# A New Energy-Efficient MIMO-Sensor Network Architecture M-SENMA


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*Abstract*— **In this paper we present a new large-scale low power sensor network architecture called MIMO-Sensor Networks with Mobile Agents (M-SENMAs), which select several neighboring sensor nodes to transmit information cooperatively and equip the mobile agents (MAs) with multiple receive-antennas. The M-SENMA system enables various space-time processing techniques and advanced detection algorithms. A comparison of M-SENMA with the flat MIMO sensor network architecture and Sensor Networks with Mobile Agents (SENMA) shows a substantial gain in the energy efficiency. Its upper and lower energy bounds under various antenna schemes and MA heights are discussed, which would help the future system design for sensor networks.**


## I. Introduction

Sensor Networks can be envisioned as thousands or more of inexpensive wireless nodes with the low-cost and low-energy equipment to realize the functions of sensing, computation and communication. Since the sensors have to operate without battery replacement in many applications, their energy efficiency becomes one of the predominant concerns in the design of sensor networks.

The Sensor Networks with Mobile Agents (SENMAs) have been studied intensively in recent years due to their potential in the energy efficiency. By introducing the mobile agents (MAs) in the sensor networks, SENMA saves the energy at the receiver side and are capable of further exploiting the data redundancies among the sensor nodes [1].

Meanwhile, the Multiple-input-multiple-output (MIMO) techniques, including various space-time coding schemes, layered space-time architectures, have significantly improved the spectrum efficiency of the wireless systems in recent years. Recent researches have also indicated their potential in the energy efficiency, among which S. Cui and A. Goldsmith have proposed a flat MIMO Sensor Network architecture denoted as Flat-M-SN in this paper. Its energy efficiency has been demonstrated to outperform the uncooperative sensor networks if the distance between the sensor-node-clusters that are called in this paper the cells is long enough [2].

In this paper, we propose a new kind of energy efficient sensor network architecture called MIMO-Sensor Networks with Mobile Agents (M-SENMA), which combines the advantages of both SENMA and Flat-M-SN. In M-SENMA, some modifications are made to adopt the MIMO techniques, including equipping the mobile agents with multiple receive antennas and selecting several sensor nodes to transmit information cooperatively.

Most existing energy analysis for the MIMO sensor networks utilizes the Alamouti code and is limited to the case with less than four antennas [2][3]. In this paper, however, we explore the energy performance for various MIMO sensor network architectures with a much wider range of antenna schemes by utilizing Vertical Bell Labs Layered Space-Time (V-BLAST) techniques. We will show in the later section that V-BLAST is one of the best applicable MIMO techniques for this system.

This paper is organized as follows: In section II, we present the M-SENMA system model and discuss the applicable MIMO techniques. In section III, we investigate the energy efficiency for the MIMO sensor networks, closely following the model developed in [2]. In section IV, we compare M-SENMA with the other sensor network architectures through numerical simulation and discuss their upper and lower bounds with various antenna schemes. Finally, we make conclusions in section V.

## II. System Description and Signal Model

Similar to SENMA, the M-SENMA system contains two types of nodes: the mobile agents and the sensor nodes. The mobile agents are aerial or ground vehicles traversing over the sensor nodes to collect data, which are then transmitted to the control center faraway. The MAs that are equipped with sophisticated terminals, power generators and multiple receive antennas are able to adopt advanced detection techniques. In the following discussion we assume the MAs are helicopters with $M_r$ receive antennas. Their heights are much larger than the distances between the neighboring sensor nodes, thus can be viewed approximately as the distance between the transmit antennas and the receive antennas.

The sensor nodes are distributed uniformly in the destination area, which is divided dynamically into many virtual cells by the MAs. Each sensor node is equipped with one transmit antenna and limited power supply. Since the data collected from the sensor nodes in the same cell have great degree of redundancy, there is no need to transmit all of them to the MA. The SENMA system in [1] selects only one sensor node from each cell. In M-SENMA, we utilize the antennas from $M_t$ sensor nodes in one cell to transmit the same amount of information cooperatively. Thus various space-time processing techniques can be adopted and the transmission for that cell can be viewed as an $M_t \times M_r$ MIMO system with total throughput regardless of $M_t$. The criteria to select the $M_t$ sensor nodes are based on the channel conditions and network topology. SENMA can be viewed as a special case of M-SENMA, with $M_t = 1$ and $M_r = 1$ for each transmission.

The structure of M-SENMA is illustrated in figure 1, where the helicopter serving as MA divides the sensor nodes into two virtual cells surrounded with dashed line. The black dots are the sensor nodes selected to transmit data in the following transmission period while the white dots will keep silence. That is the simplest example in M-SENMA. There can be more than one MA in each time, each of which also collects data from several cells simultaneously. By assigning the spreading codes to the simultaneously transmitting cell, the MAs enable various advanced multi-user detection (MUD) algorithms regardless of their complexity. Detailed discussion for the medium access control algorithms and MUD issues will appear in our later work.

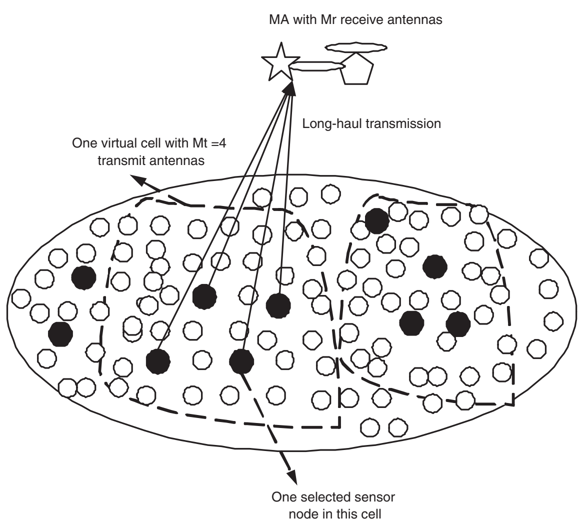


Fig. 1. Structure of M-SENMA

MIMO techniques contain various space-time coding and layered space-time architectures, but M-SENMA has some restrictions on their detection complexity. Thus the block code, BLAST and Linear Dispersion Codes (LDC) are options. As we know, most existing energy analysis for MIMO sensor networks utilizes the Alamouti codes, which is the simplest block codes with $M_t, M_r = 2$. But the performance of the block codes decreases with the number of antennas growing. Because the MAs have the potential to install a huge number of antennas and talk to many sensors simultaneously, it will hurt the network capacity and efficiency to limit the number of the antennas. Therefore in this paper, we utilize the V-BLAST technique that is flexible with the antenna number. Another option is the LDC, where the codes break the data stream into substreams that are dispersed in linear combinations over space and time. It generally outperforms both V-BLAST and block codes and we will study it in our future work.

We assume a flat-Raleigh fading model with square-law path loss, where channel is constant within one symbol. The long-haul transmission model is

$$Y = \sqrt{\bar{E}_b} H X + Z \tag{1}$$

where $Y$ is a $M_r$-vector of received complex signal. The transmitted signal is $X$, the complex $M_t$-vector. $H$ is a $M_r$ by $M_t$ matrix, representing the channel states from $M_t$ transmit antennas to $M_r$ receive antennas. Each element in $H$ is a zero-mean complex Gaussian random variable with variance 1/2 per dimension. $Z$ is supposed to be $M_r$-vector of zero-mean unit-variance complex-Gaussian distributed additive receive noise. Both $H$ and $Z$ comprise independent random variables with unit mean-square. In this system, we utilize V-BLAST scheme with zero-forcing detection and M-QAM as the modulation scheme.

## III. Energy Efficiency of MIMO Sensor Networks

In the following section, we study the energy efficiency for M-SENMA and Flat-M-SN in the fixed rate transmission with V-BLAST techniques. For simplicity in the discussion, we analyze M-SENMA in the scenario with single MA and cell where all the sensor nodes are selected to send the same amount of data to MA cooperatively with the same data rate. The error correction code (ECC) block and the baseband signal processing block including the source coding, pulse shaping and digital modulation are omitted intentionally.

We should notice that with MA to collect and relay data, the sensor nodes in M-SENMA saves both the energy for the local flow in the receive cell and the energy at the receive side of the long-haul transmission. The energy consumption per information bit for M-SENMA and Flat-M-SN can be estimated as

$$\bar{E}_{MSENMA} = \frac{N_{tx}\bar{E}_{tx} + N_{lh}\bar{E}_{lh}}{N_{lh}} \tag{2}$$

$$\bar{E}_{FMSN} = \frac{N_{tx}\bar{E}_{tx} + N_{lh}\bar{E}_{lh} + N_{rx}\bar{E}_{rx}}{N_{rx}} \tag{3}$$

where $\bar{E}_{tx}$,$\bar{E}_{lh}$,$\bar{E}_{rx}$, $N_{tx}$,$N_{lh}$, and $N_{rx}$ denote the energy per bit and the total number of transmitted data, in the local transmission among the sensor nodes in the transmit cell, the long-haul transmission between the transmit cell and the receive cell in Flat-M-SN or from the transmit cell to the MA in M-SENMA, and the local transmission among the sensor nodes in the receive cell in Flat-M-SN respectively.

Each energy term in the above equations can be further divided into two parts: the power consumed by the power amplifiers $P_{PA}$ and that by all the other circuit blocks $P_c$. Thus they can be estimated as

$$\bar{E} = \bar{E}_{PA} + \bar{E}_c = (P_{PA} + P_c)/R_b \tag{4}$$

where $R_b$ is the data rate in the corresponding transmission.

$P_{PA}$ can be given as

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

$$\alpha = \frac{\zeta}{\eta} - 1 \tag{6}$$

where $\eta$ is the drain efficiency of the RF power amplifier and $\zeta$ is the Peak-to-Average Ratio (PAR) relating to the modulation scheme and the associated constellation size[3].

### A. Energy Consumption of the Long-haul Transmission

In the long-haul transmission for the MIMO sensor networks, we get $R_s = R_b/M_t$, where $R_s$ is the data rate of a single sensor node. Assuming the frequency synthesizer (LO) is shared among all the antenna paths, we obtain the energy consumption of circuit blocks in Flat-M-SN from

$$P_c \approx M_t(P_{dac} + P_{mix} + P_{filt}) + 2P_{syn} + M_r(P_{lna} + P_{mix} + P_{ifa} + P_{filr} + P_{adc}) \tag{7}$$

where $P_{dac}, P_{mix}, P_{lna}, P_{ifa}, P_{filt}, P_{filr}, P_{adc}$ and $P_{syn}$ are the power consumption values for D/A converter (DAC), the mixer, the low noise amplifier, the intermediate frequency amplifier (IFA), the active filters at the transmitter side, the active filters at the receiver side, the A/D converter (ADC), and the frequency synthesizer, respectively [2].

Similarly, $P_c$ from $\bar{E}_{lh}$ in M-SENMA can be estimated approximately as

$$P_c \approx M_t(P_{dac} + P_{mix} + P_{filt}) + P_{syn} \tag{8}$$

The transmit power $P_{out}$ can be calculated with the link budget relationship

$$P_{out} = \bar{E}_b R_b \times \frac{(4\pi)^2 d^2}{G_t G_r \lambda^2} M_l N_f \tag{9}$$

where $\bar{E}_b$ is the required average energy per bit for a given BER requirement $P_b$, $d$ is the transmission distance, $G_t$ is the transmitter antenna gain, $G_r$ is the receiver antenna gain, $\lambda$ 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 defined as $N_f = N_r/N_o$. $N_o$ is the single-sided thermal noise power spectral density (PSD) at room temperature and $N_r$ is the PSD of the total effective noise at the receiver input.

### B. Energy Consumption of the Local Transmission

Next, we will study the energy efficiency for the local transmission. Assuming each sensor node transmits in different slots on the Additive White Gaussian Noise (AWGN) channel, we can see through simulation that the power consumed by the circuit blocks is the predominant component. Therefore, we omit the power amplifiers in the following discussion.

We assume that all the nodes at the receive cell in Flat-M-SN send the receiving data to a fixed sensor node to carry out the space-time processing. Thus $P_c$ at the receive cell is given by

$$P_c \approx P_{dac} + P_{mix} + P_{filt} + 2P_{syn} + P_{lna} + P_{mix} + P_{ifa} + P_{filr} + P_{adc} \tag{10}$$

In the transmit cell, these two MIMO sensor network schemes are similar in energy efficiency, which is related to the specific local information exchange scheme. It is not easy to determine the exact value of $P_c$, but we can obtain its upper bound, where the $M_t$ selected sensor nodes exchange all their future long-haul transmission data, i.e. $N_{tx} = N_{lh}$ and

$$P_c \approx P_{dac} + P_{mix} + P_{filt} + 2P_{syn} + (M_t - 1)(P_{lna} + P_{mix} + P_{ifa} + P_{filr} + P_{adc}) \tag{11}$$

Although this practice has been carried out in many works in MIMO sensor networks, it is not always necessary considering the data redundancy among the neighboring sensor nodes. If a cell defined by MA is small enough, the data from all its sensor nodes are approximately same. Even though the occasional information flow is still necessary, the large-scale data exchange should be avoided in an energy efficient transmission scheme, i.e., $N_{tx}$ is approaching to zero, which is the lower bound. In another word, the upper bound is quite loose.

## IV. Numerical Results

We resort to Monte Carlo simulations to compute $\bar{E}_b$ in Eq.(9) due to the difficulty in obtaining the close-form solutions. In the simulation, we set $f_c$=2.5 GHz, $G_tG_r$=5 dBi, $B$=10 kHz, $P_{mix}$=30.3 mW, $P_b = 0.001$, $P_{filt} = P_{filr}$=2.5 mW, $N_f$=10 dB,$P_{syn}$=50.0 mW, $M_l$=40 dB, $T_s = 1/B$, $P_{lna}$=20 mW. We use 4-QAM in the modulation part.

Figure 2-5 show the lower and upper bound respectively of the energy consumption per bit for M-SENMA and Flat-M-SN when the long-haul transmission distance $d$ changes from 10 m to 100 m. Seven antenna schemes are studied with $M_t$ and $M_r$ varying from 1 to 32, if regarding SENMA as $1 \times 1$ M-SENMA. Since MAs in M-SENMA are powerful enough for any number of receive antennas, we focus our attention on $M_t \leq M_r$.

Figure 2-3 show the lower bound of M-SENMA and Flat-M-SN, respectively. We can see that with the same $M_t$, $M_r$ and $d$, M-SENMA consumes less energy than Flat-M-SN. For instance, with $M_t$=16, $M_r$=16 and $d$=100 m, M-SENMA in figure 2 saves about 40% of the energy than Flat-M-SN in figure 3. This fact is consistent with our conclusion that M-SENMA outperforms Flat-M-SN due to the energy saved for the receiver in the long-haul transmission and the local broadcast at the receive cell.

Figure 2 also indicates that M-SENMA is more energy efficient than SENMA when $d$ exceeds a certain threadhold value. The threadhold decreases as $M_t$ rises, from less than 50 m at $M_t$=2 to less than 10 m when $M_t$=16. The 16×16 M-SENMA systems save about 70% of the energy at the lower bound at $d$ =100 m. This result illustrates that V-BLAST can also be used to improve the energy efficiency.

Furthermore, figure 2 shows that the energy efficiency of M-SENMA increases as $M_t$ rises, i.e., the number of selected sensor nodes in a cell. For example, the $16\times16$ scheme saves approximately 40% of the energy consumed by the $2\times16$ scheme at $d = 100$ m. But this gain becomes very small when $M_t$, $M_r \leq 16$, because the fixed circuits energy consumption $P_c$ becomes the dominant factor, which increases with $M_t$ seen from Eq.(11). This conclusion will help MA to determine the number of selected sensor nodes in a neighboring area.

In addition, figure 2 shows the $2\times2$ M-SENMA has distinct energy loss over distance, even though the degree is much smaller than SENMA. We could solve this problem by either rising $M_t$ or $M_r$. The figure shows $M_t = 2, M_r = 16$ is enough to obtain a relatively robust power performance over distance, with loss less than 5% when $d$ rises from 10 m to 100 m. Therefore, the MAs in M-SENMA have a wider range of working height than SENMA, leading to a safe flight and the capability to talk to more cells simultaneously, which leads to a larger networks capacity.

Finally, figure 4-5 give the upper bound of energy consumption for M-SENMA and Flat-M-SN. Compared with the lower bound in figure 2-3, these performances are much worse because of the redundant transmission in the transmit cell. On the other hand, it illustrates the importance of MIMO sensor networks to utilize the characteristics of data redundancy in their transmission. With a suitable local information exchange scheme, the performance of M-SENMA can approximately approach the lower bound.

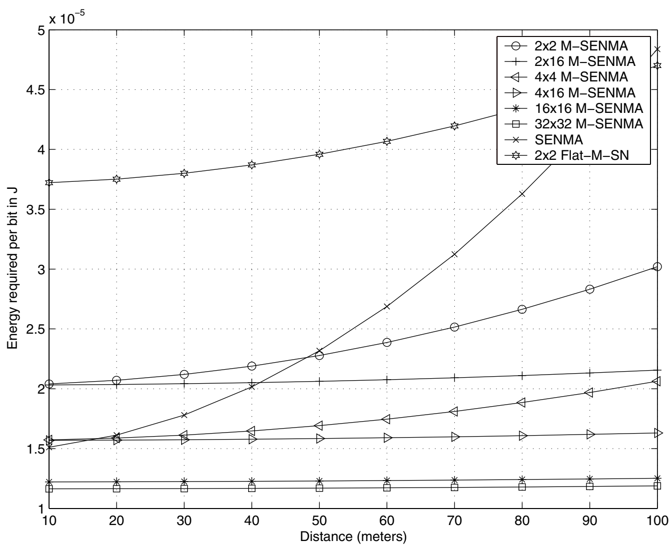


Fig. 2. Lower bound of the energy consumption for M-SENMA over distance

## V. Conclusion

We have described M-SENMA, an energy efficient MIMO sensor network architecture, which combines the advantages of MIMO techniques and SENMA. We studied its performance in the single MA and single cell condition with Zero-Forcing detection for V-BLAST on the flat Raleigh fading channel model with square-law path loss. Numerical results show its energy efficiency increases as the number of selected sensor nodes in the cell rises. In addition, its energy loss over distance is much smaller than SENMA, which enables the MA to fly in a wider range and thus leads to a safer and more efficient data transmission. These two characteristics give M-SENMA potential in the large-scale sensor networks. Comparison result shows that M-SENMA is more efficient in energy than both SENMA and Flat-M-SN when the long-haul communication distance exceeds some threadhold. For instance, the $16 \times 16$ M-SENMA saves about 70% of the total energy in SENMA or 40% of that in $16 \times 16$ Flat-M-SN, when the distance is 100 m.

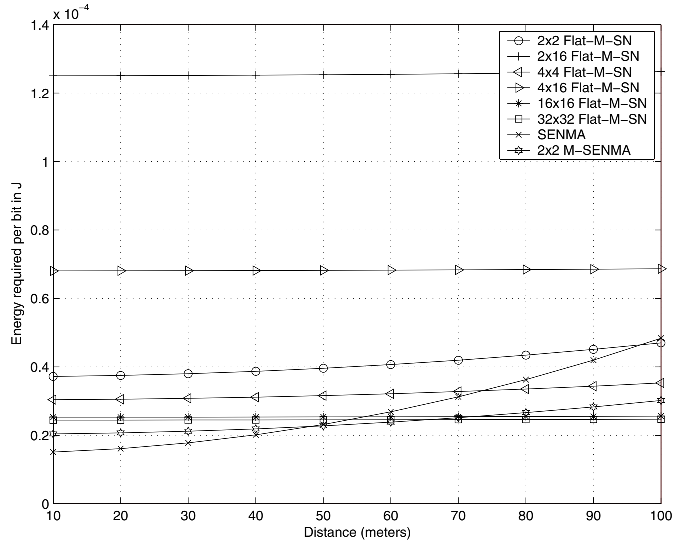


Fig. 3. Lower bound of the energy consumption for Flat-M-SN over distance

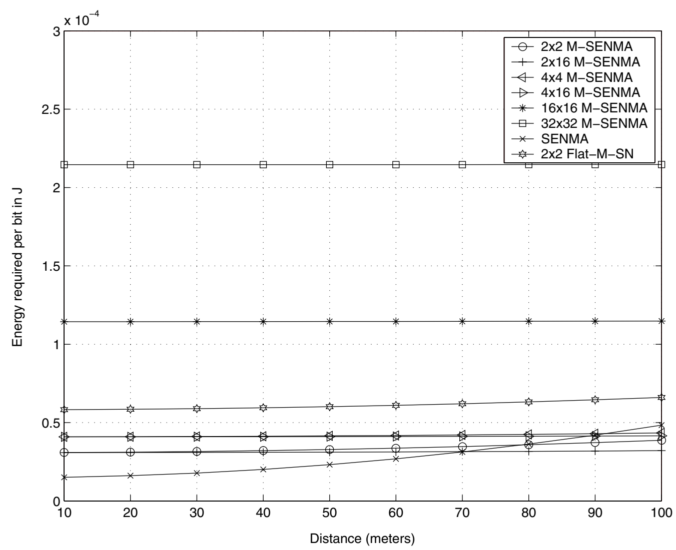


Fig. 4. Upper bound of the energy consumption for M-SENMA over distance

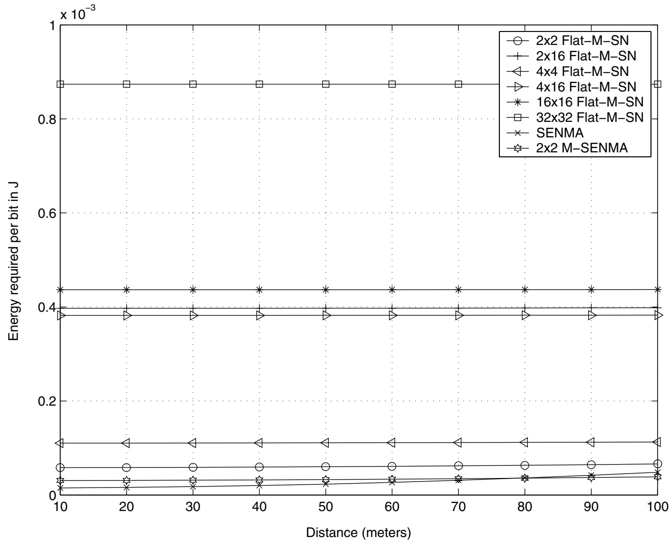


Fig. 5. Upper bound of the energy consumption for Flat-M-SN over distance


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