Cooperative MIMO schemes optimal selection for wireless sensor networks

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***Abstract*— A cooperative MIMO scheme selection is proposed for wireless sensor networks where energy consumption is the most important design criterion. Space-Time Block Codes are designed to achieve maximum diversity for a given number of transmit and receive antennas with very simple decoding algorithm. In radio fading channel, STBC require less transmission energy than SISO technique for the same Bit Error Rate and can be employed practically in Wireless Sensor Networks by using the cooperative MIMO scheme. Considering Alamouti and Tarokh space-time block codes, the number of antennas at both the transmission and the reception sides are selected with respect to the transmission distance. By using cooperative MIMO transmission instead of SISO, it is shown that the distance between nodes can be increased and a large amount of the total energy can be saved for middle and long distance transmission. The energy efficiency of cooperative MIMO over SISO and multi-hop SISO is proved by simulations, and a multi-hop technique for cooperative MIMO is also proposed for good energy-efficiency and limited number of available cooperative nodes.**

I. Introduction

On radio fading channel transmission, multi-antenna techniques (MIMO) have been shown to have the potential of greatly increasing the channel capacity [1]. Under the same Signal to Noise Ratio (SNR), MIMO systems can be far more reliable than Single-Input Single-Output (SISO) systems and they need less transmission energy for the same Bit Error Rate (BER) requirement. The MIMO energy-efficiency transmission scheme is particularly useful for Wireless Sensor Network (WSN) where each wireless node has to operate without battery replacement for a long time and energy consumption is the most important constraint. However, the direct application of multi-antenna technique to WSN is impractical due to the limited physical size of sensor nodes which can typically support a single antenna. Fortunately some individual sensor nodes can cooperate for the transmission and the reception in order to set up a cooperative-MIMO scheme.

Cooperative MIMO scheme can deploy the energy-efficiency of MIMO technique which plays an important role in long range transmission where transmit energy is dominant in the total consumption. In various applications, such as area surveillance for agriculture or intelligent transportation systems, middle and long range transmissions are indeed often required because of the weak density of the wireless sensor networks. Nonetheless, cooperative MIMO scheme requires extra energy for the local cooperative data exchange, extra circuit consumption of the cooperative nodes, and extra energy of the more complex digital processing [2]. Therefore, it is not practical for short range transmission in which circuit energy consumption is dominant in the total energy consumption. Another trade-off of the cooperative MIMO technique is the delay of the cooperative local data exchange.

The energy-efficiency of cooperative MIMO scheme versus non multi-hop SISO scheme was shown in [3]. The result is limited to the case of 2 antennas using Alamouti Space-Time Block Code (STBC) [4]. Depending on the energy model of [5], the present paper proposes an extension of this cooperative principle to MIMO systems with 3 and 4 antennas using Tarokh orthogonal STBC [6]. An energy-efficient antenna subset selection that depends on the distance of transmission is performed.

If the number of available transmission nodes is reduced, a new multi-hop MIMO technique is proposed that represents a good compromise between classical multi-hop SISO and more complex MIMO cooperative schemes. In multi-hop MIMO, only two nodes are cooperating both at transmission (TX) and reception (RX) sides. The performances of MIMO cooperative schemes, multi-hop MIMO and more classical multi-hop SISO are compared in term of energy-efficiency.

The advantages and drawbacks of cooperative MIMO schemes are introduced in Section II. The structure of Orthogonal STBC (O-STBC) of Alamouti and Tarokh and their application to the cooperative MIMO scheme are presented and simulation results of the comparison between MIMO and SISO in the Rayleigh fading channel are performed. The transmission-reception energy model and the energy calculation for non-cooperative and cooperative MIMO system are explored in Section III . In order to prove the energy-efficiency superiority of cooperative MIMO techniques versus SISO and multi-hop techniques for long-range transmission, simulation results are given in Section IV.

II. Cooperative MIMO and Space-Time Block Codes for Wireless Sensor Networks

A. Cooperative MIMO scheme

For data transmission from source node S to destination node D over distance d, instead of SISO direct transmission

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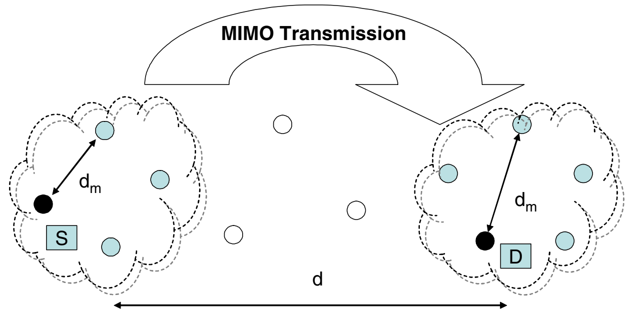

Fig. 1. Cooperative MIMO scheme for wireless sensor networks

which is not practical for long range or multi-hop SISO transmission, we can create a cooperative MIMO transmission, as illustrated by Fig. 1, to reduce the transmit energy. In the transmission side, node S can cooperate with its neighbors and exchange its data (the distance between cooperating nodes $d_m << d$). MIMO techniques (STBC, STTC, Spatial Multiplexing ...) are then employed to transmit their data simultaneously to the destination node (or multi-destination cooperative nodes) like a multi-antenna diversity system (each cooperative node plays role of one antenna of MIMO system). In the reception side the cooperative neighbors of destination node D receive the MIMO modulated symbols and respectively retransmit them to the destination node D for joint MIMO signals combination.

However, if the cooperative MIMO scheme can exploit the energy-efficiency transmission of MIMO technique, the local data transmission at TX and RX sides of cooperative MIMO scheme costs an extra transmission energy due to the extra circuit consumption of the cooperative nodes and the more complex MIMO digital signal processing. For short range transmission, this extra energy consumption can be greater than the transmission energy saved by using cooperative MIMO (or MISO) instead of SISO technique. Another cooperative MIMO trade-off is the delay of the cooperative local data transmission. Nevertheless, transmission delay is a less important design criterion than energy consumption and in comparison to multi-hop technique, cooperative MIMO technique outperforms not only in the energy consumption, but also in the delay of transmission.

B. Application of STBC

Among MIMO diversity coding techniques (Space-Time Block or Treillis Codes, Spatial Multiplexing), STBC is the most practical for WSN [7]. The simplicity of ST coding and combination is very interesting due to the calculation limitation of the sensor node (decoding algorithm of STBC is only based on linear processing).

For systems with 2 transmission antennas, the diversity Alamouti code [4] is used, whereas the orthogonal STBC developed by Tarokh for complex symbol signal [6] is used for systems with 3 or 4 transmission antennas.

The performance of STBC with 2, 3 and 4 transmission antennas over Rayleigh fading channel is shown on Fig. 2

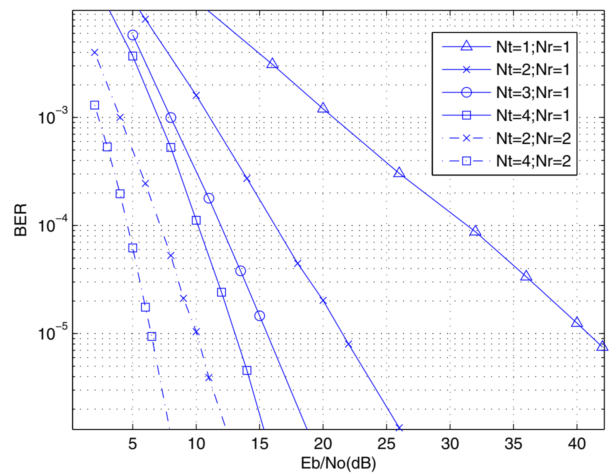

Fig. 2. BER of STBC for various N_t , N_r over Rayleigh fading channel

and the required E_b/N_0 for $BER = 10^{-5}$ is presented in Tab. I. Modulation is uncoded QPSK and we assume that we have perfect synchronization, perfect channel estimation and Maximum Likelihood detection in the receiver.

E_b/N_0	$N_t = 1$	$N_t = 2$	$N_t = 3$	$N_t = 4$
$N_r = 1$	41 dB	21 dB	15.7 dB	13.1 dB
$N_r = 2$	18 dB	10 dB	7.6 dB	6.4 dB
$N_r = 3$	10.5 dB	5.8 dB	4.4 dB	3.7 dB
$N_r = 4$	6.9 dB	3.6 dB	2.5 dB	1.9 dB

TABLE I

E_b/N_0 REQUIREMENT OF STBC FOR $BER = 10^{-5}$

Due to the diversity of transmission and reception, BER performance of MIMO STBC can easily outperform SISO system under the same Signal-to-Noise Ration per bit E_b/N_0. Other says, with the same BER requirement, MIMO system requires less energy for the transmission than SISO system. It is obvious that MIMO technique is very useful for long range transmission where transmission energy dominates the total energy consumption of the system.

III. Energy consumption model

A. Non-cooperative system

We used the energy model in [5] with same system parameters for the energy evaluation of cooperative MIMO system. The typical RF system block of transmitters and receivers is shown in Fig. 3, where N_t and N_r stand for the number of transmitter and receiver antennas, respectively. For the simplicity of estimation, the digital signal processing blocks (coding, pulse-shaping, digital modulation, combination, detection ...) are omitted. The total power consumption of typical RF non-cooperative system consists of two components : the transmission power P_{pa} of the power amplifier and the circuit power P_c of all RF circuit blocks.

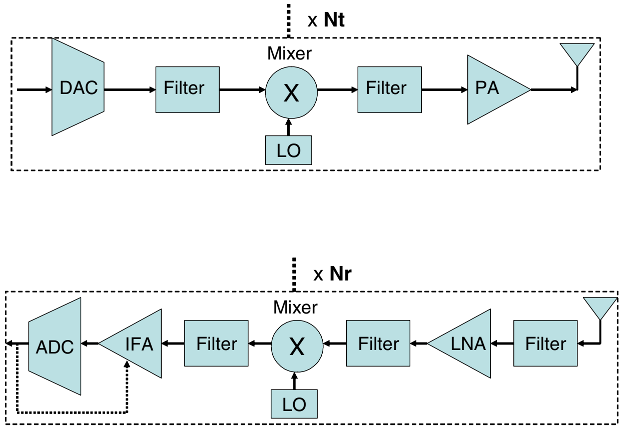

Fig. 3. Transmitter and receiver blocks

P_{pa} is dependent on the transmit power P_{out}. If the channel is square law path loss, it can be calculated as follows

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

where $\bar{E}_b$ is the mean required energy per bit for the given BER requirement, R_b is the bit rate, d is the transmission distance, G_t and G_r are the transmission and reception antenna gain, λ is the carrier wave length, M_l is the link margin, N_f is the receiver noise figure defined as $N_f = N_r/N_0$ with $N_0 = -171$ dBm/Hz single-side thermal noise PSD and N_r is the PSD of the total effective noise at receiver input [5]. Depending on N_t and N_r and the Power Spectral Density (PSD) of noise N_0, we can calculate $\bar{E}_b$ based on E_b given by Tab. I.

P_{pa} can be approximated as

$$P_{pa} = (1+\alpha)P_{out} \tag{2}$$

where $\alpha = \frac{\xi}{\eta} - 1$ with ξ the drain efficiency of the RF power amplifier and η the Peak-to-Average Ratio (PAR) which depends on the modulation scheme and the associated constellation size.

The total circuit power is given by

$$\begin{aligned} P_c \approx\ & N_t(P_{DAC} + P_{mix} + P_{filt} + P_{syn}) \\ & + N_r(P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC} + P_{syn}) \end{aligned} \tag{3}$$

where P_{DAC}, P_{mix}, P_{LNA}, P_{IFA}, P_{filt}, P_{filr}, P_{ADC}, P_{syn} stand respectively for the power consumption values of the DAC, the mixer, the low noise amplifier, the intermediate frequency amplifier, the active filter at the transmitter and receiver, the ADC and the frequency synthesizer whose values are presented in [5].

For traditional non-cooperative system, the total energy consumption per bit E_{bt} can be obtained as

$$E_{bt} = (P_{pa} + P_c)/R_b \tag{4}$$

B. Cooperative MIMO system

The extra energy of the local cooperative data exchange is dependent on the number of cooperative antennas and the local inter-node distance d_m between two cooperating nodes at both TX and RX sides. d_m is expected to vary from 1 meter to 10 meters depending on the geographical configuration of the network. We assume that we have N_b bits to transmit from node S to node D (separated by distance d) and there are N_t nodes and N_r nodes to cooperate at TX and RX sides, respectively.

In the transmission side, node S must firstly broadcast its N_b bits to $N_t - 1$ cooperative nodes. For the short range local distance d_m, we know that SISO is the most energy-efficient technique [3]. We assume that there are just single hops SISO transmissions between two cooperative nodes and an uncoded 16-QAM modulation was used over the Additive White Gaussian Noise (AWGN) channel with K-law path loss ($K = 3.5$). The 16-QAM allows to decrease circuit consumption [5] (we need $E_b/N_0 = 10.5$ dB for $BER = 10^{-5}$ requirement over an AWGN channel). Based on the SISO non-cooperative model, we can calculate energy per bit for local cooperative transmission $E_{pb_{coop}T_x}$ ($d = d_m$ and $N_t - 1$ reception nodes).

The extra cooperative energy consumption in the transmission side E_{coopT_x} is dependent on the energy consumption per bit $E_{pb_{coop}T_x}$ and can be calculated as

$$E_{coopT_x} = N_b E_{pb_{coop}T_x} \tag{5}$$

After receiving N_b bits from node S, N_t cooperative nodes will modulate and arrange their bits to the QPSK STBC symbols and then transmit simultaneously to the destination node (or multi-destination nodes) over MIMO Rayleigh fading channel.

In the RX side, the $N_r - 1$ cooperative nodes firstly receive the MIMO modulated symbols, quantize one STBC symbols to N_{sb} bits and then retransmit their quantized bits respectively to the destination node D using uncoded SISO 16-QAM modulation. The extra cooperative energy consumption in the RX side $E_{coop}R_x$ is dependent on N_r, N_{sb} and the energy consumption per bit SISO $E_{pb_{coop}R_x}$ which can be calculated by using SISO 16-QAM transmission for distance $d = d_m$. $E_{coop}R_x$ can then be calculated as

$$E_{coopR_x} = N_{sb}(N_r - 1)N_b E_{pb_{coop}R_x} \tag{6}$$

The transmission and circuit power of cooperative MIMO can be calculated like non-cooperative MIMO system

$$E_{pa} + E_c = N_b E_{bt} \tag{7}$$

Finally, the total energy consumption of cooperative MIMO system is

$$E_{total} = E_{pa} + E_c + E_{coopT_x} + E_{coopR_x} \tag{8}$$

IV. Simulation results

The simulation were performed using the parameters presented in [5]. The following figures represent the energy consumed to transmit 10^7 bits with $BER = 10^{-5}$ from a source node S to a destination node D separated by a distance d (Rayleigh quasi-static channel). The local distance between cooperative nodes is $d_m = 5$m and $N_{sb} = 10$.

A. MISO vs SISO

On Fig. 4, we see that when $d < 30$ m, the cooperative MISO is less energy-efficient than the traditional SISO because of the extra circuit consumption and the cooperative consumption. However, when $d > 30$m, the transmission energy saved by MISO technique can be greater than the extra cooperative energy cost and the cooperative MISO outperforms SISO. At the distance $d = 100$m, 85% energy is saved by using 2-1 MISO strategy instead of SISO. The more the distance increases, the more the transmission energy dominates in the total energy consumption. This is the reason why the cooperative 3-1 MISO outperforms 2-1 and the cooperative 4-1 MISO outperforms 3-1 respectively in the distance $d = 300$m and $d = 700$m.

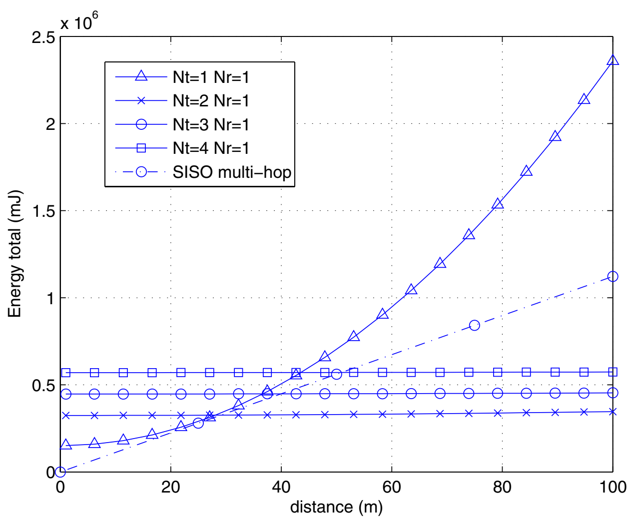

Fig. 4. Energy consumption of MISO, SISO and multi-hop SISO systems

B. MIMO vs MISO

In Fig. 5, the cooperative MIMO 3-2 outperforms 2-2 and the cooperative MIMO 4-2 outperforms 3-2 respectively at distances $d = 1300$m and $d = 2200$m. We can see that for $d > 1800$m, the cooperative MIMO 2-2 outperforms the best 4-1 cooperative MISO. Similar results are obtained for 3 or 4 reception antennas.

For each range of transmission distance d, based on the energy calculation result, we can find the best energy-efficient antenna selection strategy, as shown by Fig. 6. The lower bound of total energy consumption in the cooperative MIMO system is represented on Fig. 7.

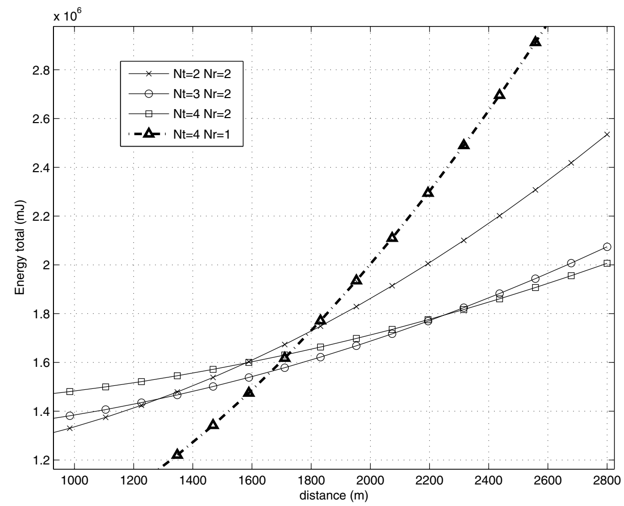

Fig. 5. Energy consumption of MIMO and MISO systems

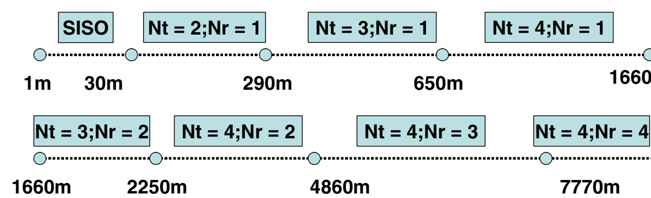

Fig. 6. Optimal $N_t - N_r$ set selection vs distance

As illustrated on this figure, increasing the number of transmission nodes is better than increasing the number of reception nodes because of the smaller cooperative energy consumption (the number of transmit cooperative bits $Nb_{coop}Rx = N_{sb}(Rx - 1)N_b$ at the reception side is greater than $Nb_{coop}Tx = N_b$ at the transmission side).

C. Cooperative MIMO vs multi-hop SISO and multi-hop MIMO

For long range data transmission in typical WSN, multi-hop SISO technique has been used to reduce the transmission energy (which increases order 2 for square law path loss channel). If E_h is the energy consumption of one SISO hop and we have k hops to transmit data form S to D, the total energy consumption is kE_h. For the best geographical configuration of the network (the middle nodes are aligned and equally spaced between node S and D), total energy consumption of multi-hop technique is the tangent of SISO energy consumption curve. The comparison between multi-hop SISO and the cooperative MISO is presented on Fig. 4.

The best range of SISO single hop is around 25m and for de transmission distance $d = 100$m, 4 hops are needed to transmit the data to the destination. We can see that multi-hop technique is clearly more energy-efficient than SISO technique. For $d = 100$m, multi-hop technique can save 53% of the total consumption of the SISO system. However, multi-hop SISO is still 69% less energy-efficient than the

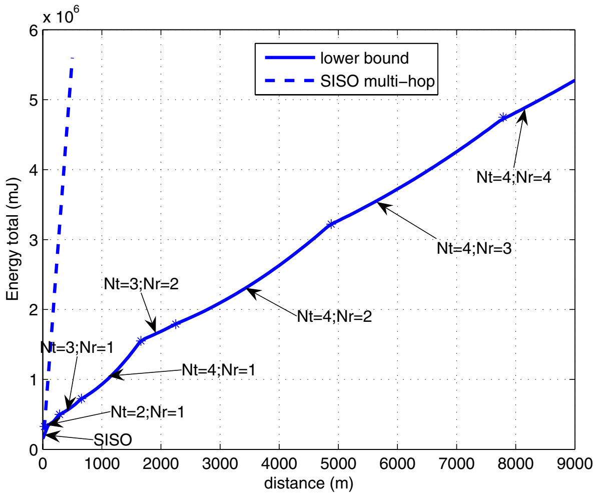

Fig. 7. Total Energy consumption lower bound

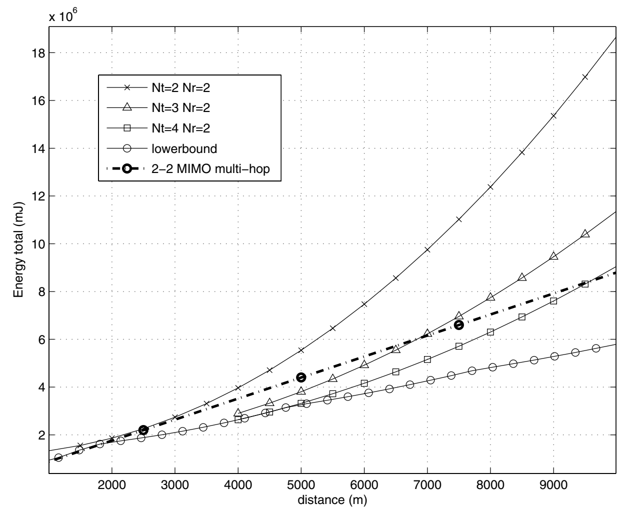

Fig. 8. Energy consumption of MIMO and multi-hop MIMO systems

cooperative 2-1 MISO. Moreover, for $d = 200$m, $d = 500$m and $d = 1000$m, multi-hop SISO technique is 83%, 89% and 92% less energy efficient than cooperative 2-1 MISO, cooperative 3-1 MISO and cooperative 4-1 MISO respectively. Like cooperative MISO, the multi-hop technique trade-off is also the delay of long distance transmission due to the number of hops to destination. In addition, it is evident that the cooperative MISO transmission delay (just in transmitter side) is less than the 5 hops delay of multi-hop technique.

For long range transmission (d from 5000 to 10000m), the best energy-efficiency strategy is to use 4-3 and 4-4 cooperative MIMO schemes. However, due to the geographical configuration of WSN, we sometimes cannot have enough neighbor nodes to set up a 4-3 or 4-4 cooperative MIMO scheme. Therefore, it is very interesting to joint cooperative MIMO and multi-hop technique to create multi-hop MIMO technique, which is very useful for long range transmission without the high demand on the number of cooperative antennas. The most interesting antenna solution of multi-hop MIMO is the 2-2 configuration which requires less resources in the network.

On Fig. 8, we can see the best range of one 2-2 cooperative MIMO hop is around 2500m and for the distance $d = 7500$ m (3 hops), 2-2 multi-hop technique can save 39% energy consumption in comparison with 2-2 cooperative technique and just 32% less energy efficient than the best 4-4 cooperative solution. It is also interesting to note that in terms of energy consumption, 2-2 multi-hop technique can outperform 3-2 cooperation and 4-2 cooperation for 3 and 4 hops, respectively.

V. Conclusion

Cooperative MIMO techniques can exploit the energy-efficiency of MIMO transmission in wireless distributed sensor networks. As cooperative MISO and MIMO are more energy-efficient than SISO technique and traditional multi-hop SISO technique for long range transmission, a MIMO scheme selection can be performed to find the best N_t-N_r subset for a given transmission distance. We also introduced the multi-hop cooperative MIMO technique for 2-2 antennas configuration which demands less the network resource and has better energy-efficiency in comparison with 3-2 or 4-2 cooperative configuration.

The cooperative MIMO approach seems better than the traditional SISO technique, but it is more sensible to channel estimation errors and demands precise MIMO transmission synchronization. Another trade-off is the delay of cooperative transmission. However, comparing with multi-hop SISO technique, cooperative MIMO technique is better in terms of not only energy consumption but transmission delay as well. It is also interesting to investigate the impact of the mobility of the nodes (more realistic fading channels, channel estimation errors, …) on such cooperative schemes.

References

[1] T. L. Marzetta and B. M. Hochwald, "Capacity of a mobile multiple-antenna communication link in Rayleigh flat fading," *IEEE Transactions on Information Theory*, vol. 45, pp. 139–157, January 1999.

[2] S. K. Jayaweera, "Energy analysis of mimo techniques in wireless sensor networks," in *38th Annual Conference on Information Sciences and Systems*, Princeton University, USA, March 2004.

[3] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of mimo and cooperative mimo techniques in sensor networks," *IEEE Jour. on Selected Areas in Communications*, vol. 22, no. 6, pp. 1089 – 1098, August 2004.

[4] S. M. Alamouti, "A simple diversity technique for wireless communications," *IEEE Jour. on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, 1998.

[5] S. Cui, A. J. Goldsmith, and A. Bahai, "Modulation optimization under energy constraints," in *IEEE International Conference on Communications*, Anchorage, AK, USA, May 2003, pp. 2805 – 2811.

[6] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, July 1999.

[7] L. X. H. Dai and Q. Zhou, "Energy efficiency of mimo transmission strategies in wireless sensor networks," in *International Conference on Computing, Communications and Control Technologies (CCCT)*, Austin, TX, USA, August 2004.