Virtual MIMO-based Cooperative Communication for Energy-constrained Wireless Sensor Networks

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***Abstract*— An energy-efficient virtual multiple-input multiple-output (MIMO)-based communication architecture is proposed for distributed and cooperative wireless sensor networks. Assuming a space-time block coding (STBC) based MIMO system, the energy and delay efficiencies of the proposed scheme are derived using semi-analytic techniques. The dependence of these efficiency values on physical channel propagation parameters, fading coherence time and the amount of required training is also investigated. The results show that with judicious choice of design parameters the virtual MIMO technique can be made to provide significant energy and delay efficiencies, even after allowing for additional training overheads.**

***Index Terms*— Cooperative MIMO, energy efficiency, MIMO, virtual MIMO, wireless sensor networks.**

I. INTRODUCTION

ENERGY optimization is a critical issue in the design of low-power, wireless sensor networks. However, in a wireless sensor network, unlike in cellular mobile communications, the circuit energy consumption may not be negligible compared to the actual transmit power. Thus, usual energy optimization techniques that minimize transmission energy may not always guarantee to be effective in the case of wireless sensor networks.

Motivated by information theoretic predictions on large spectral efficiency of multiple-input-multiple-output (MIMO) systems, recently there has been a great amount of research on various MIMO techniques for wireless communication systems. However, the fact that MIMO techniques could require complex transceiver circuitry and signal processing leading to large power consumptions at the circuit level, has precluded the application of MIMO techniques to energy-limited wireless sensor networks. Moreover, physical implementation of multiple antennas at a small node may not be realistic. As solutions to the latter problem cooperative MIMO [1] and virtual antenna array [2] concepts have been proposed to achieve MIMO capability in a network of single antenna (single-input/single-output or SISO) nodes. A closer look at the total energy and delay comparisons between cooperative MIMO and SISO communications was recently taken in [1]. The results showed that in some cases cooperative MIMO-based sensor networks may in fact lead to better energy optimization and smaller end-to-end delay.

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In this letter we investigate a variation of virtual MIMO-based cooperative communication for energy-limited wireless sensor networks proposed in [1] that is suitable for a commonly encountered sensor network model. Our first contribution is an investigation of dependance of energy and delay efficiencies of virtual MIMO scheme on system and propagation parameters such as transmission distance, constellation size (transmission rate) and channel path loss exponent. The second contribution is to refine the results in [1] by taking into account the training overhead required in any MIMO-based system. Although these were ignored in [1], a rigorous energy optimization needs to take into account the energy spent on training since the knowledge of channel state information (CSI) is crucial for the proper operation of MIMO-based techniques. We develop a semi-analytical approach that takes into account this extra training energy overhead for a MIMO-based system in order to obtain a fair comparison with a SISO-based sensor network. Our analysis and numerical results suggest that with judicious choice of parameters at the system design level, proposed virtual MIMO-based communication can provide significant energy and delay efficiencies in wireless sensor networks.

This presentation is organized as follows: In Section II we investigate the energy efficiency of fixed- and variable-rate MIMO systems compared to that of SISO systems including the overhead terms associated with MIMO training requirements via a semi-analytical approach. In Section III we present the proposed virtual MIMO-based cooperative communication scheme for a wireless sensor network. Expressions for the total energy consumption and end-to-end delay of the proposed virtual MIMO scheme are derived and numerical examples are provided comparing them to those of traditional SISO based schemes. Section IV concludes the letter.

II. ENERGY COMPARISON OF MIMO VS. SISO SYSTEMS

In this section we develop a refined model for energy efficiency comparison between MIMO and SISO taking into account the extra training overhead required in MIMO systems. Let us assume a wireless communication link between two nodes in which the transmitter and receiver are equipped with N_T and N_R antennas, respectively. The MIMO technique that we consider throughout this paper is the Alamouti scheme for $N_T = 2$ antennas.

In [1] comparison of MIMO and SISO systems was performed assuming that the receiver has perfect CSI, which is critical for the proper operation of the Alamouti scheme, but ignoring the training overhead required for the channel estimation. This effects the comparison results since a MIMO system could require more training symbols compared to

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a SISO system leading to extra energy consumption. For example, [3] suggests that in general we may need the number of training symbols greater than or equal to the number of transmit antennas if both training and data symbols were to use the same transmit energy. However, the required number of training bits is a function of the operating SNR and could be much higher than this minimum required value. In order to incorporate this extra energy term, suppose that the block size is equal to F symbols and in each block we include pN_T training symbols where we assume that p symbols are used to train each transmitter and receiver antenna pair. Note that, the results in [3] suggest that $p = 1$ if both training and data symbols were to use the same transmit energy, while [1] sets $p = 0$. If R_b is the actual bit rate, then the effective bit rate of the system is given by $R_b^{eff} = \frac{F-pN_T}{F} R_b$. If the fading coherence time is T_c, then we may obtain a best case energy consumption value by setting $F = \lfloor T_c R_s \rfloor$, where R_s is the symbol rate. The fading coherence time can be estimated as $T_c = \frac{3}{4 f_m \sqrt{\pi}}$ where the maximum Doppler shift f_m is given by $f_m = \frac{v}{\lambda}$ with v being the velocity and λ being the carrier wavelength [4].

The total power consumption along a signal path can be divided into two main components [1], [5]: the power consumption of all the power amplifiers P_{PA} and the power consumption of all other circuit blocks P_C. The total power consumption of the power amplifiers can be approximated as [1], [5]

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

where P_{out} is the transmit power, $\alpha = \xi/\eta - 1$ with η being the drain efficiency of the RF power amplifier and ξ being the peak-to-average ratio (PAR) that depends on the modulation scheme and the constellation size. Throughout this paper we assume M-QAM systems, so that $\xi = 3\frac{M-2\sqrt{M}+1}{M-1}$ [1]. The transmit power P_{out} in (1) can be calculated according to the link budget relationship

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

where d is the transmission distance, κ is the channel path loss exponent, G_t and G_r are the transmitter and receiver antenna gains respectively, M_l is the link margin compensating the hardware process variations and other additive background noise or interference, N_f is the receiver noise figure, $\bar{E}_b$ is the average energy per bit required for a given bit-error-rate (BER) specification and R_b is the system bit rate. Note that the receiver noise figure N_f is given by $N_f = \frac{N_r}{N_o}$ where N_r is the power spectral density (PSD) of the total effective noise at the receiver input and N_o is the single-sided thermal noise PSD at room temperature [1]. The signal attenuation parameter κ could usually lie in the range $2-4$ for wireless communications channels, with $\kappa = 2$ corresponding to free space propagation.

Assuming that the frequency synthesizer is shared among all the antenna paths in a MIMO system, we may estimate the total circuit power consumption as $P_c \approx N_T(P_{DAC} + P_{mix} + P_{filt}) + 2P_{synth} + N_R(P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC})$ where P_{DAC}, P_{mix}, P_{filt}, P_{synth}, P_{LNA}, P_{IFA}, P_{filr} and P_{ADC} are the power consumption values for the D/A converter (DAC), the mixer, the active filters at the transmitter side, the frequency synthesizer, the low noise amplifier (LNA), the intermediate frequency amplifier (IFA), the active filters at the receiver side and the A/D converter (ADC), respectively [1]. We may use the models developed in [6], [7] for estimating the power consumption values P_{DAC} and P_{ADC}.

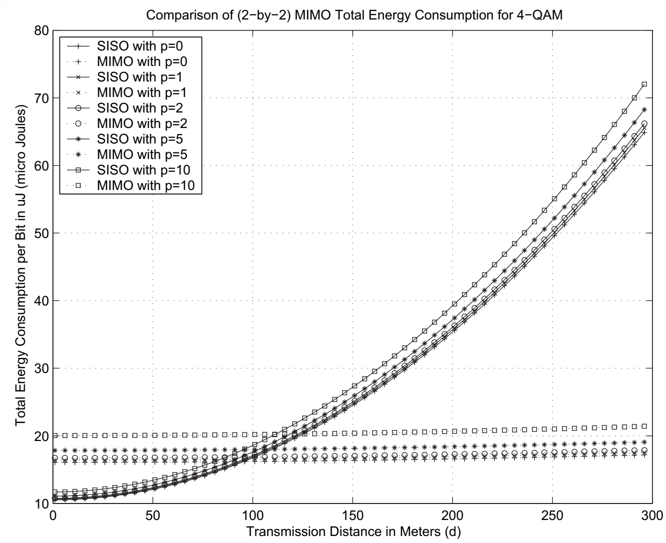

Fig. 1. Comparison of 2×2 MIMO Vs. SISO total energy consumption for 4-QAM ($\kappa = 2$).

Total energy per bit for a fixed rate system can then be estimated as $E_{bt} = \frac{P_{PA}+P_c}{R_b^{eff}}$. For simplicity, let us concentrate on an M-ary QAM, 2×2 MIMO system based on the Alamouti scheme. For $b \geq 2$, the bit error rate of an M-ary QAM MIMO system ($M = 2^b$) with a square constellation (i.e. b is even) in Rayleigh fading is given by

$$\bar{P}_b = \frac{4}{b}\left(1 - \frac{1}{2^{b/2}}\right)\frac{1}{2^{2N_R}}\left(1 - \frac{1}{\sqrt{1+\frac{1}{\bar{E}_b/2N_o}}}\right)^{2N_R} \times \sum_{k=0}^{2N_R-1} \frac{1}{2^k}\binom{2N_R-1+k}{k}\left(1 + \frac{1}{\sqrt{1+\frac{1}{\bar{E}_b/2N_o}}}\right)^{k} \tag{3}$$

When $b \geq 2$ is odd, we may use (3) as an upper-bound for the BER after dropping the term $\left(1 - \frac{1}{2^{b/2}}\right)$ (for $b = 1$, M-ary QAM system reduces to a BPSK system). By inverting (3) we can obtain the required $\bar{E}_b$ for a specified BER value $\bar{P}_b$.

As an example, consider a fixed-rate system with a 4-QAM constellation and a symbol rate of $R_s = B$ so that the bit rate $R_b = bR_s$. Figure 1 compares the total energy consumption in this system with a 2×2 MIMO and a SISO based communication when $\kappa = 2$. Note that in all our simulations we have assumed $B = 10$ kHz, $f_c = 2.5$ GHz, $P_{mix} = 30.3$ mW, $P_{filt} = 2.5$ mW, $P_{filr} = 2.5$ mW, $P_{LNA} = 20$ mW, $P_{synth} = 50$ mW, $M_l = 40$ dB, $N_f = 10$ dB, $G_t G_r = 5$ dBi and $\eta = 0.35$, as in [1]. We observe from Fig. 1 that for $p = 0$ training symbols, the MIMO system starts to outperform the corresponding SISO system at about $d \approx 96$ meters. For $p = 10$ training symbols this minimum required

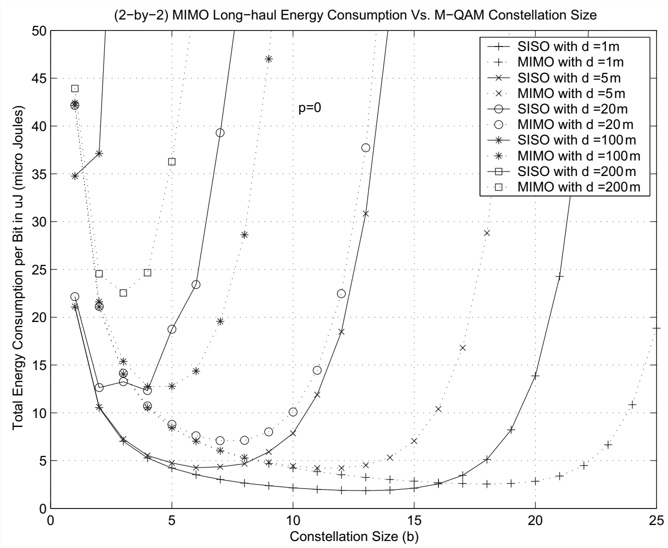

Fig. 2. Total energy consumption vs. M-QAM constellation sizes for 2×2 MIMO and SISO ($p = 0$, $\kappa = 3$).

TABLE I
OPTIMIZED M-QAM LONG-HAUL CONSTELLATION SIZES ($p = 0$, $\kappa = 3$).

d (m)	1	5	10	20	40	80	100	150	200
b_{SISO}	13	6	4	2	1	1	1	1	1
$b_{2\times 2}$	18	12	9	6	4	2	2	2	1

transmission distance for the MIMO system to outperform the SISO system has increased to about 112 meters.

Results in [1] suggested that by optimizing the rate (constellation size) of the communication system over the transmission distance we may be able to reduce the minimum transmission distance at which the MIMO outperforms the SISO. For example, it can be shown that if we were to use BPSK in the system in Fig. 1, the MIMO will only be better than SISO for $d > 220$ meters. In order to consider rate-optimized system performance, denote by T_{on} total on-time of the system in order to transmit a total of L data bits so that the energy consumption per data bit in all circuit blocks is given by $\frac{P_c T_{on}}{L} = \frac{P_c}{R_b^{eff}}$. Then, the total energy consumption per bit in an M-ary QAM MIMO system is

$$E_{ta} = \frac{1}{\mu}\left[\frac{3}{\eta}\frac{(4\pi)^2 d^{\kappa} M_l N_f}{G_t G_r \lambda^2}\frac{\left(M - 2\sqrt{M} + 1\right)}{M-1}\bar{E}_b + \frac{P_c}{bR_s}\right], \quad (4)$$

where we have defined $\mu = \frac{R_b^{eff}}{R_b} = \frac{F - pN_T}{F}$ (note that μ specifies the energy penalty incurred due to extra symbols needed for channel estimation). In a variable rate system we use the constellation size M that minimizes E_{ta} in (4) for each transmission distance d.

Figure 2 shows how E_{ta} depends on the constellation size b for various transmission distances d for both a 2×2 MIMO system and a SISO system assuming that no training symbols were used ($p = 0$) and $\kappa = 3$. It is clear from Fig. 2 that there is an optimal constellation size for each transmission distance for which the total energy per bit is minimized. Table I summarizes these optimal constellation sizes for each transmission distance d.

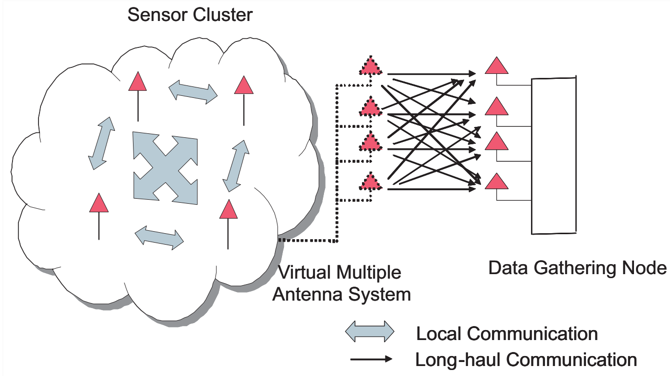

Fig. 3. A virtual MIMO communication-based wireless sensor network.

III. VIRTUAL MIMO COMMUNICATION BASED WIRELESS SENSOR NETWORK MODEL

Since nodes in a wireless sensor network may not be able to accommodate multiple antennas, the implementation of MIMO-based communication in a wireless sensor network requires sensor cooperation. A common scenario in distributed wireless sensor networks is that of a set of low-end *data collection* sensors connected over a wireless link with a high-end *data gathering* node (DGN) that acts as a lead sensor, as in Fig.3. The set of low-end *data collection* sensors is connected over a wireless link with a high-end *data gathering* node (DGN) that act as a lead-sensor. The data collection sensors are typically subjected to strict energy constraints while data gathering node is not.

In this wireless sensor network model, cooperative MIMO-based communication can be achieved as follows: Suppose a set of data collection nodes has data to be sent to the data gathering node. Each of these sensors which are assumed to be close to each other broadcasts their data to the others in the set using a time-division multiple-access scheme. This step is known as the local communications at the transmitter side [1]. At the end of this step each node has data from all other sensor nodes enabling space-time block coding as if each node were a distinct transmit antenna element in a centralized antenna array. Once the space-time coding is done, each node transmits the encoded symbols corresponding to a specific transmit antenna element over the wireless channel to the DGN. This step is known as the long-haul communication. The DGN is assumed not to have any energy constraint attached to it, or has relatively much longer battery life, and can be of larger physical dimensions to accommodate multiple receiver antennas. This allows realization of true MIMO capability with only the transmitter side local communications.

It should be noted that the above model is one of the simplest of this type. In a practical system there may be a number of data gathering nodes. In such a system there are different ways to realize MIMO-based energy-efficient communication. Also, all data collection nodes need not cooperate as one transmit antenna system. In most distributed wireless sensor networks there might be a large number of data collection sensors scattered over a large area, making it more convenient (and efficient) to have a number of virtual transmit antenna arrays. In our energy efficiency analysis below, we do not delve into these complications but rather concentrate on the simple model decribed above.

Since wireless channels can be subjected to fading it is realistic to assume that the long-haul communications in the second stage of the proposed scheme is over a fading channel (in particular, Rayleigh fading). However, if local communications at the data collection nodes are over a very short distance, it may be realistic to assume that the local communications are over an AWGN channel. If the data collection sensors are located in a dense scatterer environment even the short-range communication channel may best be modelled by a fading channel.

Energy consumption of the proposed cooperative MIMO-based scheme consist of two terms: the energy required for local communication among data collection sensors and the energy required for long-haul communications from data collection nodes to the data gathering node. To be consistent with earlier MIMO notation we will assume that there are N_T number of data collection sensors and the data gathering node is equipped with N_R number of receiver antenna elements. The average energy per bit per sensor node for local communications is denoted by $\bar{E}_i^T$, for $i = 1, \ldots, N_T$. Let us denote by $\bar{E}^l$ the average energy per bit for the long-haul communication. If we assume that each sensor node has L_i number of bits to transmit to the data gathering node then the total energy required in order to communicate the data from all nodes to the data gathering node is given by $E^{MIMO} = \sum_{i=1}^{N_T} L_i \bar{E}_i^T + \bar{E}^l \sum_{i=1}^{N_T} L_i$. We assume that the maximum separation between two data collection sensors is d_m meters and that the constellation size for local communications b_i^T is optimized for this worst-case distance. Similarly, let us assume that the long-haul communication distance is d meters (note that since $d \gg d_m$ we assume that this distance is the same for each pair of data collection nodes and the data gathering node) and the constellation size for long-haul communications b^l is optimized for this transmission distance.

During the local communications of sensor i, for $i = 1, \ldots, N_T$, other $N_T - 1$ sensor nodes act as receivers. Thus, the circuit energy consumption in this case is $P_{i,c}^T \approx (P_{DAC} + P_{mix} + P_{filt} + P_{synth}) + (N_T - 1)(P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC} + P_{synth})$. The power consumed in power amplifiers during local communication is $P_{i,PA}^T = \left(1 + \alpha_i^T\right) P_{i,out}^T$, for $i = 1, \ldots, N_T$, where the transmit power $P_{i,out}^T$ is again given by (2) with $d = d_m$ and α_i^T is computed using $M_i^T = 2^{b_i^T}$. Note that, in computing $P_{i,out}^T$ via (2) the term average energy per bit required for a given bit-error-rate, denoted by $\bar{E}_{i,b}^T$, is computed differently depending on whether the local communication channel is modelled as AWGN or Rayleigh fading. In case of AWGN local channel we have, for $i = 1, \ldots, N_T$,

$$\bar{E}_{i,b}^T = \frac{\left(M_i^T - 1\right) N_o}{3 b_i^T} \left[Q^{-1} \left(\frac{\bar{P}_b \, b_i^T}{4\left(1 - \frac{1}{\sqrt{2^{b_i^T}}}\right)} \right) \right]^2 \quad (5)$$

where $\bar{P}_b$ is the target average bit error rate. Note that (5) is valid (and exact) when b_i^T is even. When b_i^T is odd we may obtain an approximate $\bar{E}_{i,b}^T$ value by dropping the term $\left(1 - \frac{1}{\sqrt{2^{b_i^T}}}\right)$ in the denominator of the argument of inverse Q-function in (5). Similarly, when the local channel is Rayleigh we have, for $i = 1, \ldots, N_T$,

$$\bar{E}_{i,b}^T = \frac{2\left(M_i^T - 1\right) N_o}{3 b_i^T} \left(\left(1 - \frac{\bar{P}_b \, b_i^T}{2\left(1 - \frac{1}{\sqrt{2^{b_i^T}}}\right)} \right)^{-2} - 1 \right)^{-1}. \quad (6)$$

The total energy per bit for local communication is then given by $\bar{E}_i^T = \frac{P_{i,PA}^T + P_{i,c}^T}{R_i^{eff,T}}$ for $i = 1, \ldots, N_T$ where $R_i^{eff,T} = b_i^T R_s^{eff,T}$ is the effective bit rate for the local communication.

Similarly, the energy per bit $\bar{E}^l$ required for long-haul communication can be computed via $\bar{E}^l = \frac{P_{PA}^l + P_c^l}{R^{eff,l}}$ where P_{PA}^l, P_c^l and $R^{eff,l} = b^l R_s^{eff,l}$ are the energy consumption in power amplifiers, energy consumption in circuits and the effective bit-rate during long-haul communication. Since, there are N_R number of receiver antenna elements at the data gathering node are listening while the virtual multiple transmit antenna system created by the set of N_T data collection sensors is transmitting $P_c^l \approx N_T (P_{DAC} + P_{mix} + P_{filt} + P_{synth}) + P_{synth} + N_R (P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC})$, where we have used the fact that N_R receiver antennas are co-located at the data gathering node thus sharing the same frequency synthesizer. The power amplifier energy consumption P_{PA}^l is also given by (1) with P_{out} replaced by P_{out}^l, the required transmit power for the long-haul communication. For computing P_{out}^l, we obtain $\bar{E}_b^l$ by inverting the general probability of error expression for a Rayleigh fading channel given by (3).

In contrast to this cooperative MIMO-based scheme, the total energy required in communicating the same amount of data by a traditional wireless sensor network based on SISO techniques will be $E^{SISO} = \sum_{i=1}^{N_T} L_i \bar{E}_i^{SISO}$, where the average energy per bit $\bar{E}_i^{SISO}$ for the transmission from sensor node i to data gathering node can be obtained as a special case of the above long-haul distance communications with $N_T = N_R = 1$. Note that, to be fair in our comparisons we assume that the SISO-based system also employs an optimized constellation size b_i^{SISO} for the long-haul distance d.

In comparing the performance of virtual MIMO with that of the SISO-based communication, the delay efficiency is also important due to the extra local communication step needed in virtual MIMO. With SISO, the total time required for

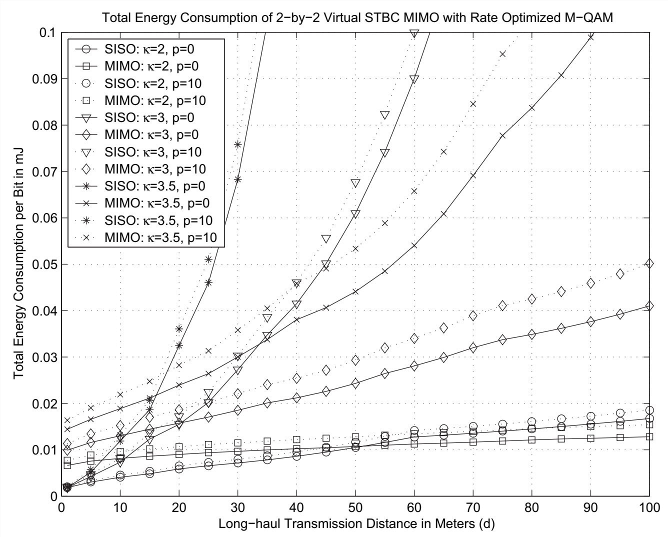

Fig. 4. Energy comparison of 2×2 virtual MIMO- and SISO-based systems with rate optimized M-QAM as a function of d when local channel is Rayleigh fading

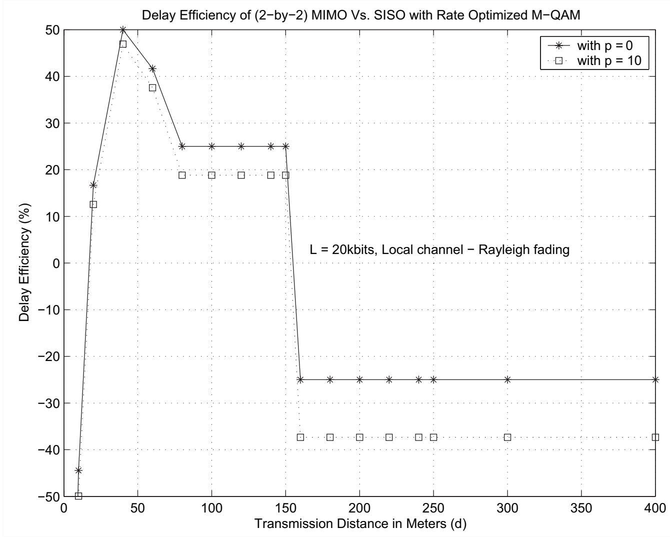

Fig. 6. Delay efficiency of 2×2 virtual MIMO vs. SISO with rate optimized M-QAM ($\kappa = 3$ and local channel is Rayleigh).

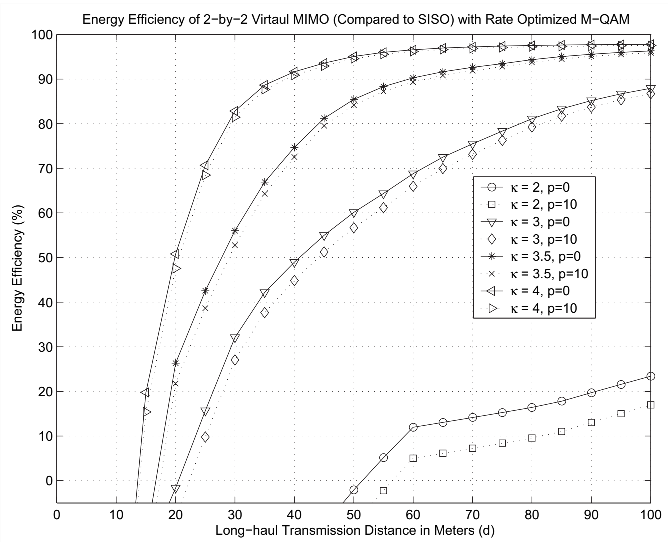

Fig. 5. Energy efficiency of 2×2 MIMO vs. SISO with rate optimized M-QAM as a function of d when local channel is Rayleigh fading.

transferring all the data is given by

$$T^{SISO} = T_s \sum_{i=1}^{N_T} \frac{L_i}{b_i^{SISO}} \quad (7)$$

where $T_s \approx \frac{1}{B}$ is the symbol time. Similarly, the total time required in virtual MIMO-based approach is

$$T^{MIMO} = T_s \left(\sum_{i=1}^{N_T} \frac{L_i}{b_i^T} + \frac{\sum_{i=1}^{N_T} L_i}{b^l} \right). \quad (8)$$

When training overhead is taken into account, the total delay values can be obtained from (7) and (8) by replacing T_s with the effective symbol time T_s^{eff}.

In Figs. 4 and 5 we have shown the energy comparison between a sensor network using proposed 2×2 virtual MIMO communication and the traditional SISO assuming that the local transmissions are over a Rayleigh fading channel. While Fig. 4 shows the actual total energy Fig. 5 shows the corresponding energy savings (defined as $\frac{E^{SISO} - E^{MIMO}}{E^{SISO}}$).

Figure 5 shows the enormous energy savings a virtual MIMO-based system can offer in a well-designed wireless sensor network as a function of the long-haul transmission distance d. For example, as can be seen from Fig. 5, when $\kappa = 3$ and $p = 0$, the 2×2 MIMO system offers 50% of energy savings compared to a SISO-based system for $d = 41$ meters. Note that the performance of virtual MIMO is worse than that of SISO for very short distances d (in particular for $d < d_m$), due to thes local communications penalty. If we were to take into account the extra training overhead incurred in a virtual MIMO system, the same 50% of energy saving is achieved at a slightly increased long-haul transmission of $d = 44$ (for a conservative value of $p = 10$ training symbols per each antenna pair). Thus, even with training overheads, the virtual MIMO architecture can improve the energy-efficiency of wireless sensor networks significantly. If the local channel were to be AWGN instead of Rayleigh fading, then the local communication energy penalty in the virtual MIMO system would be smaller. This will further decrease the distance at which the virtual MIMO system outperforms the SISO system.

In [1] the results were based on an ideal propagation channel in which $\kappa = 2$. However, as we observe from Fig. 5, for more realistic values of κ the energy savings offered by virtual MIMO (compared to SISO) can be even more significant. For a typical value of $\kappa = 3.5$, for instance, more than 70% of energy can be saved at a mere distance of $d \approx 40$ by using the proposed virtual MIMO communication architecture. Another important observation from Fig. 5 is that as κ increases the reduction in energy savings due to the training overhead penalty in virtual MIMO system decreases and the maximum achievable energy savings improves.

The delay efficiency (defined as $\frac{T^{SISO} - T^{MIMO}}{T^{SISO}}$) of the virtual MIMO-based scheme is shown in Fig. 6. As we see from Fig. 6 there is a window of transmission distances in which the virtual MIMO scheme outperforms the SISO-based scheme in terms of the end-to-end delay (roughly $20 <$

$d < 150$ for the parameters in Fig. 6). Thus, in situations where both delay and energy efficiency are important it is still possible to carefully design a sensor network so that virtual-MIMO based communication architecture can provide significant improvement in terms of both performance metrics. In less delay restrictive applications however, it is possible to operate beyond the delay-efficient distance window and achieve much greater energy efficiencies.

IV. CONCLUSIONS

We have developed a semi-analytical method to obtain the energy consumption values of both virtual MIMO and SISO based sensor networks taking into account the effect of extra training overhead required in MIMO systems. The energy and delay efficiencies of the virtual MIMO-based sensor network compared to a traditional SISO-based sensor network were computed using the techniques developed in this paper for different channel propagation conditions. Our results show that even with extra energy overhead required for MIMO training, the proposed virtual MIMO-based communication architecture can offer substantial energy savings in a wireless sensor network provided that the system is designed judiciously. These include careful consideration of transmission distance requirements, rate optimization as well as end-to-end delay constraints.

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