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IMPACT OF PROPAGATION PARAMETERS ON ENERGY EFFICIENCY IN VIRTUAL MIMO-BASED WIRELESS SENSOR NETWORK

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Abstract

Propagation parameters, i.e. transmission distance, constellation size and channel path loss exponent, dictate the design of energy efficient transmision techniques for WSN. In this paper, by considering these parameters we investigate to obtain the best modulation scheme and transmission strategy that minimizes the total energy consumption of the network, comprised of transmission energy and circuit energy. Analysis of virtual MIMO systems, where the sensor with a single antenna are cooperating to send the data to the Fusion Center (FC) having multiple antenna, for WSN with Alamouti-diversity scheme-based is presented, which has better spectrum efficiency but larger circuit energy consumption than Single Input Single Output (SISO) systems. Our study shows that in certain transmission distance with appropriate selection of constellation size, virtual MIMO systems for WSN have better energy efficient than SISO and Multi Input Single Output (MISO).

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Key words: propagation, energy, efficiency, MIMO, sensor networks.

INTRODUCTION

The main challenge in developing the technology of Wireless Sensor Networks (WSN) is a limitation of network energy, due to the a limited lifetime of the battery. In many cases battery replacement or recharging is either relatively difficult or costly to implement. Therefore the sensors are usually designed to operate within a few years without battery replacement. As a consequence, minimizing energy consumption is a very important task in WSN design and deployment [1].

Multi-antenna communication systems, or better known as Multiple Input Multiple Output (MIMO) system have been proved successfully able to increase the channel capacity of wireless communication systems over fading channels. MIMO can also provide higher data rates comparde to Single Input Single Output (SISO) using the same transmission power and bit error rate. MIMO system transmission requires lower energy to get the same throughput with SISO [2]. At present, MIMO system cannot be applied directly on WSN due to sensors limitation which only has a single antenna. However, MIMO can be applied by allowing multiple sensors to collaborate in transmitting or receiving data or known as a virtual MIMO system, to achieve better energy efficiency in WSN operation.

Energy efficient technique in wireless communication systems focuses on techniques to minimize the transmission energy per bit. In [3], the author proposes several strategies to optimize the energy efficient strategies in wideband area. In [4], an optimal scheduling algorithm is presented to minimize the transmission energy by maximizing the transmission time per packet of data. [5] - [6] provide alternative methods to minimize transmission energy. While in a long-distance wireless communication network ($\geq 100\,m$), the transmission power is more dominant than the circuit power, the situation is different in WSN, because the sensor communication range is limited under 100m $(\leq 100\,m)$ and in this distance communication, circuit power has a significant influence and cannot be negligible [7]. Energy efficient for WSN requires a different approach with wireless communication systems in general because WSN energy optimization technique must consider the transmission power and the circuit power.

Circuit energy/power includes all energy used by all transmitters and receiver circuit blocks, such as ADC, DAC, Synthezier Frequency, Mixer, Low Noise Amplifier and baseband DSP[7]. Several energy efficient schemes that also take into account the circuit energy consumption in SISO systems have been done in [8]-[11]. The problem is MIMO system has a higher circuit complexity than SISO which then requires higher circuit power consumption. Implementation of MIMO energy efficient on WSN is not a guarantee to become the optimum energy efficient because in WSN circuit energy consumption must be considered too.

This paper investigates the energy efficient techniques used in Virtual MIMO system for WSN. Due to the small size of the sensor, it is difficult to be attached with more than one antenna. Alternatively multiple sensors with single antenna can collaborate to estimate or to detect unknown phenomenon or phenomena to be measured. The measurement result is then quantized and transmitted to a data processing center or Fusion Center that has more than one antenna. Our contribution in this paper is to investigate the influence of propagation parameters into energy efficient of virtual MIMO system for WSN. The propagation parameters include transmission distance, constellation size (transmission rates) and channel path loss exponent. This paper focuses on obtaining the optimum constellation size in order to minimize the total energy for MIMO implementation on WSN with relatively short range transmission. We will demonstrate that the optimization problem to obtain the optimal value for the constellation size, which subsequently will minimize the total energy consumption of the network, is a convex one. This kind of problem can be solved by numerical methods interior point algorithm.

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range transmission. We will demonstrate that the optimization problem to obtain the optimal value for the constellation size, which subsequently will minimize the total energy consumption of the network, is a convex one. This kind of problem can be solved by numerical methods interior point algorithm.

The paper is organized as follows. Insection I is an introduction. Section II, we present the system model. The modeling of energy efficient and completion of optimization constellation size problems are introduced in Section III. The simulations results are presented in Section IV and the paper is concluded in Section V.

SYSTEM MODEL

The implementation of virtual MIMO in WSN can be simply described as follows: a set of sensors, having only single antenna, transmit data simultaneously or in a coordinated way, to a data processing center or FC which has more than one antenna. The number of antennas at the transmitter is equal to the number of sensors, N_T. The number of antennas at the receiver is N_R. The distance between sensors is assumed to be closer that the distance between sensors with the Fusion Center. The system configuration can be seen in Fig.1.

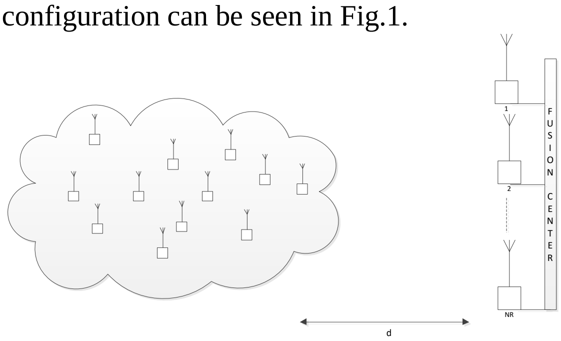


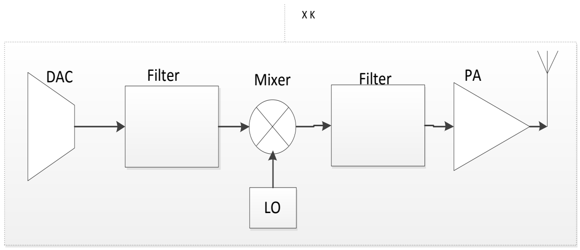
Figure 1. Virtual MIMO Communication Based Wireless Sensor Networks

To simplify the calculation, it is assumed to use Alamouti scheme to get diversity from Alamouti MIMO code system with 2 transmitter antennas proposed by [12], using two different symbols transmitted from the first and second antenna. Alamouti-based MIMO system over Rayleigh fading channels provides higher data rates with the same energy consumption with SISO system.

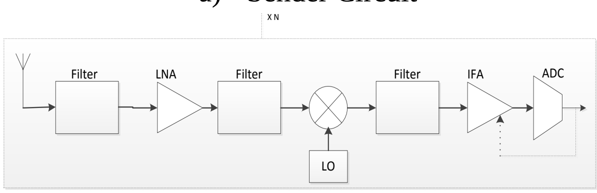
However, if transmission energy and circuit energy are both considered, we need to look further whether MIMO system still has energy efficiency advantage than SISO system, considering MIMO system has more complex circuits. We will analyze the energy efficient ratio in the following section.

ENERGY MODELS

In WSN, energy optimization is carried out by considering the total energy consumption of the whole signal processing blocks on the transmitter and receiver. However, since the throughput requirement is relatively low so that the baseband symbol rate is also low. This model also assumes that no complex signal processing technique such as multi user detection or iterative decoding are used. The power requirement for baseband processing is primarily only for symbol rate and complexity of digital logic circuit. This power requirement is very small compared to the power consumption of RF circuit. Therefore, in this paper, the energy consumption of the baseband signal processing blocks such as source coding, pulse-shaping and digital modulation are neglected. The circuit on the transmitter and receiver is shown in Figure2 [13].



a) Sender Circuit



b) Receiver Circuit

Figure 2. a) Sender Circuit, b) Receiver Circuit

The transmitter and receiver circuit work in three modes. If there is a signal to be transmitted, all circuits are in active mode, if there is no signal to be transmitted, the circuit will be in sleep mode. The transition from sleep-mode to on-mode is called transient mode. This mode is done in order to save energy.

If it is assumed there are Lbits of data to be sent in time T, on WSN, sensors periodically take measuring, quantizing the measurement result data into L bits of data and sends to the FC. In this paper, the sensor has time $T_{on} \leq T$ to finish sending the data, and then all circuits will be shutdown to save energy. Transition time from active to sleep is very short so that it can be neglected. The time from sleep to active is relatively long because the settling time of PLL on frequency synthesizer. The total transmission time is $T = T_{on} + T_{sleep} + T_{tr}$, where $T_{tr}$is the time for transient mode with settling time of frequency synthesizer. Therefore, the total energy consumption of the sensor nodes consists of three components, namely energy on active-mode, sleep-mode and transient-mode. The total energy consumption can be written as follows [13]:

$$E = P_{on} \times T_{on} + P_{sleep} \times T_{sleep} + P_{tr} \times T_{tr} \quad (1)$$

whereP_{on}, $P_{sleep}$and P_{tr} are sensor power to the condition on, sleep and transient.

In this paper, to simplify the problem/calculation between sleep time and transient time is not taken into account. Power when sensor is in on condition consists of two components, namely transmission power and circuit power.

$$P_{on} = P_t + P_C \quad (2)$$

Where P_t is transmission power and P_C is circuit power.

If it is assumed that the frequency synthesizer is shared on all antennas in MIMO system. Then the circuit power can then be estimated as follows: [7]

$$\begin{aligned} P_C = & (P_{DAC} + P_{mix} + P_{filt}) \\ & + 2P_{syn} + (P_{LNA} + Pmix \\ & + P_{IFA} + P_{filt} + P_{ADC}) \end{aligned} \quad (3)$$

where P_{DAC}, P_{mix}, P_{LNA}, P_{IFA}, P_{filt}, P_{filr}, P_{ADC}, and P_{syn} are the power of DAC, mixer, Low Noise Amplifier (LNA), Intermediate Frequency Amplifier (IFA), active filters on the transmitter side, active filters on the receiver side, ADC, and frequency synthesizer [7], P_t can be seen in Equation (4) [7]:

$$P_t = (1 + \beta)P_{out} \quad (4)$$

where $\beta = (\zeta/\eta) - 1$ with η is the drain efficiency of the RF amplifier and the Peak to Average Ratio (PAR), which depends on the modulation scheme and the constellation size, b , which is used [7]. P_{out}can be calculated based on the link budget in Equation (5) [14].

$$P_{out} = \bar{E}_b R_b \times \frac{(4\pi)^2 d^\alpha}{G_t G_r \lambda^2} M_l N_f \quad (5)$$

So that :

$$P_{on} = (1 + \beta)\bar{E}_b R_b \times \frac{(4\pi)^2 d^\alpha}{G_t G_r \lambda^2} M_l N_f + P_C \quad (6)$$

Where $\overline{E}_b$ is the average energy per bit required if certain BER value is desired. R_b is the bit rate, d is the distance between the transmitter and the receiver, G_T is the transmitter antenna gain, G_T is the receiver antenna gain, λ is the carrier wavelength, M_l is the link margin and N_f is the receiver noise figure which is defined as $N_f = \frac{N_r}{N_0}$with $N_0 = -171\, dBm/Hz$ is single-sided thermal noise Power Spectral Density (PSD) at room temperature and N_r is the PSD of the total effective noise at the input receiver. Simulation parameter used here is the same as used in [13].

PROPOSED METHOD OF ENERGY OPTIMIZATION

This section will analyze in detail the algorithm energy optimization in Rayleigh channel with MQAM modulation. The study focuses on the system without Error Control Coding (ECC) but the result of this study can be developed for system with ECC.

Probability of bit error of MQAM in Rayleigh channel can be seen in Equation (7) [14].

$$\bar{P}_b \approx \varepsilon_H \left\{ \frac{4}{b} \left(1 - \frac{1}{2^{\frac{b}{2}}}\right) Q\left(\sqrt{\frac{3b}{M-1}\gamma_b}\right) \right\} \quad (7)$$

Equation (10) is to value $b \geq 2$while for b = 1 is as follows:

$$\bar{P}_b \approx \varepsilon_H \left[Q\left(\sqrt{2\gamma_b}\right)\right] \quad (8)$$

where $\gamma_b = \frac{\|H\|_F^2}{M_t}\frac{E_b}{N_0}$ and $M = 2^b$. To simplify, the analysis will focus on M-ary QAM, MIMO with Alamouti scheme. $\bar{P}_b$value can be simplified by applying the Chernoff bound and obtain:

$$\bar{P}_b \leq \frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)\left(\frac{1.5\bar{E}_b b}{N_T N_R N_0(2^b-1)}\right)^{N_T N_R} \quad (9)$$

From Equation (9), we can derive the upper bound for $\bar{E}_b$ as:

$$\bar{E}_b \leq \frac{2}{3}\left(\frac{\bar{P}_b}{\frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)}\right)^{-\frac{1}{N_T N_R}} \frac{2^b-1}{b^{\frac{1}{N_T N_R}}+1} N_T N_R N_0 \quad (10)$$

Equation (10) can be simplified again by taking $1-\frac{1}{2^{\frac{b}{2}}} \leq 1$ into:

$$\bar{E}_b \leq \frac{2}{3}\left(\frac{\bar{P}_b}{4}\right)^{-\frac{1}{N_T N_R}} \frac{2^b-1}{b^{\frac{1}{N_T N_R}}+1} N_T N_R N_0 \quad (11)$$

if we approach (11) with the equation, it obtains the average of energy per bit for certain BER value is:

$$\bar{E}_b = \frac{2}{3}\left(\frac{\bar{P}_b}{4}\right)^{-\frac{1}{N_T N_R}} \frac{2^b-1}{b^{\frac{1}{N_T N_R}}+1} N_T N_R N_0 \quad (12)$$

In MQAM, the number of bits per symbol or constellation size is $b = log_2 M$. The number of symbols on MQAM which is required to send L bits of data is $L_s = L/b$. If symbol period is $T_s$then $L_s = T_{on}/T_s$and $L/b = T_{on}/T_s$. so that $b = LT_s/T_{on}$. If rectangular pulses are used and assuming that $T_s \approx 1/B$ then $b = L/BT_{on}$if bandwidth efficiency is defined as $B_e = L/BT_{on}$, it can be seen that the MQAM $b \approx B_e$. Total energy consumption of the network can be formulated as follows:

$$E = P_{on} \times T_{on}$$
$$= \left[(1+\beta)\bar{E}_b R_b \frac{(4\pi)^2 d^\alpha}{G_t G_r \lambda^2} M_l N_f + P_C\right] T_{on} \quad (13)$$

Therefore, total energy consumption per bit can be shown as follows:

$$E_{bt} = \frac{2}{3}(1+\beta)\left(\frac{\bar{P}_b}{4}\right)^{-\frac{1}{N_T N_R}} \frac{2^b-1}{\frac{1}{b^{N_T N_R}}+1} \times N_T N_R \frac{(4\pi)^2 d^\alpha}{G_T G_R \lambda^2} N_0 M_l M_f + \frac{P_C T_{on}}{L} \quad (14)$$

If it is assumed that $X = \frac{2}{3}(1+\beta)\frac{(4\pi)^2}{G_T G_R \lambda^2} N_0 M_l M_f$ the Equation (14) will be

$$E_{bt} = \left(\frac{\bar{P}_b}{4}\right)^{-\frac{1}{N_T N_R}} \frac{2^b-1}{\frac{1}{b^{N_T N_R}}+1} X N_T N_R d^\alpha + \frac{P_C T_{on}}{L} \quad (15)$$

From equation (15) if value $L$and $B$are set, then by maximizing the value of T_{on} will minimize the total energy consumption per bit E_{bt}. The problem of total energy optimization per bit can be formulated as follows:

$$\begin{array}{ll} \min & E_{bt} \\ subject\,to & 0 \leq T_{on} \leq T \\ & 0 \leq P_{on} \leq P_{maxt} \end{array} \quad (16)$$

Where P_{maxt} is the maximum power to transmit a signal which value is equal to maximum power of output battery on the sensor to transmit signal minus the total circuit power on the sensor.

For MQAM, based on Equation (14) then Equation (15) can be written that:

$$E_{bt} = \left(\frac{\bar{P}_b}{4}\right)^{-\frac{1}{N_T N_R}} \frac{2^{\frac{L}{BT_{on}}}-1}{\frac{1}{(\frac{L}{BT_{on}})^{N_T N_R}}+1} X N_T N_R d^\alpha + \frac{P_C}{bB} \quad (17)$$

Therefore, the optimization problem in Equation (18) is changed into:

$$\begin{array}{ll} \min_b & E_{bt} \\ \text{subject to} & b_{min} \leq b \leq b_{max} \end{array} \quad (18)$$

Where $b_{max} = \lfloor L/BT_{min} \rfloor$and $b_{min} = max\{\lceil L/B(T-T_{tr})\}$. E_{bt} is convex function of $b$for $b \geq 2$and $\partial^2 E_{bt}/\partial b^2 \geq 0$, see Figure 4. Optimization problem Equation (18) can be written in Equation (19).

$$\begin{array}{ll} \min & E_{bt} \\ \text{subject to} & b - b_{min} \geq 0 \\ & b_{max} - b \geq 0 \end{array} \quad (19)$$

As long as all constraints are simple linear constrains, the optimization problem is a convex problem that can be solved efficiently by using the interior point method [14].

NUMERICAL RESULT

This section gives an example of numerical simulation with parameters as in Table 1. The average energy per bit corresponding to the desired BER, $\bar{E}_b$can be calculated by numerical techniques. If certain $\bar{P}_b$is desired, $\bar{E}_b$value can be obtained by generating a random channel as in Equation (7) on a certain transmission distance and inverses if to get $\bar{E}_b$ with will given a desired value of $\bar{P}_b$.

Figure 4 shows the effect of constellation size selection to the energy efficient of MIMO-based for WSN. The total energy consumption per bit (E_{bt}) according to equation (19) on Alamouti-based MIMO system with 2x2 transmission distance $d = 50\,m$and the path loss exponent $\alpha = 3.5$ reaches minimum at a constellation value size $b = 8$. In other word $b = 8$ is $b$optimal (b_{opt}). Table 2 shows the optimal constellation size for another value d in 2x2 MIMO and SISO.

Figure 5 shows the total energy consumption per bit (E_{bt}) in SISO system and 2x2 MIMO with selected constellation size value optimal $b_{opt} = 8$and $\alpha = 3.5$. It is seen that in transmission distance below 50 m, SISO system has better energy efficient compared to MIMO. However, in transmission distance above 50 m, MIMO system is better than SISO. Figure 6 shows the energy efficient in 2x2 MIMO and 2x1 MISO with selected optimal constellation size value $b_{opt} = 8$and $\alpha = 3.5$. It is seen that the energy efficient of MIMO is better at transmission distance above 20m. Figure 7 shows that if the constellation size $b = 1$or BPSK then SISO has the best energy efficient compared to MISO and MIMO. From these results, it can be seen that by selecting appropriate constellation size then MIMO system performs better than SISO or MISO.Figure 8 shows the energy efficient in MISO and MIMO in various value of pathloss exponent. It is seen that the energy efficient of MIMO is better than MISO. From these results, it can be seen that by selecting appropriate constellation size then MIMO system performs better than SISO or MISO.

Table 1. Parameter System

Parameter	Value
B	10 KHz
η	0.35
N_f	10 dB
σ^2	$\frac{N_0}{2} = -174\,dBm/Hz$
α	$2 \sim 5$
$G_t G_r$	5 dBi
P_b	10^{-3}
f_c	2.5 GHz
N_0	-171 dBm/Hz
λ	0.12 m
M_l	40 dB
$P_{filt} = P_{filr}$	2.5 mW
β	1
P_{syn}	50 mW
T_s	$\frac{1}{B}$
P_{LNA}	20 mW
P_{mix}	30.3 mW
P_{maxt}	250 mW
T_{tr}	5 mikro s
T	100 ms
L	2 Kb
P_{IFA}	3 mW

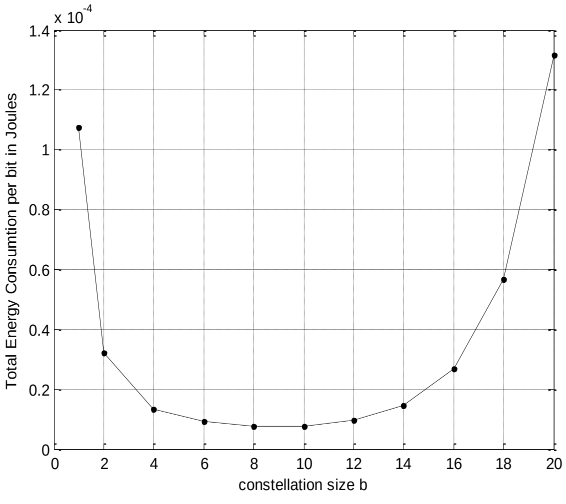


Figure 4. Total energy Consumption per bit over size constellation MIMO 2 x 2, $d = 50\,m$, $\alpha = 3.5$

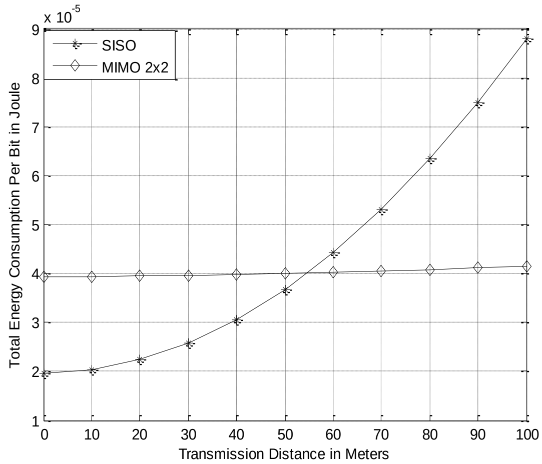


Figure 5. Total Energy Consumption per bit on SISO dan MIMOsystem2x2, $b = 8$, $\alpha = 3.5$in various values d

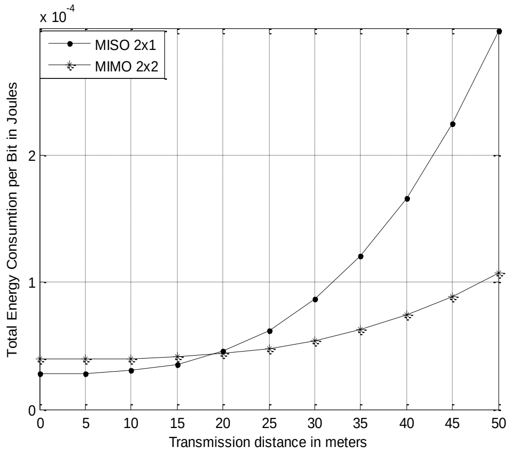


Figure 6. Energy per bit MISO 2x1 and MIMO 2x2, $b = 8$,$\alpha = 3.5$on various values of d

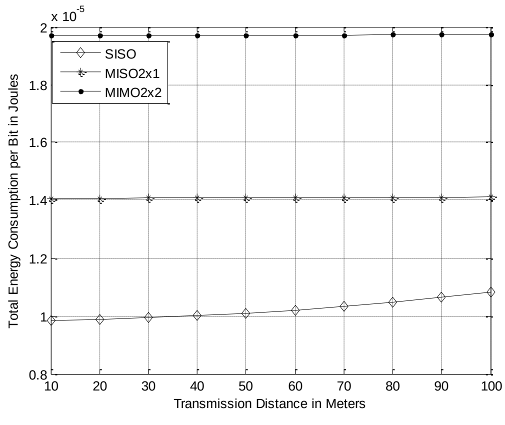


Figure 7. Energy per bit in MISO 2x1 and MIMO 2x2, $b = 1$ (BPSK),$\alpha = 3.5$ on various values of d

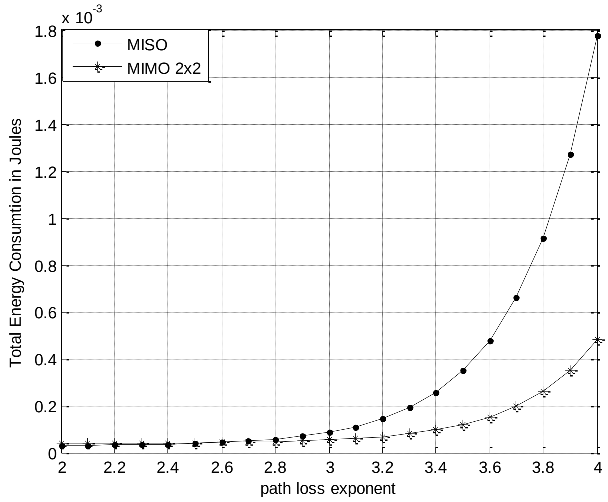


Figure 8. Total Energy per bit in MISO system 2x1 and MIMO 2x2, $b = 8$on various values ofpath loss exponent

The novelty of this paper is taking into account both the energy transmission and the circuit energy consumption because it is not clear which system is more energy-efficient, since the MIMO system has much more energy-consuming circuitry. The result show that in short-range applications, especially when the data rate and the modulation scheme are fixed SISO systems may outperformMIMO systems as far as the energy efficiency is concerned. However, by optimizing the constellation size, we can extend the superiority of MIMO systems in terms of energy efficiency down to very short distances.

CONCLUSION

In this paper, a semi-analytical method is proposed to obtain energy efficient in MIMO system for WSN. In this research, it is assumed that the channel between sensors and FC is a Rayleigh channel and sensors have a proper knowledge about the channel condition. The does not include with error control coding scheme. The analysis is observing the effect of the propagation parameters such as transmission distance, channel path loss exponent and the constellation size (transmission rate). Energy consumption includes transmission energy and circuit energy. MIMO system which has more complex circuits obviously requires more circuit energy, especially for short-range communication system where the circuit energy has equal effect compare to the transmission energy. However, in this paper, it is shown that by choosing a proper constellation

size, virtual MIMO system can provide better energy efficient compared to SISO/MISO on relatively short range communication, $\pm 50m$. For $\pm 100\,m$range communication, MIMO can save the energy until up to 50%. By applying virtual MIMO strategy onWSN where a set sensor on the transmitter transmit the data to the Fusion Center which occupy with multiple antennas will result in a energy efficiency that proportional to the distance between sensor and Fusion Center.

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