Energy-efficiency of MIMO and Cooperative MIMO Techniques in Sensor Networks

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March-5-2012

Outline

Introduction

- 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.

System Model

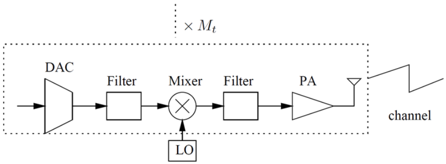

Figure: Transmitter Circuit Blocks(Analog)

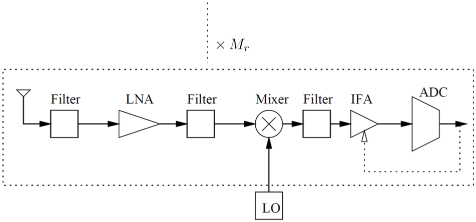

Figure: Receiver Circuit Blocks(Analog)

- 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}

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

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
- λ 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 themal 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 η the drain efficiency of the RF power amplifier and ξ the Peak to Average power ratio (PAR).

Power consumption of all other circuit blocks P_c

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

$$P_{DAC} \approx \beta \left(\frac{1}{2} V_{dd} I_0 (2^{n_1} - 1) + n_1 C_p (2B + f_{cor}) V_{dd}^2 \right) \quad (3)$$

$$P_{ADC} \approx \frac{3V_{dd}^2 L_{min}(2B + f_{cor})}{10^{-0.1525 n_2 + 4.838}} \quad (4)$$

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 2×1

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

$$\begin{aligned} \bar{P}_b &= \mathbf{E_H}\left[Q\left(\sqrt{2\gamma_b}\right)\right] \\ &\leq \left(\frac{\bar{E}_b}{M_t N_0}\right) \quad \texttt{since Chernoff bound} \end{aligned} \tag{5}$$

$$\bar{E}_b \leq \frac{M_t N_0}{\bar{P_b}^{1/M_t}} \tag{6}$$

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

$$\leq (1+\alpha)\frac{M_t N_0}{\bar{P_b}^{1/M_t}} \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f + P_c/R_b \tag{8}$$

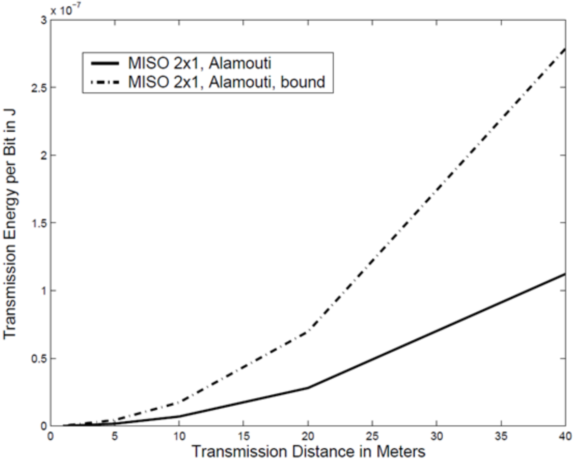

Figure: Transmission energy consumption per bit over d

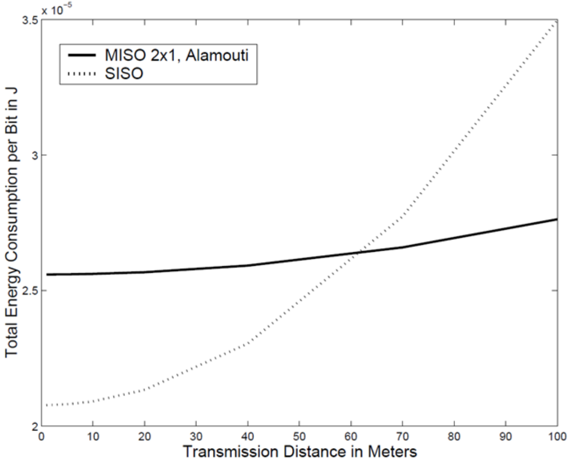

Figure: Transmission energy consumption per bit over d, MISO v.s. SISO

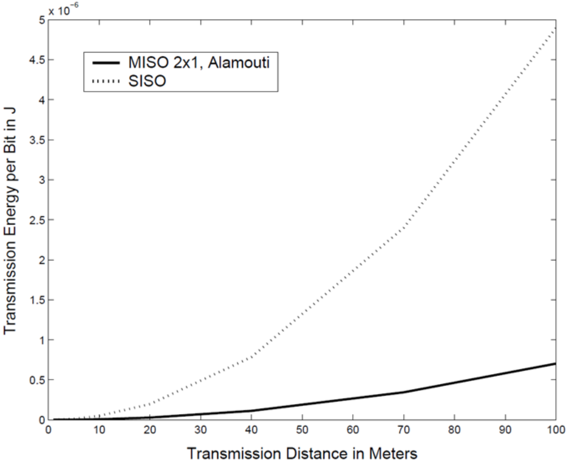

Figure: Transmission energy consumption per bit over d, MISO v.s. SISO

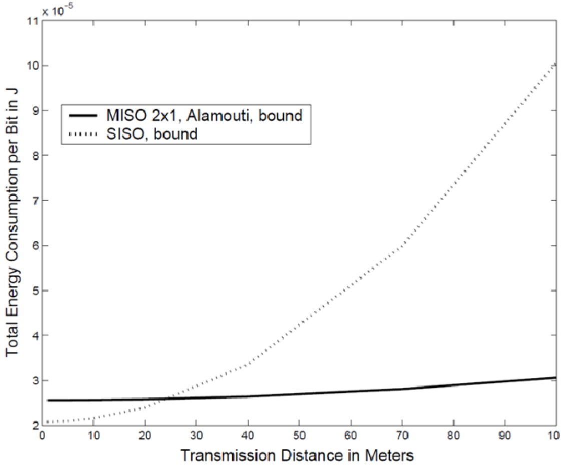

Figure: Transmission energy consumption per bit over d, MISO bound v.s. SISO bound

Fixed-rate System with BPSK Modulation: Alamouti 2×2

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

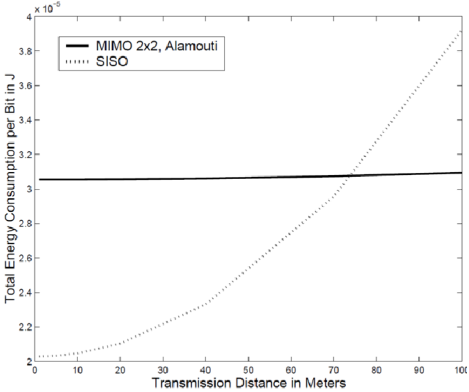

Figure: Total energy consumption over d, MIMO v.s. SISO

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 $E_c = P_c T_{on}$.

$$\bar{P}_b \approx \mathbf{E_H}\left[\frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)Q\left(\sqrt{\frac{3b}{M-1}\gamma_b}\right)\right] \quad \texttt{for } b \geq 2 \tag{9}$$

$$\approx \mathbf{E_H}\left[Q\left(\sqrt{2\gamma_b}\right)\right] \quad \texttt{for } b = 1 \tag{10}$$

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

$$E_{bt} = (P_{PA} + P_c)/R_b \tag{11}$$

$$= (1+\alpha)\bar{E}_b \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f + P_c T_{on}/L \tag{12}$$

$$\leq \frac{2}{3}(1+\alpha)\left(\frac{\bar{P}_b}{4}\right)^{-\frac{1}{M_t}} \frac{2^b - 1}{b^{\frac{1}{M_t}+1}} M_t N_0 \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f + \frac{P_c T_{on}}{L} \tag{13}$$

where $T_{on} = \frac{L}{bB}$

Optimized Alamouti 2×1

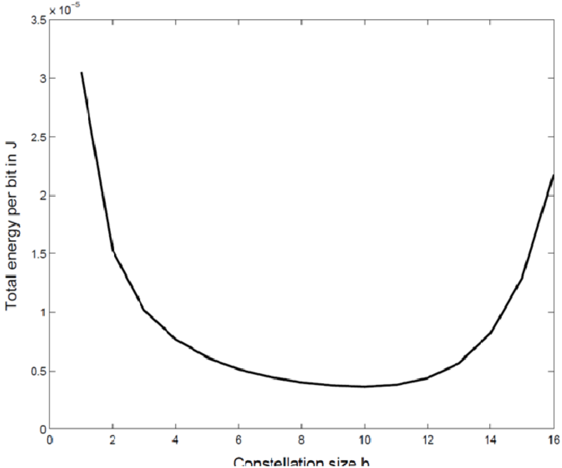

Figure: Total Energy consumption over b, MISO 2x1

Optimized Alamouti 2×1

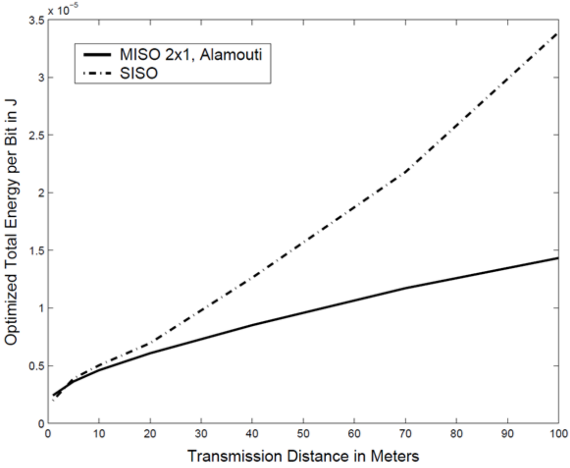

Figure: Optimized total energy consumption over d, MISO v.s. SISO

Optimized Alamouti 2×2

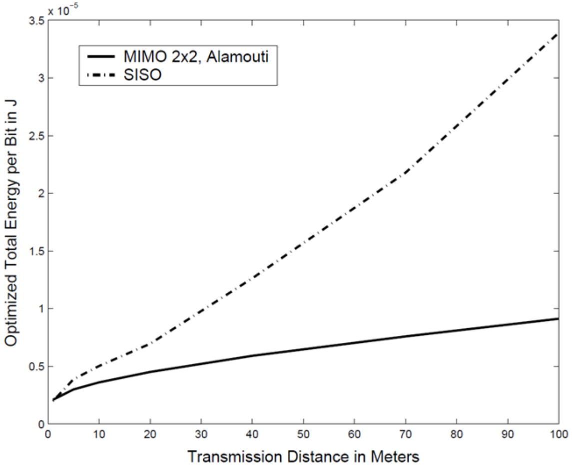

Figure: Optimized total energy consumption over d, MIMO v.s. SISO

Optimized Alamouti 2×2

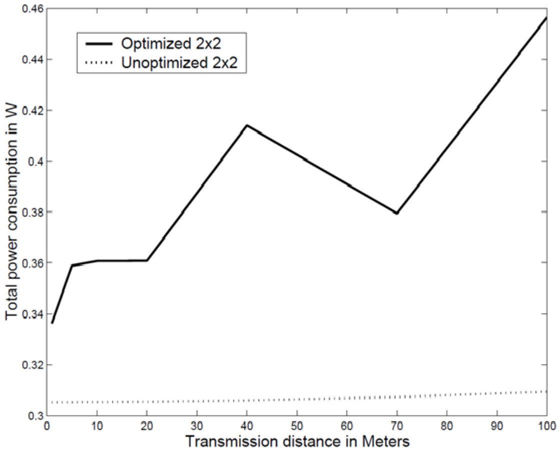

Figure: Total power consumption over d, the optimized system v.s. the unoptimized system

MIMO with Multi-node Cooperation

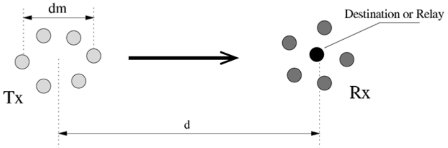

Figure: Information Flow in a sensor network

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_i^t
- The energy cost per bit or local information flow on the Rx side is E_i^r
- The energy cost per bit for the MIMO long-haul transmission is E_b^r
- The energy cost per bit for the SISO long-haul transmission in non-cooperative approach is E_i^0

Total Energy

The total energy consumption for the non-cooperative approach:

$$E_{tra} = \sum_{i=1}^{M_t} N_i E_i^0 \tag{14}$$

The energy of cooperative approach:

$$E_{MIMO} = \sum_{i=1}^{M_t} N_i E_i^t + E_b^r \sum_{i=1}^{M_t} N_i + \sum_{j=1}^{M_r-1} E_j^r n_r N_s \tag{15}$$

where $N_s = \frac{\sum_{i=1}^{M_t} N_i}{b_m}$

Total Delay

For non-cooperative approach:

$$T_{tra} = \sum_{i=1}^{M_t} \frac{N_i}{b_i^0} T_s \tag{16}$$

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

$$T_{MIMO} = T_s \left(\sum_{i=1}^{M_t} \frac{N_i}{b_i^t} + \frac{\sum_{i=1}^{M_t} N_i}{b_m} + \sum_{j=1}^{M_r - 1} \frac{n_r N_s}{b_j^r} \right) \tag{17}$$

MISO case

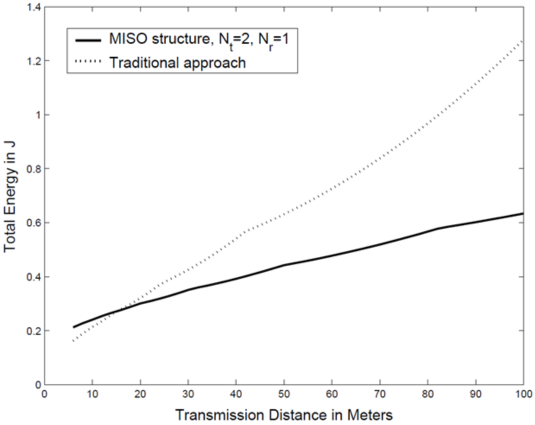

Figure: Total energy consumption over d (MISO)

MISO case

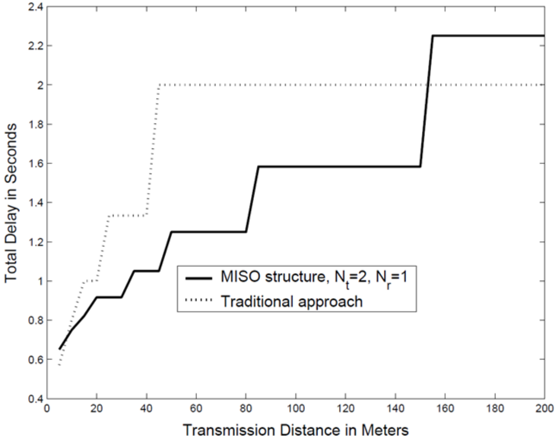

Figure: Total delay over d (MISO)

SIMO case

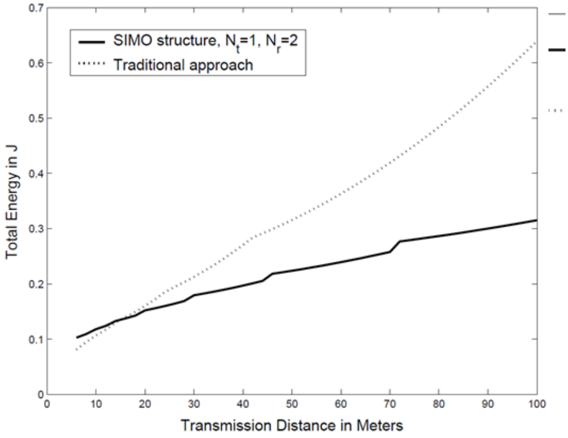

Figure: Total energy consumption over d (SIMO)

SIMO case

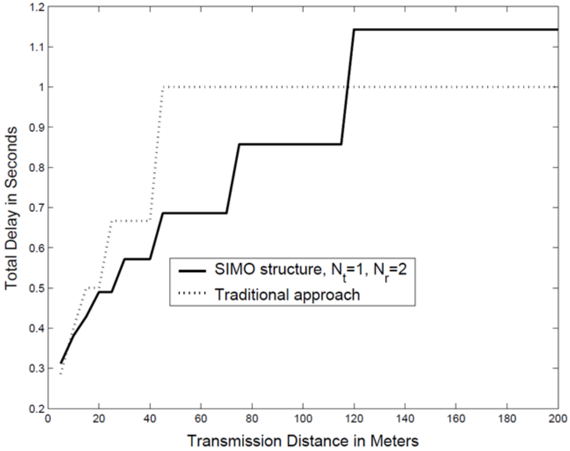

Figure: Total delay over d (SIMO)

MIMO case

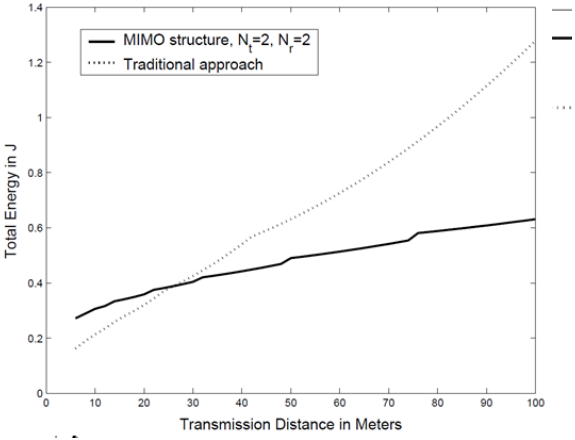

Figure: Total energy consumption over d (MIMO)

MIMO case

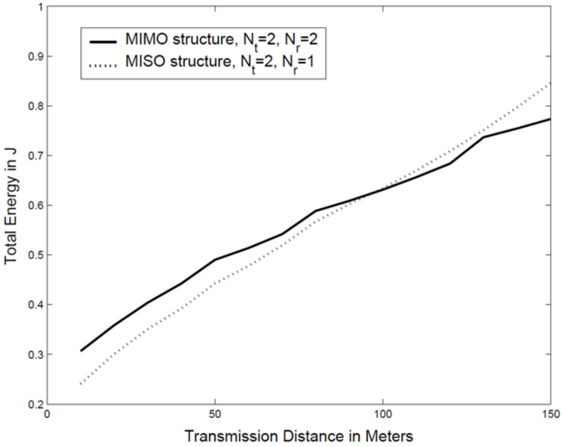

Figure: Total energy consumption over d (MIMO v.s. MISO)

MIMO case

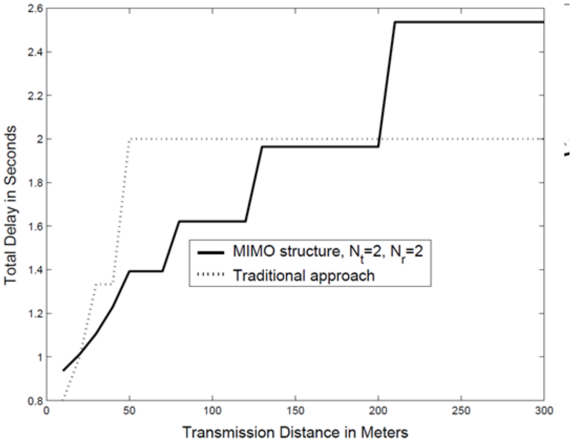

Figure: Total delay over d (MIMO)

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.