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

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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

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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

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

\( \alpha \) \hspace{2cm} \text{Losses due to the amplifier}

\( P_t \) \hspace{2cm} \text{Transmitted power}

\( T_{on} \) \hspace{2cm} \text{Transmission time \((T_{on} \leq T)\)}

\( P_c \triangleq P_{cr} + P_{ct} \) \hspace{2cm} \text{Circuit power consumption}

\( L \) \hspace{2cm} \text{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

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

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

\( \bar{\gamma} \) \hspace{1cm} \text{Average received SNR}

\( f(P_e, b) \) \hspace{1cm} \text{\( \Rightarrow \) channel, code, BER, \ldots}

\( N_0 B \) \hspace{1cm} \text{AWGN power}

\( N_f \) \hspace{1cm} \text{Receiver noise figure}

\( G_d \) \hspace{1cm} \text{Free path gain, proportional to} \ d^{3.5}

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

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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:**
  \[
  p_{\gamma}(\gamma) = \left(\frac{m}{\bar{\gamma}}\right)^m \gamma^{m-1} \frac{\Gamma(m)}{\Gamma(m)} \exp\left(-m\frac{\gamma}{\bar{\gamma}}\right)
  \]

- **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 \( K \triangleq \frac{\text{Line of Sight Power}}{\text{Scattered Power}} \)
Nakagami-$m$ fading and Ricean fading

- Nakagami-$m$ fading:
  \[
  \begin{aligned}
  m = 1 & \quad \text{Rayleigh fading} \\
  m = \infty & \quad \text{AWGN channel} \\
  1 \leq m < \infty & \quad \text{approximately Ricean fading, with:}
  \end{aligned}
  \]

  \[K = \frac{\sqrt{m^2 - m}}{m - \sqrt{m^2 - m}}\]
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 \( n \)th 4-D trellis code approximated by

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

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

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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

Energy-optimized coded modulation for short-range communications on Nakagami-\(m\) fading channels
Coded MQAM, \( d = 0.1 \text{ m} \).

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

\[
\begin{align*}
E = b \cdot T_{on} \\
L &= \frac{b \cdot T_{on}}{T_s}
\end{align*}
\]

\( P_e = 10^{-3} \)
Coded MQAM, $d = 1.0\ m$. 

Energy-optimized coded modulation for short-range communications on Nakagami-$m$ fading channels
Coded MQAM, $d = 3.0\ m$. 
Coded MQAM, $d = 5.0\, m$. 

Energy-optimized coded modulation for short-range communications on Nakagami-$m$ fading channels
Coded MQAM, $d = 10.0\ m$. 

- Energy-optimized coded modulation for short-range communications on Nakagami-\m fading channels
Coded MQAM, $d = 20.0 \text{ m}$. 

Energy-optimized coded modulation for short-range communications on Nakagami-$m$ fading channels
Coded MQAM, \( d = 30.0 \) m.
Coded MQAM, \( d = 50.0 \text{ m.} \)
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 \(\rightarrow\) “early breakoff”

- When a LOS component is present, the results are closer to the AWGN than to the Rayleigh case \(\rightarrow\) 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