EFFECT OF MUTUAL COUPLING ON THE ENERGY REQUIREMENT OF MIMO-BASED WIRELESS SENSOR NETWORKS

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ABSTRACT

A theoretical model was developed to estimate effect of the mutual coupling on the energy requirement of a multiple-input multiple-output (MIMO) based wireless sensor network (WSN). Clustered channel modeling with Rician fading distribution is assumed to include the effect of the line-of-sight (LOS) ray paths. The effect of propagation environments is included in the analysis by assuming a two-slope path loss model. The effect of knowing the channel state information (CSI) in the MIMO system ($MIMO_{csi}$) is also included in the analysis. It is shown that the presence of mutual coupling between elements of MIMO array decreases the energy required by the MIMO based WSN. Simulation results also show that it is possible to use a compact circular antenna array with a quarter wavelength diameter to build a $MIMO_{csi}$ based WSN that requires almost constant energy for applications that cover a range from few meters up to around 100m.

Index Terms— Energy efficiency, multiple-input multiple-output (MIMO), wireless sensors networks.

1. INTRODUCTION

Wireless sensor networks are an emerging application area which has received recent attention. The idea is to use a collection of cheap, stationary, tiny sensors to sense, coordinate and transmit some physical characteristics about the surrounding environment to an associated node. One of the most cited examples is the battlefield surveillance of enemy territory wherein a large number of sensors are dropped there so that ground based activities are detected and communicated. Other commercial applications include machinery diagnosis, bio sensing, and environmental monitoring. One of the main issues in using these units is how to maximize their operational lifetime. The power demand is a major driving issue behind design methods and protocols tailored to these networks, since the lifetime of the battery usually defines the sensor lifetime.

A number of techniques have been proposed to minimize the power requirements of wireless monitoring systems. Some techniques focus on using different modulation techniques [1]. Others propose modifications on the operating system or the software that control the operation of those systems [2]. The possibility of using MIMO systems in limited-energy applications was also

investigated as it is widely known that MIMO systems require less transmission energy per data byte than SISO systems [3-5].

As the space available for MIMO antenna elements is limited, often antennas are located close together and so mutual coupling between the antennas must be considered. This factor was neglected in the analysis and simulations presented in the previous papers [3-5]. The main objective of this paper is to present a theoretical model for MIMO based WSN, which includes the effect of the antenna array design by considering the mutual coupling effect. Different propagation conditions are included in the model. In contrast to the model presented in [3], the effect of line-of-sight signals is included by considering Rician fading distribution.

2. PROPAGATION MODEL

The propagation channel model used in this paper is based on the clustered channel model [6]. This model describes propagation paths as channel taps grouped in clusters. Each cluster is characterized by a mean angle-of-arrival (AOA) and consists of multiple paths, with AOA values randomly distributed. The power azimuth spectrum (PAS) within each cluster is assumed to have a Laplacian distribution as it coincides with many measurements [7]. The number of clusters, the values of PAS and its standard deviation used in this calculation, are assumed according to model F of IEEE.802.11n [6] as it describes accurately most of the wide area indoor and outdoor environments in which the WSN is used. Rician fading distribution is assumed because when WSN work in short range environments there is a high probability of line of sight propagation.

The first step when simulating the performance of a MIMO system is to find the channel matrix. In this paper we will deal only with antenna arrays with a total length of less than one wavelength. The channel matrix $\mathbf{H}$ can be found using the following method [8];

$$\mathbf{H} = \mathbf{R}_r^{1/2} \mathbf{H}_G \mathbf{R}_t^{1/2} \quad (1)$$

where $\mathbf{H}_G$ is the channel matrix with elements that are independent zero mean circularly symmetric complex Gaussian random variables, $\mathbf{R}_r$ is the $N \times N$ receive covariance matrix and $\mathbf{R}_t$ is the $M \times M$ transmit covariance matrix, assuming N receive antennas and M transmit antennas. These matrices are calculated using the method discussed in [8] after making the following

modifications so that it would be suitable for the *UCA* shown in Fig. 1. Note that the *AOA*, ϕ_{ULA} , is measured relative to the reference direction defined by elements i and j in the *UCA*;

$$\phi_{UCA} = \phi_{ULA} - \left[\frac{2\pi}{n} (j-i) \right] \quad (2)$$

where n is number of elements in the array, i and j are the sequence of elements in the array (1, 2, 3 ... n). Also in this simulation, we will assume a fixed diameter D for the array with elements of the array distributed uniformly on the circumference. The spacing d between the i and j elements in the array can be found from the following relation, see Fig. 1;

$$d = D * \sin \left[\frac{2\pi}{n} (j-i) \right] \quad (3)$$

From the channel matrix, the instantaneous receiver signal to noise ratio (SNR_i) is calculated using the following equation [8];

$$SNR_i = \frac{\sum_{i=1}^k \lambda_i}{M} * \frac{\bar{E}_b}{N_o} \quad (4)$$

where $\bar{E}_b$ is the required energy per bit at the receiver to achieve the required bit rate, N_o is the noise energy, λ_i is the i^{th} eigen value of the channel matrix, and k is $\min(N, M)$. Note that for the *SISO* system $M = 1$ in (4).

For *MIMO_{est}*, the water-filling algorithm can be used to maximize the capacity and in this case [8];

$$SNR_i = \sum_{i=1}^k \frac{\bar{E}_{bi}}{MN_o} \lambda_i \quad (5)$$

where $\bar{E}_{bi}$ is the portion of energy allocated to the data transmitted from the i^{th} antenna.

The two-slope path-loss model [6] is used to calculate the path loss L_p . This model assumes that the received power is proportional inversely with the distance squared up to the break-point distance r_{br} . At larger distances the power falls by a rate proportional to $r^{3.5}$. The break-point distance depends on many parameters including the transmitter antenna height, the receiver antenna height and the wavelength. In this paper r_{br} is taken to be 10m which is suitable for many *WSN*.

The effect of cochannel interference is included in the channel model by considering that many *WSNs* may be located in a nearby area and some might use the same frequency band. The signal to interference and noise ratio (*SINR*) can then be calculated from (5) after taking into consideration effect of all the interfering signals. In this paper, a seven cell reuse model is considered. The details of the calculation can be found in the companion paper [9].

3. MUTUAL COUPLING

When the array is compact in size due to the limited space available, then the inter-element spaces will be small. In this case the current excited or induced in an element is not only due to the incident field or the applied voltage; it also depends on the currents of the adjacent elements due to the mutual coupling. While the effect of mutual coupling on the performance of an array of antennas is well known in the literature, the analysis hereafter presents a simple closed-form model that shows the effect of mutual coupling on the channel matrix of *MIMO* systems depending on the electrical circuit analogy of the *MIMO* array. Following the mutual coupling theory [10], [11] at the transmitter side, and assuming the circuit equivalent shown in Fig.2, we can write;

$$\begin{bmatrix} Z_{11} + Z_{L1} & Z_{12} & \dots & Z_{1M} \\ Z_{21} & Z_{22} + Z_{L2} & \dots & Z_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{M1} & Z_{M2} & \dots & Z_{MM} + Z_{LM} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_M \end{bmatrix} = \begin{bmatrix} v_{S1} \\ v_{S2} \\ \vdots \\ v_{SM} \end{bmatrix} \quad (6)$$

or simply;

$$(Z_{CT} + Z_{LT}) \mathbf{I}_T = \mathbf{V}_{ST} \quad (7)$$

where Z_{CT} is the mutual coupling matrix in the transmitter side, $\mathbf{I}_T$ is the vector of elements currents, Z_{LT} is a vector and its elements are the load impedances and/or signal generator internal impedances connected to elements of the transmitter array and $\mathbf{I}$ is the identity matrix while $\mathbf{V}_{ST}$ is a vector and its elements are the signal voltages as shown in Fig.4.

From (7);

$$\mathbf{I}_T = (Z_{CT} + Z_{LT})^{-1} \mathbf{V}_{ST} \quad (8)$$

If there is no coupling between array elements then (6) becomes;

$$\begin{bmatrix} Z_{11} + Z_{L1} & 0 & \dots & 0 \\ 0 & Z_{22} + Z_{L2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & Z_{MM} + Z_{LM} \end{bmatrix} \begin{bmatrix} i_{1nc} \\ i_{2nc} \\ \vdots \\ i_{Mnc} \end{bmatrix} = \begin{bmatrix} v_{S1} \\ v_{S2} \\ \vdots \\ v_{SM} \end{bmatrix} \quad (9)$$

Or simply;

$$(Z_{SCT} \mathbf{I} + Z_{LT}) \mathbf{I}_{Tnc} = \mathbf{V}_{ST} \quad (10)$$

Where Z_{SCT} is vector of self coupling impedances and $\mathbf{I}_{Tnc}$ is vector of elements currents when there is no mutual coupling. Equation (10) can be modified to;

$$\mathbf{I}_{Tnc} = (Z_{SCT} \mathbf{I} + Z_{LT})^{-1} \mathbf{V}_{ST} \quad (11)$$

The same analysis can be repeated for the receiver side with a unique difference, that is the vector of signal generator voltages that appeared in the transmitter equations is replaced by the vector of generated or induced voltages in elements of the receiving array $\mathbf{V}_{GR}$. So, from (8) and (11) one can conclude the following equations for the receiving side;

$$\mathbf{I}_R = (Z_{CR} + Z_{LR})^{-1} \mathbf{V}_{GR} \quad (12)$$

$$\mathbf{I}_{Rnc} = (Z_{SCR} \mathbf{I} + Z_{LR})^{-1} \mathbf{V}_{GR} \quad (13)$$

where $\mathbf{I}_R$ and $\mathbf{I}_{Rnc}$ are vectors of receiving array currents in case of coupling and no coupling respectively,

Z_{CR} is receiver coupling matrix and Z_{SCR} is vector of receiver self impedances.

The channel matrix given in (1) can now be modified to include the effect of mutual coupling on the overall performance of the system. When there is no mutual coupling, the basic relation between the channel matrix H and the element currents at the transmitter and receiver is;

$$I_{Rnc} = HI_{Tnc} \quad (14)$$

Substituting (11) and (13) into (14) and using some manipulations;

$$V_{GR} = (Z_{SCR}I + Z_{LR}I)H(Z_{SCT}I + Z_{LT}I)^{-1}V_{ST} \quad (15)$$

When mutual coupling has to be taken into consideration then (14) is modified to;

$$I_R = H_{mod}I_T \quad (16)$$

where H_{mod} is the modified channel matrix which includes the effect of the propagation environments and mutual coupling. Substituting (7) and (12) into (15) with rearrangements gives;

$$I_R = (Z_{CR} + Z_{LR}I)^{-1}(Z_{SCR}I + Z_{LR}I)H(Z_{SCT}I + Z_{LT}I)^{-1}(Z_{CT} + Z_{LT}I)I_T \quad (17)$$

Comparing (16) with (17);

$$H_{mod} = (Z_{CR} + Z_{LR}I)^{-1}(Z_{SCR}I + Z_{LR}I)H(Z_{SCT}I + Z_{LT}I)^{-1}(Z_{CT} + Z_{LT}I) \quad (18)$$

In the simulations that follow, it is assumed that antenna elements at the transmitter and receiver side are similar which means that they have equal self impedance. Also, the load and the signal generator impedances connected to all elements are assumed to be equal to the conjugate of the self antenna impedance to get the best matching.

4. ELECTRONIC CIRCUITRY

The transmitter and receiver electronics assumed in this paper are as shown in Fig. 4. For the *MIMO* system there are N parallel branches of the receiver circuits and M branches of the transmitter circuits as shown in Fig. 4. The power requirements for different parts of the electronic circuitry of *MIMO* system are as given in [1].

The following equations are used to estimate the energy requirements [1], [3].

$$E_b = (1 + \alpha)[\bar{E}_b * \frac{Mar * N_f}{G_t G_r} * L_p] + \frac{P_c}{R_b} \quad (19a)$$

$$P_c = MP_t + 2P_s + NP_r \quad (19b)$$

$$B_e = Mean[Q(\sqrt{2 * SINR})] \quad (19c)$$

where the parameter to be minimized is E_b , the total energy consumption per bit, α defines the amplification characteristics of the power amplifier at the transmitter, Mar is the safety margin for the system, N_f is noise figure of the receiver, G_t, G_r are the gains of an antenna element at the transmitter and receiver side respectively, R_b is the bit rate. P_c, P_t, P_s, P_r are the power consumption values of the circuit sections for one branch of the transmitter digital-to-analog converter, mixer and filter; the synthesizer; and the receiver low-noise amplifier, mixer, intermediate frequency amplifier, filter and analog-to-digital converter. The Q function in (19c) is the

Gaussian error integral and B_e is the bit error rate. The word (*Mean*) in (19c) indicates that the estimation should be averaged over all the channel matrix possibilities.

5. RESULTS AND DISCUSSIONS

The performance of the *MIMO* based *WSN* was simulated using a frequency of 2.5GHz, the maximum bit error rate was 0.001, and the bit rate was 10Kbps. Channel simulations assume Rician distribution with a rice factor equal to 10dB. In all results that follow, antenna elements of the *MIMO* are distributed uniformly on the circumference of the circle specified by a certain diameter value.

The effect of mutual coupling on the performance of *MIMO* systems in energy-limited conditions is shown in Fig. 4. It is clear from Fig. 4a that the mutual coupling has no significant effect on the performance when the distance between elements of the antenna is approximately half a wavelength. On the other hand, when the distance between antenna elements is equal or less than quarter of the wavelength, mutual coupling increases the *SNR* of *MIMO* systems, and hence improves its performance, see Fig. 4b. This conclusion becomes more obvious when the number of antenna elements is increased while the array dimension remains constant, as in Fig. 4c. This conclusion coincides with the results in [12] and [13] which indicate that decorrelation on the channel coefficient due to mutual coupling can increase the capacity or the effective signal to noise ratio of *MIMO* systems. It is clear from the results shown in Fig. 4c that the *MIMO* array can be made significantly more compact without degradation in performance.

6. CONCLUSION

Wireless monitoring systems usually offer limited space for the antenna arrays and therefore, mutual coupling should be considered when building *MIMO* based wireless sensor networks. In this paper, a theoretical model has been presented to show the effect of mutual coupling on the energy requirement of these systems. The results introduced in this paper have shown that *MIMO* can work effectively in the limited space available for the antenna elements as the mutual coupling appears to have a positive effect on the overall performance for antennas spacing equal to, or less than, quarter of the wavelength.

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Fig.1: Uniform circular array configuration.

Fig.2: Representation of (a) a receiving antenna array, and (b) a transmitting antenna array as an electrical network.

Fig.4: Block diagram of the transmitter (upper part) and the receiver (lower part).

(a)

(b)

(c)

Fig.4 Effect of mutual coupling on performance of MIMO based WSN. A two-slope model is assumed. (a) $N=M=2$, diameter of array = $\lambda/2$, (b) $N=M=2$, diameter of array = $\lambda/4$, (c) $N=M=4$, diameter of array = $\lambda/4$.