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Energy Efficiency of Cooperative MIMO with Data Aggregation in Wireless Sensor Networks

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***Abstract*— An energy model for wireless sensor networks based on the cooperative MIMO (multiple-in-multiple-out) technique is proposed, taking into consideration of both the transmission and data aggregation energy. Based on the model, two cooperative wireless sensor network schemes, namely, MIMO approach and SISO (single-in-single-out) approach are compared. It is shown that the overall energy consumption in the systems is related to not only the transmission range but also the correlation among the raw sensor data, and can be solved as a nonlinear programming problem. Furthermore, a critical value above which MIMO approach outperforms SISO approach is analyzed. Simulation results show that jointly considering both data aggregation and cooperative MIMO techniques will further reduce the total energy consumption and thus prolong the network lifetime.**

I. Introduction

Wireless sensor networks (WSN) are increasingly envisioned to have many applications in diverse areas including surveillance, intrusion detection and environmental monitoring [1]. The size of sensors is typically small, and the operations rely on batteries which are difficult to replenish in most applications. As a result, energy efficiency is critical in WSNs.

Recent research on MIMO demonstrates a great improvement of energy efficiency in WSNs [2]-[5]. However, when cooperative MIMO is used for both diversity gain and spatial multiplexing gain, the circuit energy consumption and the extra energy consumption for processing and cooperating have to be considered. In [2], the energy-efficient communication techniques to minimize the sum of the transmission energy and the circuit processing energy for both MIMO and SISO systems have been proposed. And a closer look at the effect of increased training overhead required in MIMO systems is further considered in [3]. In [5], the efficiency of cooperative transmission under space-time block code-encode (STBC) is discussed and the synchronization requirements are analyzed. However, none of these techniques take into consideration of data aggregation, which is a fundamental technique for WSNs.

To our best knowledge, this paper makes the first attempt at exploring the energy efficiency of cooperative MIMO techniques with data aggregation schemes for WSNs. Based on the energy consumption of each part of the systems, mathematical models are formulated to calculate the total energy consumption of cooperative MIMO systems with data aggregation consideration. In order to minimize the total energy consumption, a comparison study is conducted between the MIMO approach and the SISO approach for cluster based WSNs. It is shown that given the correlation among raw sensor data, there exists a critical distance between the transmitted cluster and the receiver, above which the MIMO solution is superior to the SISO solution. Simulation results show that the joint consideration of the energy consumption of data aggregation and cooperative MIMO techniques will further save the total energy and thus prolong the network lifetime.

The rest of the paper is organized as follows. The system model is described in Section II. By integrating data aggregation energy into a cooperative MIMO communication system, detail energy analysis of point-to-point communication systems is investigated and the critical distance for justifying the application of MISO schemes is compared in Section III. Simulation setups and results of the proposed scheme are also presented in Section III. Section IV introduces the energy optimization scheme for our joint approach and compares the results with traditional schemes. Finally Section V concludes the paper.

II. System Model

In a typical energy-limited wireless sensor network, data collected by sensors are transmitted to a remote node (sink) through multi-hop relaying. Recent research progress in wireless cooperative MIMO transmission can be exploited to greatly reduce the energy consumption and bit error rate (BER) for the same transmission throughput [2]-[4]. Throughout the paper, we assume a system with narrowband, frequency-flat Rayleigh fading channels and perfectly synchronized transmission/reception between wireless sensor nodes. As in [2], we assume the energy consumption for baseband signal processing can be omitted, and the system is equipped with M_T transmission antennas and M_R receiving antennas, with an optimally chosen constellation size. For the MIMO system, the received discrete-time signal is attenuated by a $M_T \times M_R$ channel matrix $\mathbf{H}$ of complex fading coefficients. We assume each element in $\mathbf{H}$ is a zero-mean circulant symmetric complex Gaussian random variable with unit variance.

Given that in a WSN, close-by sensors generate highly correlated data, and raw sensor data can be aggregated to reduce the transmission energy. Therefore, we consider the data aggregation energy in our model, which, together with transmission energy, composes the overall energy.

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Considering a general communication scheme similar to [2], [3], which can be MIMO, multiple-in-single-out (MISO), single-in-multiple-out (SIMO) or SISO, the energy consumed in both transmission and processing should be considered to achieve the optimal joint design. The total power consumption can be categorized into two main parts, namely, the power consumption of all the power amplifiers P_{PA} which is a function of the transmission power P_{out}, and the power consumption of all other circuit blocks P_c. When the channel only experiences a k^{th}-power path loss with additive white Gaussian noise (AWGN), P_{out} can be calculated according to the link budget relationship:

$$P_{out} = \bar{E}_b R_b \times \frac{(4\pi)^2 d^k}{G_t G_r \lambda^2} M_l N_f, \qquad (1)$$

where $\bar{E}_b$ is the average energy per bit required for a given BER specification, R_b is the transmission bit rate, 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 compensating the hardware process variations and other additive background noise or interference, N_f is the receiver noise figure defined as $N_f = \frac{N_r}{N_0}$ where N_r is the power spectral density (PSD) of the total effective noise at the receiver input and N_0 is the single-sided thermal noise PSD at the room temperature with a typical value $N_0 = -171$ dBm/Hz.

The power consumption of all the power amplifiers can be approximately calculated as

$$P_{PA} = (1+\alpha) P_{out}, \qquad (2)$$

where $\alpha = \frac{\xi}{\eta} - 1$ with ξ being the Peak to Average Ratio (PAR) and η being the drain efficiency of the RF power amplifier. It is important to note that ξ depends on the modulation scheme and the associated constellation size, and hence P_{PA} is also a function of constellation size. For the rest of the paper, all the statements about modulation are referring to the uncoded MQAM. For MQAM, $\xi = 3\frac{\sqrt{M}-1}{\sqrt{M}+1}$ and the number of bits per symbol for optimal constellation size is defined as $b = \log_2 M$.

As discussed in [7], we estimate the term P_c in the total power consumption as

$$\begin{aligned} P_c \approx\ & M_t(P_{DAC} + P_{mix} + P_{filt}) + 2P_{syn} \\ & + M_r(P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC}) \end{aligned}, \qquad (3)$$

where P_{DAC}, P_{mix}, P_{filt}, P_{syn}, P_{LNA}, P_{IFA}, P_{filr} and P_{ADC} are the power consumption values of the D/A converter, the mixer, the active filters at the transmitter side, the frequency synthesizer, the low noise amplifier, the intermediate frequency amplifier, the active filters and the A/D converter at the receiver side, respectively.

Then the energy consumption per bit for a general communication link can be fomulated as

$$E_{bt} = \frac{P_{PA} + P_c}{R_b}. \qquad (4)$$

The total energy consumption is estimated by multiplying E_{bt} by the number of bits to be transmitted.

The energy dissipation of data aggregation depends on the algorithm complexity and is much more difficult to estimate. According to the high-level software energy macro model given by [9], if the data aggregation algorithm complexity is $O(n^2)$, where n is an algorithm related parameter, the energy dissipation is estimated as

$$E_{DF}(l) = C_0 + C_1 \times l + C_2 \times l^2, \qquad (5)$$

where l is the number of transmission bits and C_0, C_1 and C_2 are coefficients depending on the software and CPU parameters. Note that if the data aggregation algorithm complexity is $O(n)$, the energy dissipation can be formulated as $E_{DF}(l) = C_0 + C_1 \times l$. Hence the energy consumption per bit for data aggregation is determined as $E_{bf}(l) = \frac{C_0 + C_1 \times l}{l}$. When l is large, C_0/l is negligible. Thus, the energy consumption per bit of algorithm complexity with $O(n)$ is approximately constant.

Although for different applications, the data aggregation algorithm complexity is different , many data aggregation algorithms are with complexity of $O(n)$, such as the beamforming algorithm in LEACH [8], Discrete Wavelet Transform (DWT) for image compression [10], and data aggregation algorithms in PEGASIS. According to the experiment results described in [13], we use the beamforming in LEACH and $E_{bf}(l)$ is set to 5 nJ/bit/signal for simulation experiments.

Finally, the total energy is given by summing up the total energy consumption along the entire signal path and the total energy dissipation of data aggregation.

III. Energy Efficiency of Cooperative MIMO Systems with Data Aggregation

Previous research [2], [6] have proposed the tradeoff in MIMO systems, that is, MIMO systems require less long-haul transmission energy than SISO systems under the same BER performance requirements, while in order to allow sensor nodes to cooperate, local data exchange is necessary before the long-haul transmission and thereby leads to extra energy consumption comparing with SISO systems. In this paper, the energy consumption of cooperative MIMO transmission and data aggregation are jointly considered, which compose the major difference from previous work. In this section, it is shown that this difference leads to a shift of the critical distance for choosing energy efficient communication approach.

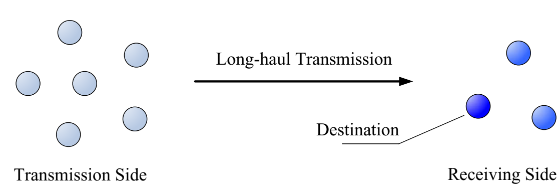

Fig. 1. Cooperative MIMO communication with data aggregation scheme in a sensor network.

As illustrated in Fig. 1, we assume there are N sensor nodes in a data aggregation cluster, each of which has N_i bits to transmit, where $i = 1, 2, \ldots, N$. Data collected by multiple local sensors will firstly be transmitted to a cluster head for aggregation. Then the aggregated data will be transmitted to a remote destination node under a cooperative MIMO approach or non-cooperative SISO approach.

For the MIMO approach, four parts of energy consumption are considered according to four stages in the scheme. In the first stage, raw sensor data are transmitted to the cluster head for aggregation. In the second stage, the aggregated data are transmitted by the cluster head to $M_t - 1$ nodes, which compose the distributed antenna array. After each node receives all the bits, these M_t nodes (including the cluster head) encode the transmission sequence according to some diversity scheme, such as the Alamouti, STBC or V-BLAST scheme. Then in the third stage, each node transmits the sequence according to its preassigned index i. Finally in the fourth stage, the destination node and its $M_r - 1$ nearby assisting nodes jointly receive the signal, quantize each symbol they receive into n_r bits, and then transmit with uncoded MQAM to the destination node for joint detection.

According the 4-stage communication procedure above, the total energy can be calculated step by step and thus is

$$E_{DF+MIMO} = \sum_{i=1}^{N-1} N_i E_i^t + E_{bf} \sum_{i=1}^{N} N_i + \sum_{j=1}^{M_t-1} E_j^{t0} \sum_{i=1}^{N} N_i \gamma_i + E_b^r \sum_{i=1}^{N} N_i \gamma_i + \sum_{h=1}^{M_r-1} E_h^r n_r N_s , \quad (6)$$

where for $i = 1, 2, \ldots, N-1$, E_i^t denotes the local transmission energy cost per bit for aggregation on the transmission side, and E_{bf} denotes the energy cost per bit for data aggregation. For $j = 1, 2, \ldots, M_t - 1$, E_j^{t0} denotes the local transmission energy cost per bit for cooperation communication, γ_i is the percentage of remaining data after aggregation, which reflects the correlation between data amongst different sensors, and E_b^r denotes the energy cost per bit for the long-haul MIMO transmission. For $h = 1, 2, \ldots, M_r - 1$, E_h^r denotes the local transmission energy cost per bit for joint detection on the receiving side and $N_s = \frac{\sum_{i=1}^{N} N_i \gamma_i}{b_m}$ is the total number of symbols received by each node at the receiving side with b_m as the constellation size used in the space-time code. Note that E_i^t, E_j^{t0}, E_h^r can be calculated according to the results for SISO communication links as a special case of MIMO links where $M_t = M_r = 1$. E_b^r can be calculated directly according to (4). However, when calculating E_j^{t0}, because there are always $M_t - 1$ receivers listening during the local transmission, the total circuit energy consumption should be changed to include $M_t - 1$ sets of receiver circuits.

For the SISO approach, the communication procedure is much simpler. The cluster head will transmit all the aggregated data directly to the destination node without any cooperation. So the total energy consumption $E_{DF+SISO}$ is

$$E_{DF+SISO} = \sum_{i=1}^{N-1} N_i E_i^t + E_{bf} \sum_{i=1}^{N} N_i + E_0 \sum_{i=1}^{N} N_i \gamma_i, \quad (7)$$

where E_0 denotes the SISO long-haul transmission. E_0 can be calculated as a special case of MIMO results in Section II where $M_t = M_r = 1$. Note that the first and second term in (7) are exactly the same as those in (6), since the communication processes are the same at these steps. Hence the difference in energy consumption between cooperative communication and non-cooperative communication has nothing to do with the first two terms in (6) and (7).

In all the calculations above, the optimal constellation size is used according to the different communication distance so that at any give distance, the communication energy consumption is minimized under its constellation size. The values of optimal constellation size are not reported here for simplicity.

To achieve mathematical tractability and engineering feasibility, we apply the Alamouti schemes for distributed cooperative MIMO transmissions in WSNs. As proposed in [12], Alamouti code with two transmitting antennas uses two different symbols s_1 and s_2 to transmit simultaneously during the first symbol period, followed by $-s_2^*$ and s_1^* during the next symbol period.

A. Alamouti 2×1 MISO Systems with Data Aggregation

In order to get the total communication energy consumption, the average energy per bit required for a given BER $\bar{E}_b$ need to be determined. In a 2×1 MISO system with Alamouti schemes, the channel matrix of 2×1 MISO system can be written as $\mathbf{H} = [\ h_1 \quad h_2\ ]$, and the instantaneous received SNR can be written as $\gamma_b = \frac{\bar{E}_b}{2N_o} \|\mathbf{H}\|_F^2$, where $\|\mathbf{H}\|_F^2$ is the Frebenius norm of the matrix $\mathbf{H}$ and the probability distribution function (PDF) of $\|\mathbf{H}\|_F^2$ can be determined according to the PDF of $\mathbf{H}$ [11]. The average BER of a MIMO system using Alamouti schemes with MQAM is given by [14]

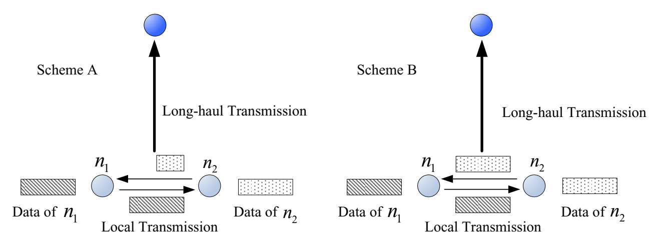

Fig. 2. Two communication schemes with data aggregation using cooperative MIMO techniques.

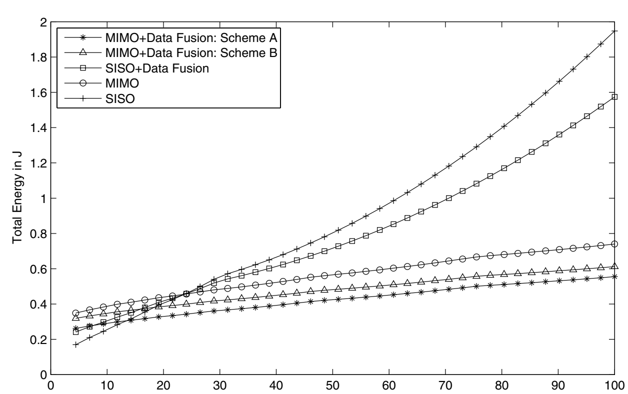

Fig. 3. Comparison of energy consumption for different approaches.

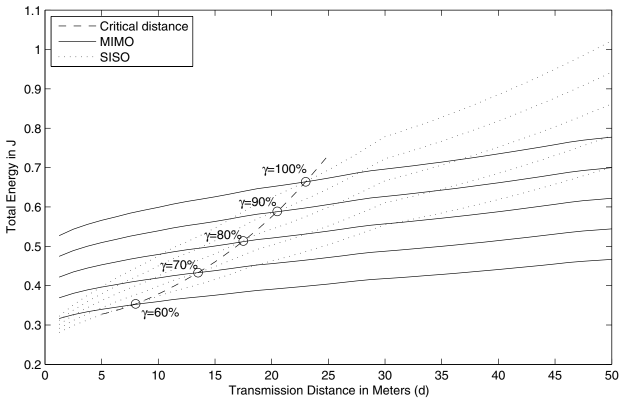

Fig. 4. Energy consumption of scheme A with γ.

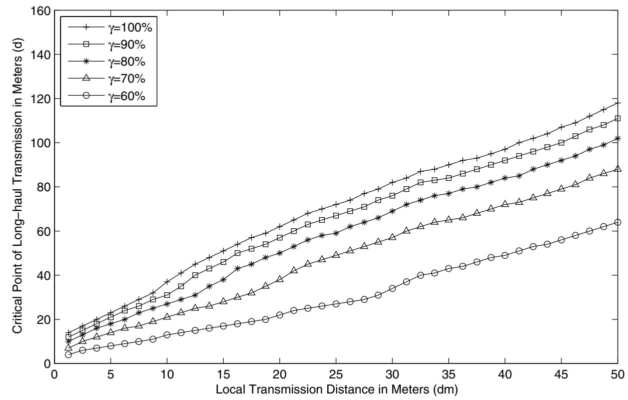

Fig. 6. The critical distance over d_m in scheme A (2×1) with γ.

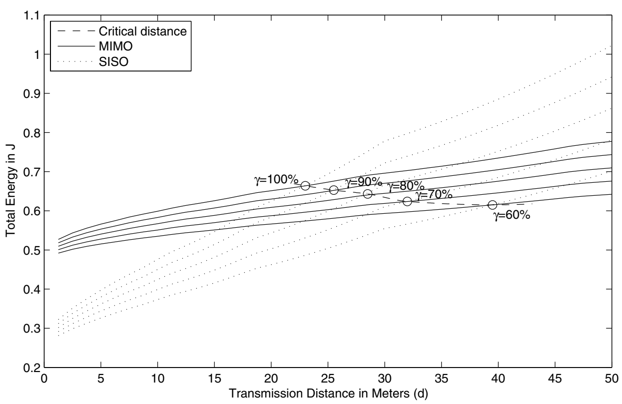

Fig. 5. Energy consumption of scheme B with γ.

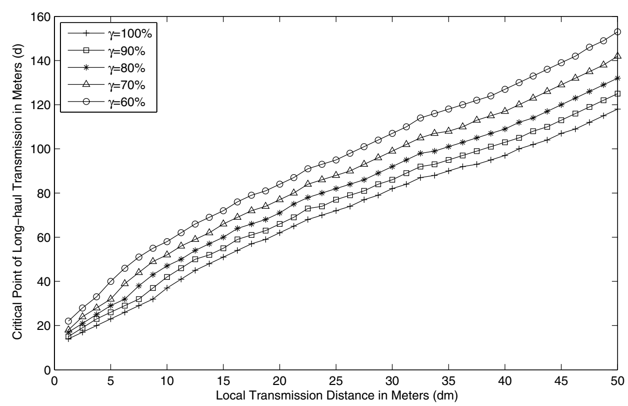

Fig. 7. The critical distance over d_m in scheme B (2×1) with γ.

$$\bar{P}_b \approx E_{\mathbf{H}}\left[\frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right) Q\left(\sqrt{\frac{3b}{M-1}\gamma_b}\right)\right] \tag{8a}$$

for $b \geq 2$ and

$$\bar{P}_b \approx E_{\mathbf{H}}\left[Q\left(\sqrt{2\gamma_b}\right)\right] \tag{8b}$$

for $b = 1$, where $E_{\mathbf{H}}[\cdot]$ denotes the expectation with variable $\mathbf{H}$, and $Q(\cdot)$ is the Q-function, defined as $Q(x) = (1/\sqrt{2\pi})\int_x^{\infty} e^{-t^2/2}dt$. Note that in most cases, the direct analytical expression of $\bar{E}_b$ with the variable $\bar{P}_b$ can not be obtained. In our approach, we get the value of $\bar{E}_b$ by evaluating $\bar{P}_b$ over 20,000 randomly generated channel samples according to (8) at each transmission distance for the best accuracy. The energy consumption of cooperative MISO transmission then can be calculated based on (4) and constellation size optimization is done simultaneously. d_m is used to denote the distance between two close-by nodes in MIMO system.

Two different communication schemes with data aggregation are illustrated in Fig. 2 to analysis the energy consumption of cooperative communications. There are two nodes on the transmission side in 2×1 MISO system . As the transmission process described at the beginning of this section, one of the two nodes (denoted as n_1) will firstly transmit its data to the other node (denoted as n_2) to do data aggregation to eliminate redundancy. Because both nodes should have the aggregated data to do cooperative transmission while n_1 does not have the data of n_2, n_2 need to transmit some data back to n_1 in order that n_1 has the same aggregated data as n_2. However, in most cases as shown in scheme A, n_2 need not transmit all its data to n_1, since after the data aggregation, n_2 already knows which datum is redundant and thus does not transmit the overlapped data to save energy. While in a real-time system where the data aggregation algorithm is complex and time-consuming, n_2 will transmit all its data as shown in scheme B to n_1 to meet the critical delay requirements. The total energy consumptions in scheme A and scheme B then are given by $E_A = N_1 E_1^t + E_{bf}\sum_{i=1}^{2} N_i + E_2^{t0}\left(N_2 - (1-\gamma)(N_1+N_2)\right) + E_b^r \sum_{i=1}^{2} N_i \gamma$ and $E_B = N_1 E_1^t + E_{bf}\sum_{i=1}^{2} N_i + E_2^{t0} N_2 + E_b^r \sum_{i=1}^{2} N_i \gamma$, where $1-\gamma$ is the percentage of redundant data in the total raw data, and other symbols have the same meanings as in (6). Note that, when we consider a communication system with $M_t > 2$, (6) should be used to calculate the total energy consumption, or the transmission approach will be very complex and difficult to be determined.

The channel matrix of reference SISO system can be written as $\mathbf{H}= [h_1]$ and the SNR is $\gamma_b = \frac{\bar{E}_b}{N_o}\|\mathbf{H}\|^2$. Based on the numerical approach similar to previous discussion of MIMO systems, $\bar{E}_b$ can be obtained and the total energy consumption is determined according to (7).

Fig. 3 compares the energy consumptions for 2×1 MISO with data aggregation scheme A, 2×1 MISO with data aggregation scheme B, SISO with data aggregation, traditional 2×1 MISO and traditional SISO. In all these schemes, $d_m = 1$ and $\gamma = 75\%$ are assumed. In all the simulation throughout the paper, we assume $B = 10$ KHz, $f_c = 2.5$ GHz, $k = 3.5$ for local transmission, $k = 2$ for long-haul transmission, $M_l = 40$ dB, $N_f = 10$ dB, $N_0 = -171$ dBm/Hz, $G_tG_r = 5$ dBi, $\bar{P}_b = 10^{-3}$ and $\eta = 0.35$. The circuit parameters are typical values assumed as $P_{mix} = 30.3$ mW, $P_{filt} = P_{filr} = 2.5$ mW, $P_{syn} = 50$ mW, $P_{LNA} = 20$ mW and $P_{IFA} = 3$ mW. The calculation of P_{DAC} and P_{ADC} is based on [7].

Fig. 4 shows the total energy consumption of scheme A with $\gamma = 100\%$, 90%, 80%, 70% and 60%. In the case $\gamma = 100\%$ which indicates the data of two nodes are totally irrelevant, the MISO system will be preferable for transmission distance above $d = 22.8$ meters. As we include more and more correlation between data and thus γ decrease from 100% to 60%, we observe that the critical distance also decreases. For example, if $\gamma = 60\%$ is used to indicate the correlation between data, d must be at least 8 meters in order to justify the use of MISO schemes. To compare with scheme A, Fig. 5 shows the total energy consumption of scheme B with $\gamma = 100\%$, 90%, 80%, 70% and 60%. When $\gamma = 100\%$, the critical distance $d = 22.8$ is the same as scheme A. However, as γ decreases from 100% to 60%, we find the case is totally different that the critical distance increases. When $\gamma = 60\%$, the critical point increases to about $d = 39.5$ meters.

The value of the critical distance is very important in determining whether to use cooperative MIMO or SISO solution. As shown in the analysis above, the critical distance is related to data redundancy γ. Furthermore, it is also related to the local distance d_m. In Fig. 6, we examine the critical distance with respect to the local distance d_m for different values of γ under scheme A. It is observed that the critical distance decreases when γ decreases under all values of d_m. The curve with the greater value of γ is above the curve with the smaller value, and the curves are all below the one with $\gamma = 100\%$. Fig. 7 shows the comparison results under scheme B. Note that, the curve with $\gamma = 100\%$ is totally the same since all data of n_2 need to be transmit back to n_1 under scheme A. The results in Fig. 7 are different from those in Fig. 6, that the critical distance increases when γ decreases under all values of d_m, and the curves are all above the one with $\gamma = 100\%$.

B. Alamouti 2×2 MIMO Systems with Data Aggregation

The channel matrix of 2×2 MIMO system is written as $\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$, and the instantaneous received SNR can be written as $\gamma_b = \frac{\bar{E}_b}{2N_o} \|\mathbf{H}\|_F^2$, where PDF of $\|\mathbf{H}\|_F^2$ is the give in [11] as $f(x) = \frac{x^{M_tM_r-1}}{(M_tM_r-1)!} e^{-x} u(x)$, when $\mathbf{H}$ is the spatially white channel.

The critical distance curves with respect to the local distance d_m under scheme A and scheme B using 2×2 Alamouti MIMO schemes are plotted in Fig. 8 and Fig. 9 respectively, where the critical distance for justifying the use of MIMO schemes is higher when the value of d_m is small, but does not increase as fast as in 2×1 Alamouti MIMO schemes. The reason for this is that while the 2×2 MIMO systems offers additional receiver diversity over MISO system to achieve less transmission energy, its extra receiver branch consumes more circuit energy according to (3). We can also observe that critical distance curves bear the same tendency as those in MISO schemes for both scheme A and B, showing that when γ decreases under all values of d_m, the critical distance decreases in scheme A, while increases in scheme B.

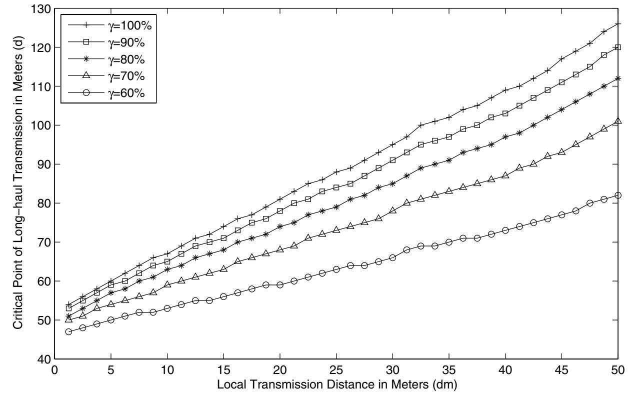

Fig. 8. The critical distance over d_m in scheme A (2×2) with γ.

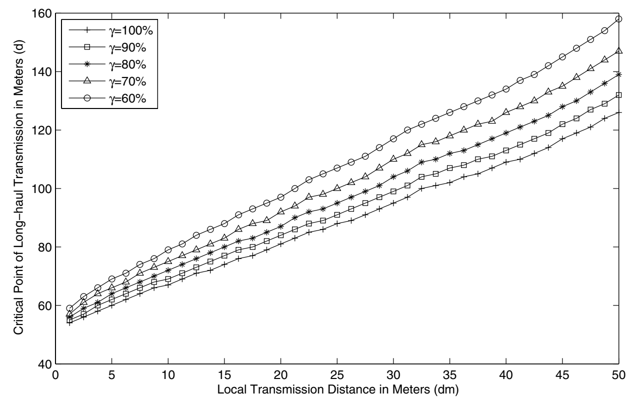

Fig. 9. The critical distance over d_m in scheme B (2×2) with γ.

IV. Energy Optimization of Cluster Based Cooperative MIMO Systems

The selection of cluster head and cooperative transmission nodes is critical in the proposed scheme. This problem can be formulated as a nonlinear programming problem as follows:

$$\min_p E_{DF+MIMO} = \sum_{i=1, i \neq p}^{N} N_i E_i^t + E_{bf} \sum_{i=1}^{N} N_i + \sum_{j=1, j \neq p}^{M_t} E_j^{t0} \sum_{i=1}^{N} N_i \gamma_i + E_b^r \sum_{i=1}^{N} N_i \gamma_i + \sum_{h=1}^{M_r-1} E_h^r n_r N_s \quad (9)$$

To solve the problem, we can simply try every node as the cluster head, where in (9) p denotes the data aggregation cluster head and is also one node on the transmitting side.

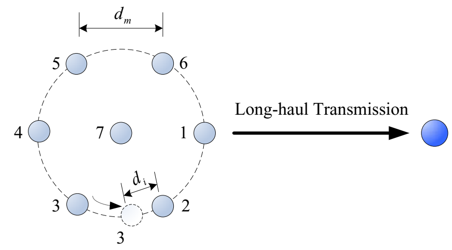

Fig. 10. A cluster of sensor nodes in WSN.

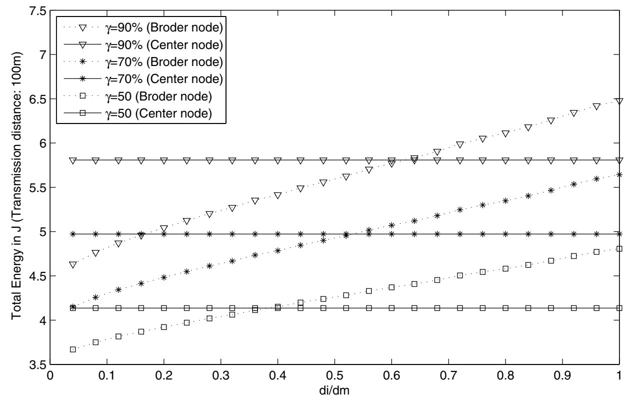

Fig. 11. Total energy consumption over d_i/d_m.

Consider a sensor network composed of seven nodes, the difference between the joint energy model and the traditional model can be illustrated by Fig. 10. Six nodes locate at the six vertices of a hexagon and the seventh node is at the center so that the distances between any two close-by nodes are the same. We assume 2×1 Alamouti MISO system is used in cooperative transmission. When we separately consider in the traditional scheme, the center node will obviously be chosen as the cluster head since if we choose the node on the edge, the local communication energy for data aggregation will increase. When we jointly consider the selection of the cluster head and cooperative transmission nodes, we will find the result of selection is the same because the center node is energy efficient for data aggregation and cooperative transmission with any border node due to the symmetry in geographical distribution. However, if node 3 approaches node 2 along the circle to keep the same distance from the center node, the center node will still be obviously preferable according to the traditional scheme, but may not be superior in our jointly consideration.

Simulation results are based on the 2×1 Alamouti MISO communication schemes and d_m is assumed to be 5 meters. Assuming the distance between node 2 and node 3 is 0.5 meter and $\gamma = 75\%$, we observe that in our approach, node 2 will be selected instead, and node 3 will be chosen for cooperative communication. The total energy consumption of the traditional scheme exceeds that of the joint scheme by a constant value 0.8 J because of the different energy consumptions of local communication. Fig. 11 compares the total energy consumption when the long-haul transmission distance is 100 meters. The critical proportion (d_i/d_m) below which the broder node 2 is preferable for energy efficiency ranges from 0.38 to 0.62 when γ ranges from 50% to 90%.

V. Conclusion

In this paper, we integrated the energy model of data aggregation into cooperative MIMO schemes to further optimize the total energy consumption. Based on our approach on the energy consumption model of systems with data aggregation under both SISO and cooperative MIMO communication techniques, we developed the total energy consumption models and analyzed the energy efficiency of the point-to-point communication systems. Simulation results show the comparisons of the critical distances at which the cooperative MIMO system outperforms the SISO system according to different parameters. With the model and formulations, we studied the optimization problem for cluster head selection to further show the energy efficiency of cooperative communication systems with data aggregation.

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