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Letter

An Energy-Efficient Cooperative MIMO Transmission with Data Compression in Wireless Sensor Networks

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In this letter, a novel metric for energy-efficient cooperative transmission with data compression in wireless sensor networks (WSNs) is proposed. Under the guidance of the new metric, energy consumption is optimized by considering the correlation between data generated by the sensor nodes. The distance between sensor nodes inside the cluster affecting the data correlation as a key factor is analyzed, and the corresponding optimal value is used to reduce the energy consumption. © 2015 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

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1. Introduction

Multi-input and multi-output (MIMO) systems based on antenna arrays have been proved to be a key technique to minimize the energy consumption in wireless sensor networks (WSNs) under given performance requirements such as bit error ratio (BER) and throughput. However, one general problem in WSN is that the sensor node is not practical to design with multiple antennas due to the physical size limitation. As a solution, cooperative MIMO (CMIMO) in Ref. [1] realized by the cooperation of the individual antennas is proposed to overcome the problem existing in the sensor node using traditional MIMO transmission. Recently, motivated by spatial modulation (SM), a novel CMIMO transmission scheme, named CMIMO-SM, was proposed in Ref. [2], which is able to avoid transmitting inter-channel interference (ICI) and also improve the energy efficiency. This letter utilizes the strength of CMIMO-SM and develops it from the angle of data compression to optimize the energy consumption.

2. System Model and Simulation Result

2.1. Proposed CMIMO-SM with data compression.

As shown in Fig. 1, a clustered WSN is considered where each sensor node has a pre-assigned index using a binary number. Applying the CMIMO-SM scheme, each node broadcasts its data to other nodes using different time slots to exchange the data, and then each node separately compresses the data by taking off the redundancy. For each time instant, the compressed data is composed of the multiple quadrature amplitude modulation (MQAM) or multiple phase shift keying (MPSK) modulated part and antenna index part and then only the first part of the compressed data will be transmitted via the MIMO channel as the long-haul transmission while the second part of the compressed data indicated by using antenna index will be detected at the receiver. Finally, the joint cooperative reception will be done at receiver.

As an example, consider a two-sensor cluster with each sensor having an index either 0 or 1. Assume that 01 is the data sequence to transmit after data exchange and compression, where only the 0 will be modulated using binary phase shift keying (BPSK) and transmitted via the antenna 1 while the 1 as the antenna index will be detected at the receiver.

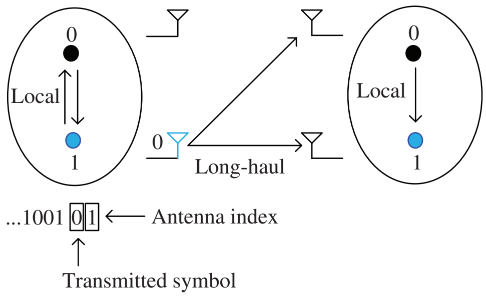

Fig. 1. CMIMO-SM transmission with data compression

For the energy consumption analysis, the local phase is considered first. When M_t sensor nodes try to cooperate with each other at the transmitter and M_r sensor nodes try to decode the data at receiver, the total energy consumption of the local phase including local transmission (first and third parts in (1)) and data compression (the second part in (1)) can be expressed as

$$E_{l(total)} = \sum_{i=1}^{M_t} N_i E_i^t + \sum_{i=1}^{M_t} N_i E_i^c + \sum_{j=1}^{M_r-1} E_j^r \sum_{i=1}^{M_t} N_i^c \quad (1)$$

where E_i^t and E_j^r represent the local transmission energy cost per bit on the transmitting side and the receiving side, respectively. E_i^c denotes the energy cost per bit for data compression. N_i and N_i^c denote the amount of data to transmit from each node before compression and after compression, respectively. Then the energy consumption of long-haul cooperative transmission is considered and shown as

$$E_{lh(total)} = E_{lh} \sum_{i=1}^{M_t} N_i^c \quad (2)$$

where the E_{lh} denotes the energy consumption per bit in the long-haul phase. According to Refs [2,3], E_i^t, E_j^r, and E_{lh} can be calculated by utilizing the link budget relationship as shown

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below:

$$E_{\mathrm{bt}} = (1+\alpha)\bar{E}_b \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f + P_c/R_b \tag{3}$$

where $\bar{E}_b$ is the average energy per bit required for a given BER at receiver, α equals $\xi/\eta - 1$, with ξ being the peak to average ratio (PAR) and η being the drain efficiency of the RF power amplifiers, d is the transmission distance, G_t and G_r are the transmitter and receiver antenna gains, respectively, λ is the carrier wavelength, M_l is the link margin, and N_f is the receiver noise figure. P_c and R_b denote the power consumption of the circuit block and the transmission bit rate, respectively. After considering the energy consumption per bit for detection E_d, the total energy consumption can be expressed as

$$E_{csm(total)} = E_{l(total)} + E_{lh(total)} + E_{d(total)} \tag{4}$$

where $E_{d(total)} = E_d \times N_i$ is the energy consumption for detection and E_d can be calculated according to Ref. [2].

Intuitively, the data correlation should be related to the distance between the sensors. To construct the relationship between the data correlation and distance, the rainfall model in Ref. [4] is adopted in this paper, which is shown as

$$\sum_{i=1}^{M_t} N_i^c = \sum_{i=1}^{M_t-1} N_i^c + \left[1 - \frac{1}{\left(\frac{D_i}{c}+1\right)}\right] N_i \quad i = 1,2,3,\ldots M_t, \tag{5}$$

where c is a constant that represents the degree of spatial correlation in the data, and D_i is the average distance among the sensor nodes and can be approximately treated as the cluster diameter.

Substituting (5) into (1) and (2), and then combining with (4), the total energy consumption can be rewritten as

$$E_{csm(total)} = \sum_{i=1}^{M_t} N_i E_i^t + \sum_{i=1}^{M_t} N_i E_i^c + E_{d(total)} + \left(\sum_{j=1}^{M_r-1} E_j^r + E_{lh}\right)\left(\sum_{i=1}^{M_t-1} N_i^c + \left[1 - \frac{1}{\left(\frac{D_i}{c}+1\right)}\right] N_i\right). \tag{6}$$

The minimization of $E_{csm(total)}$ can be expressed as

$$\begin{aligned} &\arg\min_{D_i} E_{csm(total)} \\ &\text{s.t.}\, D_{\min} \le D_i \le D_{\max} \end{aligned} \tag{7}$$

where $D_{\max}$ is the maximum distance allowed for a cluster, and $D_{\min}$ is the guaranteed minimum distance according to the maximum node density $\rho_{\max}$ requirement and calculated using

$$D_{\min} = 2\sqrt{\frac{M_t}{\rho_{\max}\pi}}. \tag{8}$$

Proposition: $E_{csm(total)}$ is the function having the minimum values with respect to D_i.

Proof: Taking first derivate of $E_{csm(total)}$ with respect to D_i, the following equation can be obtained:

$$\frac{\partial E_{csm(total)}}{\partial D_i} = \frac{\left(\sum_{j=1}^{M_r-1} E_j^r + E_{lh}\right) c N_{\mathrm{i}}}{(D_i + c)^2} > 0. \tag{9}$$

Therefore (6) is a monotone increasing function within [$D_{\min}$, $D_{\max}$] and has a minimum value.

2.2. CMIMO-SM. The local communication in CMIMO-SM operates in the same way as described in Section 2.1 but without data compression. Because of this difference, CMMO-SM will transmit more data than the proposed one during long-haul communication. The energy consumption for local phase $E_{l(total),o}$ and long-haul phase $E_{lh(total),o}$ of CMIMO-SM can be derived using the approach described in Section 2.1 as

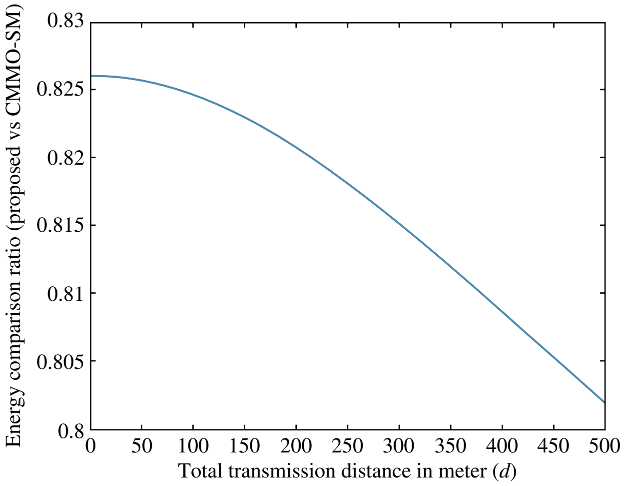

Fig. 2. Ratio of energy comparison versus transmission distance

$$E_{l(total),o} = \sum_{i=1}^{M_t} N_i E_i^t + \sum_{j=1}^{M_r-1} E_j^r \sum_{i=1}^{M_t} N_i \tag{10}$$

$$E_{lh(total),o} = E_{lh} \sum_{i=1}^{M_t} N_i \tag{11}$$

and the total energy consumption for the CMIMO-SM is

$$E_{csm(total),o} = E_{l(total),o} + E_{lh(total),o} + E_{d(total)}. \tag{12}$$

2.3. Simulation result The simulation is given for energy comparison, and the parameters are as follows: $M_l = 40$ dB, $N_f = 10$ dB, $G_t G_r = 5$ dBi, $\eta = 0.35$, $E_J = 1.215$ nJ, $N_i = 20$ kb, $E_i^c = 5$ nJ/bit/signal, $c = 2$, $\rho_{\max} = 2/\pi$, and $D_{\max} = 10$ m. Also, some indirectly used parameters are same as the ones in CMIMO-SM, which can be obtained from Ref. [2] due to space limitation. For fair comparison, the same setup $M_t = M_r = 2$ with BPSK is used. Figure 2 shows the energy comparison ratio versus the total transmission between the proposed metric and CMIMO-SM. The proposed scheme will be preferable because the additional energy spent for energy compression has little effect on the total energy consumption, while the energy saving due to the smaller data transmission after data compression affects much of the total energy consumption and becomes apparent as the transmission distance increases.

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