extensions