Energy-Efficiency and Transmission Strategy Selection in Cooperative Wireless Sensor Networks

Yanbing Zhang and Huaiyu Dai

Abstract: **Energy efficiency is one of the most critical concerns for wireless sensor networks. By allowing sensor nodes in close proximity to cooperate in transmission to form a virtual multiple-input multiple-output (MIMO) system, recent progress in wireless MIMO communications can be exploited to boost the system throughput, or equivalently reduce the energy consumption for the same throughput and BER target. However, these cooperative transmission strategies may incur additional energy cost and system overhead. In this paper, assuming that data collectors are equipped with antenna arrays and superior processing capability, energy efficiency of relevant traditional and cooperative transmission strategies: Single-input-multiple-output (SIMO), space-time block coding (STBC), and spatial multiplexing (SM) are studied. Analysis in the wideband regime reveals that, while receive diversity introduces significant improvement in both energy efficiency and spectral efficiency, further improvement due to the transmit diversity of STBC is limited, as opposed to the superiority of the SM scheme especially for non-trivial spectral efficiency. These observations are further confirmed in our analysis of more realistic systems with limited bandwidth, finite constellation sizes, and a target error rate. Based on this analysis, general guidelines are presented for optimal transmission strategy selection in system level and link level, aiming at minimum energy consumption while meeting different requirements. 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.**

Index Terms: **Energy efficiency, sensor networks, virtual multiple-input multiple-output (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 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 multiple-input multiple-output (MIMO) communications can be exploited to boost the system throughput, or equivalently reduce the energy consumption for the same throughput and bit error rate (BER) target.

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. The circuit power utilization increases linearly with the number of cooperative nodes, which is significant especially for short-range transmission. Furthermore, as the elements of the virtual antenna array are not wired together, 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.

Energy analysis on cooperative MIMO in sensor networks was investigated in [2], where it is shown that the Alamouti space-time block coding (STBC) scheme on a cooperative MIMO is more energy efficient than the traditional single-input single-output (SISO) approach when the transmission distance is larger than a small threshold. [3] and [4] extend the idea of virtual MIMO to the V-BLAST (or more general spatial multiplexing (SM)) architecture. In [5], the authors consider the energy efficiency of cooperative STBC with the low-energy adaptive clustering hierarchy (LEACH) protocol. An explicit distance threshold over which cooperative transmission is advantageous is given. Synchronization problem is also addressed. More recent work in this subject [6] endeavors to investigate the diversity-multiplexing trade-off [7] considering the energy consumption. Their results show that both diversity and multiplexing gain should be exploited to obtain optimal energy efficiency.

Our paper assumes the following differences from previous work. First, we introduce a powerful mobile agent (MA) at the receive side as advocated in [8], which are assumed to be equipped with antenna arrays and complex processors and transceivers. Therefore, while sophisticated detection techniques can be safely employed at the receiver, its energy consumption can be excluded from the budget of the overall sensor network, which allows us to focus on the energy analysis at the cooperative transmit end. This architecture assumes certain advantages in energy efficiency over the traditional flat multi-hop ad hoc network [8]. Furthermore, it also well addresses the so-called reachback problem in wireless sensor networks, where information collected by multiple sensors needs to be sent back to a (potentially more capable) collecting node or base station within a given period. Secondly, we provide a unified and practical framework to analyze and compare the energy efficiency of various transmission strategies in wireless sensor networks. And lastly, we take an initial step to quantify the switching thresholds among three representative transmission strategies: Traditional non-cooperative transmission, space-time block coding, and spatial multiplexing, the latter two of which fall within the

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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.

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 Sections IV and V, general guidelines are proposed for optimal transmission strategy selection in some typical scenarios, based on system-level demand and link-level knowledge, respectively. Some numerical results are given in Section VI. Finally, Section VII contains some concluding remarks.

II. SYSTEM MODEL

A. Channel Model

We assume a hierarchical network structure, in which most plain sensor nodes, equipped with single antenna, are stringently limited in processing capability and power, while a few powerful mobile agents 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. 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 designed 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

$$\mathbf{Y} = \mathbf{HX} + \mathbf{N} \quad (1)$$

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 zero mean and variance N_0 for each component. The common path loss is incorporated in the power of $\mathbf{X}$. It is assumed that slotted time division duplexing is employed for communication purpose. The optimal transmission strategy is decided at the MA, based on (available) relevant information at the system or link level, and fed back to the sensor group via a reverse signaling channel, which is also used to transmit beacons for synchronization purpose (as assumed in [8]).

As mentioned before, three basic transmission strategies are considered in this paper: Single-input multi-output (SIMO), which corresponds to traditional non-cooperative transmission with the SENMA structure, STBC and SM, which exploit diversity and spatial multiplexing gains in MIMO systems, respectively [9]. In the cooperative STBC scheme, N_T nodes collaborate to send out an $N_T \times p$ space-time block $\mathbf{X}$ with orthogonal rows to realize full diversity gain, where p represents the number of time slots in transmission. As is known, the maximum likelihood (ML) detection of each transmitted symbol is decoupled, equivalently represented as

$$y = \|\mathbf{H}\|_F x + n \quad (2)$$

where $\|\mathbf{H}\|_F$, the Frobenius of $\mathbf{H}$, is gamma distributed with parameter $N_T N_R$ and 1, and the equivalent noise n still has variance N_0. It can be shown that the spectral efficiency (bits/s/Hz) of the STBC system is given by [9]

$$C^{STBC}(\text{SNR}) = rE[\log(1 + \|\mathbf{H}\|_F^2 \text{SNR}/N_T)]^2 \quad (3)$$

where r is is the code rate of STBC, and SNR denotes the identical energy *per user per block symbol* divided by N_0. This expression should be compared to that of a SIMO system (corresponding to direct communications between a sensor node and an MA) with maximum ratio combining [9]

$$C^{SIMO}(\text{SNR}) = E[\log(1 + |A|^2 \text{SNR})] \quad (4)$$

where $|A|^2$ is Gamma distributed with parameters N_R and 1. For the cooperative SM scheme, each sensor node sends an independent symbol each time, which can be viewed as a space-only code without loss of generality:

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} \quad (5)$$

where $\mathbf{y}$, $\mathbf{x}$, and $\mathbf{n}$ denote column vectors. The spectral efficiency of SM is given by [9]

$$C^{SM}(\text{SNR}) = E[\log|\mathbf{I} + \mathbf{H}^H\mathbf{H} \cdot \text{SNR}|] \quad (6)$$

where SNR is defined on the per-user basis as before to make a fair comparison.

B. Energy Model

The transmit energy consumption per bit of a communication link is given by [10]

$$E_{TX} = \frac{\xi}{\eta}\left(\frac{\bar{E}_b}{N_0} \cdot N_r\right)\frac{(4\pi)^2 d^n}{G_t G_r \lambda^2} M_g \quad (7)$$

where $\bar{E}_b/N_0$ is the energy efficiency of signaling schemes to be discussed in the following, N_r is the single-sided power spectral density of the receiver noise, $(4\pi)^2 d^n / G_t G_r \lambda^2$ 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

[1] Rayleigh fading is commonly assumed in MIMO and SENMA studies whenever rich scattering exists in environments. This is a pretty accurate assumption when the distance between MA and the sensor fields is fairly large while sensors are densely deployed. More complex channel models can be readily incorporated, which will complicate the expression but otherwise is not expected to influence the results qualitatively.

[2] $E[x]$ denotes the expectation of a random quantity x.

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}. According to [2], P_{CT} typically includes that of the digital-to-analog converter, the mixer, the transmit filters, and the frequency synthesizer, while P_{CR} typically includes that of the analog-to-digital converter, the mixer, the receive filters, the frequency synthesizer, the low noise amplifier, and the intermediate frequency amplifier. 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

$$E_C = N_T \frac{P_{CT}}{R_b}. \tag{8}$$

To quantify the extra cost for cooperative MIMO transmission, we assume a simple cooperation protocol for illustration purpose, for which K_T out of N_T nodes have data to transmit (while others serve as relays). It is also assumed that cooperative nodes only communicate with one single MA at any moment, or they can choose the one with the best signal quality, if in the coverage of multiple MAs. 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

$$E_{CP} = K_T \Big(\frac{P_{CT}}{R_b} + E_{TX,SISO} + (N_T - 1) \frac{P_{CR}}{R_b} \Big) \tag{9}$$

where $E_{TX,SISO}$ accounts for the required transmit energy per bit for the local SISO communications among cooperative sensor nodes. Note that while one node transmits, the other (N_T-1) nodes receive simultaneously. Other system overhead is ignored for simplicity. Depending on applications the local transmission channels can be modeled with either additive Gaussian noise or Rayleigh fading.

III. ENERGY EFFICIENCY OF NON-COOPERATIVE AND COOPERATIVE TRANSMISSION

In this section, we first analyze the energy efficiency of several relevant transmission strategies in the wideband regime to obtain some insights, then turn to more realistic system settings.

A. Wideband Asymptote

The wideband asymptotic analysis is to approximate the Shannon capacity C as an affine function of energy per bit normalized to the noise spectral density (i.e., $\bar{E}_b/N_0$) in the zero SNR neighborhood (corresponding to high-to-optimal energy efficiency) as [11]

$$\log \frac{\bar{E}_b}{N_0}(C) = \frac{\bar{E}_b}{N_0}_{\min} + \frac{C}{S_0} \log 2 + o(C)^3 \tag{10}$$

where $(\bar{E}_b/N_0)_{\min}$ is the (normalized) minimum required energy for reliable communications, and S_0 stands for the wideband slope of the spectral efficiency-energy efficiency curve (in terms of bits/s/Hz/3 dB). These two key parameters can be obtained as [11]

$$\frac{\bar{E}_b}{N_0}_{\min} = \beta \frac{\ln 2}{\dot{C}(0)}, \; S_0 = \frac{2[\dot{C}(0)]^2}{-\ddot{C}(0)} \tag{11}$$

with $\dot{C}$ and $\ddot{C}$ the first and second derivatives of the spectral efficiency, (e.g., (3), (4), and (6)) at SNR=0, and β the parameter relating E_b/N_0, SNR and $C(\text{SNR})$ as

$$\frac{\bar{E}_b}{N_0} = \beta \frac{\text{SNR}}{C(\text{SNR})} \tag{12}$$

which equals to 1 for SIMO, r for STBC, and N_T for SM. We summarize these two key parameters for relevant transmission strategies (with Rayleigh fading) in Table 1.

Table 1. Wideband analysis of communications systems subject to Rayleigh fading.

	SISO	SIMO	STBC	SM
$(\bar{E}_b/N_0)_{\min}$	$\ln 2$	$\ln 2/N_R$	$\ln 2/N_R$	$\ln 2/N_R$
S_0	1	$\frac{2N_R}{N_R+1}$	$\frac{2rN_TN_R}{N_TN_R+1}$	$\frac{2N_TN_R}{N_T+N_R}$

Wideband analysis shows that receive diversity effectively lowers the minimum required energy by a factor of N_R. However, $(\bar{E}_b/N_0)_{\min}$ 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

$$1 \le \frac{2N_R}{N_R+1} \le \frac{2N_TN_R}{N_TN_R+1} \le \frac{2N_TN_R}{N_T+N_R}. \tag{13}$$

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 Rayleigh 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 visualized in Fig. 1 for $N_T = 2$, $N_R = 4$, and will be further confirmed for realistic system settings through the analysis below.

[3]The basis of logarithm is 10 unless specifically indicated in the following, and $o(C)$ denotes higher-order terms of C.

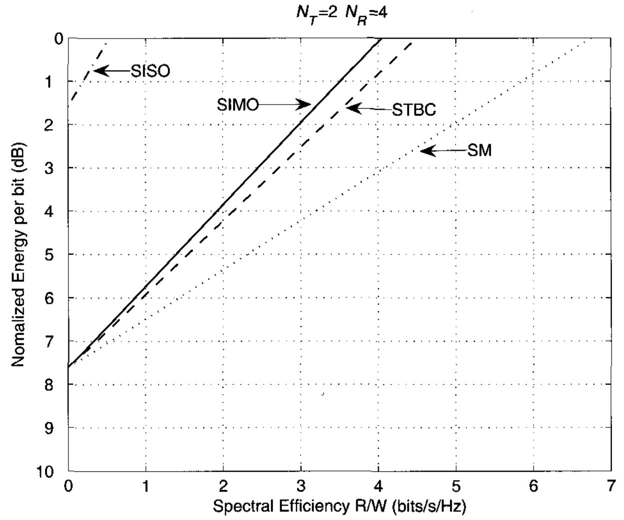

Fig. 1. Wideband behaviors with Rayleigh fading.

B. Realistic Setting

Data throughput, bit error rate and power consumption are three important and often competing optimization objectives in the design of a wireless network. In this section, we relate $\bar{E}_b/N_0$ 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 of generality, we assume M-ary square 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 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 [12]. The reader is referred to [4] for discussions of suboptimal detection methods for SM.

The average BER of an orthogonal STBC, following the performance analysis for diversity techniques in fading channels, can be very accurately approximated as [10], [13]

$$P_{e,STBC} \doteq \frac{4}{\log_2 M}\left(1-\frac{1}{\sqrt{M}}\right)\left(\frac{1-\mu}{2}\right)^{N_T N_R} \times \sum_{l=0}^{N_T N_R-1}\binom{N_T N_R-1+l}{l}\left(\frac{1+\mu}{2}\right)^l \quad (14)$$

with

$$\mu=\sqrt{\frac{\alpha}{1+\alpha}} \text{ and } \alpha=\frac{1}{N_T}\frac{3\log_2 M}{2(M-1)}\frac{E_b}{N_0}. \quad (15)$$

For most applications of interest, we can further simplify (14) as

$$P_{e,STBC} \approx \frac{4}{\log_2 M}\left(1-\frac{1}{\sqrt{M}}\right) \times \left(\frac{1}{4(\alpha+1)}\right)^{N_T N_R}\binom{2N_T N_R-1}{N_T N_R}. \quad (16)$$

The required $\bar{E}_b/N_0$ with target BER P_e for STBC can in turn be obtained as

$$\frac{\bar{E}_b}{N_0}|_{STBC} \approx N_T\frac{2(M-1)}{3\log_2 M} \times \left(\frac{1}{4}\left(\frac{4\left(1-\frac{1}{\sqrt{M}}\right)\binom{2N_T N_R-1}{N_T N_R}}{P_e \log_2 M}\right)^{1/N_T N_R}-1\right). \quad (17)$$

Note that by taking $N_T = 1$ in (17), we readily get the analytical results for a SIMO system with MRC, and further letting $N_R = 1$ gives us results for SISO.

The performance of SM with ML detection can be tightly upper-bounded by a (weighted) sum of pairwise error probability (PEP). The summation can be over all pairwise error events (union bound) or over just a few dominant events (typically with minimum distance). An exact formula for the average PEP has been obtained in [14]

$$\overline{P(\mathbf{x}_j \to \mathbf{x}_i)} = \left(\frac{1}{1+r}\right)^{2N_R-1}\sum_{l=0}^{N_R-1}\binom{2N_R-1}{l}r^l \quad (18)$$

with

$$r=\sqrt{(\Gamma/2)^2+\Gamma}+\Gamma/2+1 \text{ and } \Gamma=\|\mathbf{x}_i \to \mathbf{x}_j\|^2/N_0. \quad (19)$$

Seeming different, (18) is actually the same as the average PEP for SIMO, given by (c.f. (14) with $N_T = 1$)

$$\overline{P(x_j \to x_i)} = \left(\frac{1-\mu}{2}\right)^{N_R}\sum_{l=0}^{N_R-1}\binom{N_R-1+l}{l}\left(\frac{1+\mu}{2}\right)^l \quad (20)$$

when

$$\mu=\frac{r-1}{r+1}. \quad (21)$$

A detailed proof is given in Appendix A. After some algebra, (21) readily leads to $\alpha = \Gamma/4$ (c.f. (15) and (19)), which in turn admits

$$\|\mathbf{x}_i \to \mathbf{x}_j\|^2 = d_{\min}^2 = \frac{6\log_2 M}{M-1}\bar{E}_b \quad (22)$$

the right hand side of which is readily recognized as the squared minimum distance of a square QAM symbol with average energy per bit $\bar{E}_b$. Since error performance is typically dominated by the minimum-distance error events, we make the following assumption for the performance of equal-power and equal-rate SM with ML detection:

$$\frac{\bar{E}_b}{N_0}|_{SM-ML} \approx \frac{\bar{E}_b}{N_0}|_{SIMO} \quad (23)$$

which is sufficient for our following study and has been verified through simulations.

Based on the above analysis, we obtain the following simple linear relationship between energy efficiency and spectral efficiency for the three transmission strategies of interest, which bears a similar form with the wideband analysis (see Appendix B for details).

$$\log\frac{\bar{E}_b}{N_0}|_{SIMO} \approx S_0(1)R + E_{\min}(1), \quad (24)$$

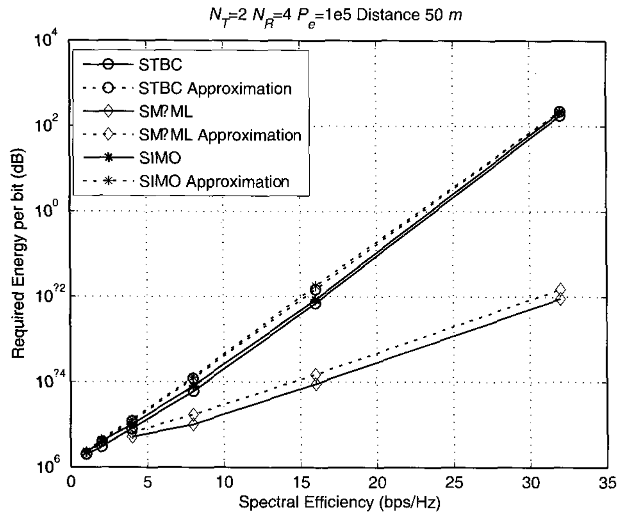

Fig. 2. Transmit energy comparison with different spectral efficiency.

$$\log \frac{\bar{E}_b}{N_0}|_{STBC} \approx \frac{S_0(1)}{r} R + E_{\min}(N_T), \quad (25)$$

$$\log \frac{\bar{E}_b}{N_0}|_{SM} \approx S_0(N_T) R + E_{\min}(1) \quad (26)$$

where

$$S_0(N_T) = \frac{\log 2}{N_T}, \quad (27)$$

$$E_{min}(N_T) = \log(N_T) + \frac{1}{N_T N_R} \log\left(4 \binom{2N_T N_R - 1}{N_T N_R} / P_e\right). \quad (28)$$

Note that again (24)–(26) are obtained with some simplifications. Nonetheless it is sufficient for our study and further verified through simulations. An example is given in Fig. 2 , where transmission energy E_{TX} of the three transmission strategies as a function of spectral efficiency is plotted (see Section VI for parameter settings). 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,[4] when high spectral efficiency is also desired.

IV. OPTIMAL TRANSMISSION STRATEGY SELECTION-SYSTEM LEVEL

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. For simplicity, we will assume $K_T = 1$ and ignore $E_{TX,SISO}$ in (9), as this term is typically negligible compared to the circuit energy part if the local communication radius is small enough. We further assume that the coding rate $r = 1$ for STBC without loss of generality.

[4]Note the difference in the slope: $S_0(1)$ and $S_0(N_T)$.

A. 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 when spectral efficiency or delay is not a concern; the other two schemes will employ 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 IV.1: 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. By solving $E_{TX,SIMO} + E_{C,SIMO} + E_{CP,SIMO} < E_{TX,STBC} + E_{C,STBC} + E_{CP,STBC}$ with respect to distance, the selection criterion is obtained as follows.

Criterion IV.2: Regarding total energy consumption, given a transmission distance d, choose SIMO when

$$d < d_{th1} = \frac{\alpha}{2^{R_{\min}/n}} \frac{\beta_1}{\left(\left(e^{E_{\min}(1)} - e^{E_{\min}(N_T)}\right) R_{\min}\right)^{1/n}} \quad (29)$$

where

$$\alpha = \left(\frac{G_t G_r \lambda^2 \eta}{\xi (4\pi)^2 N_r M_g B}\right)^{1/n}, \quad (30)$$

$$\beta_1 = \left(N_T P_{CT} + (N_T - 1) P_{CR}\right)^{1/n} \quad (31)$$

and choose STBC otherwise.

B. Spectral Efficiency Demand

In many applications a specific spectral efficiency demand R is also imposed, due to either the Quality-of-Service requirements or the network stability concerns. If only the transmit energy is concerned, STBC is uniformly better than SIMO for any spectral efficiency, and the switching threshold between STBC and SM turns out not to depend on the transmission distance (c.f. (25) and (26)).

Criterion IV.3: Regarding transmit energy consumption, given a spectral efficiency demand R, choose STBC when

$$R < R_0 = \frac{E_{\min}(1) - E_{\min}(N_T)}{S_0(1) - S_0(N_T)}, \quad (32)$$

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 (32) and is independent of d. The following selection criterion follows after some algebra.

Criterion IV.4: 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.(29)–(31))

$$d < d'_{th1} = \frac{\alpha}{2^{R/n}} \frac{\beta_1}{\left(\left(e^{E_{\min}(1)} - e^{E_{\min}(N_T)}\right)R\right)^{1/n}}, \quad (33)$$

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

$$d < d_{th2} = \frac{\alpha}{e^{E_{\min}(1)/n}} \frac{\beta_2}{\left(\left(2^R - 2^{R/N_T}\right)R\right)^{1/n}} \quad (34)$$

where

$$\beta_2 = \left((N_T + 1 - 1/N_T)P_{CT} + (N_T - 1)P_{CR}\right)^{1/n} \quad (35)$$

choose SIMO, otherwise, choose SM.

C. 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. From the definition of cooperative MIMO transmission strategies, they can be explicitly derived as below:

$$T_{SIMO} = \frac{N}{R_{SIMO}} T_s, \quad (36)$$

$$T_{STBC} = T_s\left(\frac{N}{R_{STBC}} + \frac{N}{R_{STBC,l}}\right), \quad (37)$$

$$T_{SM} = T_s\left(\frac{N}{R_{SM}} + \frac{(N_T - 1)N/N_T}{R_{SM,l}}\right) \quad (38)$$

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.[5] The second terms in T_{STBC} and T_{SM} represent the additional delay incurred by cooperation. Therefore, for each given spectral efficiency-delay pair, there is an achievable region dictated by (36), (37), and (38), 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 $\bar{D} = T/(T_s N)$ to remove the system dependence, we formalize the selection rule for a given $\bar{D}$ below. For simplicity we assume the spectral efficiency for local transmission is the same for STBC and SM, denoted as R_l . Substituting the above equations into (24), (25), and (26) leads to the relationship of delay and energy efficiency for different transmission strategies:

$$\log \frac{\bar{E}_b}{N_0}|_{SIMO} = \frac{S_0(1)}{\bar{D}_{SIMO}} + E_{\min}(1), \quad (39)$$

$$\log \frac{\bar{E}_b}{N_0}|_{STBC} = \frac{S_0(1)}{\bar{D}_{STBC} - \frac{1}{R_l}} + E_{\min}(N_T), \quad (40)$$

$$\log \frac{\bar{E}_b}{N_0}|_{SM} = \frac{S_0(N_T)}{\bar{D}_{SM} - \frac{(N_T-1)/N_T}{R_l}} + E_{\min}(1). \quad (41)$$

From (39), (40), and (41), 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. Similarly, by solving the cross-points of delay-energy curves, we can get the following switching criterion.

Criterion IV.5: Regarding transmit energy consumption, given a delay constraint $\bar{D}$, choose SIMO when

$$\bar{D} < \bar{D}_0 = \frac{1}{R_l}, \quad (42)$$

choose STBC when (cf. (32))

$$\bar{D} > \bar{D}_1 = \frac{1}{R_0} + \frac{1}{R_l}, \quad (43)$$

otherwise, choose SM.

The selection criteria regarding total energy consumption and joint delay-distance consideration can be similarly addressed and the details are omitted here since they don't provide further insights.

V. OPTIMAL TRANSMISSION STRATEGY SELECTION-LINK LEVEL

In certain circumstances, when the channel is quasi-static and sufficient feedback is affordable, transmission strategies can be determined based on instantaneous channel characteristics. The problem of switching between STBC and SM to minimize the error rate has been addressed in [15] and [16]. Here we extend the work to selecting among STBC, SM or SIMO to minimize the required transmit energy for a given BER and spectral efficiency. The problem regarding total energy consumption minimization follows a similar approach as discussed above and thus will not be explicitly addressed here.

With an MRC receiver, the (conditional) error rate for SIMO is bounded as [9]

$$P_{e|SIMO}(\mathbf{h}_{SIMO}) \leq \bar{N}_e Q\left(\sqrt{\frac{E_{s|SIMO}}{N_0}\|\mathbf{h}_{SIMO}\|^2 \frac{d^2_{\min,SIMO}}{2}}\right) \quad (44)$$

where $\bar{N}_e$ is the average number of nearest neighbors in constellation, $E_{s|SIMO}$ is energy per symbol per transmit antenna, $\|\mathbf{h}_{SIMO}\|^2$ is the squared norm of the channel, and $d_{\min,SIMO}$ is the minimum distance of a unit-energy symbol. For a target P_e and spectral efficiency R, we have

$$E_{b|SIMO} \geq \frac{2N_0}{d^2_{\min,SIMO}\|\mathbf{h}_{SIMO}\|^2 R}\left(Q^{-1}\left(\frac{P_e}{\bar{N}_e}\right)\right)^2. \quad (45)$$

[5] Here we only consider the time for data transmission and ignore the associated overhead for simplicity.

Similarly, an upper bound of the (conditional) error rate for STBC is given by

$$P_{e|STBC}(\mathbf{H}_{MIMO}) \leq \bar{N}_e Q\left(\sqrt{\frac{E_{s|STBC}}{N_0} \max_{1\leq k\leq N_T} \|h_k\|^2 \frac{d^2_{\min,STBC}}{2}}\right) \quad (46)$$

where h_k is the kth column of $\mathbf{H}_{MIMO}$, and other symbols are defined as before. It is known that $\max_{1\leq k\leq N_T} \|h_k\|^2 \leq \lambda^2_{\max}(\mathbf{H}_{MIMO})$, where $\lambda_{\max}(\mathbf{H}_{MIMO})$ is the maximum singular value of the channel. So we have

$$E_{b|STBC} \geq \frac{2N_T N_0}{d^2_{\min,STBC}\lambda^2_{\max}(\mathbf{H}_{MIMO})R}\left(Q^{-1}\left(\frac{P_e}{\bar{N}_e}\right)\right)^2. \quad (47)$$

An upper bound of the (conditional) BER for SM with ML detection is given by [15]

$$P_{e|SM}(\mathbf{H}_{MIMO}) \leq \bar{N}_e Q\left(\sqrt{\frac{E_{s|SM}}{2N_0}\frac{\lambda^2_{\min}(\mathbf{H}_{MIMO})d^2_{\min,SM}}{N_T}}\right) \quad (48)$$

where $\lambda_{\min}(\mathbf{H}_{MIMO})$ is the minimum singular value of the channel, from which we can obtain

$$E_{b|SM} \geq \frac{2N_T^2 N_0}{d^2_{\min,SM}\lambda^2_{\min}(\mathbf{H}_{MIMO})R}\left(Q^{-1}\left(\frac{P_e}{\bar{N}_e}\right)\right)^2. \quad (49)$$

Based on these results, a qualitative selection rule is given below.

Criterion V.1: 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.[6]

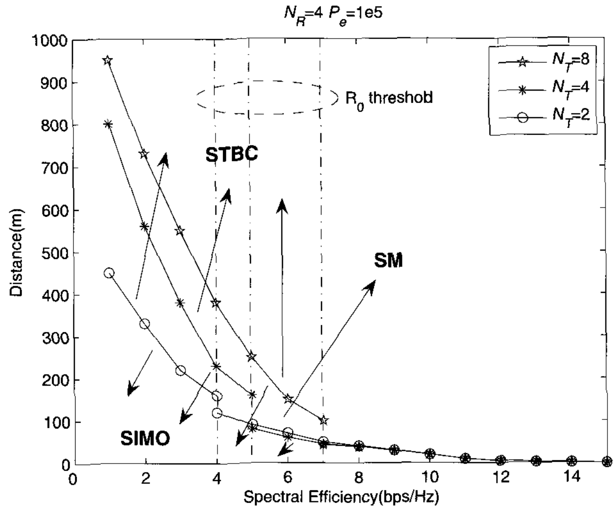

Fig. 3. Switching bound based on spectral efficiency and distance.

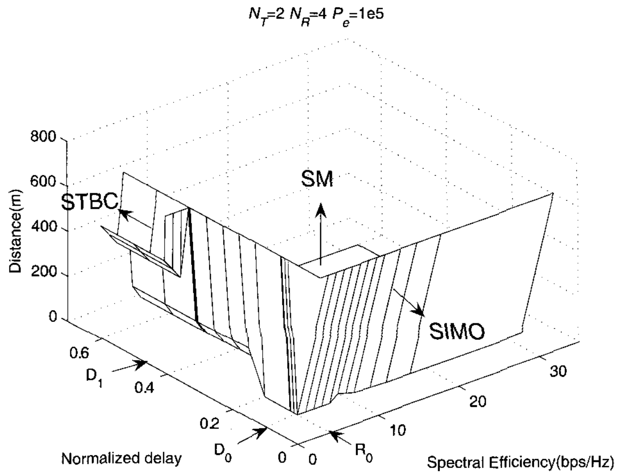

Fig. 4. Switching surface based on spectral efficiency, delay and distance.

VI. NUMERICAL RESULTS

In this section, some numerical examples are provided to better illustrate our main results above. In simulations, a real system operating at 2.5 GHz is assumed with bandwidth $B = 10$ kHz. The following values are taken for the parameters in Equation (7); $\eta = 0.35$, $N_r = -161$ dBm/Hz, $G_tG_r = 5$ dBi and $M_g = 40$ dB. For square QAM, we have

$$\xi = \frac{\Xi_{max}}{\Xi_{min}} = \frac{3(\sqrt{M}-1)}{\sqrt{M}+1}. \quad (50)$$

The typical energy consumption values of various circuit blocks are quoted from [2], with $P_{CT} = 97.8$ mW and $P_{CR} = 112.8$ mW.

First, the switching bounds given spectral efficiency demand and transmission distance are exemplified for some values of N_T in Fig. 3. Based on Criterion IV.3, the potential transmission scheme category (STBC/SIMO or SM/SIMO) is determined by R_0 (c.f. (32)), while the distance thresholds are plotted according to Criterion IV.4 (c.f. (33) and (34)). Delimited by these thresholds, the preferable working regions of different transmission strategies are indicated in the figure (by arrows). It can be seen that with spectral efficiency growing, the curves converge to the 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.

We visualize the distance, spectral efficiency and delay-based criterions jointly in Fig. 4, where unachievable regions have been ignored. From this figure, we can draw a comprehensive conclusion on the preference of transmission strategies for cooperative wireless sensor networks: 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.

Finally, we examplify the link-level selection criterion by studying the statistical probabilities of selecting SM, STBC, and SIMO with different spectral efficiency demands. In Fig. 5 , it is

[6]For square QAM modulation $d^2_{\min,SM} = \frac{6}{2^{R/N_T}-1}$, $d^2_{\min,SIMO} = d^2_{\min,STBC} = \frac{6}{2^R-1}$.

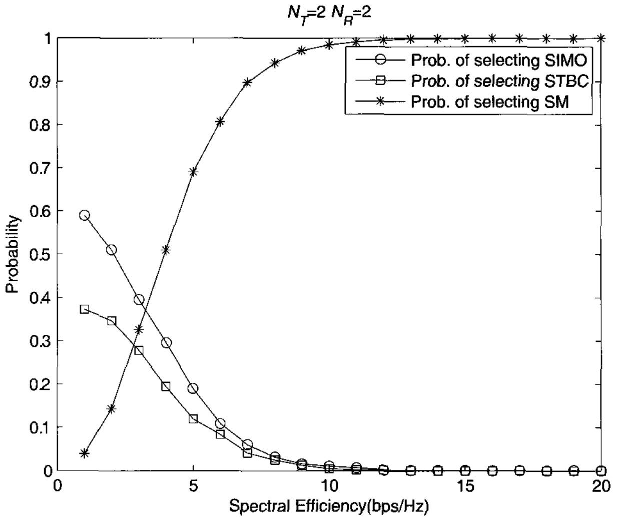

Fig. 5. Probability of selecting SIMO, STBC and SM.

seen that the probability of choosing SM tends to be 1 as spectral efficiency demand grows.

VII. CONCLUSIONS

In this paper, we have investigated the energy efficiency of different transmission strategies in wireless sensor networks. We have shown that, even though STBC and SM assume some advantages in transmit energy efficiency over the corresponding SIMO approach, such advantages fail to justify the additional circuit energy consumption and cooperation penalty in some cases. On the other hand, we have found that SM does offer substantial energy savings for high-rate communications,which significantly reduces the critical distance over which MIMO transmission overtakes the corresponding SIMO in sensor networks. We have also 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.

APPENDIX

A. A Proof of the equivalence of PEP for SM-ML and SIMO

Proof: Comparing (18) and (20) with (21), we just need to verify:

$$(1+r)^{L-1}\sum_{l=0}^{L-1}\binom{L-1+l}{l}\left(\frac{r}{1+r}\right)^l=\sum_{l=0}^{L-1}\binom{2L-1}{l}r^l. \tag{51}$$

We use mathematical induction for this proof. The case of $L=1$ is trivial. Starting from $L=2$, we can see that the left hand side (LHS) is $(1+r)\left[\binom{1}{0}+\binom{2}{1}\frac{r}{1+r}\right]=1+3r$, while the right hand side (RHS) is $\binom{3}{0}+\binom{3}{1}r=1+3r$.

Assume (51) is satisfied for $L=p$, i.e.,

$$(1+r)^{p-1}\sum_{l=0}^{p-1}\binom{p-1+l}{l}\left(\frac{r}{1+r}\right)^l=\sum_{l=0}^{p-1}\binom{2p-1}{l}r^l. \tag{52}$$

Consider the case of $L=p+1$

$$\begin{aligned}LHS=&(1+r)^p\binom{2p}{p}\left(\frac{r}{1+r}\right)^p\\&+(1+r)^p\sum_{l=0}^{p-1}\binom{p+l}{l}\left(\frac{r}{1+r}\right)^l\\=&\binom{2p}{p}r^p+(1+r)^p\sum_{l=0}^{p-1}\frac{p+l}{p}\binom{p-1+l}{l}\left(\frac{r}{1+r}\right)^l.\end{aligned} \tag{53}$$

Substitute (52) in, we get

$$\begin{aligned}LHS=&\binom{2p}{p}r^p+(1+r)^2\sum_{l=0}^{p-1}\binom{2p-l}{l}r^l\\&-\binom{2p-2}{p-1}\left(\frac{2p-1}{p}\right)r^p(1+r)\\=&\binom{2p}{p}r^p+\sum_{l=0}^{p-1}\binom{2p-1}{l}r^l\\&+2r\sum_{l=0}^{p-1}\binom{2p-l}{l}r^l+r^2\sum_{l=0}^{p-1}\binom{2p-1}{l}r^l\\&-\binom{2p-2}{p-1}\left(\frac{2p-1}{p}\right)r^p(1+r).\end{aligned} \tag{54}$$

Using the formula $\binom{x}{y}+\binom{x}{y-1}=\binom{x+1}{y}$, we have

$$\binom{2p-1}{1}+2\binom{2p-1}{0}=\binom{2p+1}{1}$$

$$\binom{2p-1}{2}+2\binom{2p-1}{1}+\binom{2p-1}{0}=\binom{2p+1}{2}$$

$$\vdots$$

$$\binom{2p-1}{p-1}+2\binom{2p-1}{p-2}+\binom{2p-1}{p-3}=\binom{2p+1}{p-1}.$$

And also note $\binom{2p}{p}+2\binom{2p-1}{p-1}+\binom{2p-1}{p-2}-\binom{2p-1}{p-1}\times\left(\frac{2p-1}{p}\right)=\binom{2p+1}{p}$. Substitute these expressions into the last line of (54), we obtain

$$LHS=\sum_{l=0}^{p}\binom{2p+1}{l}r^l \tag{55}$$

which equals to the RHS of (51) for $L=p+1$.

B. Derivation of (24), (25), and (26)

Equation (17) can be further approximated as

$$\frac{\bar{E}_b}{N_0}|_{STBC} \approx N_T \frac{M}{6\log_2 M}\left(\frac{4\binom{2N_TN_R-1}{N_TN_R}}{P_e \log_2 M}\right)^{1/N_TN_R} \quad (56)$$

Taking logarithm on the both sides of (56), we have

$$\log\frac{\bar{E}_b}{N_0} \approx \log M + \log(N_T) + \frac{1}{N_TN_R}\log\left(4\binom{2N_TN_R-1}{N_TN_R}/P_e\right) \quad (57)$$

where compared to (56), we further neglect $\log\log M$ in (57). Denote

$$E_{\min}(N_T) = \log(N_T) + \frac{1}{N_TN_R}\log\left(4\binom{2N_TN_R-1}{N_TN_R}/P_e\right) \quad (58)$$

and a simple expression of $\log \bar{E}_b/N_0$ can be obtained as

$$\log\frac{\bar{E}_b}{N_0} \approx \log M + E_{\min}(N_T). \quad (59)$$

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 for STBC is $M = 2^{R/r}$ where r is the rate of STBC, for SIMO $M = 2^R$ and for SM $M = 2^{R/N_T}$. So, if we denote $S_0(N_T) = \log 2/N_T$, (24), (25), and (26) can be obtained from (59) directly.

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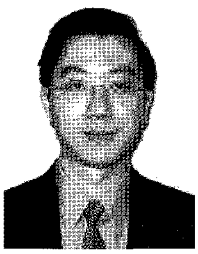

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