An Energy-efficient Virtual MIMO Communications Architecture Based on V-BLAST Processing for Distributed Wireless Sensor Networks

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***Abstract*— An energy-efficient virtual multiple-input multiple-output (MIMO) communication architecture based on V-BLAST receiver processing is proposed for energy-constrained, distributed wireless sensor networks. The proposed scheme does not require transmitter-side sensor cooperation unlike previously proposed virtual MIMO schemes for wireless sensor networks. In sensor networks with single-antenna data gathering nodes the virtual MIMO operation is realized via receiver-side local communication assuming node cooperation. Numerical results show that significant energy savings are offered by the proposed virtual MIMO architecture in distributed wireless sensor networks. These results also indicate that while rate optimization over transmission distance may offer improved energy efficiencies in some cases, this is not essential in achieving energy savings as opposed to previously proposed Alamouti scheme-based virtual MIMO implementations. In fact, in most scenarios a fixed-rate virtual MIMO system with binary phase-shift-keying (BPSK) can achieve performance very close to that of a variable-rate system with optimized rates. However, these results also indicate that the proposed scheme can lead to larger delay penalties compared to a traditional SISO communication based sensor network as the order of the virtual MIMO architecture grows. This results in a trade-off between the achievable energy efficiency and the delay incurred, making the proposed virtual V-BLAST based MIMO scheme an especially good candidate communication architecture for energy-starved and delay-tolerant wireless sensor networks having no inter-sensor communication.**

I. INTRODUCTION

Virtual multiple-input-multiple-output (MIMO)-based communication architectures have recently been proposed as a means for improving energy-efficiency of energy-constrained, distributed wireless sensor networks [1], [2]. In these implementations, however, the underlying MIMO concept used has been the simple Alamouti scheme [3]. The reason is basically the simple encoding and decoding requirements of the Alamouti scheme that are well-suited for energy-limited wireless sensor network nodes. However, in situations where required processing can be transferred to a less energy-constrained data gathering node it is worthwhile to investigate the possibility of other MIMO-based communications schemes for distributed wireless sensor networks. In this paper we propose the well-known V-BLAST (Bell Labs Layered Space-time) architecture as the MIMO processing technique for such energy-limited wireless sensor networks [4], [5].

Although the main power consumption term in a traditional wireless system is due to the energy required for actual transmissions, this may not be the case in energy-limited wireless sensor networks. In fact, in some cases it is the circuit energy needed for receiver and transmitter processing that is dominant. Due to this reason MIMO, or multiple antenna, communication has not gained significant attention as a viable technology for energy-limited wireless sensor networks since MIMO techniques require complex transceiver circuitry and large amount of signal processing that lead to increased power consumption at the circuit level. Moreover, physical implementation of multiple-transmit or receiver antennas on a small, energy-limited sensor might not be realistic. However, in a recent paper Cui and Goldsmith showed that it is possible to implement MIMO techniques in wireless sensor networks without physically having multiple antennas at the sensor nodes via cooperative communication techniques [1]. As reported in [1], [2] such distributed MIMO techniques can offer considerable energy savings in cooperative wireless sensor networks even after allowing for additional circuit power, communication and training overheads.

The Alamouti scheme-based virtual MIMO communications architecture is well suited for node-to-node communication in an energy-constrained sensor network. However, a common wireless sensor network architecture encountered in a number of different applications is one in which communication is mainly between low-end sensor nodes and a high-end data gathering node. In such a system usually it is the low-end data-collection nodes that are subjected to strict energy constraints while data gathering nodes are, at least comparatively, less energy-constrained. This type of wireless sensor networks have recently been proposed for various data collection applications and collaborative target tracking [6]–[10]. One way to improve the energy-efficiency of such systems is to transfer most of the computational burden to the less-energy constrained data gathering node.

In order to improve the energy-efficiency at the local sensors in an energy-limited wireless sensor network of the above type, in this paper we propose a new V-BLAST processing based virtual MIMO communication architecture and develop techniques for evaluating the energy and delay efficiencies of the proposed virtual MIMO-based sensor network. We propose V-BLAST scheme for this type of networks, as opposed to the Alamouti scheme, since in V-BLAST-based processing there is no joint encoding requirement at the sensor nodes (unless one wants to reduce the probability of error even further). This eliminates the local processing and local communication steps involved in a distributed Alamouti-based virtual MIMO system as in [1], [2]. Almost all V-BLAST processing can be performed at the data gathering node resulting in high energy efficiencies for low-end data collection sensors. Unlike the Alamouti scheme based previous virtual MIMO communication architectures for distributed sensor networks this method also does not necessarily require inter-node cooperation among the low-end data collection sensors.

The dependance of energy and delay efficiencies of the proposed virtual MIMO architecture on system and propagation parameters such as transmission distance, constellation size (transmission rate) and channel path loss parameter is investigated. Our numerical results suggest that the proposed virtual V-BLAST MIMO based communication scheme can provide significant energy savings in wireless sensor networks.

This presentation is organized as follows: In Section II we present the proposed V-BLAST processing based virtual MIMO communication scheme for wireless sensor networks. Section III derives the bit error rate (BER) of the V-BLAST detector that is needed for the energy analysis of the proposed virtual MIMO architecture. Next, Section IV derives the energy efficiency of the proposed V-BLAST receiver processing based virtual MIMO architecture taking into account both transmission and circuit power consumption at the sensor nodes for fixed rate quadrature amplitude modulation (QAM) systems. In Section IV we also propose a rate optimized implementation of the proposed scheme and analyze the energy-efficiency achieved by such a system. Next, Section V analyzes the delay efficiency of the proposed V-BLAST based virtual MIMO communications architecture. The numerical results are provided in Section VI to demonstrate the potential performance gains offered by the proposed virtual MIMO scheme followed by concluding remarks in Section VII.

II. V-BLAST PROCESSING BASED VIRTUAL MIMO COMMUNICATIONS ARCHITECTURE FOR WIRELESS SENSOR NETWORKS

The nodes in a wireless sensor network can be of small dimensions. Thus, it may not be realistic to assume that these sensor nodes are equipped with multiple antennas. However, [1] proposed to realize MIMO communication in a wireless sensor network consisting of single-antenna sensor nodes via sensor cooperation. The obtained energy analysis results showed clearly the possible energy savings of such virtual MIMO techniques in distributed wireless sensor networks. Below, we consider a different wireless sensor system model that is applicable in several wireless sensor network models with either cooperative or non-cooperative processing.

A commonly encountered distributed wireless sensor network model consists of a lead-sensor and a set of data collection nodes. For example, in [8]–[10] such a system model was employed for investigating the energy efficiency of distributed coding and signal processing. A similar model was employed in [7] in order to develop a collaborative and distributed tracking algorithm for energy-aware wireless sensor networks. In this model, a number of low-end *data collection* sensors are connected with a high-end *data gathering* node which may act as a lead-sensor or a fusion center over a wireless link. In such networks, the data collection sensors are typically subjected to strict energy constraints while the data gathering node is not. The data collection nodes collect data on a physical phenomenon that is of interest and communicate them to the data gathering node over a wireless link which performs required joint processing. In such a wireless sensor network model, V-BLAST-based virtual MIMO communication can be achieved easily by assuming timing synchronism among data-collection nodes [5]. Although achieving the timing (or symbol) synchronism in a co-located multiple transmitter antenna array system can be straightforward [5], in a distributed sensor network this may require additional overhead. However, in this paper we do not consider such complications and assume that it has already been achieved (for example, the data gathering node may provide this symbol synchronism).

Suppose a set of data collection nodes (possibly close to each other) has data to be sent to the data gathering node. All these sensors transmit their data simultaneously to the data gathering node as in a conventional V-BLAST system. Analogous to the terminology used in [1], [2], this step is called the *long-haul communications*. Since each node directly transmits its own data no inter-sensor encoding or inter-sensor communication among low-end sensor nodes is assumed or required as in an Alamouti scheme-based (or, in general, space-time coding based) virtual MIMO systems. Which sets of nodes can transmit simultaneously may be designed in several ways. One way is to pre-assign nodes into different groups during initialization stage of the sensor network. In self-organizing sensor networks dynamic algorithms should be provided for this purpose. Different groups of sensor nodes may send their data to the data gathering node via time-division multiplexing. In sensor networks where data gathering node performs periodic polling of data collection nodes, at any given time the data gathering node itself may request simultaneous data transmissions from a set of chosen nodes. It should be noted that throughout this paper we only consider M-QAM communication.

The data gathering node is assumed to be different from the low-end data collection nodes primarily because compared to the data collection nodes, the data gathering node has a much longer battery life (or it may not have any significant energy constraint attached to it). While in some cases it may also be of larger physical dimensions enabling it to have multiple receiver antenna capability, here we will assume that even the data gathering node is of small dimensions and thus is equipped with only a single antenna. In such a system, the proposed V-BLAST based virtual MIMO architecture can be realized via local sensor cooperation on the data gathering node side if data gathering node is willing to bare the burden of most of the involved computational complexity (this may be a reasonable assumption in situations where the data gathering node is too small to have multiple antennas but may be subjected to a less severe energy constraint than the data collection sensor nodes). It should be emphasized that even in this case the data collection sensors at the receiver side need only to cooperate with the data gathering node but not among themselves.

We assume that there are $N_R - 1$ number of local sensors surrounding the data gathering node which are willing to assist it in realizing a virtual receiver antenna array of size N_R (including the data gathering node itself). Each of these N_R sensor nodes receive transmissions during the long-haul communication. The $N_R - 1$ assisting nodes quantize their received signal samples using q bits per sample and re-transmit these bits to the data gathering node via time-division multiplexing. Following the terminology in [1], we call this step the *local communications at the receiver side*. The data gathering node treats these sample values (combined with its own received sample value) as the received signal vector $\mathbf{y}(i)$ by a receiver antenna array and proceeds with the V-BLAST detection process described in the next section. This allows realization of true MIMO capability with only the receiver-side local communication.

The key to achieving energy efficiency in this type of implementation is to choose the local sensor communication among sensors that are very close to each other compared to the long-haul communication distance. Thus, if we denote by d_l and d_L the local and long-haul communications distances, respectively, we assume that $d_l \lll d_L$.

The above described model is of course one of the simplest of this type. There are several ways in which one can generalize this model of V-BLAST based virtual MIMO communication for wireless sensor networks. For example, a network may consist of a number of data gathering nodes as opposed to a single data gathering node that is assumed here. In such a system there may be different ways to realize energy-efficient communication with proposed V-BLAST-based virtual MIMO architecture.

Since wireless channels can be subject to fading it is realistic to assume that the long-haul communication in step one of this architecture is over a fading channel. However, if local communication at the data gathering node side is over a very short distance, then the channel in this situation may either be an AWGN or a fading channel. Note that, in the proposed V-BLAST processing based virtual MIMO systems the number of nodes that can transmit simultaneously will be limited by the number of cooperating sensor nodes on the data gathering node side. For convenience, in our analysis of the V-BLAST receiver below we will assume that $N_T = N_R$.

III. BER Analysis of the Decorrelating Decision Feedback Detector for MIMO Systems

In this section we briefly revisit the V-BLAST receiver and derive an approximation to its BER. This bit error rate (BER) of the V-BLAST receiver will be needed for the energy analysis of the V-BLAST processing based virtual MIMO system in the next section.

We consider a narrow-band, flat fading, wireless communication link connecting sensor nodes to the data gathering node. Assuming there are N_T simultaneously transmitting sensor nodes and N_R receiver antennas at the data gathering node, the received discrete-time signal in a MIMO system can be written as

$$\mathbf{y}(i) \;=\; \mathbf{H}(i)\mathbf{x}(i) + \mathbf{n}(i)\ , \qquad (1)$$

where $\mathbf{y}(i)$, $\mathbf{x}(i)$ and $\mathbf{n}(i)$ are the complex N_R-vector of received signals on the N_R receive antennas, the complex N_T-vector of transmitted signals from the N_T transmitting sensor nodes, and the complex N_R-vector of additive receiver noise, respectively, at symbol time i. The components of $\mathbf{n}(i)$ are independent, zero-mean, circularly symmetric complex Gaussian random variables with independent real and imaginary parts having equal variance $N_o/2$. The noise is also assumed to be independent with respect to the time index. The matrix $\mathbf{H}(i)$ in the model (1) is the $N_R \times N_T$ matrix of complex fading coefficients. The (r,t)-th element of the matrix $\mathbf{H}(i)$, denoted by $[\mathbf{H}(i)]_{r,t}$, represents the fading coefficient value at time i between the r-th receiver node antenna and the t-th transmit sensor node.

A. Decorrelating Decision Feedback Detector for MIMO Systems

The zero-forcing-and-cancelling V-BLAST detector used in [4], [5], [11] is the decorrelating decision feedback detector (D-DFD) proposed in [12], [13] for multiuser detection in code-division-multiple-access (CDMA) systems. Applying the QR decomposition we may write $\mathbf{H} = \mathbf{U}\mathbf{T}$ where $\mathbf{U}$ is an $N_R \times N_T$ matrix with orthonormal columns, i.e. $\mathbf{U}^H\mathbf{U} = \mathbf{I}_{N_T}$, and $\mathbf{T}$ is an $N_T \times N_T$ complex, upper-triangular matrix. Then we may transform the received signal in (1) to obtain

$$\tilde{\mathbf{y}} \;=\; \mathbf{U}^H\mathbf{y} \;=\; \mathbf{T}\mathbf{x} + \boldsymbol{\eta}, \qquad (2)$$

where we have let $\boldsymbol{\eta} = \mathbf{U}^H\mathbf{n}$. It is easy to see that $\boldsymbol{\eta} \sim \mathcal{N}_c(\mathbf{0}, N_0\mathbf{I}_{N_T})$ and has independent real and imaginary parts.

Since $\mathbf{T}$ is upper triangular it is clear from (2) that $\tilde{\mathbf{y}}_k$, the k-th element of $\tilde{\mathbf{y}}$, only depends on symbols x_t for $t = k, \ldots, N_T$. Denoting the output decision of the receiver for symbol x_t by $\hat{x}_t$, for $t = 1, \ldots, N_T$, the decorrelating decision feedback detector decision statistic for the symbol x_k is given, for $k = N_T, N_T - 1, \ldots, 1$, by

$$z_k \;=\; \tilde{y}_k - \sum_{t=k+1}^{N_T} t_{k,t}\hat{x}_t \;=\; t_{k,k}x_k + \sum_{t=k+1}^{N_T} t_{k,t}\tilde{x}_t + \eta_k,$$

where $\eta_k \sim \mathcal{N}_c(0, N_0)$ denotes the k-th element of the noise vector $\boldsymbol{\eta}$ and we have let $\tilde{x}_t = x_t - \hat{x}_t$ for $t = 1, \ldots, N_T$. Next, minimum distance decisions are made for x_k's based on the statistics z_k's.

B. Joint Probability of Error of Decorrelating Decision Feedback Detector

In [11] an analytical expression was derived for the exact BER of the above V-BLAST receiver in the presence of Rayleigh fading. However, since that expression is too complicated, in the following we obtain a simpler approximation to the BER via the average probability of joint symbol errors, $\bar{P}_s^{joint}$, (i.e. the probability that not all detected symbols in a received signal vector $\mathbf{x}(i)$ are correct) of the above V-BLAST detector (this joint symbol error probability for both Rayleigh and Rician fading channels has been considered in [11] and [14]). For our purposes here, we start with the following approximation to the average probability of joint symbol errors of the D-DFD receiver in Rayleigh fading assuming an M-ary QAM constellation

$$\bar{P}_s^{joint} \;\approx\; 1 - \prod_{t=1}^{N_T}\left(1 - \bar{P}_t^g\right) \qquad (3)$$

with, for $t = 1, \cdots, N_T$,

$$\bar{P}_t^g = 4\left(1 - \frac{1}{\sqrt{M}}\right)\left(\frac{1-\gamma_t}{2}\right)^{\mathcal{D}_t}\sum_{j=0}^{\mathcal{D}_t - 1}\binom{\mathcal{D}_t - 1 + j}{j}\left(\frac{1+\gamma_t}{2}\right)^j, \qquad (4)$$

where we have defined $\mathcal{D}_t = N_R - N_T + t$, $\gamma_t = \frac{\beta_t}{1+\beta_t}$, $\beta_t = \frac{3\log_2(M)}{2(M-1)N_0}\bar{E}_b$ and $\bar{E}_b$ is the average energy per bit. The above expression for joint symbol error probability of the D-DFD receiver is in fact exact in the case of a square QAM constellation and can be derived following the same steps used in [11]. While in the case of binary phase-shift-keying (BPSK) above expression for joint symbol error is exact after replacing β_t with $\beta_t = \frac{\bar{E}_b}{N_0}$, in the case of non-square constellations ($\log_2(M) > 2$ and odd) we may use it to obtain an upper-bound to the joint probability of error after dropping the term $\left(1 - \frac{1}{\sqrt{M}}\right)$ in (4).

In general, the average bit error probability $\bar{P}_b$ of the D-DFD receiver can be a complicated function of $\bar{P}_s^{joint}$. However, for the average BER values of interest to us it can be verified that following expression provides a good approximation to the true $\bar{P}_b$:

$$\bar{P}_b \;\; \approx \;\; \bar{P}_s^{joint} \left(\frac{1}{8} + \frac{1}{N_T \log_2(M)} \right). \tag{5}$$

Note that, (5) essentially assumes that out of all joint symbol errors half are due to just one bit being in error in one of the $x_k(i)$ symbols, one fourth is due two bits being in error and the remaining one fourth is due to an $\frac{N_T \log_2(M)}{2}$ bits being in error. In order to obtain the required average energy per bit $\bar{E}_b$ for a given BER requirement we may invert (5).

IV. ENERGY EFFICIENCY OF V-BLAST-BASED COOPERATIVE VIRTUAL MIMO COMMUNICATIONS ARCHITECTURE

As in [1], we will omit the energy consumption in baseband signal processing blocks and will assume uncoded communication. Note that due to the involved V-BLAST processing, the energy consumption in the baseband processing blocks in the data gathering node may not be negligibly small. Nevertheless we ignore this in our energy analysis since it is assumed that the data gathering node is not subjected to a strict energy constraint. Energy consumption of the proposed cooperative MIMO-based scheme then consists of two terms: the energy required for the long-haul communication from data collection nodes to the receiver side and the energy required for local communications from receiver side data collection sensors to the data gathering node. As before, we will assume that there are N_T number of data collection sensors, each having L bits to transmit to the data gathering node, at the transmitter side and $N_R - 1$ cooperating sensor nodes around the data gathering node at the receiver side. Let us denote by $E_{bt}^{(L)}$ and $E_{bt}^{(l)}$ the average total energy per bit for long-haul and receiver-side local communications, respectively. Then the total energy required in order to communicate the data of all the data collection nodes to the data gathering node is given by

$$E_t^{mimo} \;\; = \;\; N_T L E_{bt}^{(L)} + \frac{(N_R - 1) q L}{\log_2(M^{(L)})} E_{bt}^{(l)}, \tag{6}$$

where we have denoted by $M^{(L)}$ the QAM constellation size used for long-haul communications and thus $N_s = \frac{L}{\log_2(M^{(L)})}$ is the total number of signal samples received by the receiver side sensor nodes.

A. Total Energy Consumption of D-DFD based Virtual MIMO Communications

As discussed in [1], [2], [15]–[17], the total power consumption along the signal path can be divided into two main components: the power consumption of all the power amplifiers P_{PA} and the power consumption of all other circuit blocks P_C. Let us first consider the long-haul communications step. Assuming that the power consumed by the power amplifiers is linearly dependent on the transmit power $P_{out}^{(L)}$, the total power consumption of the power amplifiers can be approximated as [1], [15]

$$P_{PA}^{(L)} \;\; = \;\; N_T \left(1 + \alpha^{(L)} \right) P_{out}^{(L)} \tag{7}$$

where $\alpha^{(L)} = \xi^{(L)}/\eta - 1$ with η being the drain efficiency of the RF power amplifier and $\xi^{(L)}$ being the peak-to-average ratio (PAR) that depends on the modulation scheme and the constellation size. For the M-ary QAM systems assumed in this paper we may take $\xi^{(L)} = 3\frac{M^{(L)} - 2\sqrt{M^{(L)}} + 1}{M^{(L)} - 1}$ [16].

The transmit power $P_{out}^{(L)}$ in (7) can be calculated in terms of the $\bar{E}_b^{(L)}$ required for a specified BER as [18]

$$P_{out}^{(L)} \;\; = \;\; c_1 d_L^{\kappa} \bar{E}_b^{(L)} R_b^{(L)}, \tag{8}$$

where κ is the signal attenuation parameter (path loss parameter) and $R_b^{(L)}$ is the bit rate of each node during the long-haul communication. The constant $c_1 = \frac{(4\pi)^2 M_l N_f}{G_t G_r \lambda^2}$ where G_t and G_r are the transmitter and receiver antenna gains respectively, λ is the carrier wavelength, M_l is the link margin compensating the hardware process variations and other additive background noise or interference and N_f is the receiver noise figure. Note that the receiver noise figure N_f is given by $N_f = \frac{N_r}{N_0}$ where N_r is the power spectral density (PSD) of the total effective noise at the receiver input and N_0 is the single-sided thermal noise PSD at the room temperature. For typical wireless communication channels, the signal attenuation parameter κ may lie in the range $2 \leq \kappa \leq 5$, with $\kappa = 2$ representing free space propagation. Since a fading channel is assumed for the long-haul communications, $\bar{E}_b^{(L)}$ for a given BER requirement can be obtained by inverting (5).

The total power consumption in all the circuit blocks during the long-haul communications step consists of power consumption in N_T number of transmitter circuits and N_R number of receiver circuits:

$$\begin{aligned} P_c^{(L)} \approx\; & N_T \left(P_{DAC} + P_{mix} + P_{filt} + P_{synth} \right) + \\ & N_R \left(P_{synth} + P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC} \right) \end{aligned} \tag{9}$$

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. Note that, the models developed in [17], [19] can be used to estimate the power consumption values P_{DAC} and P_{ADC}.

Total energy per bit for a fixed rate $M^{(L)}$-ary QAM system can then be estimated by combining (7), (8) and (9):

$$\begin{aligned} E_{bt}^{(L)} &= \frac{P_{PA}^{(L)} + P_c^{(L)}}{R_{bt}^{(L)}} \\ &= \frac{3c_1}{\eta} \frac{\left(M^{(L)} + 1 - 2\sqrt{M^{(L)}}\right)}{M^{(L)} - 1} d_L^{\kappa} \bar{E}_b^{(L)} + \frac{P_c^{(L)}}{R_s N_T \log_2(M^{(L)})} \end{aligned} \tag{10}$$

where we have used the fact that if the symbol rate of each individual sensors is R_s symbols/sec, then the total bit rate of the MIMO system is given by $R_{bt}^{(L)} = N_T \log_2(M^{(L)}) R_s$. For a system operating with a transmission bandwidth of B Hz we will assume that $R_s = B$ bauds in our numerical analysis.

It is easy to verify that the total energy per bit E_{bt}^{l} for the local communications on the data gathering node side can also be obtained from (10) after substituting for the parameters $M^{(L)}$, d_L, $\bar{E}_b^{(L)}$ the corresponding quantities $M^{(l)}$, d_l, $\bar{E}_b^{(l)}$, respectively and modifying the circuit power consumption term $P_c^{(L)}$. Since during each individual receiver side local sensor communications only one transmitter is communicating with the data gathering node, the circuit power consumption during local communications P_c^{l} can be written as

$$\begin{aligned} P_c^{(l)} \approx\; & P_{DAC} + P_{mix} + P_{filt} + 2P_{synth} \\ & + P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC} \end{aligned} \tag{11}$$

In case of an AWGN local channel we have

$$\bar{E}_b^{(l)} = \frac{\left(M^{(l)} - 1\right) N_0}{3 \log_2(M^{(l)})} \left[Q^{-1} \left(\frac{\bar{P}_b \, \log_2(M^{(l)})}{4\left(1 - \frac{1}{\sqrt{M^{(l)}}}\right)} \right) \right]^2 . \tag{12}$$

Note that (12) is valid (and exact) when $\log_2(M^{(l)})$ is even. When $\log_2(M^{(l)})$ is odd we may obtain an approximate $\bar{E}_b^{(l)}$ value by dropping the term $\left(1 - \frac{1}{\sqrt{M^{(l)}}}\right)$ in the denominator of the argument of inverse Q-function in (12). Since local communication step is essentially a SISO scheme, when the local channel is Rayleigh fading $\bar{E}_b^{(l)}$ can be obtained by (13) derived in subsection IV-B below for the bit error rate of a SISO system after replacing $M^{(s)}$ by $M^{(l)}$.

From (10) it is clear that the total energy per bit in a virtual MIMO based sensor system is a complicated function of the constellation size $M^{(L)}$. In previously proposed virtual MIMO implementations for cooperative sensor networks this fact was exploited in order to achieve greater energy efficiencies by optimizing the rate (constellation size) of the communications system over the transmission distance [1], [20].

In order to design rate-optimized virtual MIMO systems based on V-BLAST processing we can also optimize the long-haul and local communications constellation sizes $M^{(L)}$ and $M^{(l)}$ by minimizing the total energy per bit values $E_{bt}^{(L)}$ and $E_{bt}^{(l)}$ for each transmission distance d_L and d_l. In our numerical results we will usually assume a fixed local communications distance d_l and use the optimized constellation size for d_l in receiver side communications. The constellation size for long-haul communications $M^{(L)}$ is assumed to be optimized for the long-haul communications distance of d_L meters (note that since $d_L \gg d_l$, we assume that this distance is the same for each pair of data collection nodes on receiver and transmitter sides).

B. Reference SISO System

The average BER of a reference single antenna, $M^{(s)}$-ary QAM system, with $M^{(s)} > 2$, in Rayleigh fading can shown to be

$$\bar{E}_b^{siso} = \frac{2N_0(M^{(s)} - 1)}{3 \log_2(M^{(s)})} \left(\left(1 - \frac{\bar{P}_b \log_2(M^{(s)})}{2(1 - \frac{1}{\sqrt{M^{(s)}}})} \right)^{-2} - 1 \right)^{-1} . \tag{13}$$

Note that again in the case of non-square constellations ($\log_2(M^{(s)}) > 2$ and odd) we may use (13) as a lower bound to the required average energy per bit $\bar{E}_b^{siso}$ after dropping the term $\left(1 - \frac{1}{\sqrt{M^{(s)}}}\right)$ in (13). For a BPSK-based ($M^{(s)} = 2$) reference SISO system $\bar{E}_b^{siso} = \frac{N_0}{\frac{1}{(1-2\bar{P}_b)^2} - 1}$. As mentioned above, since the local communications is in effect SISO, (11) is also the total power consumption in all the circuit blocks in a SISO system denoted by P_c^{siso}. Then, the total energy per bit E_{bt}^{siso} in a fixed-rate $M^{(s)}$-ary QAM SISO system can be obtained from (10) by substituting $\bar{E}_b^{siso}$ and P_c^{siso} in place of $\bar{E}_b^{(L)}$ and $P_c^{(L)}$, respectively and setting $N_T = N_R = 1$. The bit rate R_b^{siso} of an $M^{(s)}$-ary QAM SISO system is given by $R_b^{siso} = \log_2(M^{(s)}) R_s$.

Then the total energy required in communicating the same amount of data using a traditional wireless sensor network based on SISO techniques will be $E_t^{siso} = N_T L E_{bt}^{siso}$ where E_{bt}^{siso} is the average total energy per bit required for the transmission from sensor nodes to data gathering node in the SISO-based system. The energy efficiency of the proposed virtual V-BLAST scheme can then be defined as $\eta_E = \frac{E_t^{siso} - E_t^{mimo}}{E_t^{siso}} \times 100\%$.

To be fair in comparisons whenever we assume optimized rates in the virtual MIMO architecture based system, we will assume that the SISO-based system also employs an optimized QAM constellation size of $M^{(s)}$ for the long-haul distance d_L.

V. DELAY EFFICIENCY OF THE PROPOSED VIRTUAL MIMO COMMUNICATIONS ARCHITECTURE

The total time required for transferring all the data in the case of traditional approach is given by

$$T^{siso} = \frac{N_T L}{\log_2(M^{(s)})} T_s \tag{14}$$

where T_s is the symbol time. Similarly, the total time required in the virtual MIMO architecture based approach is given by

$$T^{mimo} = \left(\frac{L}{\log_2(M^{(L)})} + (N_R - 1)\frac{qN_s}{\log_2(M^{(l)})} \right) T_s \tag{15}$$

where N_s is the total number of signal samples received by each receiver side sensor node mentioned above. The delay efficiency of the proposed virtual V-BLAST scheme is then defined as $\eta_D = \frac{T^{siso} - T^{mimo}}{T^{siso}} \times 100\%$.

VI. NUMERICAL RESULTS

Note that in all 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 mentioned in Section IV-A we investigate the performance of both fixed and variable-rate virtual MIMO systems that use optimized rates that minimizes E_{bt} in (10) for each value of transmission distance d.

Figure 1 shows the dependence of E_{bt} in (10) on the constellation size b for various transmission distances d for both a SISO and a 4×4 MIMO system with the proposed V-BLAST-based receiver processing. Note that Fig. 1 corresponds to the long-haul communication over a Rayleigh channel and assumes a path loss parameter of $\kappa = 2$. Indeed, from Fig. 1 we observe that there is an optimal constellation size for each transmission distance for which the total energy per bit E_{bt} is minimized.

In Fig. 2 we have shown the energy efficiency of a sensor network employing the proposed V-BLAST-based virtual MIMO architecture for different virtual MIMO implementations using both a fixed-rate system employing BPSK and a variable-rate system employing optimized M-QAM modulations. Note that, Fig. 2 corresponds to a Rayleigh long-haul channel and an AWGN local channel, and assumes $q = 8$ bits per sample, $\kappa = 4$ and $d_l = 10$ meters. The energy efficiency of the virtual MIMO scheme is given as a function of the long-haul transmission distance d_L.

Based on Fig. 2 we can make several important observations regarding the performance of V-BLAST based cooperative virtual MIMO communications architecture. First, and foremost, is that the proposed V-BLAST based scheme can provide significant energy savings compared to a traditional SISO-based scheme even after taking

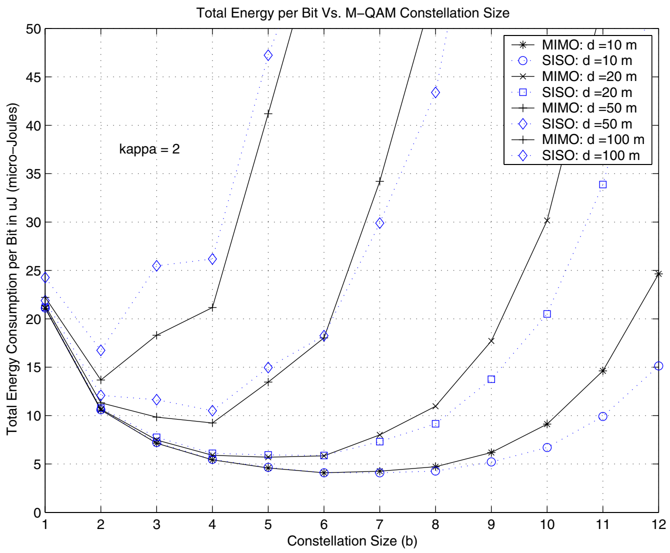

Fig. 1. Total Energy Consumption Vs. M-QAM Constellation Size for 4×4 Virtual MIMO and SISO for $\kappa = 2$

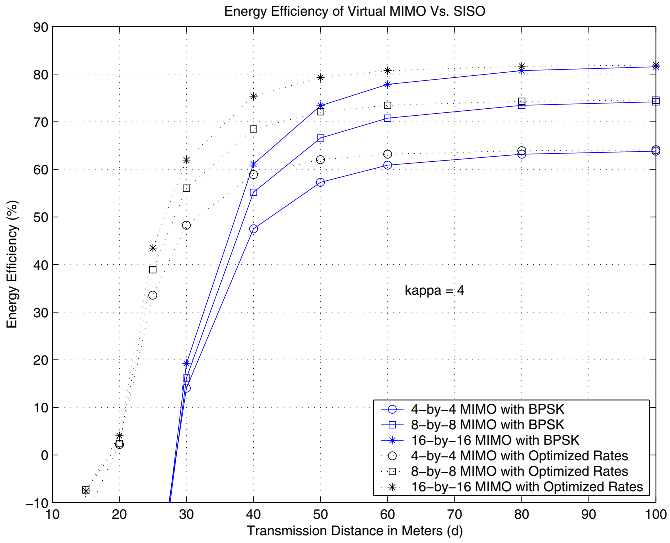

Fig. 2. Energy Efficiency of V-BLAST-based Virtual MIMO Vs. SISO with Both BPSK and Rate-optimized M-QAM Modulation When Local and Long-haul Channels are AWGN and Rayleigh, Respectively ($\kappa = 4$, $q = 8$ Bits Per Sample and $d_l = 10$ Meters).

into account both circuit and transmission power consumption terms. Second, similar to previously proposed Alamouti scheme based virtual MIMO schemes [1], [2] there is a critical distance $d_L = d_c$ below which a conventional SISO based scheme will be superior to the virtual MIMO based scheme in terms of the energy-efficiency. As can be seen from Fig. 2, this is especially true with a fixed-rate system employing BPSK modulation. Figure 2 shows that d_L needs to be at least about 28 meters to justify the use of cooperative MIMO in this case. In the case of rate-optimized systems however, this critical distance has been reduced to less than 20 meters. Since $d_l = 10$ meters in this figure, we may consider that for almost all values of d_L the optimized cooperative MIMO system may be preferable over a SISO system.

From Fig. 2 it is also clear that in general larger virtual MIMO schemes will result in greater energy savings with both fixed and variable rate systems. The effect is more visible for moderate to large values of d_L. For example, while the rate-optimized 4×4 virtual MIMO system provides only about 63% of energy savings for large d values, the 16×16 system achieves about 80% of savings. Since the proposed V-BLAST based virtual MIMO architecture assumes distributed sensor nodes at both transmitter and receiver ends, it may be possible to achieve very large effective MIMO constellations in dense sensor networks thus resulting in greater energy efficiencies. However, it should be noted that ultimately the power consumption due to V-BLAST processing at the data gathering node may become non-negligible for very large virtual MIMO systems.

One other important conclusion we can draw from Fig. 2 is that as long as d_L is not too small a fixed rate BPSK system may achieve almost the same energy efficiency as a rate-optimized system. For example, both fixed and variable rate systems achieve almost the same energy efficiency for all distances greater than 80 meters in all three MIMO systems depicted in Fig. 2. Thus, unless d_L is very small the rate optimization is not crucial for achieving considerable energy savings with the V-BLAST based virtual MIMO architecture. This observation is in contrast to the corresponding result for Alamouti scheme based virtual MIMO systems that have been proposed earlier. There the rate optimization was critical to achieving significant energy savings at reasonable transmission distances. One of the reasons for this was that with the Alamouti scheme based virtual MIMO systems the implementation requires local communications at both transmitter and receiver sides. In the proposed V-BLAST processing based virtual MIMO systems the local communications at the transmitter side is not required which eliminates this additional energy term.

This non-critical dependence of the achievable energy-efficiency at each transmission distance d_L on optimized rates gives an additional reason to prefer proposed V-BLAST based virtual MIMO architecture over the previously proposed Alamouti scheme based (or in general STBC-based) architectures [1]. A variable-rate system with optimized rates would require reasonably accurate relative position estimations for cooperating sensors in order to choose the correct constellation size. With energy-constrained nodes such estimation requirements may not be always justifiable. Thus, the results in Fig. 2 suggests that simple PBSK-based fixed-rate modulation may be preferable in most cases in terms of energy-efficiency as well as implementation complexity.

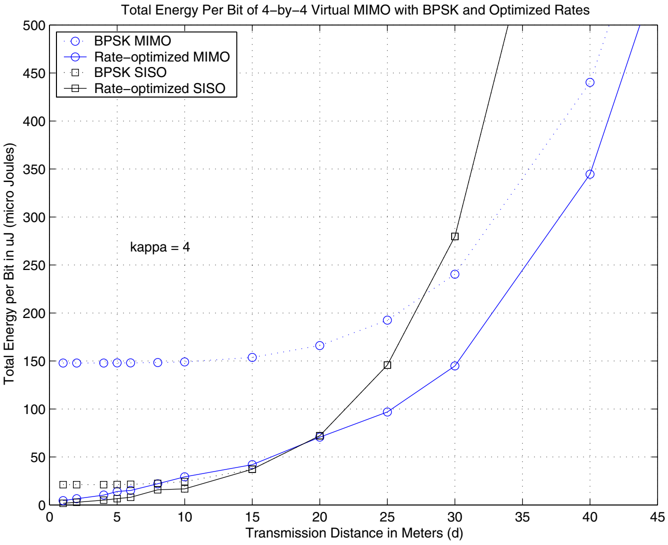

Fig. 3. Total Energy Consumption Per Bit in 4×4 V-BLAST-based Virtual MIMO and SISO with both BPSK and Optimized MQAM Modulation When Local and Long-haul Channels are AWGN and Rayleigh, Respectively ($\kappa = 4$, $q = 8$ Bits Per Sample and $d_l = 10$ Meters)

Although rate optimized systems do not offer significant improvement over the fixed-rate BPSK systems in terms of energy efficiency, it is important to note that the rate optimized systems could still offer better energy performance if one were to look at the actual energy per bit values E_{bt}. In Fig. 3 we have shown E_{bt} values achieved with BPSK and with optimized rates for for both MIMO and SISO systems (Note that for virtual MIMO systems we have defined $E_{bt}^{mimo} = \frac{E_t^{mimo}}{N_T L}$). As can be seen from Fig. 3 the rate optimization offers a significant energy reduction per bit especially in the case of virtual MIMO systems for small to moderate distances d_L. However, in both MIMO and SISO systems the difference in total energy values with fixed and variable-rate systems becomes smaller as d_L increases. The reason is that for large d_L the optimal constellation size in both cases approaches $M = 2$ (i.e. BPSK).

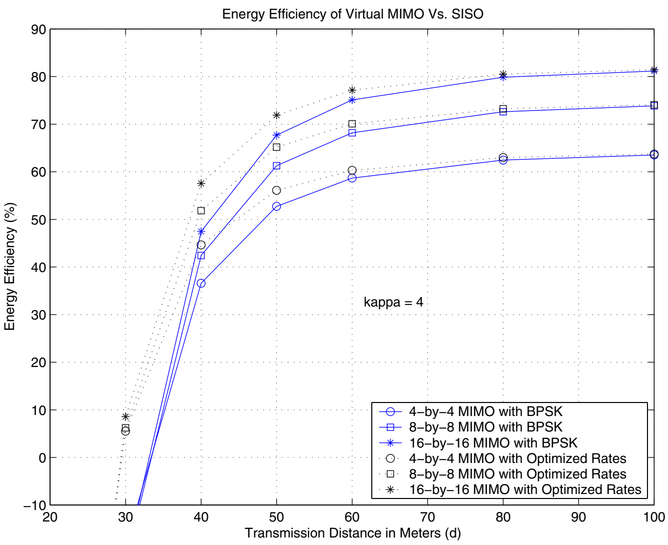

Fig. 4. Energy Efficiency of V-BLAST-based Virtual MIMO Vs. SISO with both BPSK and Rate-optimized M-QAM Modulation When Both Local and Long-haul Channels are Rayleigh ($\kappa = 4$, $q = 12$ Bits Per Sample and $d_l = 10$ Meters).

In Fig. 4 we have shown the energy efficiency of the same sensor network but this time assuming both local and long-haul channels are Rayleigh and that $q = 12$ bits per sample. Comparing Fig. 4 with Fig. 2 we may observe that unless d_L is very small the achievable energy savings are almost insensitive to both these parameters. The critical distance below which a SISO based communication might be preferable has slightly increased in this case, but the final achievable efficiencies are almost unchanged.

The average delay per bit of the proposed virtual MIMO-based communication architecture is shown in Fig. 5 corresponding to the system assumed in Fig. 2. As can be seen from Fig. 5 there is a trade-off between the achievable energy savings and the delay incurred. For example, 4×4 and 8×8 virtual MIMO systems has better delay efficiencies compared to a SISO system. Thus, virtual MIMO architectures of these sizes are suitable if one were to achieve both energy and delay savings at the same time. This could be applicable in situations where real-time sensor communication is needed in addition to the energy efficiency.

However, if the goal is to achieve the best energy efficiency, at the expense of somewhat increased delay values, then higher order virtual MIMO systems may be preferable. Thus, in various dense sensor network applications where node energy preservation is more critical than delay efficiency, the proposed V-BLAST-based cooperative virtual MIMO communications architecture can be used to achieve better performance. The reason why large virtual MIMO implementations incur delay penalties compared to a SISO system can be explained by noticing that as d_L becomes large usually the optimal modulation order for both SISO and MIMO schemes tend to be the same and thus the delay incurred due to the local communications step can not be sufficiently compensated by the virtual MIMO delay gain achieved in the long-haul communications.

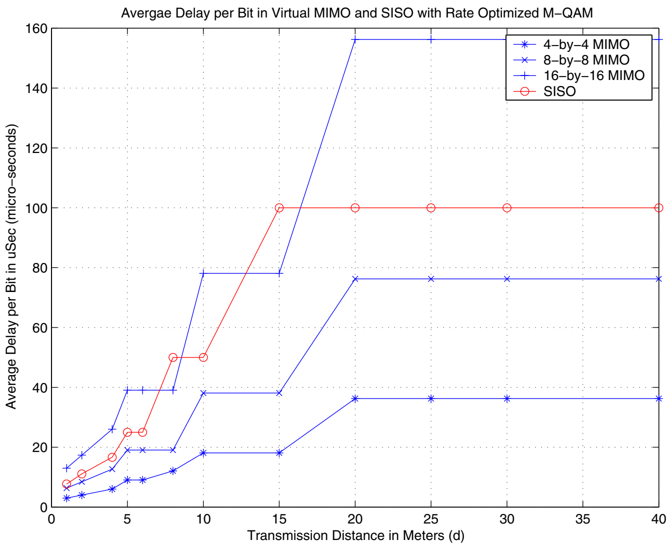

Fig. 5. Average Delay per Bit of V-BLAST-based Virtual MIMO Vs. SISO with both BPSK and Rate-optimized MQAM Modulations When Local and Long-haul Channels are AWGN and Rayleigh, Respectively ($\kappa = 4$, $q = 8$ Bits Per Sample and $d_l = 10$ Meters)

VII. CONCLUSIONS

We have proposed a new virtual MIMO communication architecture for energy-limited wireless sensor networks based on V-BLAST receiver processing. The V-BLAST processing based scheme does not rely on transmitter side sensor cooperation and thus is well-suited for distributed sensor networks with energy-constrained nodes and no inter-sensor communication among data collection nodes. Taking into account both transmission and circuit power consumption, we have presented an energy efficiency analysis of the proposed virtual MIMO communication architecture based wireless sensor networks. Our numerical results show that the proposed V-BLAST processing based virtual MIMO architecture can offer significant energy savings over traditional SISO communication based wireless sensor networks. Moreover, these results indicate that while rate optimization over transmission distance can offer improved energy efficiencies in some cases, this is not essential in achieving energy savings unlike in previously proposed Alamouti scheme-based virtual MIMO implementations. In most scenarios a fixed-rate BPSK-based system can achieve performance close to that of a variable-rate system with optimized rates. Our results also indicate that due to the local communications step involved on the receiver-side the proposed scheme can have larger delay values compared to a traditional SISO communications based sensor network as the order of the virtual MIMO architecture grows. This results in a trade-off between the achievable energy efficiency and the delay incurred. Thus the proposed virtual MIMO scheme can especially be a good candidate communication architecture for energy-starved and delay-tolerant wireless sensor networks having no inter-sensor communication among data collection nodes.

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