Selecting Optimal Transmission Strategies for Cooperative Sensor Networks

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Abstract –**Recent research has shown that cooperation of sensor nodes can potentially achieve much better energy efficiency, which is a major concern for wireless sensor networks (WSN). But whether the cooperation is really beneficial or not highly depends on system demands and network topology. In this paper, we study the selection of optimal transmission strategies with respect to energy efficiency for WSN where the nodes can cooperate in transmission. Energy efficiency of cooperative transmission schemes are analyzed and compared using a realistic energy model. The criterions for selecting optimal strategy under various performance constraints are proposed. The criteria for choosing the optimal strategy according to instantaneous channel knowledge are also addressed.**

I. INTRODUCTION

Energy efficiency is perhaps the most critical issue for sensor applications [1]. Direct communications between sensor nodes and the (possibly) distant data collector is in general energy inefficient, as each node needs to transmit the highly redundant data. By allowing sensor nodes in close proximity to cooperate on communication, not only can the collected data be efficiently fused, but recent progress in wireless MIMO communications can be exploited to improve the system performance, which can be equivalently traded for energy efficiency [2][3].

In our recent work [4], the energy efficiency of existing MIMO transmission strategies is analyzed for cooperative sensor networks, both for the wideband asymptotes and more realistic system settings. It is found that different transmission schemes, such as space-time block coding (STBC), spatial multiplexing (SM), or simple diversity techniques, may assume advantage in terms of energy efficiency depending on system demand and network topology.

In this paper, we investigate the selection of optimal transmission strategies in cooperative sensor networks to achieve the minimization of the energy consumption under some system or link level constraints. The energy efficiency of different transmission schemes is analyzed and compared using a realistic energy model. Criteria for choosing the preferable scheme given system-level parameters are proposed and further illustrated through numerical results. In addition, in certain circumstances where channel is quasi-static and known at the receiver, and sufficient feedback to the transmitters is affordable, we further study the optimality regions with respect to instantaneous channel characteristics. We expect these results are helpful to theoretical and practical explorations on wireless sensor networks.

The remainder of this paper is organized as follows: Section II describes the system model and general assumptions. The optimal transmission strategies with three important system-level parameters are investigated in Section III. Section IV addresses the criteria for choosing the optimal transmission scheme based on instantaneous channel information. A brief conclusion is given in Section V.

II. SYSTEM MODEL

We use the same model as [4]. Suppose there is a powerful mobile agent (MA) at the receiver side, which is equipped with multiple antennas and complex processing circuits. But we exclude the energy consumption in MA from the overall budget of the sensor network, and only focus on the energy analysis at the cooperative transmitter side. We assume N_T neighboring nodes intend to cooperate in transmission to an MA equipped with N_R antennas. Then the equivalent discrete-time MIMO system can be described as

$$\mathbf{Y} = \mathbf{HX} + \mathbf{N}\,, \tag{1}$$

where $\mathbf{Y}$ is the received signal at the MA; $\mathbf{X}$ contains the sub-streams transmitted by cooperative nodes; $\mathbf{H}$ is an $N_R \times N_T$ channel matrix which captures the channel characteristics between transmit and receive antenna arrays, whose entries are modeled as independent and identically distributed (i.i.d.) complex normalized Gaussian random variables. To make the selection feasible, we assume $\mathbf{H}$ is quasi-static. $\mathbf{N}$ is the background noise.

The transmitter can employ one of these three schemes: traditional non-cooperative transmission (which corresponds to a single-input multi-output (SIMO) system), STBC and SM. Furthermore, we assume M-QAM (with two independent equal-distance M_1- and M_2- PAM sub-channels) modulation is used throughout this paper. At the receiver side, maximum ratio combining (MRC) is employed for SIMO, and maximum-likelihood (ML) detection for STBC and SM.

III. OPTIMAL STRATEGY SELECTION BASED ON SYSTEM-LEVEL PARAMETER

A. *Energy Efficiency Analysis for MIMO Transmission Strategies*

From [4], the required $\overline{E}_b / N_0$ with target BER P_e for STBC is given by

$$\frac{\overline{E}_b}{N_0}|_{STBC} \approx N_T \frac{\left[(M_1^2-1)+(M_2^2-1)\right]}{3\log_2 M}\left(\frac{1}{4}\left(\frac{4\left(1-\frac{1}{2M_1}-\frac{1}{2M_2}\right)\binom{2N_TN_R-1}{N_TN_R}}{P_e \log_2 M}\right)^{1/N_TN_R}-1\right). \quad (2)$$

Note that by taking $N_T = 1$, we can readily get the analytical result for a SIMO system with MRC. Also it is sufficient to assume

$$\frac{\overline{E}_b}{N_0}|_{SM-ML} = \frac{\overline{E}_b}{N_0}|_{SIMO}, \quad (3)$$

since the error performance is typically dominated by the minimum-distance error events, as verified in [4].

Equation (2) can be approximated as

$$\frac{\overline{E}_b}{N_0}|_{STBC} \approx N_T \frac{M}{6\log_2 M}\left(\frac{4\binom{2N_TN_R-1}{N_TN_R}}{P_e \log_2 M}\right)^{1/N_TN_R}. \quad (4)$$

Taking logarithm operation on the both sides of (4), we have

$$\log \overline{E}_b \approx \log M + \log(N_T N_0) + \frac{1}{N_T N_R}\log\left(4\binom{2N_TN_R-1}{N_TN_R}/P_e\right). \quad (5)$$

Compared to (4), we neglect $\log\log M$ terms in (5). Numerical results verify its effectiveness (see Fig. 1).

Denote

$$E_{\min}(N_T) = \log(N_T N_0) + \frac{1}{N_T N_R}\log\left(4\binom{2N_TN_R-1}{N_TN_R}/P_e\right), \quad (6)$$

a simple expression of $\log \overline{E}_b$ can be obtained as

$$\log \overline{E}_b \approx \log M + E_{\min}(N_T). \quad (7)$$

Note $E_{\min,SM} = E_{\min,SIMO} = E_{\min}(1)$ and $E_{\min,STBC} = E_{\min}(N_T)$.

For a given spectral efficiency R (bps/Hz), the constellation size (per antenna) for STBC is $M = 2^{R/r}$ where r is the rate of STBC. Also we have $M = 2^R$ for SIMO and $M = 2^{R/N_T}$ for SM. For simplicity, we only consider full-rate STBC ($r = 1$) here, then the energy efficiency of the three transmission strategies can be expressed as:

$$\log \overline{E}_b |_{SM} = S_0(N_T)R + E_{\min}(1), \quad (8)$$

$$\log \overline{E}_b |_{STBC} = S_0(1)R + E_{\min}(N_T), \quad (9)$$

and

$$\log \overline{E}_b |_{SIMO} = S_0(1)R + E_{\min}(1), \quad (10)$$

where $S_0(N_T) = \frac{\log 2}{N_T}$. Equation (8), (9) and (10) reveal that the spectral efficiency and energy efficiency hold a linear relationship with slope S_0 and minimum energy (dB) $E_{\min}$.

From [6], the end-to-end transmit energy consumption is given by

$$E_{TX} = \frac{\xi}{\eta}\left(\frac{\overline{E}_b}{N_0}N_r\right)\frac{(4\pi)^2 d^n}{G_t G_r \lambda^2}M_g, \quad (11)$$

where $\xi = 3\frac{\sqrt{M}-1}{\sqrt{M}+1}$ is the peak-to-average ratio of the modulation scheme, η is the drain efficiency of the RF amplifier, d is the transmission distance, G_t and G_r are the transmitter and receiver antenna gain respectively, λ is the carrier wavelength, M_g is the link budget margin, and N_r is the single-side power spectral density of the receiver noise.

Fig. 1 plots the link transmission energy E_{TX} of various transmission strategies according to Equation (11), with the typical parameter values quoted from [2]. It is seen that the linear relationship between spectral efficiency and $\log E_b$ is validated, and the approximation expressions match the accurate ones pretty well.

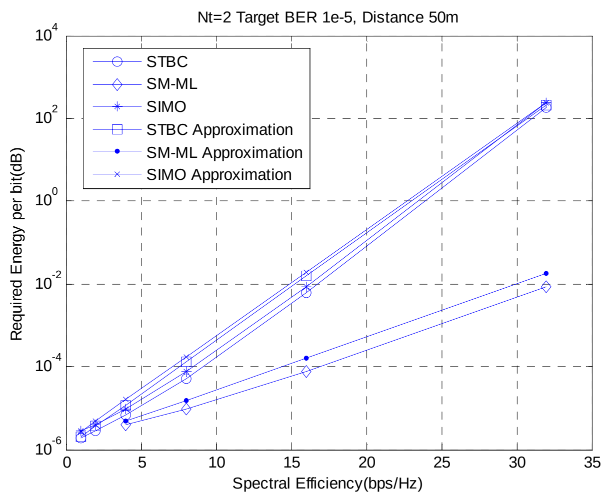

Fig. 1 Transmit energy comparison under different spectral efficiency

In the following sections, we assume a fixed target BER and discuss the optimal strategy selection problem under various circumstances.

B. *Optimal Transmission Strategy Selection based on Spectral Efficiency Demand*

In this section, we investigate the optimal transmission strategy given a specific spectral efficiency demand. Comparing (9) and (10), we can see that with equal slope, $\overline{E}_b|_{SIMO}$ is uniformly larger than $\overline{E}_b|_{STBC}$ due to the fact $E_{\min}(1) > E_{\min}(N_T)$. So we only need to consider SM and STBC here.

Since $S_0(N_T) < S_0(1)$, we expect $\overline{E}_b|_{SM}$ is smaller than $\overline{E}_b|_{STBC}$ in high spectral efficiency region. Furthermore, by letting $\log \overline{E}_b|_{SM} = \log \overline{E}_b|_{STBC}$, we can get their crossover point

$$R_0 = \frac{E_{\min}(1) - E_{\min}(N_T)}{S_0(1) - S_0(N_T)}. \quad (12)$$

Therefore we obtain the following selection criterion:

Criterion 1: Given a target BER, when spectral efficiency requirement $R < R_0$, choose STBC, otherwise choose SM.

The switching threshold R_0 is depicted in Fig. 2 as a function of target BER for some values of N_T.

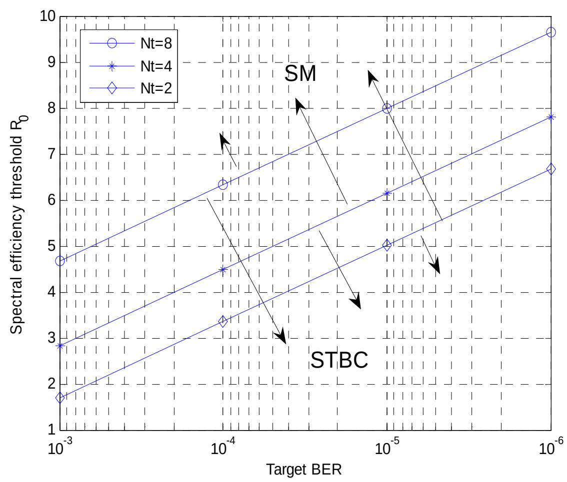

Fig. 2 Switching threshold based on spectral efficiency

C. Optimal Transmission Strategy Selection based on Delay

Some real-time traffic in the sensor network may have a requirement for the total transmission delay. Assume the transmission bandwidth is B, then the symbol period can be approximated as $T_s = \frac{1}{B}$. As discussed in [2], the total transmission delay for SIMO scheme is

$$T_{SIMO} = \frac{N}{R_{SIMO}} T_s, \tag{13}$$

where N is the total number of bit that need to be transmitted, R_{SIMO} is the spectral efficiency (bps/Hz). The total transmission delay for spatial multiplexing transmission can be obtained as

$$T_{SM} = T_s \left(\frac{N}{R_{SM}} + \frac{(N_T - 1)N / N_T}{R_{SM,l}} \right), \tag{14}$$

where R_{SM} is the long-haul SM transmission spectral efficiency and $R_{SM,l}$ is the local cooperation transmission spectral efficiency (bps/Hz). In this expression, the first term is the long-haul transmission delay and the second term stands for the local information exchange delay. Similarly, the total transmission delay for STBC transmission can be expressed as

$$T_{STBC} = T_s \left(\frac{N}{R_{STBC}} + \frac{N}{R_{STBC,l}} \right). \tag{15}$$

To remove the influence of system-dependent parameters T_s and N, we define the average normalized delay per bit as

$$\overline{D}_{SIMO,b} = \frac{T_{SIMO}}{T_s N} = \frac{1}{R_{SIMO}}, \tag{16}$$

$$\overline{D}_{SM,b} = \frac{T_{SM}}{T_s N} = \frac{1}{R_{SM}} + \frac{(N_T - 1)/N_T}{R_{SM,l}}, \tag{17}$$

$$\overline{D}_{STBC,b} = \frac{T_{STBC}}{T_s N} = \frac{1}{R_{STBC}} + \frac{1}{R_{STBC,l}}. \tag{18}$$

Substituting the above equations into (8), (9) and (10) leads to the relationship of delay and energy for different transmission strategies:

$$\log \overline{E}_b \,|_{SIMO} = \frac{S_0(1)}{\overline{D}_{SIMO,b}} + E_{\min}(1), \tag{19}$$

$$\log \overline{E}_b \,|_{SM} = \frac{S_0(N_T)}{\overline{D}_{SM,b} - \frac{(N_T - 1)/N_T}{R_{SM,l}}} + E_{\min}(1), \tag{20}$$

$$\log \overline{E}_b \,|_{STBC} = \frac{S_0(1)}{\overline{D}_{STBC,b} - \frac{1}{R_{STBC,l}}} + E_{\min}(N_T). \tag{21}$$

From (19), (20) and (21), a tradeoff between delay and energy consumption can be observed. Stringent delay requirement results in large energy consumption. With delay constraint relaxed, more energy savings can be achieved.

The cross-point of SIMO and SM curves can be obtained as

$$\overline{D}_0 = \frac{S_0(1)(N_T - 1)/R_{SM,l}}{N_T\left(S_0(1) - S_0(N_T)\right)} = \frac{1}{R_{SM,l}}. \tag{22}$$

Assuming $R_{SM,l} = R_{STBC,l} = R_l$, we can also get the delay threshold to control the switching between SM and STBC:

$$\overline{D}_1 = \frac{S_0(1) - S_0(N_T)}{E_{\min}(1) - E_{\min}(N_T)} + \frac{1}{R_l}. \tag{23}$$

In Fig. 3, we fix the local transmission spectral efficiency and give the D_1 vs. BER curves. As a comparison, we also draw the D_0 in the same figure, which is the inverse of R_l.

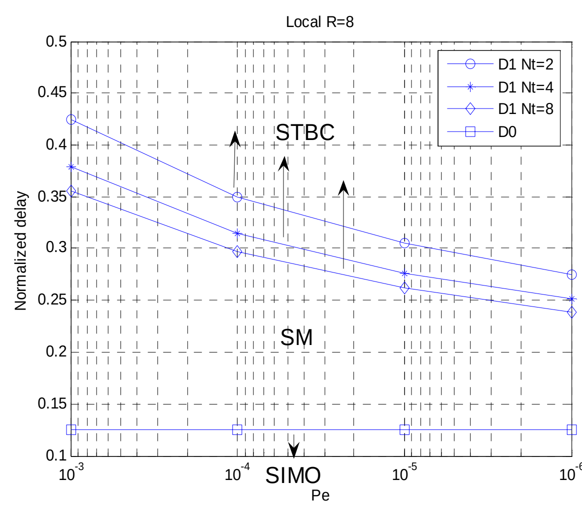

Fig. 3 Switching threshold based on delay

Conclusively, the selection criterion when considering delay constraint is:

Criterion 2: Given a target BER, if the normalized delay constraint $\tau < \overline{D}_0$, choose SIMO; if $\tau > \overline{D}_1$, choose STBC; if $\overline{D}_0 < \tau < \overline{D}_1$, choose SM.

It is worth pointing out that delay highly depends on spectral efficiency. (16), (17) and (18) give the minimum delay that can be achieved given a certain spectral efficiency. So Criterion 2 is only valid in these achievable regions. In the unachievable region, we have to choose to meet one of the constraints while violating the other.

D. *Optimal Transmission Strategy Selection based on Distance and Spectral Efficiency*

The above selection rules do not change with the transmission distance if only transmit energy is concerned. However, for cooperative STBC and SM transmission schemes in WSN, there are two additional energy consumption parts that should be considered. One is circuit energy and the other is cooperation penalty [2][4]. Typically, the transmission circuit energy consumption P_{CT} includes that of the digital-to-analog converter, the mixer, the transmit filters and the frequency synthesizer, while the reception circuit energy P_{CR} includes that of the analog-to-digital converter, the mixer, the receiver filters, the frequency synthesizer, the low noise amplifier and the intermediate frequency amplifier. Assuming these two values are the same for each sensor node, the circuit energy consumption per bit for cooperation transmission strategy is given by

$$E_c = N_T \frac{P_{CT}}{R_b}. \quad (24)$$

Obviously, the local transmission for sharing and exchanging data among cooperative nodes also consumes additional energy. This cooperation penalty is given by

$$E_{CP} = \frac{P_{CT}}{R_b} + E_{TX,SISO} + (N_T - 1)\frac{P_{CR}}{R_b}, \quad (25)$$

where $E_{TX,SISO}$ is the required transmit energy per bit for the local SISO communications among cooperative sensor nodes. We found by simulation that, if the cooperative group has a small radius, say 1m, this term is small enough to be ignored compared with P_{CT} and P_{CR}. So the total energy consumption per bit for cooperation transmission strategy is given by

$$E_{TOTAL} = E_{TX} + (N_T + 1)\frac{P_{CT}}{R_b} + (N_T - 1)\frac{P_{CR}}{R_b}. \quad (26)$$

As for SIMO, the total energy consumption is given by

$$E_{TOTAL} = E_{TX} + \frac{P_{CT}}{R_b}. \quad (27)$$

With the circuit energy consumption and cooperative penalty considered, the influence of transmission distance should be included for selections. When the transmission distance is short, E_c dominates the total energy consumption; with the increase of the transmission distance, E_{TX} gradually takes over and if the distance exceeds a certain threshold, the redundant energy consumption for cooperation transmission strategies will be compensated by their transmission energy saving. With some algebra, we can derive the following distance threshold which separates SIMO and SM when $R > R_0$ as

$$d_{th1} = \frac{\alpha}{e^{E_{\min}(1)/n}} \frac{\beta_1}{\left((2^R - 2^{R/N_T})R\right)^{1/n}}, \quad (28)$$

where α and β are system-specific constants which satisfy

$$\alpha^n = \frac{G_t G_r \lambda^2 \eta N_0}{\xi (4\pi)^2 N_r M_g B}, \quad (29)$$

and

$$\beta_1^n = \left(N_T + 1 - \frac{1}{N_T}\right)P_{CT} + (N_T - 1)P_{CR}. \quad (30)$$

The distance threshold separating SIMO and STBC for $R < R_0$ case can be obtained similarly as

$$d_{th2} = \frac{\alpha}{2^{R/n}} \frac{\beta_2}{\left((e^{E_{\min}(1)} - e^{E_{\min}(N_T)})R\right)^{1/n}}, \quad (31)$$

where α is a constant given above and

$$\beta_2^n = N_T P_{CT} + (N_T - 1)P_{CR}. \quad (32)$$

The corresponding selection criterion is given by:
Criterion 3: Considering total energy consumption, when $R > R_0$, if the transmission distance d satisfies $d > d_{th1}$, choose SM, otherwise choose SIMO; when $R < R_0$, if transmission distance d satisfies $d > d_{th2}$, choose STBC, otherwise choose SIMO.

In Fig. 4, the switching bounds of Criterion 4 are exemplified for some values of N_T. It can be seen that with spectral efficiency growing, the curves converge to x-axis. So the system tends to have only one choice-SM. Also note that since the advantage of STBC over SIMO in terms of transmit energy is marginal, it overtakes SIMO only for a large distance.

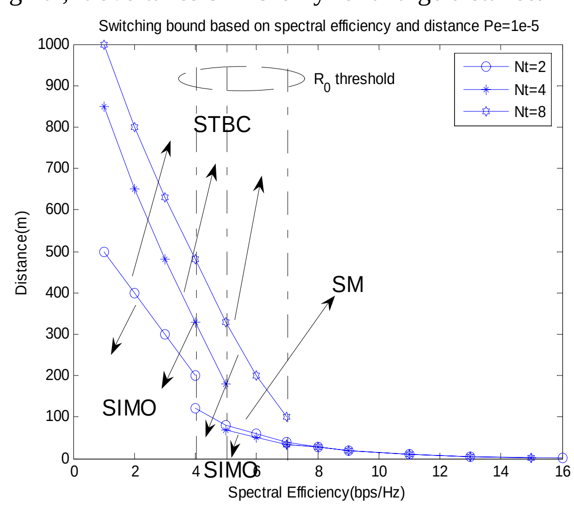

Fig. 4 Switching bound based on spectral efficiency and distance

E. *Optimal Transmission Strategy Selection based on Spectral Efficiency, Delay and Distance*

Finally, we visualize the above criterions jointly in Fig. 5. Here we ignore the unachievable region, so it's only a coarse switching bound. From this figure, we can see that with stringent delay constraint, SIMO is the only feasible strategy; at the large-delay low-spectral efficiency corner, STBC is preferable; and under other conditions, SM is the optimal scheme.

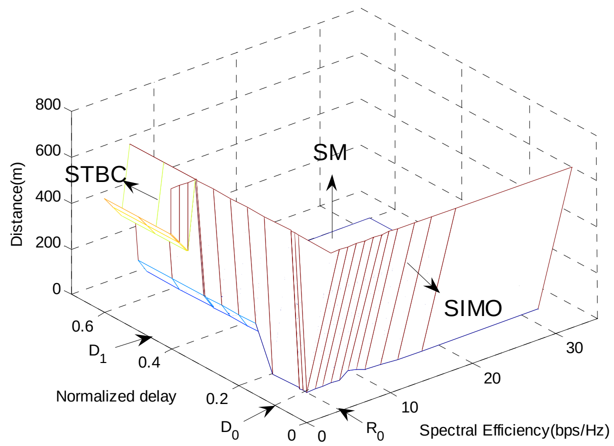

Fig. 5 Switching surface based on spectral efficiency, delay and distance

IV. OPTIMAL STRATEGY SELECTION BASED ON INSTANTANEOUS CHANNEL INFORMATION

The results obtained in previous sections are based on the average performance of the virtual MIMO system, which can be viewed as "system-level" selections. In this section, we consider "link-level" selection of optimal strategies which is based on the instantaneous channel state information (CSI). Health *et al.* have studied the problem of switching between transmit diversity and spatial multiplexing in [5] and [7]. Here, we extend their work to selecting STBC, SM or SIMO to minimize the required transmit energy. As in [7], we assume there exists a low-bit feedback channel between receiver and transmitter.

A. Energy Requirement for STBC

For QAM modulation, the upper bounder of BER for STBC is given by ([7])

$$P_e^{(d)}(\mathbf{H}) \le \overline{N}_e Q\left(\sqrt{\frac{E_s^{(d)}}{N_0}\max_{1\le k\le N_T}\|h_k\|^2\frac{d_{\min}^2}{2}}\right), \qquad (33)$$

where $\overline{N}_e$ is the average number of nearest neighbors in constellation, $d_{\min}$ is the minimum distance of modulation signals and h_k is the kth column of $\mathbf{H}$, E_s is energy per symbol per antenna. We can approximate the required $\overline{E}_s / N_0$ as

$$\frac{E_s^{(d)}}{N_0} \approx \frac{2}{d_{\min}^2 \max_{1\le k\le N_T}\|h_k\|^2}\left(Q^{-1}\left(\frac{P_e}{\overline{N}_e}\right)\right)^2. \qquad (34)$$

From [7], $\max_{1\le k\le N_T}\|h_k\|^2 \le \lambda_{\max}^2(H)$. So

$$\frac{\overline{E}_s^{(d)}}{N_0} \ge \frac{2}{d_{\min}^2\lambda_{\max}^2(H)}\left(Q^{-1}\left(\frac{P_e}{\overline{N}_e}\right)\right)^2. \qquad (35)$$

For N_T transmit antennas, the total energy satisfies

$$N_T\overline{E}_s^{(d)} \ge \frac{2N_T N_0}{d_{\min}^2\lambda_{\max}^2(H)}\left(Q^{-1}\left(\frac{P_e}{\overline{N}_e}\right)\right)^2. \qquad (36)$$

B. Energy Requirement for SM

The BER bound for Spatial Multiplexing is given by

$$\begin{aligned} P_e^{(m)}(\mathbf{H}) &\le 1-\left(1-\overline{N}_e Q\left(\sqrt{SNR_{\min}\frac{d_{\min}^2}{2}}\right)\right)^{N_T} \\ &\approx \overline{N}_e N_T Q\left(\sqrt{SNR_{\min}\frac{d_{\min}^2}{2}}\right) \end{aligned}. \qquad (37)$$

So

$$SNR_{\min} = \min_{1\le k\le N_T}\frac{E_s^{(m)}}{N_T N_0\left[H^H H\right]_{k,k}^{-1}} \ge \frac{2}{d_{\min}^2}\left(Q^{-1}\left(\frac{P_e}{\overline{N}_e N_T}\right)\right)^2 \text{ and}$$

$$\frac{E_s^{(m)}}{N_0} \approx \max_{1\le k\le N_T}\left[H^H H\right]_{k,k}^{-1}\frac{2N_t}{d_{\min}^2}\left(Q^{-1}\left(\frac{P_e}{\overline{N}_e N_T}\right)\right)^2. \qquad (38)$$

Since $\max_{1\le k\le N_T}\left[H^H H\right]_{k,k}^{-1} \le \lambda_{\min}^{-2}(H)$ ([7]), we can get a safe lower bound of E_s / N_0

$$\frac{E_s^{(m)}}{N_0} \ge \lambda_{\min}^{-2}(H)\frac{2N_T}{d_{\min}^2}\left(Q^{-1}\left(\frac{P_e}{\overline{N}_e N_T}\right)\right)^2. \qquad (39)$$

Similarly, for N_T transmit antennas, the total energy

$$N_T E_s^{(m)} \ge \lambda_{\min}^{-2}(H)\frac{2N_T^2 N_0}{d_{\min}^2}\left(Q^{-1}\left(\frac{P_e}{\overline{N}_e N_T}\right)\right)^2. \qquad (40)$$

C. Energy Requirement for SIMO

For maximal ratio combining (MRC) receiver, the error performance is bounded as [8]

$$P_e^{(s)}(H) \le \overline{N}_e Q\left(\sqrt{\frac{E_s^{(s)}}{N_0}\sum_{k=1}^{N_R}\|h_k\|^2\frac{d_{\min}^2}{2}}\right). \qquad (41)$$

Then

$$\frac{E_s^{(s)}}{N_0} \approx \frac{2}{d_{\min}^2\sum_{k=1}^{N_R}\|h_k\|^2}\left(Q^{-1}\left(\frac{P_e}{\overline{N}_e}\right)\right)^2. \qquad (42)$$

As $\sum_{k=1}^{N_R}\|h_k\|^2 = \sum_{k=1}^{N_R}\mu_k$, where μ_k is the eigen-value of HH^H.

And because H here is a $N_R \times 1$ dimension vector, HH^H has only one non-zero eigen-value which is equal to the square of H's maximum singular value $\lambda_{\max}^2(H)$. So the above equation can be written as

$$\frac{E_s^{(s)}}{N_0} \ge \frac{2}{d_{\min}^2\lambda_{\max}^2(H)}\left(Q^{-1}\left(\frac{P_e}{\overline{N}_e}\right)\right)^2. \qquad (43)$$

Combining Equation (36), (40) and (43), we can get the following selecting criterion:

Criterion 4: Given channel state matrix from source node to the destination H_{SIMO}; channel state matrix from source node and relay nodes to the destination H_{MIMO}; calculating three following metrics $d_{\min,SIMO}\lambda_{\max}(H_{SIMO})$, $\frac{d_{\min,STBC}\lambda_{\max}(H_{MIMO})}{\sqrt{N_T}}$, $\frac{d_{\min,SM}\lambda_{\min}(H_{MIMO})}{N_T}$ and choose the scheme that can make the corresponding metric largest.

Obviously, this selection is applicable for quasi-static channel. And note for QAM modulation $d^2_{\min,SM} = \frac{6}{2^{R/N_T}-1}$, $d^2_{\min,SIMO} = d^2_{\min,STBC} = \frac{6}{2^R-1}$.

The probabilities to select SM, STBC and SIMO under different spectral efficiency are shown in Fig. 6. It is seen that the probability of choosing SM tends to be 1 as spectral efficiency grows.

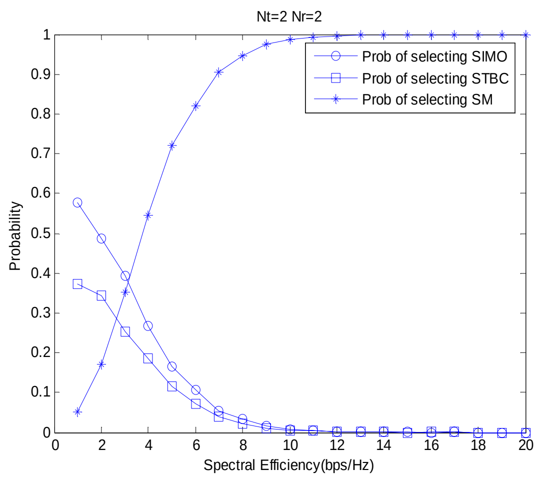

Fig. 6 Probability of selecting SIMO, STBC and SM

V. CONCLUSIONS

In this paper, we have investigated the energy efficiency of different transmission strategies in cooperative sensor networks. Under specific performance constraints, the most suitable working conditions for cooperative STBC, SM and SIMO are quantitatively characterized. Selection criteria based on instantaneous CSI are also addressed. Our results show that transmission strategy should be judiciously selected to achieve the optimal energy efficiency in wireless cooperative sensor networks.

REFERENCES

[1] A. J. Goldsmith and S. B. Wicker, "Design challenges for energy-constrained ad hoc wireless networks", *IEEE Wireless Communications Magazine*, Vol. 9, No. 4, pp. 8-27, Aug. 2002.

[2] S. Cui, A. J. Goldsmith and A. Bahai, "Energy-efficiency of MIMO and Cooperative MIMO in Sensor Networks", *IEEE Journal on Selected Areas of Communications*, Vol. 22, No. 6, August, 2004.

[3] Sudharman K. Jayaweera. "Energy Analysis of MIMO Techniques in Wireless Sesor Networks", 38th Annual Conference on Information Sciences and System (CISS'04), Princeton, NJ,March, 2004.

[4] H. Dai, L. Xiao and Q. Zhou, "Energy Efficiency of MIMO Transmission Strategies in Wireless Sensor Networks," invited paper, *2004 International Conference on Computing, Communications and Control Technologies* (CCCT), Austin, TX, Aug. 2004.

[5] Robert W. Heath Jr., A.J. Paulraj, "Switching Between Multiplexing and Diversity Based on Constellation Distance", in Proc. *of Allerton Conf. on Communication, Control and Computing*, 2000.

[6] J. G. Proakis, Digital Communications, 4th Edtion, New York:McGraw-Hill, 2001.

[7] Robert W. Heath Jr., David J. Love, "Dual-Mode Antenna Selection for Spatial Multiplexing Systems with Linear Receivers", Proc. of *IEEE Asilomar Conf. on Signals, Systems, and Computers*, Pacific Grove, CA, Nov. 9-12, 2003.

[8] A. J. Paulraj, R. Nabar and D. Gore, Introduction to Space-Time Wireless Communications, Cambridge, UK: Cambridge University Press,2003.