ENERGY EFFICIENT VIRTUAL MIMO-BASED COOPERATION COMMUNICATION IN WIRELESS SENSOR NETWORKS

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Abstract

For energy limited, distributed and cooperative wireless sensor networks, an energy efficient virtual multiple input multiple output (MIMO) based communications architecture is proposed. The energy and delay efficiencies of the proposed MIMO-based communications scheme are derived using analytical techniques while assuming a space time block coding (STBC) for the MIMO system. The communication system and the channel propagation parameters define the efficiency of the proposed system. MIMO techniques can be used to save energy and reduce delay efficiencies at the same time with the right choice of the system at the design level. MIMO-based wireless sensor network’s energy is dependent on fading coherence time. Thus, application of proposed cooperative MIMO-based scheme in wireless sensor networks is thus justified by seeing all calculations.

Introduction

The term power consumption in the early systems is due to the energy required for actual transmissions but this is not possible for the energy limited wireless sensor networks. Rather, it is the circuit energy needed for receiver and transmitter processing that is sometimes dominant. Thus while designing energy efficient sensor networks it is important to consider both circuit and transmission power consumption terms. In the recent years, multiple input and multiple output (MIMO) or multiple antenna communication has gained a lot of importance. But there is a very huge disadvantage of the MIMO systems that due to complex transceiver circuitry and large amount of signal processing power, a great power is required at the circuit level. Thus, while designing MIMO techniques for energy limited wireless sensor networks, circuit power consumption as well as transmission power consumption is taken into account. Also, physical implementation of multiple-transmit or receiver antennas on a small, energy-limited sensor is not feasible. Thus dual antenna MIMO techniques in wireless sensor networks are impractical due to limited physical size of a sensor node which typically can only support a single antenna. But fortunately if we allow individual single-antenna nodes to cooperate on information transmission or reception, a cooperative MIMO system can be constructed such that energy efficient MIMO schemes can be developed. A new virtual MIMO-based cooperative communication architecture for energy-limited wireless sensor has been proposed in this paper. Virtual multiple transmit antenna arrays are created out of single antenna sensor nodes via local transmissions in this distributed MIMO technique. The energy and delay efficiencies of the proposed virtual MIMO-based sensor network have been evaluated by using these techniques. These constraints are dependent on the parameters such as transmission distance, constellation size (transmission rate) and channel path loss. The basic virtual MIMO concept to suit to a specific sensor network architecture consisting of a set of data collection nodes and a data gathering node followed by analytical energy efficiency evaluation is modified first and secondly, several realistic modifications to the simplified energy analysis technique have been developed in [1].

This paper is organized as follows:
The proposed virtual MIMO-based cooperative communications scheme for a wireless sensor network is presented in Section II. The energy and delay efficiencies of the proposed virtual MIMO communications based wireless sensor networks compared to that of a traditional SISO communications based sensor network is analyzed in Section III. The optimization process needed in order to achieve these energy efficiencies in a virtual MIMO-based system is also described in Section III. Numerical examples are provided for comparing these energy and delay values with those of traditional wireless sensor networks employing SISO-based communications schemes in Section IV. Finally, in Section V some concluding remarks are given.

Virtual MIMO Communications Architecture for Cooperative Wireless Sensor Networks

Let us consider a narrow-band, flat fading, and communication link connecting two wireless sensor nodes. The energy consumption in baseband signal processing blocks is omitted and encoded communication is assumed. A flat Rayleigh fading model unless stated is always assumed otherwise. The MIMO technique used is the Alamouti scheme or space-time block codes that provide its generalization to more than 2
transmit antennas as given in [2]. The sensor nodes in a wireless sensor network can be of small dimensions. Thus, for these sensor nodes to have multiple antennas is not practical. However, it is possible to implement a virtual MIMO communication architecture in such energy-limited, distributed wireless sensor networks via sensor cooperation. Thus, a new wireless sensor system model that is relevant in a number of wireless sensor network applications with cooperative processing is discussed below.

A common scenario in distributed wireless sensor networks is that of a lead-sensor and a set of data collection nodes (see Fig. 1). Earlier such a system model was employed for investigating the energy efficiency of distributed coding and signal processing in [3]. This model consists of a large collection of low-end data collection sensors that are connected over a wireless link with a high-end data gathering node (DGN) which may act as a lead-sensor or a fusion center.

**Figure 1. A Virtual MIMO Communications Based Wireless Sensor Network**

In this type of sensor networks, the data collection sensors are typically subjected to strict energy constraints while DGN is not. On a physical phenomenon of interest, the data collection nodes collect data. This physical data is communicated to the DGN which performs required joint and cooperative processing over a wireless link. Thus, the proposed virtual MIMO-based communications can be achieved as follows: Suppose a set of data collection nodes have data to be sent to the DGN. 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. At the end of this step each of the data collection nodes have data from all the sensor nodes. This enables space-time block coding assuming each data collection node corresponds to a specific transmit antenna element in a centralized multiple transmit antenna system. Once the space time coding is performed each sensor node transmits the space-time code symbols corresponding to a specific transmit antenna element to the DGN. This step is known as the long haul communication [6]. The DGN is assumed to be different from the low-end data collection nodes. It does not have any energy constraints attached to it (or compared to the data collection nodes, the DGN has much longer battery life) firstly. Second, this sensor can be of larger physical dimensions thus enabling it to have multiple receiver antenna capability. This allows realization of true MIMO capability with only the transmitter side local communications. This model is one of the simplest of this type.

There are several ways in which one can generalize this type of a cooperative MIMO-based wireless sensor network [4]. For example, a network may consist of a number of data gathering nodes as opposed to a single data gathering node that is assumed above. In such a system there are different ways to realize MIMO-based energy-efficient communications. Another possibility is that not all data collection nodes cooperate as one virtual transmits antenna system. In some distributed wireless sensor networks there might be a large number of data collection sensors scattered over a large area. It may be more convenient (and efficient) to design the system so that the sensor nodes that are close to each other will group together to create a virtual multiple-transmit antenna system. Thus, in a given wireless sensor network we may have a collection of such virtual multiple-transmit antenna systems as depicted in Fig. 1. All these groups will be communicating with either a single or multiple DGN’s. In our energy efficiency analysis below, however, we focus on a simple model where we have only one DGN and all data collection sensors form a single virtual transmit antenna array. Since wireless channels can be subject to fading it is realistic to assume that the long-haul communications in step two of our architecture is over a fading channel. However, if local communications at the data collection nodes are over a very short distance, then the channel in this situation may either be best modeled by an AWGN or a fading channel. We will consider both these possibilities for local communications among data collection nodes.

**Energy and Delay Efficiency of the Proposed Virtual MIMO Communications Architecture**

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 the long-haul communications from data collection nodes to the DGN [5]. If we assume that each sensor node has \( L_i \) number of bits to transmit to the DGN then the total energy required in order to communicate the data from all nodes to the DGN is given by

\[
E_{\text{MIMO}} = \sum_{i=1}^{N_f} L_i E_i^T + \sum_{i=1}^{N_f} L_i E_i
\]

(1)

Where we assume that there are \( N_f \) number of data collection sensors and the DGN is equipped with \( N_R \) number of receiver antenna elements (\( N_R \) can be unity). The average energy per bit per sensor node for local communications is denoted by \( \bar{E}_i \), for \( i = 1, \ldots, N_f \). Let us denote by \( \bar{E}_i^T \) the average energy per bit for the long-haul communication. We assume that the maximum separation between two data
collection sensors is \( d_m \) meters and that the constellation size for local communications is optimized for this worst-case distance \([1]\). The optimized constellation size used by the \( i \)-th sensor node for local communications is denoted by \( b_i^T \). Similarly, let us assume that the long-haul communications distance is \( d \) meters (note that \( d > 3d_m \) and thus we assume that this distance is the same for all data collection nodes) and the constellation size for long-haul communications is optimized for this transmission distance. As we know, 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 \( P_C \). During the local communications of sensor \( i \), for \( i = 1, \ldots, N_T \), other \( N_T - 1 \) sensor nodes all act as receivers. Thus, the circuit energy consumption in this case consists of that of one transmitter circuit and that of \( N_T - 1 \) receiver circuits:

\[
P_i^{EC} = (P_{DAC} + P_{mix} + P_{filt} + P_{synth}) + (N_T - 1) (P_{LNA} + P_{mix} + P_{IFA} + P_{filt} + P_{AD} + P_{synth})
\]

(2)

where \( P_{DAC} \), \( P_{mix} \), \( P_{filt} \), \( P_{synth} \), \( P_{LNA} \), \( P_{IFA} \), \( P_{filt} \) and \( P_{AD} \) 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. Assuming that the power consumed by the power amplifiers is linearly dependent on the transmit power, the power consumption of the power amplifiers during local communications \( P_{i,PA}^T \) can be approximated as:

\[
P_{i,PA}^T = (1 + \alpha_i^T) P_{out}^t, \quad \text{for } i = 1, \ldots, N_T
\]

(3)

where \( \alpha_i^T = \gamma - 1 \), with \( \gamma \) being the drain efficiency of the RF power amplifier and \( \xi_{ii}^T \) being the peak-to-average ratio (PAR) for local communications that depends on the modulation scheme and the constellation size. Throughout this paper we assume M-QAM systems, so that

\[
\xi_i^T = \frac{M_i^T - 2 \sqrt{M_i^T - 1}}{M_i^T - 1}
\]

\[
M_i^T = 2 b_i^T
\]

(4)

The transmit power \( P_{out}^t \), in (3) can be calculated according to the link budget relationship

\[
P_{i,PA}^T = \alpha_i^T G_t \sigma^2 \frac{E_i^T}{b_i^T}
\]

where \( d_m \) is the local transmission distance, \( k \) is the path loss parameter, \( G_t \) and \( G_r \) are the transmitter and receiver antenna gains respectively, \( \lambda \) is the carrier wavelength, \( M_i \) is the link margin compensating the hardware process variations and other additive background noise or interference, \( N_t \) is the receiver noise figure, \( E_i^T \) 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 \( N_t \) is given by \( N_t = N_{b} / N_r \) where \( N_r \) is the power spectral density (PSD) of the total effective noise at the receiver input and \( N_b \) is the single-sided thermal noise PSD at the room temperature \([1]\). In case of an AWGN local channel we have, for \( i = 1, \ldots, N_T \),

\[
E_i^T = \frac{\left( \sum_{i=1}^{N_T} P_i^T \right)}{2 N_T}
\]

(5)

where \( \sum_{i=1}^{N_T} P_i^T \) is the target average bit error rate and is valid only when \( N_T \) is even. When \( N_T \) is odd, approximate value of \( \sum_{i=1}^{N_T} P_i^T \) is calculated by dropping the denominator term of equation 5. Similarly, when the local channel is Rayleigh, for \( i = 1, 2, \ldots, N_T \),

\[
E_i^T = \frac{1 + \sigma_i^T}{2 \sigma_i^T} \left( 1 - \frac{\sigma_i^T}{2 \left( 1 + \sigma_i^T \right)} \right)
\]

(6)

Perfect channel state information at the receiver requires the proper operation of the Alamouti scheme. In a practical the required number of training bits can be function of operating SNR and thus can be much higher than the required value \([7]\). Thus for this extra energy term to incorporate, suppose that the block size is equal to \( F \) symbols and in each block we include \( pN_T \) training symbols where it is assumed that \( p \) symbols are used to train each transmitter and receiver antenna pair. The effective bit rate of the system is then given as,

\[
R_b^{eff} = 1 - \frac{pN_T}{F} R_b
\]

If \( T_c \) is the fading time coherence then the maximum block size is \( \left[ T_c R_b \right] \) symbols where \( R_b \) is the symbol rate. Best case energy consumption is obtained when \( F = \left[ T_c R_b \right] \). The fading coherence time is estimated by the relationship \( T_c = \frac{4 f_m}{\sqrt{\pi}} \), where the maximum Doppler shift \( f_m \) is given by \( f_m = \sqrt{\pi} \) with \( \sqrt{\pi} \) being the velocity. Hence, the total energy per bit \( E_{i,b}^T \) required for local communication is given by

\[
E_{i,b}^T = \frac{P_{i,PA}^T}{R_b^{eff}} P_{out}^t, \quad \text{for } i = 1, \ldots, N_T
\]

(8)

\[
E_{i,b}^T = \frac{1}{\xi_i^T} \left( \frac{4 \pi^2 \sigma_i^2 d_i^2 M_i N_f}{M_i^T - 1} \right) \left( \frac{M_i^T - 1}{M_i^T} \right) E_i^T + \frac{P_i^T}{b_i^T N_b}
\]
\[ R_{i,b}^{\text{eff},T} \]

is effective bit rate for the local communications by M-ary QAM and \( R_{i,b} = R_{s} = F \cdot pN_{d} / F \). Here energy penalty incurred due to extra symbols needed for channel estimation is given by \( R_{i,b} \) and \( R_{i,b}^{\text{eff},T} \) is dependent on constellation size \( M_{i}^{T} \). Since for a given bandwidth \( B \),

\[ R_{i,b} = b_{i}^{T} R_{s} \]

and a symbol rate \( R_{s} = B \), the bit rate \( R_{i,b} \) is also dependent on the constellation size \( M_{i}^{T} \). But the ratio \( R_{i,b}^{\text{eff},T} / R_{i,b} \) is independent of \( M_{i}^{T} \). Thus from the earlier studies, rate optimization of the communication system over the transmission distance \( d \), is the key to achieve energy savings with virtual MIMO techniques in a distributed wireless sensor networks. The optimization leads to the determination of the constellation size \( M \) for different values of \( d \) in M-QAM system. This rate optimization transmission is possible only when each sensor has knowledge of other sensor locations.

Thus each node transmits using a constellation size \( M_{i}^{T} \) that minimizes the total energy per bit \( E_{i}^{T} \) for each transmission distance \( d_{m} \). Similarly, the energy per bit \( E_{i} \) required for long haul communication is analyzed through

\[ E_{i} = 1 + \frac{p_{i}^{P_{\text{out}}}}{P_{\text{PA}}^{\text{eff},l}} \]

where \( R_{i,b}^{\text{eff},l} \), \( P_{\text{PA}} \), \( P_{i}^{l} \) are the energy consumption in effective bit rate, power amplifiers, and in the circuits during the long haul communications. Since the number of receiver antenna elements at the data gathering node \( N_{R} \) are listening while the virtual multiple transmit antenna system created by the set of \( N_{T} \) data collection sensors is transmitting then

\[ P_{i}^{l} = N_{T} \left( P_{\text{DAC}} + P_{\text{mix}} + P_{\text{fil}} + P_{\text{syn}} \right) + P_{\text{syn}} + N_{R} \left( P_{\text{LNA}} + P_{\text{mix}} + P_{\text{fil}} + P_{\text{ADC}} \right) \]  

(9)

As we know that \( N_{R} \) receiver antennas are co-located at the DGN thus allowing them to share the same frequency synthesizer. The power amplifier energy consumption \( P_{\text{PA}}^{l} \) is given with \( P_{\text{out}}^{l} \) replaced by \( P_{\text{PA}}^{l} \), the required transmit power for the long-haul communication. The only difference in computing \( P_{\text{out}}^{l} \) is that depending on the values of \( N_{R} \) and \( N_{T} \) we will have different values for the average energy per bit required for a specified bit-error-rate \( E_{i}^{T} \). For example when \( N_{T} = 2 \), the bit error rate of an M-ary QAM, Alamouti scheme based MIMO system (\( M = 2^{b} \)) with a square constellation is given by, for \( b \geq 2 \),

\[ R_{i} = \frac{1}{b} \left( 1 - \frac{1}{2^{b}} \right) \left( 1 - \frac{1}{2^{b}} \right)^{\frac{N_{R} - 1}{2^{b}}} \sum_{i=1}^{\frac{N_{R} - 1}{2^{b}}} \frac{1}{2^{b}} \left( 2^{b} - 1 \right) \]

(10)

dropping the \( 1 - \frac{1}{2^{b}} \) term as an upper-bound for the BER (for \( b = 1 \), the M-ary QAM reduces to a BPSK).

\( E_{i}^{T} \) can be computed by inverting (10). Again, the constellation size \( b_{i}^{T} \) for the long-haul communications is optimized in order to minimize the total energy consumption obtained from (9) and (10).

**TABLE I**

<table>
<thead>
<tr>
<th>( d ) (m)</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>40</th>
<th>80</th>
<th>100</th>
<th>150</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_{i}^{\text{SISO}} )</td>
<td>13</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( b_{i}^{2 \times 2} )</td>
<td>18</td>
<td>12</td>
<td>9</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

The optimal constellation size \( b \) for each long haul transmission distance \( d \) for a SISO and a 2 * 2 MIMO system employing the Alamouti scheme assuming \( p = 0 \) and \( \kappa = 3 \) is shown in Table I

The total energy required in communicating the same amount of data by a traditional wireless sensor network based on SISO techniques in contrast to virtual MIMO-based scheme will be

\[ E_{i}^{\text{SISO}} = \sum_{i=1}^{N_{T}} L_{i} E_{i}^{\text{SISO}} \]  

(11)

where the average energy per bit \( E_{i}^{\text{SISO}} \) for the transmission from sensor node \( i \) to DGN 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 \( b_{i}^{\text{SISO}} \) for the long-haul distance \( d \). The other parameter of interest in employing cooperative MIMO-based communications in an energy-constrained wireless sensor network is the total delay encountered. In the case of traditional approach the total time required for transferring all the data is given simply by

\[ T_{\text{SISO}} = T_{S} \sum_{i=1}^{N_{T}} L_{i} b_{i}^{\text{SISO}} \]  

(12)

Where \( T_{S} \) is approximately equal to \( 1/B \), the symbol time. Similarly the total time required in cooperative MIMO-based approach is given by
When the training overhead is also taken into account the total delay values can be obtained from (12) and (12) by replacing $T_s$ with an effective symbol time $T_s^{eff}$.

### Numerical Results

The energy comparison between a sensor network using proposed virtual MIMO communications and the traditional SISO as a function of long-haul transmission distance $d$ is shown in figure 2. Fig. 2 assumes that there are only two data collection nodes in the network and that the data gathering node has 2 receiver antennas (i.e. a network with one cluster having a $2 \times 2$ virtual MIMO architecture). While Fig. 2a shows the actual total energy values Fig. 2b shows the corresponding energy savings (defined as $E_{SISO} - E_{MIMO} / E_{SISO}$). 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, $P_{LNA} = 20$ mW, $P_{sync} = 50$ mW, $M_l = 40$ dB, $N_f = 10$ dB, $G_t G_r = 5$ dBi and $\eta = 0.35$ as in [1].

Figure 2 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. 2b, when $\kappa = 3$ and $p = 0$, the $2 \times 2$ 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 $d < d_m$). This is to be expected due to the local communications penalty involved in virtual MIMO implementation.

If we were to take into account the extra training overhead incurred in 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 proposed virtual MIMO architecture can improve the energy efficiency of wireless sensor networks significantly. Earlier, the results were based on an ideal propagation channel in which $\kappa = 2$. However, for typical wireless channels we may have $2 < \kappa < 5$. As we observe from Fig. 2b, for more realistic values of $\kappa$ the energy savings offered by virtual MIMO (compared to SISO) become even more significant. For a typical value of $\kappa = 3.5$, more than 70% of energy can be saved at a mere distance of approximately equal to 40 by using virtual MIMO communications architecture. Another important observation from Fig. 2b is that as $\kappa$ increases the reduction in energy savings due to the training overhead penalty in virtual MIMO system decreases. Moreover, the maximum achievable energy savings also improves as $\kappa$ increases. The delay efficiency (defined as $T_{SISO} - T_{MIMO} / T_{SISO}$) of the virtual MIMO-based communications architecture is shown in Fig. 3. The delay efficiency is an important measure in comparing the performance of virtual MIMO scheme with that of the traditional SISO-based communications due to the extra local communication step needed in virtual MIMO communications architecture.
However, as we see from Fig. 3 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. 3). 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 communications architecture can provide significant performance improvement. In less delay restrictive applications however, it is possible to operate outside the delay-efficient distance window and achieve even higher energy efficiencies.

Conclusions

We have proposed a new virtual MIMO communications architecture for energy-limited wireless sensor networks. We have provided analytical methods to obtain the energy consumption values for such virtual MIMO communications architecture based sensor networks taking into account transmission, circuit and additional training energy requirements. Our results show that even with extra energy overhead requirements, virtual MIMO-based techniques can offer substantial energy and delay efficiencies in wireless sensor networks provided the system is designed judiciously. These include careful consideration of transmission distance requirements and rate optimization.

References


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