Energy-Based Transmission Strategy Selection for Wireless Sensor Networks

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***Abstract*—Energy efficiency is one of the most critical concerns for wireless sensor networks. While cooperative transmission strategies have the potential to significantly improve the system performance, they also incur additional energy cost and system overhead. In this paper, Energy efficiency of relevant transmission strategies is studied both for wideband asymptotes and realistic system settings. Based on this analysis, general guidelines are presented for optimal transmission strategy selection in some typical scenarios, aiming at minimum energy consumption with a target BER. The proposed selection rules, especially those based on system-level metrics, are easy to implement for sensor applications. The framework provided here may also be readily extended to other scenarios or applications.**

Keywords-sensor networks; energy efficiency; virtual MIMO

I. INTRODUCTION

Energy efficiency is one of the most critical concerns 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 multi-input multi-output (MIMO) communications can be exploited to improve the system performance, which can equivalently be traded for energy efficiency. However, concerning the analysis of energy efficiency in wireless cooperative sensor networks, two additional factors should be given special considerations: the circuit energy consumption and the cooperation penalty [2][3]. The circuit power utilization increases linearly with the number of cooperative nodes, which is significant especially for short-range transmission. Furthermore, cooperative nodes must communicate among themselves to share information and coordinate transmission, which consumes extra energy and induces additional delay. Therefore, it may not always be better to enforce cooperative transmission and vice versa. Determination of the optimal transmission strategy depends on many interacting factors including system demand, network topology, and availability of channel information.

In this paper, we take an initial step to quantify the switching thresholds among three representative transmission strategies: traditional non-cooperative transmission, space-time block coding (STBC), and spatial multiplexing (SM), the latter two of which fall within the cooperative transmission category yet are feasible to implement for sensor applications. The selection rules are decided such that the best energy efficiency is achieved with given system or link level demand or knowledge.

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The rest of this paper is organized as follows. Section II presents the system model and our assumptions on analysis. Energy efficiency of relevant transmission strategies is studied in Section III, which provides a basis for selection of energy-efficient signaling. Then in Section IV, general guidelines are proposed for optimal transmission strategy selection in some typical scenarios. Finally Section V concludes the paper.

II. SYSTEM MODEL

A. Channel Model

We assume a hierarchical network structure, in which most plain sensor nodes are stringently limited in processing capability and power, while a few powerful mobile agents (MA) take over the burden of complicated network operation and signal processing. These mobile agents, furnished with superior communication and processing units, can traverse the network to collect data, and reach back to remote control centers through high-speed connections. Examples of mobile agents include manned/unmanned airplanes or vehicles, or specially designed light nodes that can hop around in the network. This architecture assumes certain advantages in energy efficiency over the traditional flat multi-hop ad hoc network [8]. In this paper, we further investigate the possible advantages of cooperative MIMO transmission in wireless sensor networks with mobile agents (SENMA), which can be similarly coined as M-SENMA.

We assume that at some moment N_T neighboring nodes in a SENMA intend to transmit to a MA equipped with N_R antennas. Independent frequency nonselective Rayleigh fading is assumed for the channels between each node and the MA, on top of the common path loss[1]. The equivalent discrete-time MIMO system can be described as

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

where $\mathbf{Y}$ is the received signal at the MA; $\mathbf{X}$ contains the substreams transmitted by the nodes; $\mathbf{H}$ is an $N_R \times N_T$ channel matrix, whose entries are modeled as independent and identically distributed (i.i.d.) normalized complex Gaussian random variables; and $\mathbf{N}$ is the background noise, assumed to be circularly symmetric Gaussian with variance N_0 for each component. The common path loss is incorporated in the power of $\mathbf{X}$. The optimal transmission strategy is decided at the MA, based on (available) relevant information at the system or link

[1] Rayleigh fading is commonly assumed in MIMO and SENMA studies whenever rich scattering exists in environments. This can be justified when sensor nodes are distributed in a building or forest. In applications with line-of-sight communications, Ricean model can be exploited.

level, and fed back to the sensor group via a reverse signaling channel (as assumed in [8]).

B. Energy Model

The transmit energy consumption per bit of a communication link is given by [6]

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

where $\overline{E}_b$ is the energy efficiency of signaling schemes to be discussed in the following, N_f is the receiver noise figure, $(4\pi)^2 d^n / G_t G_r \lambda^2$ reflects the end-to-end loss in transmission (n is the path loss exponential), M_g is the link budget margin, and ξ / η is a coefficient accounting for the RF power amplifier effect with ξ the peak-to-average ratio of the modulation scheme and η the drain efficiency of the amplifier.

Due to the stringent energy constraints and (relatively) short transmission distances in sensor networks, the circuit energy consumption, largely neglected in previous study, should be explicitly addressed. As the SENMA architecture is assumed, we focus on the circuit energy consumption at the transmit nodes. We assume the circuit power consumption in transmission and reception are the same for each sensor node, denoted as P_{CT} and P_{CR} [2]. Therefore, the total circuit energy consumption per bit when N_T nodes simultaneously transmit at an aggregate data rate R_b (b/s) is given by

$$E_C = N_T \frac{P_{CT}}{R_b} . \qquad (3)$$

To quantify the extra cost for cooperative MIMO transmission, we assume a simple cooperation protocol, for which K_T out of N_T nodes have data to transmit (while others serve as relays). Each of the K_T data nodes broadcasts its information to all the other nodes in this group using different time slots. The energy consumption per bit required for such cooperation is given as

$$E_{CP} = K_T\left(\frac{P_{CT}}{R_b} + E_{TX,SISO} + (N_T - 1)\frac{P_{CR}}{R_b}\right), \qquad (4)$$

where $E_{TX,SISO}$ accounts for the required transmit energy per bit for the local single-input single-output (SISO) communications among cooperative sensor nodes. It is found that this term is typically negligible compared to the circuit energy part if the local communication radius is small enough. In the following discussion, we will ignore $E_{TX,SISO}$ and assume $K_T = 1$ in (4) for simplicity.

III. Energy Efficiency of Non-cooperative and Cooprative Transmission

With SENMA model, traditional non-cooperative transmission corresponds to a single-input multi-output (SIMO) system. As for cooperative transmission, we focus on two feasible technologies, STBC and SM, exploiting diversity and spatial multiplexing gains in MIMO systems, respectively [9]. We first study their energy efficiency in the wideband regime to obtain some insights, then turn to more realistic system settings.

A. Wideband Asymptote

The wideband analysis is to approximate the Shannon capacity C as an affine function of energy per bit normalized to the noise spectral density (i.e., $\overline{E}_b / N_0$) in the zero SNR neighborhood (corresponding to high-to-optimal energy efficiency) as [10]

$$\log\frac{\overline{E}_b}{N_0}(C) = \log\frac{E_b}{N_0}_{\min} + \frac{C}{S_0}\log 2 + o(C) , \qquad (5)$$

where $(\overline{E}_b / N_0)_{\min}$ is the (normalized) minimum required energy for reliable communications, S_0 stands for the wideband slope of spectral efficiency-energy efficiency curve, and *o(C)* denotes the higher order terms of *C*. Following [10], we summarize these two key parameters for relevant transmission strategies in Table 1.

TABLE I. Wideband Analysis of Communications Systems Subject to Rayleigh Fading

	SISO	SIMO	STBC[3]	SM
$(\overline{E}_b / N_0)_{\min}$	$\ln 2$	$\ln 2 / N_R$	$\ln 2 / N_R$	$\ln 2 / N_R$
S_0	1	$\frac{2N_R}{N_R+1}$	$\frac{2N_T N_R}{N_T N_R+1}$	$\frac{2N_T N_R}{N_T+N_R}$

Wideband analysis shows that receive diversity effectively lowers the minimum required energy by a factor of N_R . However, $(\overline{E}_b / N_0)_{\min}$ alone does not reveal the whole picture as it could not differentiate various communication systems with receive antenna arrays but different transmit signaling. On the other hand, S_0 demonstrates their differences in spectral efficiency given certain energy efficiency in the wideband regime. In general, we have

$$1 \le \frac{2N_R}{N_R+1} \le \frac{2N_T N_R}{N_T N_R+1} \le \frac{2N_T N_R}{N_T+N_R} . \qquad (6)$$

But as the number of antennas grows, the S_0 of SIMO and STBC approaches a limit of 2, while that of SM grows without bound. We know that the wideband slope for the AWGN SISO channel is 2, which is reduced to 1 here due to Raleigh fading. Essentially, the diversity in SIMO and STBC alleviates the fading effect and brings it back to 2. The transmit diversity of STBC facilitates this process, whose effect quickly diminishes when there are sufficient receive antennas. On the other hand, with sufficiently large N_T , the S_0 of SM approaches $2N_R$, resulting a tremendous boost of spectral efficiency even in the low-power regime. These observations are further confirmed for realistic system settings through the analysis below.

B. Realistic Setting

In this section, we relate the $\overline{E}_b / N_0$ to a target BER P_e and the size of the employed modulation constellation and antenna arrays, with the latter two essentially determining the system's spectral efficiency R (b/s/Hz) and data throughput $R_b = RB$ (when the system bandwidth B is fixed). Without loss

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[2] Please refer to [2] for details.

[3] In this paper, we assume a full-rate STBC for simplicity. In general the relevant expressions should be scaled by *r*, the rate of STBC.

of generality, we assume M-ary QAM modulation with Gray mapping in our analysis. Equal-power and equal-rate allocations are assumed for cooperative MIMO systems for ease of implementations. At the receiver side, maximum ratio combining (MRC) is employed for SIMO, and maximum-likelihood (ML) detection for STBC and SM. While ML detection is decoupled for STBC due to orthogonal designs, it can be well approximated by sphere decoding with polynomial complexity for SM systems. The reader is referred to [3] for discussions of suboptimal detection methods for SM.

The required $\bar{E}_b / N_0$ with target BER P_e for STBC can be accurately approximated as [3]

$$\frac{\bar{E}_b}{N_0}\Big|_{STBC} \approx N_T \frac{2(M-1)}{3\log_2 M} \times \left(\frac{1}{4} \left(\frac{4\left(1-\frac{1}{\sqrt{M}}\right)\binom{2N_T N_R - 1}{N_T N_R}}{P_e \log_2 M} \right)^{1/N_T N_R} - 1 \right). \quad (7)$$

Note that by taking $N_T = 1$ in (7), we readily get the analytical results for a SIMO system with MRC, and further letting $N_R = 1$ gives us results for SISO. It is also verified in [3] that

$$\frac{\bar{E}_b}{N_0}\Big|_{SM-ML} \approx \frac{\bar{E}_b}{N_0}\Big|_{SIMO}, \quad (8)$$

since the error performance is typically dominated by the minimum-distance error events, whose probability is shown to be the same for both systems.

Based on the above analysis, we obtain the following simple relationship between energy efficiency and spectral efficiency for the three transmission strategies of interest:

$$\log \bar{E}_b \,|_{SIMO} \doteq S_0(1)R + E_{\min}(1), \quad (9)$$

$$\log \bar{E}_b \,|_{STBC} \doteq S_0(1)R + E_{\min}(N_T), \quad (10)$$

$$\log \bar{E}_b \,|_{SM} \doteq S_0(N_T)R + E_{\min}(1), \quad (11)$$

where

$$S_0(N_T) = \frac{\log 2}{N_T}, \quad (12)$$

$$E_{\min}(N_T) = \log(N_T N_0) + \frac{1}{N_T N_R}\log\left(4\binom{2N_T N_R - 1}{N_T N_R} \Big/ P_e\right). \quad (13)$$

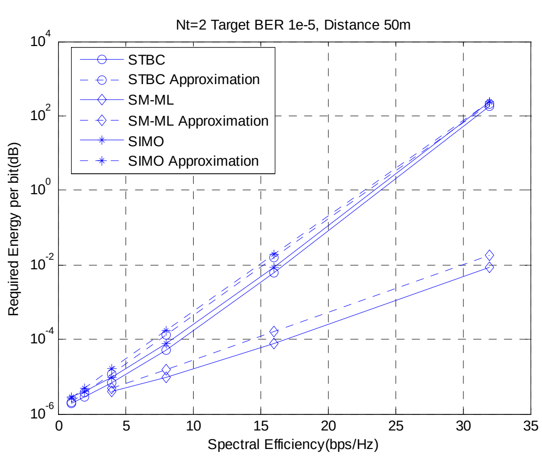

Figure 1. Transmit energy comparison with different spectral efficiency

Note that (9)~(11) are obtained with some simplifications, whose effectiveness has been verified through numerical results. An example is shown in Fig. 1, where transmission energy E_{TX} of the three transmission strategies (cf. (2)) is plotted, with the typical parameter values quoted from [2][6]. Qualitatively similar observations as revealed in the wideband analysis are made here: compared with SIMO, STBC lowers the required energy by exploiting the diversity gain, whose potential is somewhat limited; in contrast, multiplexing gain in SM improves the system energy efficiency by orders of magnitude, when high spectral efficiency is also desired.

IV. Optimal Transmission Strategy Selection

The above analysis provides us a convenient framework to make optimal transmission strategy selection with respect to some system-level metrics. In the following, aiming at minimum energy consumption with a target BER, we present design guidelines for some representative scenarios. Furthermore, 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 optimal selection with respect to instantaneous channel characteristics.

A. System Level

1) Given Transmission Distance

Suppose the distance between the sensor nodes and the MA d is given, and our objective is to find the most energy efficient transmission strategy with no other constraints. In this scenario SM is beyond consideration and the other two schemes will employ the minimum constellation size (e.g., BPSK) to save energy consumption. Denote the corresponding spectral efficiency as $R_{\min}$. If the transmit energy dominates (i.e., circuit energy consumption and cooperation penalty is relatively negligible), it turns out that STBC is always the best, as $E_{\min}(N_T)$ is a decreasing function of N_T.

Criterion 1a: Regarding transmit energy consumption, for any transmission distance, the optimal transmission strategy is STBC.

If circuit energy consumption and cooperation penalty can not be ignored, it is expected that for small transmission distance, the saving of STBC in transmit energy can not justify the extra costs. This is explicitly addressed as follows.

Criterion 1b: Regarding total energy consumption, given a transmission distance d, choose SIMO when

$$d < d_{th1} = \frac{\alpha}{2^{R_{\min}/n}} \frac{\beta_1}{\left((e^{E_{\min}(1)} - e^{E_{\min}(N_T)})R_{\min}\right)^{1/n}}, \quad (14)$$

where

$$\alpha = \left(\frac{G_t G_r \lambda^2 \eta N_0}{\xi(4\pi)^2 N_f M_g B}\right)^{1/n}, \quad (15)$$

$$\beta_1 = \left(N_T P_{CT} + (N_T - 1)P_{CR}\right)^{1/n}, \quad (16)$$

and choose STBC otherwise.

2) Spectral Efficiency Demand

In many applications a specific spectral efficiency demand R is also imposed, due to either the QoS requirements or the network stability concerns. If only the transmit energy is concerned, STBC is uniformly better than SIMO, and the switching threshold between STBC and SM turns out not to depend on the transmission distance.

Criterion 2a: Regarding transmit energy consumption, given a spectral efficiency demand R, choose STBC when

$$R < R_0 = \frac{E_{\min}(1) - E_{\min}(N_T)}{S_0(1) - S_0(N_T)}, \quad (17)$$

and choose SM otherwise.

If the total energy consumption is considered, selection among the three schemes is more complicated and generally depends on the transmission distance as well. A key observation is that the switching threshold between STBC and SM is still given by (17) and is independent of d. The following selection criterion follows after some algebra.

Criterion 2b: Regarding total energy consumption, given a transmission distance d and a spectral efficiency demand R, when $R < R_0$, if transmission distance d satisfies (c.f.(14)~(16))

$$d < d_{th1} = \frac{\alpha}{2^{R/n}} \frac{\beta_1}{\left((e^{E_{\min}(1)} - e^{E_{\min}(N_T)})R\right)^{1/n}}, \quad (18)$$

choose SIMO, otherwise choose STBC; when $R > R_0$, if the transmission distance d satisfies

$$d < d_{th2} = \frac{\alpha}{e^{E_{\min}(1)/n}} \frac{\beta_2}{\left((2^R - 2^{R/N_T})R\right)^{1/n}}, \quad (19)$$

where

$$\beta_2 = \left((N_T + 1 - 1/N_T)P_{CT} + (N_T - 1)P_{CR}\right)^{1/n}, \quad (20)$$

choose SIMO, otherwise choose SM.

These switching bounds are exemplified for some values of N_T in Fig. 2. 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 somewhat limited, it overtakes SIMO only for a large distance.

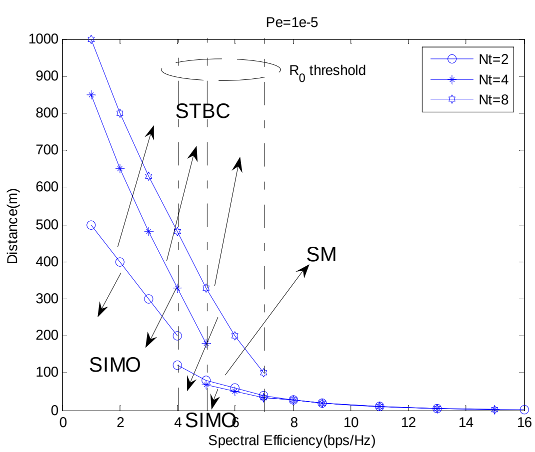

Figure 2. Switching bound based on spectral efficiency and distance

3) *Delay Constraint*

In some scenarios (emergency or real-time applications) a hard limit is put on the total transmission delay. As one expects, the delay constraints are closely related to spectral efficiency demands, as explicitly shown below:

$$T_{SIMO} = \frac{N}{R_{SIMO}} T_s, \quad (21)$$

$$T_{STBC} = T_s\left(\frac{N}{R_{STBC}} + \frac{N}{R_{STBC,l}}\right), \quad (22)$$

$$T_{SM} = T_s\left(\frac{N}{R_{SM}} + \frac{(N_T - 1)N/N_T}{R_{SM,l}}\right). \quad (23)$$

where N is the total number of bits to be transmitted, T_s is the symbol duration, R denotes the spectral efficiency for long-haul transmission while R_l for local cooperation. Therefore, for each given spectral efficiency-delay pair, there is an achievable region dictated by (21), (22) and (23), beyond which one has to meet one while violating the other. Another point worth noting is that, if the delay constraint is too stringent, then local cooperation can not be afforded, and SIMO becomes the only choice. By defining the average normalized delay per bit $\overline{D} = T/(T_s N)$ to remove the system dependence, we formalize the selection rule for a given $\overline{D}$ below. For simplicity we assume the spectral efficiency for local transmission is the same for STBC and SM, denoted as R_l.

Criterion 3: Regarding transmit energy consumption, given a delay constraint $\overline{D}$, choose SIMO when

$$\overline{D} < \overline{D}_0 = \frac{1}{R_l}, \quad (24)$$

choose STBC when (cf. (17))

$$\overline{D} > \overline{D}_1 = \frac{1}{R_0} + \frac{1}{R_l}, \quad (25)$$

otherwise choose SM.

The selection criteria regarding total energy consumption and joint delay-distance consideration can be similarly addressed and we omit the details here.

4) *Joint Consideration*

Finally, we visualize the above criterions jointly in Fig. 3, where unachievable regions have been ignored. From this figure, we can see that with stringent delay constraint, SIMO is the only feasible strategy; at the large-distance low-spectral efficiency corner, STBC is preferable; and under other conditions, SM is the optimal scheme.

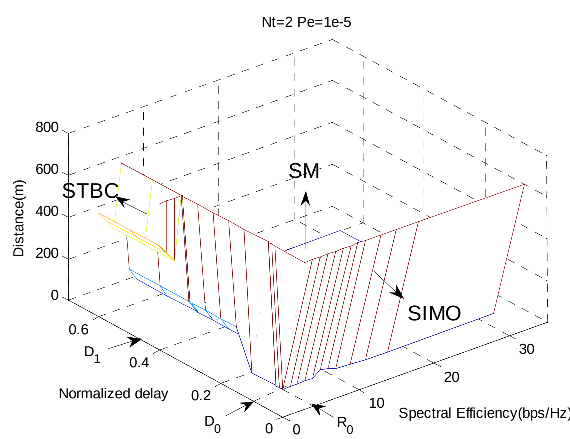

Figure 3. Switching surface based on spectral efficiency, delay and distance

B. Link Level

When instantaneous knowledge of (quasi-static) channel is available and corresponding adaptive signaling is feasible, the problem of switching between STBC and SM to minimize the error rate has been addressed in [4][5]. Here we extend the work to selecting among STBC, SM or SIMO to minimize the required transmit energy. The problem regarding total energy consumption minimization follows a similar approach as discussed above and thus will not be explicitly addressed here.

Following derivations in [5], the following results can be obtained for required energy per bit for the three schemes after some algebra:

$$E_b\,|_{SIMO} \geq \frac{2N_0}{d^2_{\min,SIMO}\,\|\mathbf{h}_{SIMO}\|^2\,R}\left(Q^{-1}\left(\frac{P_e}{\overline{N}_e}\right)\right)^2, \qquad (26)$$

$$E_b\,|_{STBC} \geq \frac{2N_T N_0}{d^2_{\min}\,\lambda^2_{\max}(\mathbf{H}_{MIMO})R}\left(Q^{-1}\left(\frac{P_e}{\overline{N}_e}\right)\right)^2, \qquad (27)$$

$$E_b\,|_{SM} \geq \frac{2N_t^2 N_0}{d^2_{\min,SM}\,\lambda^2_{\min}(\mathbf{H}_{MIMO})R}\left(Q^{-1}\left(\frac{P_e}{\overline{N}_e N_t}\right)\right)^2, \qquad (28)$$

where P_e is the target BER, $\overline{N}_e$ is the average number of nearest neighbors in constellation, $d_{\min}$ is the minimum distance of a unit-energy symbol[4], $\|\mathbf{h}_{SIMO}\|$ is the norm of the SIMO channel, while $\lambda_{\max}(\mathbf{H}_{MIMO})$ and $\lambda_{\min}(\mathbf{H}_{MIMO})$ represent the largest and smallest eigenvalues of the corresponding MIMO channels, respectively. Based on these results, a qualitative selection rule is given below.

Criterion 4: Regarding transmit energy consumption, when instantaneous channel information is available, choose the scheme that makes the corresponding metric $d_{\min,SIMO}\,\|\mathbf{h}_{SIMO}\|$, $\frac{d_{\min,STBC}\lambda_{\max}(\mathbf{H}_{MIMO})}{\sqrt{N_T}}$, $\frac{d_{\min,SM}\lambda_{\min}(\mathbf{H}_{MIMO})}{N_t}$ largest.

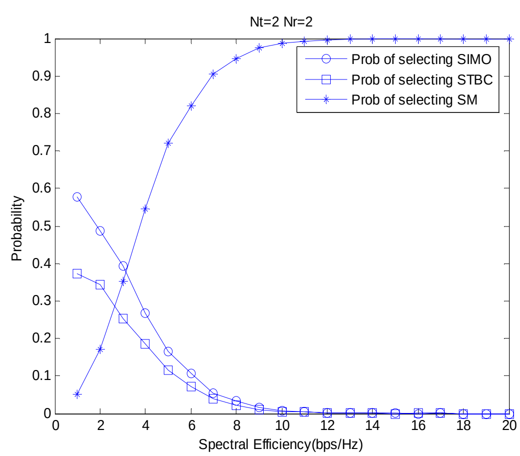

Figure 4. Probability of selecting SIMO, STBC and SM

[4] For square 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 of selecting SM, STBC and SIMO with different spectral efficiency are shown in Fig. 4. It is seen that the probability of choosing SM tends to be 1 as spectral efficiency grows.

V. Conclusions

In this paper, we have investigated the energy efficiency of different transmission strategies in wireless sensor networks, and quantified the switching thresholds among STBC, SM and SIMO under various scenarios. The proposed selection rules, especially those based on system-level metrics, are easy to implement for sensor applications. The framework provided here may also be readily extended to other scenarios or applications. Meanwhile, note that it is better to interpret the results presented here qualitatively, and applications of them on real systems might require a more careful examination of relevant channel and energy consumption models.

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