# On the design of a wireless multi-antenna monitoring system

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*Abstract*— **In this paper we investigate the design of a wireless monitoring system. This system consists of several wireless monitoring units, each transmitting data collected from sensors. This data is received and processed at a central control unit. The typical operating environment poses several challenges. The channel's delay spread is substantial and the distance between receiver and transmitter is in the order of 400 meters. In order to guarantee reliable communication, we combine multi-antenna techniques (space-time block coding) with strong coding (LDPC codes). The cost and complexity of the monitoring units is kept low, and most of the processing is performed on the central control unit. We present a system design for the monitoring units and show simulation results.**

*Keywords*—**MIMO, LDPC, wireless, STBC**

## I. Introduction

A typical scenario for a wireless monitoring system is a group of 40 sensors in a large factory hall, connected to a central control unit. Each sensor produces data at a rate of about 64 kilobits per second. Hence, the aggregate data rate of the system is in the order of 3 megabits per second. Because the sensors can be used for process control, highly reliable communication is required. In a typical operating environment the sensors are hundreds of meters apart. The wireless system should be able to communicate reliably across such distances. The system operates in the 2.4 GHz band and therefore needs to be insensitive to interference from other standards that are operating in the same frequency band.

This combination of requirements can be met by combining Orthogonal Frequency Division Multiplexing [1] (OFDM), space-time (multi-antenna) techniques and Low-Density Parity-Check [2] (LDPC) codes. When these techniques are used it is possible to achieve reliable communication at very low signal-to-noise ratios. This enables cost and power reduction in both the analog and digital domain because of less stringent linearity requirements and low dynamic range. Figure 1 gives an overview of the wireless monitoring system. The outline of this paper is as follows.

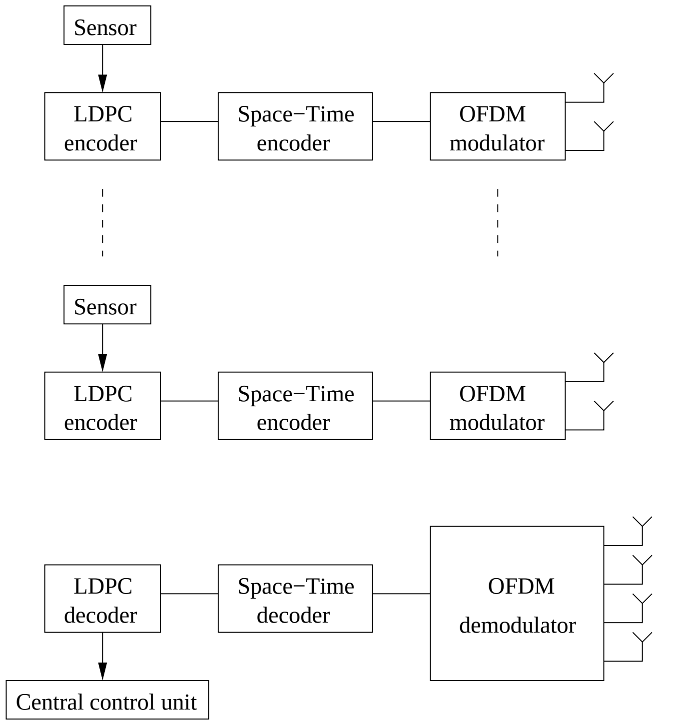


Fig. 1. Overview of the monitoring system.

First, we describe the space-time code that is used, followed by a description of the multi-user access technique that has been implemented. Subsequently, we describe the coding method and show simulation results.

## II. Notation

Vectors are denoted by bold lowercase letters, and matrices are denoted by bold uppercase letters. Other notations used are:

| | |
|---|---|
| $\mathbf{A}^H$ | Complex conjugate transpose (Hermitian) of $\mathbf{A}$ |
| $E\{\mathbf{A}\}$ | Statistical expectation of the matrix $\mathbf{A}$ |
| $\mathbf{I}_N$ | $N \times N$ identity matrix |
| $\|\|\mathbf{b}\|\|$ | Euclidian norm of the vector $\mathbf{b}$ |
| $\|\|\mathbf{A}\|\|_F$ | Frobenius norm of the matrix $\mathbf{A}$ |

## III. MIMO

Systems that employ multiple antennas at both the receiver and the transmitter are called multiple-input multiple-output (MIMO) systems. MIMO systems exploit multipath fading and have properties that make them well suited for broadband wireless systems. One of those properties is the *diversity gain* which increases the link reliability. Another property is the *multiplexing gain* which increases the spectral efficiency, and therefore enables higher bitrates. Both diversity gain and multiplexing gain can be obtained without the need for extra bandwidth or transmit power.

For the monitoring system we only use 2 antennas at the sensors in order to keep the complexity low. We employ space-time block codes (STBC) to increase the link reliability. These codes will be discussed next.

### A. Space-Time Block Codes

In [3] Alamouti presented a transmit diversity scheme for two transmit antennas that was later generalized to space-time block codes by Tarokh [4]. Space-time block codes are based on orthogonal designs and provide very simple maximum likelihood decoding, based on linear processing. It has been shown in [4] that no full-rate complex orthogonal code matrices exist for dimensions other than two. It was also shown that rate $\frac{1}{2}$ orthogonal designs exist in every dimension. A number of rate $\frac{3}{4}$ orthogonal designs has been found in three and four dimensions.

Denote $\mathcal{A}$ as the complex constellation that is used at each transmit antenna. A complex orthogonal design of size $n$ is defined as an orthogonal matrix $\mathcal{O}_n$ with entries that are linear combinations of $s_1, s_2, \ldots, s_n, s_1^*, s_2^*, \ldots, s_n^*$, $s_i \in \mathcal{A}$. The matrix $\mathcal{O}$ also needs to satisfy the following condition:

$$\mathcal{O}_n^H \mathcal{O}_n = (|s_1|^2 + |s_2|^2 + \cdots + |s_n|^2)\mathbf{I_n} \quad (1)$$

Because of the orthogonality of the columns of $\mathcal{O}$ the decoding process becomes very simple as will be shown below.

The complex orthogonal design for two transmit antennas presented by Alamouti is given by:

$$\mathcal{O}_2 = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}$$

This design uses two transmit antennas and an arbitrary number of receive antennas. In the first timeslot the symbols $s_1$ and $s_2$ are transmitted from antennas one and two, respectively. In the next timeslot $-s_2^*$ is transmitted from antenna one and $s_1^*$ is transmitted from antenna two.

A system with two transmit and one receive antenna that uses Alamouti's orthogonal design can be described as:

$$\underbrace{\begin{bmatrix} r_1 \\ r_2 \end{bmatrix}}_{\mathbf{r}} = \underbrace{\begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}}_{\mathcal{O}_2} \underbrace{\begin{bmatrix} h_1 \\ h_2 \end{bmatrix}}_{\mathbf{h}} + \underbrace{\begin{bmatrix} n_1 \\ n_2 \end{bmatrix}}_{\mathbf{n}} \quad (2)$$

where $\mathbf{r}$ is the received symbol vector, $\mathcal{O}_2$ is Alamouti's orthogonal design and $\mathbf{n}$ is i.i.d. complex Gaussian distributed noise. The two channels ($h_1$ and $h_2$) between the two transmit antennas and the receive antenna are modelled as Rayleigh fading channels. Hence, the channel coefficients $h_i$ are circularly symmetric complex Gaussian random variables with zero mean and unit variance.

Similarly, a system with two receive antennas can be described as:

$$\underbrace{\begin{bmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{bmatrix}}_{\mathbf{R}} = \underbrace{\begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}}_{\mathcal{O}_2} \underbrace{\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}}_{\mathbf{H}} + \underbrace{\begin{bmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{bmatrix}}_{\mathbf{N}} \quad (3)$$

In order to simplify the analysis, an equivalent system description is used:

$$\mathbf{r}' = \mathcal{H}\mathbf{s} + \mathbf{n}' \quad (4)$$

For a one receive antenna system this equivalent description looks like:

$$\underbrace{\begin{bmatrix} r_1 \\ r_2^* \end{bmatrix}}_{\mathbf{r}'} = \underbrace{\begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}}_{\mathcal{H}} \underbrace{\begin{bmatrix} s_1 \\ s_2 \end{bmatrix}}_{\mathbf{s}} + \underbrace{\begin{bmatrix} n_1 \\ n_2^* \end{bmatrix}}_{\mathbf{n}'} \quad (5)$$

and with two receive antennas it becomes:

$$\underbrace{\begin{bmatrix} r_{11} \\ r_{12}^* \\ r_{21} \\ r_{22}^* \end{bmatrix}}_{\mathbf{r}'} = \underbrace{\begin{bmatrix} h_{11} & h_{21} \\ h_{21}^* & -h_{11}^* \\ h_{12} & h_{22} \\ h_{22}^* & -h_{12}^* \end{bmatrix}}_{\mathcal{H}} \underbrace{\begin{bmatrix} s_1 \\ s_2 \end{bmatrix}}_{\mathbf{s}} + \underbrace{\begin{bmatrix} n_{11} \\ n_{12}^* \\ n_{21} \\ n_{22}^* \end{bmatrix}}_{\mathbf{n}'} \quad (6)$$

When equation (3) is compared with equation (6), it becomes clear that for each extra receive antenna the matrix $\mathcal{H}$ gains two extra rows. Therefore, the diversity order is increased by two, which leads to the diversity order of $2M$ for a system with $M$ receive antennas.

The maximum likelihood decoding rule can now be written as:

$$\hat{\mathbf{s}} = \underset{\mathbf{s} \in \mathcal{A}^M}{argmin} ||\mathcal{H}\mathbf{s} - \mathbf{r}'||^2 \quad (7)$$

Because of (1) the matrix $\mathcal{H}$ has the property:

$$\mathcal{H}^H \mathcal{H} = ||\mathbf{H}||_F \mathbf{I}_2 = \alpha \mathbf{I}_2 \quad (8)$$

This property can be used to simplify the decoding by applying linear filtering to $\mathbf{r}'$:

$$\begin{aligned}\mathbf{y} &= \mathcal{H}^H\mathbf{r}' \\ &= \alpha\mathbf{s} + \mathcal{H}^H\mathbf{n} \\ &= \alpha\mathbf{s} + \mathbf{v}\end{aligned} \tag{9}$$

where $\mathbf{y}$ is the result of filtering and $\mathbf{v}$ is a vector with white noise ($E\{\mathbf{v}\mathbf{v}^H\} = \alpha E\{\mathbf{n}\mathbf{n}^H\}$). Combining (9) and (7) results in:

$$\hat{\mathbf{s}} = \underset{\mathbf{s}\in\mathcal{A}^M}{argmin}||\mathcal{H}^H\mathcal{H}\mathbf{s} - \mathbf{y}||^2 = \underset{\mathbf{s}\in\mathcal{A}^M}{argmin}||\alpha\mathbf{s} - \mathbf{y}||^2 \tag{10}$$

Therefore, the decoding rule for symbol $s_i$ is:

$$\hat{s_i} = \underset{s_i\in\mathcal{A}}{argmin}||\alpha s_i - y_i||^2 \tag{11}$$

The above equation is normal demodulation with a scaling factor. Hence, the added complexity of the Alamouti scheme at the receiver is just the matrix multiplication. In the next section we discuss the modulation and multi-user access methods.

## IV. OFDMA

### A. Multi-user access

We use OFDM with a total bandwidth of 10 MHz and 256 carriers. This provides an inter-carrier spacing of 39.0625 kHz. This inter-carrier spacing is sufficient to make each carrier flat fading. OFDM provides a simple method for multi-user access. This method assigns carriers to individual users and is called Orthogonal Frequency Division Multiple Access [5] (OFDMA). Each of the sensors is assigned four carriers which are spaced 2.5 MHz apart, such that each carrier experiences uncorrelated fading. This carrier assignment is rotated in time to give extra frequency diversity and protection against possible interference. This is very similar to frequency hopping. The carriers are QPSK modulated which results in an aggregate per user raw bitrate of 312.50 kbit/second.

ETSI has characterized the channel in a large hall by an impulse response with a length in the order of 2 microseconds [6]. To prevent inter-symbol interference, a cyclic prefix of 64 samples is used which corresponds to 6.4 microseconds.

### B. Synchronization

In OFDM systems, symbol timing synchronization and frequency offset compensation has to be performed. In the wireless monitoring system there is a link from the control unit to the sensors. This link also uses OFDM as modulation method. Based on the cyclic prefix of this OFDM signal, the frequency offset at each sensor can be estimated. Each sensor will alter its carrier frequency to undo its frequency offset. Because the frequency offset will be slowly varying, this adaptation can be performed during power-on of the sensors and can be repeated every several hours. At the sensor the frequency offset estimation is performed by a method based on the cyclic prefix, which is described in [7]. To estimate the time offset at the basestation the same method is used. Each individual sensor will produce four carriers of the total OFDM signal and depending on propagation delay differences, a certain time mismatch between the signals arriving at the basestation occurs. The maximum allowable time difference between two signals from the sensors is equal to half the cyclic prefix length (3.2 microseconds). This corresponds to a maximum difference in round-trip distance from sensors to basestation of 480 meters.

## V. Low-Density Parity-Check codes

Low-Density Parity-Check codes are used as error correcting codes. LDPC codes are a subclass of linear block codes which have at least one sparse parity check matrix. The advantage of LDPC codes is that efficient decoding algorithms exist to approximate bitwise MAP decoding. In this paper only regular LDPC codes are used, which actually date back to 1963 [2].

Because of latency requirements the block length is set to 2000 bits. The sensors produce data at a rate of 64 kbit/second. With a raw bitrate of 312.50 kbit/second, code rates as low as $\frac{1}{5}$ are possible.

## VI. Simulations

We have simulated two different configurations. One configuration uses space-time block codes, as described in section III-A, with two transmit antennas and four receive antennas. The other configuration is similar but only uses one antenna at the transmitter and receiver. This enables us to analyze the effect of the added spatial diversity of the STBC system. Both systems have been simulated with code rates of $\frac{1}{4}$ and $\frac{1}{2}$. Perfect synchronization and frequency offset correction is assumed in the simulations. The channel estimation is also assumed to be perfect. The simulation results are shown in figure 2. With a code rate of $\frac{1}{2}$ the STBC system achieves a biterror rate of $10^{-5}$ at -1.25 dB. The single antenna systems needs 21 dB more to achieve the same biterror rate. When the code rate is lowered to $\frac{1}{4}$ the STBC system needs about 3.1 dB less to reach a biterror rate of $10^{-5}$ compared to the STBC system with a higher code rate. A 3 dB gain is caused by the reduction in code rate, hence the increase in coding gain is small. The single antenna system with a code rate of $\frac{1}{4}$ reaches $10^{-5}$ at 12.9 dB which is 7.7 dB less than the

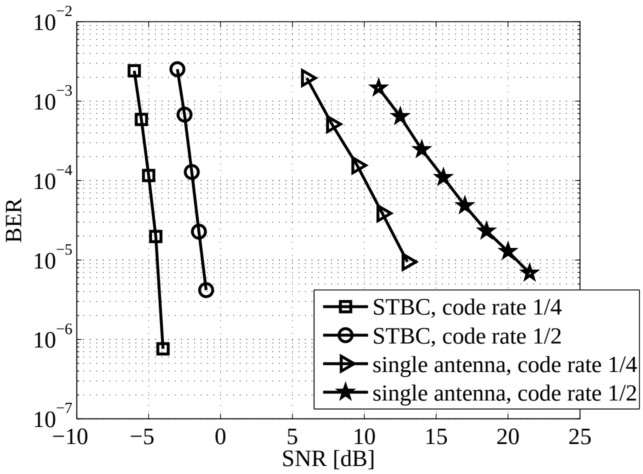


Fig. 2. Simulation results.

higher code rate single antenna system but about 17.3 dB more than the low code rate STBC system. Hence, for the low code rate single antenna system the increase in coding gain is about 4.7 dB.

## VII. Conclusions

We described a design of a wireless monitoring system which combines space-time coding, OFDM and LDPC codes to provide high reliability at very low signal-to-noise ratios. At a code rate of $\frac{1}{4}$ the proposed design performs 17.3 dB better than a similar single antenna design. For a code rate of $\frac{1}{2}$ this performance gap is about 21 dB. Therefore, it can be concluded that for an OFDMA system with a low number of carriers per user, and hence limited frequency diversity, space-time block coding dramatically improves the performance. Because the proposed design can operate at such low signal-to-noise ratios, the transmit power can be very low. This relaxes the requirements of the analog frontend resulting in lower complexity and cost.

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