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Letter

Lifetime and Energy Optimization in Multi-hop Wireless Sensor Networks with Spatial Modulation Based Cooperative MIMO

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In this letter, the optimizations of both lifetime and energy consumption are jointly considered in multi-hop clustered wireless sensor networks (WSNs), where spatial modulation (SM)-based cooperative MIMO (CMIMO-SM) is utilized as the transmission scheme. In this scheme, an only-forwarding transmission scenario is considered so that the intermediate clusters only act as deliverers to pass the data from the source to the destination. The energy consumption and lifetime of the whole network are optimized by allocating the hop lengths and selecting the appropriate number of hops. © 2015 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

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1. Introduction

Wireless sensor networks (WSNs) have received significant attention and become a hot topic because of their wide applications such as in industrial monitoring, target tracking, navigation, and so forth [1]. In a WSN, reducing energy consumption to achieve energy-efficient transmission is a key issue due to the sensor energy limitation. Besides reducing energy consumption, it is necessary to make the clusters achieve equal lifetimes and prolong the network lifetime. Recently, cooperative multi-input and multi-output (CMIMO) realized by cooperation of single nodes with single antenna has been shown as a good candidate to reduce the energy consumption and overcome the multiple antennas designing problem due to the sensor size limitation in multi-input and multi-output (MIMO) scheme. Many studies in this area have been trying to exploit the full advantages and among those studies, motivated by spatial modulation (SM), a novel CMIMO transmission scheme named CMIMO-SM was proposed in Ref. [2], which was able to avoid transmitting inter-channel interference (ICI) and improve energy efficiency as well. By extending and developing the work in Ref. [2], this letter proposes an only-forwarding multi-hop scenario wherein the hop length is allocated and the number of hops is selected to achieve the minimum energy consumption and longest lifetime.

2. System Model and Analytical Result

Figure 1 shows the multi-hop CMIMO-SM-based WSN, where the sensor nodes are deployed in discrete areas and each area is regarded as a cluster. The only-forwarding transmission, in which only the sensor nodes in source cluster transmit the data via relay clusters to destination, is considered. Each transmission between every two adjacent clusters is executed using the CMIMO-SM scheme. Especially, as shown in the left two clusters, before transmission, each sensor node has a preassigned index using a binary number to indicate it, and then each node broadcasts its data to other nodes inside the cluster using different time slots to exchange the data. Once each node receives all the other information bits, the data sequence is ready to be transmitted. For each time instant, the data sequence is composed by the multiple quadrature amplitude modulation (MQAM) or multiple phase shift keying (MPSK) modulated part and the antenna index part, and only the first part of the data sequence will be transmitted via the MIMO channel as the long-haul transmission while the second part of the data indicated using the antenna index will be recovered at receiver. Finally, the joint cooperative reception will be done at the destination.

According to Ref. [2], the energy consumption of CMIMO-SM in the one-hop situation includes local phase and long-haul phase energy consumption. When M_t nodes try to cooperative with each other at the transmitter and M_r nodes try to receive the data at the receiver, the total energy consumption of the local phase can be expressed as

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

where E_i^t and E_j^r represent the local transmission energy cost per bit on the transmitter and the receiver, respectively. N_i denotes the amount of data to transmit from each node. Then the energy cost of long-haul cooperative transmission is shown as

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

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

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

where $\bar{E}_b$ is the average energy per bit required for a given bit error ratio (BER) at the receiver and can be carried out using Ref. [2], α equals to $\xi/\eta-1$, 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

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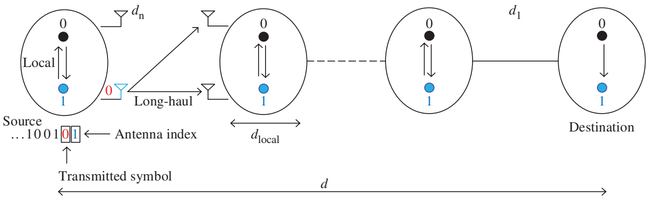

Fig. 1. CMIMO-SM-based multi-hop transmission

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].

After considering the one-hop situation, a multi-hop scenario is considered, as shown in Fig. 1. Inside the cluster, the longest distance between the nodes is defined as d_{local} and the long-haul distance is defined as d_k $(k = 1, 2, \ldots, n)$. The same assumption as in Ref. [2] that two nodes are in one cluster is made to reduce the complexity of the calculation. Since there is only one joint reception and detection, the total energy consumption in multi-hop only-forwarding transmitting scenario can be expressed as

$$\begin{aligned} E_{total} &= \sum_{k=1}^{n}\left(\sum_{i=1}^{M_t} N_i E_i^t\right) + \sum_{i=1}^{M_t} N_i E_d + \sum_{j=1}^{M_r-1} E_j^r \sum_{i=1}^{M_t} N_i \\ &+ 2\sum_{k=1}^{n}\left[(1+\alpha)\bar{E}_b \times \frac{(4\pi)^2 \times (d_k + d_{local})^2}{G_t G_r \lambda^2} M_l N_f + \frac{P_c}{R_b}\right] N_i. \end{aligned} \tag{5}$$

The minimum energy consumption can be obtained by deriving the optimal d_k, which can be formulated as

$$\begin{aligned} &\min_{d_k, k=1,2,\ldots n} 2\sum_{k=1}^{n}\left[(1+\alpha)\bar{E}_b \times \frac{(4\pi)^2 \times (d_k + d_{local})^2}{G_t G_r \lambda^2} M_l N_f + \frac{P_c}{R_b}\right] N_i \\ &\text{s.t.} \sum_{k=1}^{n} d_k + n d_{local} = d \\ &d_k > 0, k = 1, 2, \ldots, n \\ &n \text{ is a positive integer.} \end{aligned} \tag{6}$$

Proposition: Given the total distance between source and destination d, if all the hop lengths are equal, the minimum energy consumption can be achieved.

Proof: To solve the problem in (6), the Lagrange equation is

$$\begin{aligned} L &= 2\sum_{k=1}^{n}\left[(1+a)\bar{E}_b \times \frac{(4\pi)^2 \times (d_k + d_{local})^2}{G_t G_r \lambda^2} M_l N_f + \frac{P_c}{R_b}\right] N_i \\ &+ w\left(d - n d_{local} - \sum_{k=1}^{n} d_k\right) \end{aligned} \tag{7}$$

where w is a Lagrange multiplier. By taking the partial derivatives on (7) with respect to d_k and equating to 0, the optimal distance d_k can be determined as follows:

$$d_k = \frac{d}{n} - d_{local}. \tag{8}$$

Therefore the hops are equal and the proof is completed.

According to (5), the expression for the total energy consumption in terms of n can be rewritten by (9)

$$\begin{aligned} E_{total} &= 2(1+\alpha)\bar{E}_b \times \frac{(4\pi)^2 \times (d + d_{local})^2}{G_t G_r \lambda^2 n} M_l N_f N_i \\ &+ n\left(\sum_{i=1}^{M_t} N_i E_i^t + \frac{2P_c}{R_b} N_i\right) + \sum_{i=1}^{M_t} N_i E_d + \sum_{j=1}^{M_r-1} E_j^r \sum_{i=1}^{M_t} N_i. \end{aligned} \tag{9}$$

Since equal hops have been proved for achieving minimum energy, for each hop the energy consumption is E_{total}/n. If the whole network is assumed to have J joules, each cluster has J/n joules. The single-hop lifetime coefficients can be defined as the total network lifetime, which can be calculated by

$$\begin{aligned} K = \frac{J/n}{E_{total}/n} = J\Bigg/\Bigg[& 2(1+\alpha)\bar{E}_b \times \frac{(4\pi)^2 \times (d + d_{local})^2}{G_t G_r \lambda^2 n} M_l N_f N_i \\ &+ n\left(\sum_{i=1}^{M_t} N_i E_i^t + \frac{2P_c}{R_b} N_i\right) + \sum_{i=1}^{M_t} N_i E_d + \sum_{j=1}^{M_r-1} E_j^r \sum_{i=1}^{M_t} N_i\Bigg]. \end{aligned} \tag{10}$$

Proposition: The denominator in (10) is a convex function of n and has the minimum value so that the whole function of (10) has the maximum value.

Proof: Taking the second-order derivative of the denominator of (10) with respect to n, the following equation can be obtained

$$\frac{\partial^2 E_{total}}{\partial n^2} = 4(1+\alpha)\bar{E}_b \times \frac{(4\pi)^2 \times (d + d_{local})^2}{G_t G_r \lambda^2 n^3} M_l N_f N_i > 0 \tag{11}$$

because α, $\bar{E}_b$, d, d_{local}, G_t, G_r, λ, n, M_l, N_f, N_i are positive number. Therefore the denominator in (10) is a convex function [4]. The proof is completed.

Taking the first-order derivative of the denominator of (10) with respect to n and setting it to zero, the optimal value n^* for achieving longest lifetime is obtained as

$$n^* = \sqrt{\frac{2(1+\alpha)\bar{E}_b \times (4\pi)^2 \times (d + d_{local})^2 M_l N_f N_i}{G_t G_r \lambda^2 \left(\sum_{i=1}^{M_t} N_i E_i^t + \frac{2P_c}{R_b} N_i\right)}}. \tag{12}$$

Because hop should be integer, the optimal hops for getting longest network lifetime can be selected as either $\lfloor n^* \rfloor$ or $\lceil n^* \rceil$. Thus, the minimum energy and longest lifetime are guaranteed.

3. Conclusion

This letter considers a multi-hop CMIMO-SM-based WSN where the optimal hop length allocation and number of hops are found and verified to minimize the energy consumption and prolong the lifetime in only-forwarding transmission case.

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