Energy-efficiency of MIMO and Cooperative MIMO Techniques in Sensor Networks
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March-5-2012
Outline

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In sensor networks, most sensors are powered by batteries. Replacement of batteries is difficult and expensive. Energy-efficient transmission schemes are needed for data transfer. MIMO has been showed to achieve higher data rate under the same transmit power budget and BER performance requirements as SISO system. Alternatively, for the same data rate, MIMO requires less transmission energy. In sensor network, the total energy consumption is a summation of the transmission energy and the circuit energy. Our goal: Optimize both parts.
Figure: Transmitter Circuit Blocks (Analog)

Figure: Receiver Circuit Blocks (Analog)
- The system is uncoded.
- Local oscillator is shared among all the antenna paths.
- For SISO, $M_t = M_r = 1$.
- Two power consumption along the signal path:
  - power consumption of all the power amplifiers $P_{PA}$
  - power consumption of all other circuit blocks $P_c$
- The Alamouti code is used in this paper.
Power consumption of all the power amplifiers $P_{PA}$

\[ P_{PA} = (1 + \alpha) \bar{E}_b R_b \frac{(4\pi d)^2}{G_t G_r \lambda^2 M_l N_f} \] (1)

where

- $\bar{E}_b$ is the required energy per bit at the receiver for a given BER requirement
- $R_b$ is the bit rate
- $G_t$ and $G_r$ are the antenna gain at transmitter and receiver
- $\lambda$ is the carrier bandwidth
- $M_l$ is the link margin compensating the hardware process variations and other additive background noise or interference
- $N_f = \frac{N_r}{N_0}$ is the receiver noise figure with the single-sided thermal noise PSD at room temperature $N_0$ and the PSD of the total effective noise at the receiver input $N_r$
- $\alpha = \frac{\xi}{\eta} - 1$ with $\eta$ the drain efficiency of the RF power amplifier and $\xi$ the Peak to Average power ratio (PAR).
Power consumption of all other circuit blocks $P_c$

$$P_c \approx M_t(P_{DAC} + P_{mix} + P_{filt}) + 2P_{syn}$$
$$+ M_r(P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC})$$

(2)

$$P_{DAC} \approx \beta \left( \frac{1}{2} V_{dd} I_0 (2^{n_1} - 1) + n_1 C_p (2B + f_{cor}) V_{dd}^2 \right)$$

(3)

$$P_{ADC} \approx \frac{3V_{dd}^2 L_{min} (2B + f_{cor})}{10^{-0.1525n_2 + 4.838}}$$

(4)

where

- $V_{dd}$ is the power supply
- $I_0$ is the unit current source corresponding to the LSB
- $n_1$ and $n_2$ are the number of significant bits at the DAC and the ADC
- $C_p$ is the parasitic capacitance
- $f_{cor}$ is the corner frequency
- $L_{min}$ is the minimum channel length for the given CMOS technology
Fixed-rate System with BPSK Modulation: Alamouti $2 \times 1$

- For $2 \times 1$ MISO: scalar fading matrix $\mathbf{H} = [h_1 \ h_2]$.
- For SISO: $\mathbf{H} = [h_1]$.
- Instantaneous received SNR $\gamma_b = \frac{||\mathbf{H}||^2_F}{M_t} \frac{E_b}{N_0}$

$$
\bar{P}_b = \mathbb{E}_\mathbf{H} \left[ Q \left( \sqrt{2\gamma_b} \right) \right]
$$

$$
\leq \left( \frac{\bar{E}_b}{M_t N_0} \right) \quad \text{since Chernoff bound} \quad (5)
$$

$$
\bar{E}_b \leq \frac{M_t N_0}{\bar{P}_b^{1/M_t}} \quad (6)
$$

$$
E_{bt} = (P_{PA} + P_c)/R_b \quad (7)
$$

$$
\leq (1 + \alpha) \frac{M_t N_0}{\bar{P}_b^{1/M_t}} \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f + P_c/R_b \quad (8)
$$
Figure: Transmission energy consumption per bit over $d$
Figure: Transmission energy consumption per bit over $d$, MISO v.s. SISO
Figure: Transmission energy consumption per bit over $d$, MISO v.s. SISO
Figure: Transmission energy consumption per bit over $d$, MISO bound v.s. SISO bound
Fixed-rate System with BPSK Modulation: Alamouti $2 \times 2$

- $H = \begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{bmatrix}$
- Diversity order: 4; Array gain: 2.

Figure: Total energy consumption over $d$, MIMO v.s. SISO
Variable-rate Systems

- Optimal strategy: Operate on a multi-mode basis
- Deployment of sleep mode
- Optimize transceiver spends time $T_{on} \leq T$
- In MQAM, $b = \frac{L}{BT_{on}}$
- Large constellation sizes allow us to decrease $T_{on}$ to reduce the circuit energy consumption $E_c = P_c T_{on}$. 
\[
\bar{P}_b \approx E_H \left[ \frac{4}{b} \left( 1 - \frac{1}{2^b} \right) Q \left( \sqrt{\frac{3b}{M - 1}} \gamma_b \right) \right]
\]
for \( b \geq 2 \) \hfill (9)

\[
\approx E_H \left[ Q \left( \sqrt{2} \gamma_b \right) \right]
\]
for \( b = 1 \) \hfill (10)

where \( M = 2^b \). Similar with the fixed-rate system, we have

\[
E_{bt} = \frac{(P_{PA} + P_c)}{R_b}
\]

\[
= (1 + \alpha) \bar{E}_b \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_t N_f + P_c T_{on} / L
\]

\[
\leq \frac{2}{3} (1 + \alpha) \left( \frac{\bar{P}_b}{4} \right)^{-\frac{1}{M_t}} \frac{2^b - 1}{b^{\frac{1}{M_t} + 1}} M_t N_0 \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_t N_f + \frac{P_c T_{on}}{L}
\]

where \( T_{on} = \frac{L}{bB} \)
Optimized Alamouti $2 \times 1$

Figure: Total Energy consumption over $b$, MISO $2\times1$
Figure: Optimized total energy consumption over $d$, MISO v.s. SISO
Figure: Optimized total energy consumption over $d$, MIMO v.s. SISO
Figure: Total power consumption over $d$, the optimized system v.s. the unoptimized system.
MIMO with Multi-node Cooperation

Figure: Information Flow in a sensor network

Trade-off:
- Local data exchange
- Transmission delay
- $M_t$ transmitting nodes and each has $N_i$ bits to transmit
- $M_r$ receiving nodes (one destination node and $M_r - 1$ assisting nodes)
- The energy cost per bit or local information flow on the Tx side is $E^t_i$
- The energy cost per bit or local information flow on the Rx side is $E^r_i$
- The energy cost per bit for the MIMO long-haul transmission is $E^r_b$
- The energy cost per bit for the SISO long-haul transmission in non-cooperative approach is $E^0_i$
Total Energy

The total energy consumption for the non-cooperative approach:

\[ E_{tra} = \sum_{i=1}^{M_t} N_i E_i^0 \]  \hspace{1cm} (14)

The energy of cooperative approach:

\[ E_{MIMO} = \sum_{i=1}^{M_t} N_i E_i^t + E_b \sum_{i=1}^{M_t} N_i + \sum_{j=1}^{M_r-1} E_j^r n_r N_s \]  \hspace{1cm} (15)

where \[ N_s = \frac{\sum_{i=1}^{M_t} N_i}{b_m} \]
Total Delay

For non-cooperative approach:

\[ T_{tra} = \sum_{i=1}^{M_t} \frac{N_i^t}{b_i^t} T_s \]  \hspace{1cm} (16)

where \( T_s \approx 1/B \). For cooperative approach:

\[ T_{MIMO} = T_s \left( \sum_{i=1}^{M_t} \frac{N_i^t}{b_i^t} + \sum_{i=1}^{M_t} \frac{N_i}{b_m} + \sum_{j=1}^{M_r-1} \frac{n_r N_s}{b_r^j} \right) \]  \hspace{1cm} (17)
MISO case

Figure: Total energy consumption over $d$ (MISO)
MISO case

Figure: Total delay over $d$ (MISO)
SIMO case

Figure: Total energy consumption over $d$ (SIMO)
SIMO case

Figure: Total delay over $d$ (SIMO)
MIMO case

Figure: Total energy consumption over $d$ (MIMO)
MIMO case

Figure: Total energy consumption over $d$ (MIMO v.s. MISO)
MIMO case

Figure: Total delay over $d$ (MIMO)
Conclusion

- Traditional view that MIMO are more energy-efficient than SISO is misleading when we consider both the transmission energy and the circuit energy consumptions.
- In short range, the SISO systems outperform MIMO system on the respect of energy efficiency.
- With the optimization of constellation size, MIMO can achieve better performances on the total energy consumption and the total delay.