V-BLAST-Based Virtual MIMO for Distributed Wireless Sensor Networks

Sudharman K. Jayaweera, *Member, IEEE*

***Abstract*—A virtual multiple-input multiple-output (MIMO) communications architecture based on vertical Bell Laboratories layered space–time (V-BLAST) receiver processing is proposed for wireless sensor networks (WSNs). The proposed scheme does not require transmitter-side node cooperation unlike previously proposed virtual MIMO schemes. The energy and delay efficiencies of the proposed virtual MIMO scheme are derived for networks with both single- and multiple-antenna data gathering nodes (DGNs). Numerical results show the significant energy savings offered by the proposed method. These results also indicate that rate optimization over transmission distance is not essential as in virtual MIMO systems based on Alamouti scheme. In most scenarios, a fixed-rate virtual MIMO system with 4-quadrature amplitude modulation can achieve performance very close to that of an optimized, variable-rate system. In the case of single-antenna DGNs, the proposed scheme typically incur larger delay values compared to traditional single-input single-output communication, making it a good candidate for energy-starved but delay-tolerant WSNs.**

***Index Terms*—Cooperative multiple input multiple output (MIMO), MIMO, vertical Bell Laboratories layered space–time (V-BLAST), virtual MIMO, wireless sensor networks (WSNs).**

I. Introduction

Virtual multiple-input multiple-output (MIMO) communication has recently been proposed as a means for achieving energy efficiency in distributed wireless sensor networks (WSNs) [1], [2]. A similar concept named virtual antenna array (VAA) has been explored previously to improve the capacity of 3G cellular systems [3], [4]. The underlying MIMO concept used in all these has been the Alamouti scheme [5]. In this paper, we propose the well-known vertical Bell Laboratories layered space–time (V-BLAST) MIMO processing for wireless networks [6], [7].

In a low-power WSN, unlike in a traditional wireless system, the circuit energy needed for processing can be of the same order as that for actual transmissions. Hence, multiple-antenna communication is not viable in energy-limited WSNs since MIMO techniques require complex transceiver circuitry and signal processing. Moreover, physical implementation of multiple antennas on a small node may not be realistic. In [3], [4], [8], and [9], the concept of VAA was used to overcome this problem in 3G systems. Recently, it was shown in [1] that it is possible to realize MIMO techniques in WSNs without having multiple antennas at distributed nodes via cooperative communications. Such virtual MIMO techniques can offer considerable energy savings even after taking into account the additional circuit power, communications, and training overheads [1], [2]. In a typical WSN, the communication is mainly between low-power distributed nodes and a high-end data gathering node (DGN) that is less energy constrained [10], [11]. Since most of the required processing in a V-BLAST system is on the receiver side, a virtual MIMO scheme based on V-BLAST can improve energy efficiency at distributed nodes by transferring most of the computational burden to the DGN. The proposed method also does not require (spatial) encoding at distributed nodes, thus eliminating the local processing and communication steps involved in an Alamouti-scheme-based virtual MIMO system [1], [2]. As a result, the cooperation among transmitting distributed nodes is not essential.

This paper evaluates the energy and delay efficiencies of a V-BLAST-based virtual MIMO system. The dependance of these efficiencies on system parameters such as transmission distance, constellation size (transmission rate), and channel path loss exponent is investigated. The numerical results suggest that the proposed virtual-MIMO-based communication scheme can provide significant energy savings in WSNs.

In Section II, the V-BLAST-based virtual MIMO scheme for WSNs with multiple-receiver-antenna DGNs is presented, and its energy efficiency is derived. Section III analyzes the energy and delay efficiencies of the V-BLAST-based virtual MIMO communication in WSNs with single-antenna DGNs. In Section IV, we give concluding remarks.

II. Energy Efficiency of V-BLAST-Based Virtual MIMO Communication in WSNs With Multiple-Antenna DGNs

Assume a WSN made of a collection of low-end *data collection* nodes (DCNs) that are connected over a wireless link to a high-end DGN. The DCNs are typically subjected to strict energy constraints while DGN is not. Suppose that a set of DCNs (possibly close to each other) has data to be sent to the DGN. All these nodes transmit their data simultaneously to the DGN as in a conventional V-BLAST system. Since each node transmits its own data, no intersensor encoding is required as in an Alamouti-scheme-based virtual MIMO system. This eliminates the need for intersensor communication among low-end nodes. Which nodes can transmit simultaneously may be designed in several ways: one method is to preassign each node into different groups during initialization stage of the sensor network. In a self-organizing sensor network, dynamic algorithms are needed for this purpose. Each group of nodes send their data using time-division multiplexing. In an alternative approach, the DGN

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The author was with the Department of Electrical and Computer Engineering, Wichita State University, Wichita, KS 67260 USA. He is now with the Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque, NM 87131 0001 USA (e-mail: jayaweera@ece.unm.edu).

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may periodically poll DCNs and may request simultaneous data transmissions from a set of chosen nodes. The DGN is assumed to have a much longer battery life and can be of larger physical dimensions enabling it to have multiple receiver antennas. This allows realization of true MIMO capability with V-BLAST processing without requiring additional local communications as assumed in previous virtual MIMO implementations [1], [12].

Assuming that there are N_T simultaneously transmitting DCNs and N_R receiver antennas at the DGN, the received discrete time signal over a narrow-band, flat fading, wireless link is

$$\mathbf{y}(i) = \mathbf{H}(i)\mathbf{x}(i) + \mathbf{n}(i) \tag{1}$$

where $\mathbf{y}(i)$, $\mathbf{x}(i)$, and $\mathbf{n}(i)$ are the complex N_R vector of received signals, the complex N_T vector of transmitted signals from N_T transmitting nodes, and the complex N_R vector of receiver noise, respectively, at symbol time i. The components of $\mathbf{n}(i)$ are independent, zero-mean, circularly symmetric complex Gaussian with independent real and imaginary parts having equal variance $N_0/2$. The noise samples are independent with respect to the time index i. The matrix $H(i)$ in (1) is the $N_R \times N_T$ matrix of complex fading coefficients representing random attenuation of the signal on top of the inverse κ-law path loss. Throughout this paper, we will assume that $N_T \leq N_R$.

A. Decorrelating Decision Feedback Detector for MIMO Systems

Using the QR decomposition $\mathbf{H} = \mathbf{UT}$, where $\mathbf{U}$ is an $N_R \times N_T$ matrix with orthonormal columns and $\mathbf{T}$ is an $N_T \times N_T$ complex, upper triangular matrix, we may transform the received signal in (1) to obtain $\tilde{\mathbf{y}} = \mathbf{U}^H\mathbf{y} = T\mathbf{x} + \boldsymbol{\eta}$ 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, $\tilde{y}_k$, the kth 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 zero-forcing-and-canceling V-BLAST detector [6], [7], [13] [also called the decorrelating decision feedback detector (D-DFD) [14]] decision statistic for the symbol x_k is given 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 $\eta_k \sim \mathcal{N}_c(0, N_0)$ is the kth element of the noise vector $\boldsymbol{\eta}$ and $\tilde{x}_t = x_t - \hat{x}_t$, for $t = 1, \ldots, N_T$.

Assuming an M-ary quadrature amplitude modulation (QAM) constellation and Rayleigh fading, the average probability of joint symbol errors [i.e., the probability that not all detected symbols in a received signal vector $\mathbf{x}(i)$ are correct] of the aforementioned D-DFD receiver can be approximated as

$$\bar{P}_s^{\text{joint}} \approx 1 - \prod_{t=1}^{N_T} \left(1 - \bar{P}_t^g\right) \tag{2}$$

with

$$\bar{P}_t^g = 4\left(1 - \frac{1}{\sqrt{M}}\right)\left(\frac{1-\gamma_t}{2}\right)^{N_R - N_T + t} \sum_{j=0}^{N_R - N_T + t - 1} \binom{N_R - N_T + t - 1 + j}{j}\left(\frac{1+\gamma_t}{2}\right)^j \tag{3}$$

where we have defined $\gamma_t = \beta_t/(1+\beta_t)$, $\beta_t = [3\log_2(M)/\{2(M-1)N_0\}]\bar{E}_b$, and $\bar{E}_b$ is the average energy per bit required for a given bit error rate (BER) specification. The previous expression is exact for square QAM constellations, and can be used as an upper bound for nonsquare constellations [$\log_2(M) > 2$ and odd] after dropping the term $(1 - (1/\sqrt{M}))$ in (3). In the case of BPSK, earlier expression for joint symbol error is exact after replacing β_t with $\beta_t = \bar{E}_b/N_0$. In general, the average BER $\bar{P}_b$ of the D-DFD receiver is a complicated function of $\bar{P}_s^{\text{joint}}$, and was derived in [13]. However, for the average BER values of interest to us, it can be verified that a reasonable approximation is provided by:

$$\bar{P}_b \approx \frac{\bar{P}_s^{\text{joint}}}{2\log_2(M)}. \tag{4}$$

The average energy per bit $\bar{E}_b$ for a given BER requirement is obtained by inverting (4).

B. Total Energy Consumption of Proposed V-BLAST-Based Virtual MIMO Scheme

Total power consumption at a node can be divided into two main components: the power consumption of the power amplifiers P_{PA} and the power consumption of other circuit blocks P_C [1], [2], [15]–[17]. The total power consumption due to power amplifiers can be approximated as [1]

$$P_{\text{PA}} = (1+\alpha)\, P_{\text{out}} \tag{5}$$

where $\alpha = \xi/\eta - 1$, η is the drain efficiency of the RF power amplifier and ξ is the peak-to-average ratio [for M-ary QAM, $\xi = 3(M - 2\sqrt{M} + 1)/(M-1)$] [15]. The transmit power P_{out} is given by $P_{\text{out}} = c_1 d^\kappa \bar{E}_b R_b$, where c_1 is a constant, d is the transmission distance, κ is the signal attenuation parameter (path loss exponent), and R_b is the system bit rate. Typically, $2 \leq \kappa \leq 5$, with $\kappa = 2$ representing free space propagation.

Assuming that N_R receiver antennas share the same frequency synthesizer since they are colocated at the DGN and using the model proposed in [1], the total power consumption in circuit blocks is

$$P_c \approx N_T\left(P_{\text{DAC}} + P_{\text{mix}} + P_{\text{filt}} + P_{\text{synth}}\right) + P_{\text{synth}} + N_R \times \left(P_{\text{LNA}} + P_{\text{mix}} + P_{\text{IFA}} + P_{\text{filr}} + P_{\text{ADC}}\right) \tag{6}$$

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.

Total energy per bit for a fixed rate system can then be estimated using (5) and (6):

$$E_{\text{bt}} = \frac{P_{\text{PA}} + P_c}{R_b} = \frac{3c_1}{\eta}\frac{(M + 1 - 2\sqrt{M})}{M-1} d^\kappa \bar{E}_b + \frac{P_c}{R_s N_T \log_2(M)} \tag{7}$$

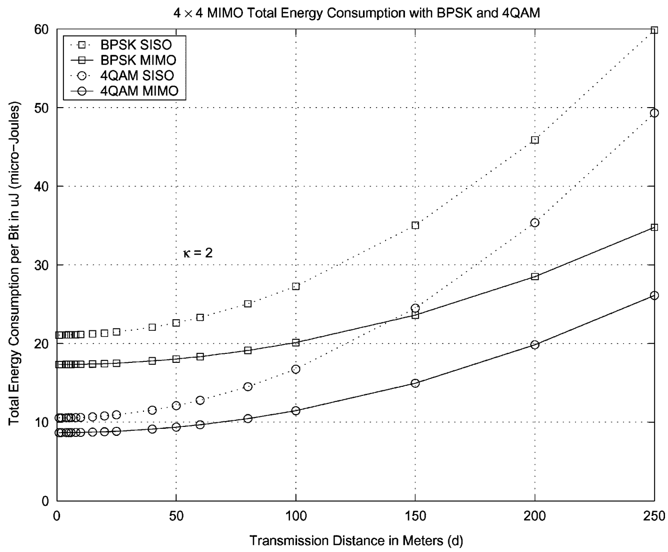

Fig. 1. Total energy comparison of V-BLAST-based 4×4 virtual MIMO with BPSK and 4-QAM modulations ($\kappa = 2$).

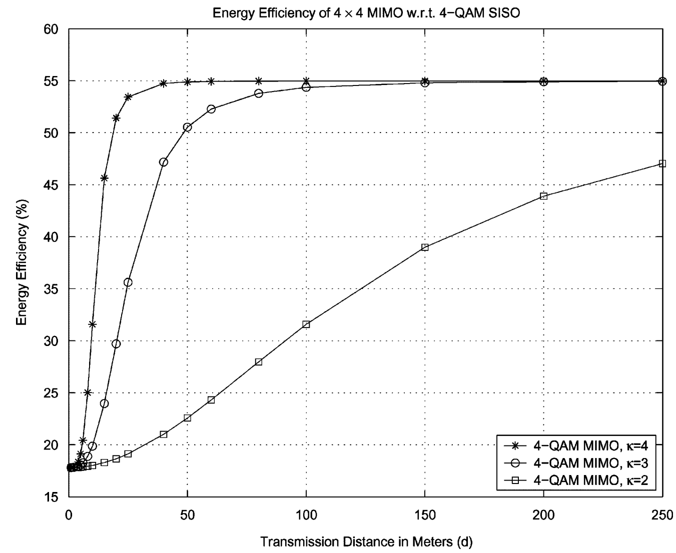

Fig. 2. Energy efficiency of V-BLAST-based 4×4 virtual MIMO with respect to BPSK-modulated SISO.

where R_s symbols per second is the symbol rate of an individual sensor. In our numerical results, we will assume that $R_s = B$ bauds for a system operating in a transmission bandwidth of B Hz.

C. Reference SISO System

The energy per bit $\bar{E}_b^{\text{SISO}}$ for a given BER of a single antenna [single input single output (SISO)], M-ary QAM system, with $M > 2$, in Rayleigh fading can be shown to be

$$\bar{E}_b^{\text{SISO}} = \frac{2N_0(M-1)}{3\,\log_2(M)} \times \left(\left(1 - \frac{\text{BER}\,\log_2(M)}{2(1-(1/\sqrt{M}))} \right)^{-2} - 1 \right)^{-1}. \quad (8)$$

In the case of a nonsquare constellation, we may use (8) as a lower bound to the required average energy per bit $\bar{E}_b^{\text{SISO}}$ after dropping the term $(1-(1/\sqrt{M}))$ in (8). For a BPSK-based SISO system, $\bar{E}_b^{\text{SISO}} = [N_0/\{(1/(1-2\text{BER})^2) - 1\}]$. The circuit power consumption P_c^{SISO} of a SISO system can be obtained by setting $N_T = N_R = 1$ in (6). The total energy per bit $E_{\text{bt}}^{\text{SISO}}$ in a fixed rate SISO system can then be obtained from (7) by substituting $\bar{E}_b^{\text{SISO}}$ and P_c^{SISO} in place of $\bar{E}_b$ and P_c, respectively, and setting $N_T = N_R = 1$. The bit rate R_b^{SISO} of an M-ary QAM SISO system is given by $R_b^{\text{SISO}} = \log_2(M)R_s$.

D. Energy Efficiency of V-BLAST-Based Virtual MIMO Systems

In all simulations, we have assumed $B = 10$ kHz, $f_c = 2.5$ GHz, $P_{\text{mix}} = 30.3$ mW, $P_{\text{filt}} = 2.5$ mW, $P_{\text{filr}} = 2.5$ mW, $P_{\text{LNA}} = 20$ mW, $P_{\text{synth}} = 50$ mW, and $\eta = 0.35$ [1]. Fig. 1 shows the total energy-per-bit values E_{bt} and $E_{\text{bt}}^{\text{SISO}}$ for a 4×4 MIMO system and a SISO system assuming $\kappa = 2$. From Fig. 1, we see that the proposed V-BLAST-based distributed sensor system offers significant energy reduction over a conventional SISO-based communications in a WSN. More importantly, unlike the Alamouti-scheme-based virtual MIMO systems, the V-BLAST-based virtual MIMO system outperforms the corresponding SISO system for all transmission distances. In Fig. 2, we have plotted the energy efficiency of the same sensor network employing the proposed 4×4 virtual MIMO architecture for different κ values, with respect to a reference 4-QAM-based SISO system. Observe from Fig. 2 that the energy savings offered by the V-BLAST-based virtual MIMO scheme grows rapidly as κ increases. The figure also shows that those efficiencies are achieved at shorter distances for large κ values, since transmission energy becomes the dominant term at shorter distances for large κ values.

If we plot E_{bt} in (7) (or $E_{\text{bt}}^{\text{SISO}}$) as a function of the constellation size b for various transmission distances d, we observe that there is an optimal constellation size for each transmission distance for which the total energy per bit E_{bt} is minimized. As was discussed in [17], usually larger constellation sizes provide better energy performance at shorter transmission distances. Also, unless d is very small, both systems achieve minimum energy per bit with 4-QAM modulation. This justifies the use of fixed-rate 4-QAM in virtual MIMO-based WSNs leading to significantly reduced implementation complexity.

The energy consumption of MIMO systems with optimized, variable rate M-QAM is given in Fig. 3. Observe that rate optimization leads to better performance compared to a fixed-rate 4-QAM system only when transmission distance is small. This distance, however, could be significantly large for smaller κ values, making rate optimization especially beneficial for smaller κ values. From Fig. 3, however, it is clear that for moderate to large distances, rate optimization does not offer any gain. This is in contrast to the previously proposed Alamouti-scheme-based virtual MIMO systems where rate optimization was critical to achieving energy savings at reasonable transmission distances. Due to extra energy required for the so-called local communication, usually there is a critical distance $d = d_c$ below which a SISO-based system outperforms

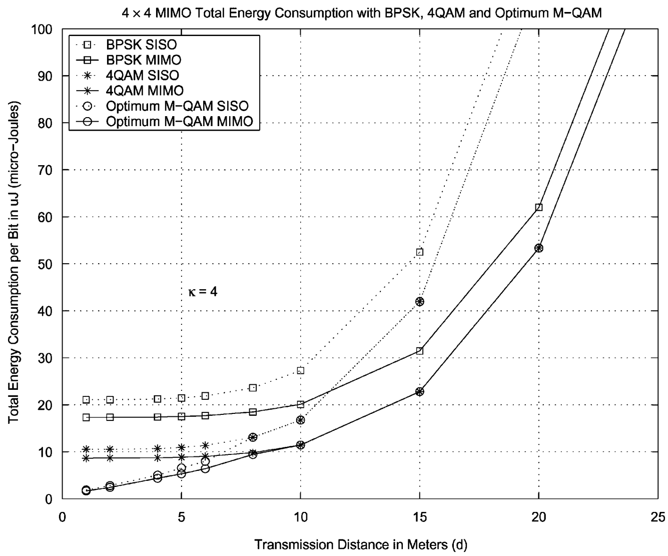

Fig. 3. Total energy consumption of V-BLAST-based 4×4 virtual MIMO with optimum M-QAM, BPSK, and 4-QAM modulations for $\kappa = 4$.

the Alamouti-scheme-based virtual MIMO even with optimized rates [1], [2]. On the other hand, the proposed V-BLAST-based virtual MIMO system always outperforms the corresponding SISO-based system irrespective of the transmission distance since there is no transmitter-side local communications. This is an additional reason to prefer the proposed V-BLAST-based virtual MIMO architecture over the previously proposed Alamouti-scheme-based [or, in general, space–time block codes (STBC) based] architectures. Fig. 3 suggests that a 4-QAM-based fixed-rate modulation is the best in terms of energy efficiency as well as implementation complexity for $d > 10$ m if $\kappa = 4$.

III. V-BLAST-Based Virtual MIMO for Systems With Single-Antenna DGNs

In WSNs with DGNs that are too small to support multiple-antennas, V-BLAST-based virtual MIMO can be implemented if the DGN can handle most of the computational complexity. A set of DCNs, identified as a virtual antenna group, transmits their data simultaneously to the DGN as before. This step is called the long-haul communication [1], [2]. At the receiver side, there are $N_R - 1$ local sensors close to DGN that will assist it in realizing a virtual antenna array of size N_R (including the DGN itself). The $N_R - 1$ assisting nodes quantize their received signal samples (q bits per sample) and relay these bits using M-QAM to the DGN via time-division multiple access (TDMA). Following [1], we call this step the local communication at the receiver side. The DGN treats these sample values (combined with its own received signal) as the received array signal vector $y(i)$, and proceeds with the D-DFD detection process. This allows realization of true MIMO capability with only receiver-side local communication and sensor cooperation. To be meaningful, we assume that $d^l \ll d^L$ where d^l and d^L are the local and long-haul communication distances, respectively.

A. *Energy Efficiency of V-BLAST-Based Cooperative Virtual MIMO Scheme*

Energy consumption of cooperative MIMO-based scheme consists of two terms: the energy required for long-haul communication from DCNs to the receiver side and the energy required for local communication from receiver-side DCNs to the DGN. As before, we assume that there are N_T number of DCNs. Let us denote by $E_{\rm bt}^L$ and $E_{\rm bt}^l$ the average total energy per bit for long-haul and receiver-side local communications, respectively. Similarly, let M^L and M^l denote the QAM constellation sizes used for local and long-haul communications, respectively. Suppose that each DCN has L data bits to transmit. The total energy required in order to communicate data from all nodes to the DGN is

$$E_t^{\rm MIMO} = N_T L E_{\rm bt}^L + (N_R - 1) q \left(\frac{L}{\log_2(M^L)} \right) E_{\rm bt}^l. \quad (9)$$

The total energy per bit values $E_{\rm bt}^L$ and $E_{\rm bt}^l$ can both be obtained from (7) after substituting for the parameters, and $\bar{E}_b$, the corresponding quantities M^L, d^L, $\bar{E}_b^L$ and M^l, d^l, $\bar{E}_b^l$, respectively, and modifying the circuit power consumption term P_c. Let us denote by P_c^L and P_c^l the circuit power consumption during long-haul and local communications steps, respectively. Then, $P_c^L \approx N_T(P_{\rm DAC} + P_{\rm mix} + P_{\rm filt} + P_{\rm synth}) + N_R(P_{\rm synth} + P_{\rm LNA} + P_{\rm mix} + P_{\rm IFA} + P_{\rm filr} + P_{\rm ADC})$ and P_c^l is the same as that of a SISO system given in Section II-C. Assuming that long-haul communication is over a fading channel, $\bar{E}_b^L$ for a given BER requirement can be obtained by inverting (4). Similarly, when local communications is over a Rayleigh channel, $\bar{E}_b^l$ is given by (8), and if it is over an AWGN channel,

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

On the other hand, total energy required by a SISO-based WSN to send the same amount of data is $E_t^{\rm SISO} = N_T L E_{\rm bt}^{\rm SISO}$.

Total energy consumption of the cooperative virtual MIMO scheme is shown in Fig. 4 for both 4-QAM and rate-optimized M-QAM along with a reference SISO system assuming that $q = 8$ bits per sample, $\kappa = 4$ and $d^l = 10$ m. As can be seen from Fig. 4, for distances greater than about 25 m, rate-optimized MIMO outperforms rate-optimized SISO. More importantly, for $d^L > 25$, a fixed-rate MIMO system based on 4-QAM outperforms even the rate-optimized SISO (as κ decreases, this critical distance increases). Thus, unless d^L is very small, the rate optimization is not crucial. This is an advantage of the proposed V-BLAST-based virtual MIMO scheme compared to Alamouti-scheme-based systems.

B. *Delay Efficiency of V-BLAST-Based Cooperative Virtual MIMO Scheme*

The total time required for transferring all the data using SISO communications is given by

$$T^{\rm SISO} = \frac{N_T L}{\log_2(M^{\rm SISO})} T_s$$

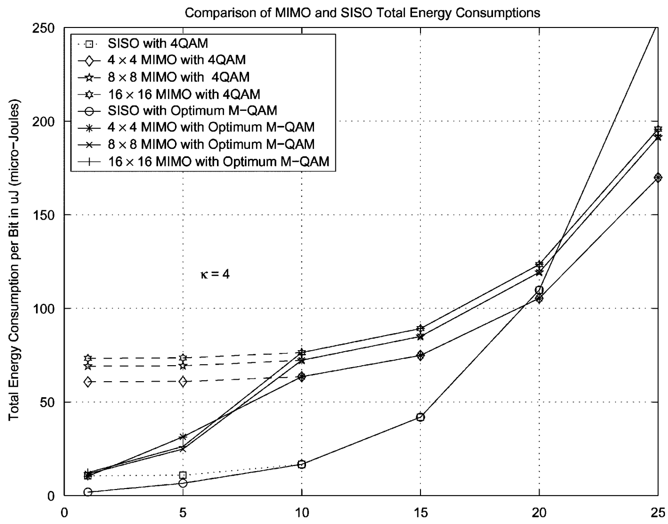

Fig. 4. Total energy consumption per bit for V-BLAST-based virtual MIMO with 4-QAM and optimized M-QAM modulation for $\kappa = 4$.

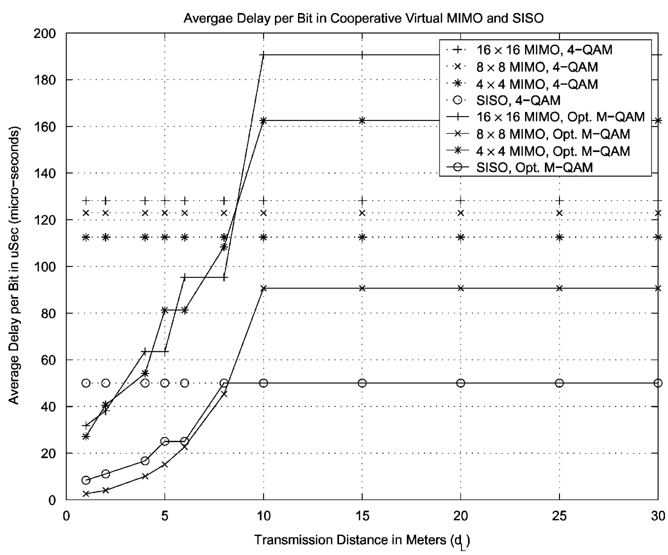

Fig. 5. Average delay per bit of V-BLAST-based cooperative virtual MIMO and SISO with both 4-QAM and rate-optimized M-QAM modulations.

where T_s is the symbol time and M^{SISO} is the QAM constellation size of the SISO system. The total time required with virtual MIMO-based approach is

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

where N_s is the total number of signal samples received by each receiver-side sensor node.

As can be seen from Fig. 5, unless distance d^L is very small, the virtual MIMO scheme results in larger delays compared to a SISO-based scheme. As d^L becomes large, usually the optimal modulation orders for both SISO and MIMO schemes tend to be the same. Hence, the delay incurred in the local communications step cannot be compensated by the delay gain achieved in the long-haul communication step of virtual MIMO. Thus, there is an inherent tradeoff between energy savings and delay in V-BLAST-based virtual MIMO systems. The scheme can be useful in applications where preservation of node energy is more critical than the delay efficiency. In Fig. 5, we have also shown the delay incurred by a virtual MIMO system using 8-QAM for local communication and 4-QAM for long-haul communication. As can be seen from Fig. 5, such a dual-rate system can provide a compromise between the SISO and virtual MIMO systems in terms of both average delay and energy efficiency as well as complexity.

IV. Conclusion

We proposed a virtual MIMO scheme for WSNs based on V-BLAST receiver processing that does not require transmitter-side sensor cooperation, and its energy efficiency is analyzed for networks with both single- and multiple-antenna DGNs. In a sensor network with a single-antenna DGN, the virtual MIMO is realized via receiver-side local communication. Numerical results show that proposed V-BLAST-based virtual MIMO scheme offers significant energy savings over traditional SISO-based networks. Moreover, rate optimization is not essential, and in most scenarios, a fixed-rate, 4-QAM-based system performs closer to that of a variable-rate system with optimized rates. Due to the local communications involved on the receiver side, the proposed scheme with single-antenna DGNs typically lead to relatively large delays. Hence, the proposed scheme is better suited for energy-starved, but delay-tolerant, WSNs.

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