MIMO Technology for Wireless Sensor Network

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Abstract

Wireless sensor network, where an access point (AP) communicates with many sensor nodes (SN), which are simple, cheap, low-complexity and low-power communication nodes. Various schemes that employ multiple antennas at the transmitter and receiver are being considered to improve the range and performance of communication systems. By far the most promising multiple antenna technology today happens to be the so called multiple-input multiple-output (MIMO) system. MIMO algorithms in a radio communication send information out over two or more antennas. The radio signals reflect off objects, creating multiple paths that in conventional radios cause interference and fading. But MIMO uses these paths to carry more information, which is recombined on the receiving side by the MIMO algorithms.

1. Introduction

Wireless sensor networks are an enabling technology for many future surveillance oriented application. The demand for capacity in cellular and wireless local area networks has grown in a literally explosive manner during the last decade. In particular, the need for wireless Internet access and multimedia applications require an increase in information throughput with orders of magnitude compared to the data rates made available by today's technology. The greatest current challenge for future wireless communication systems is therefore to provide broadband mobile data access with a quality of service as high as possible. Other challenges of wireless communication are like, the limited availability of the radio frequency spectrum and a complex space time varying wireless environment [5].

Traditional wireless communication systems use a single antenna for transmission and a single antenna for reception. Such systems are known as single input single output (SISO) systems. In recent years, significant progress has been made in developing systems that use multiple antennas at the transmitter and the receiver to achieve better performance. There are two types of benefits of using multiple antennas: link budget / spatial diversity improvement and throughput improvement from spatial multiplexing. Spatial diversity refers to the fact that the probability of having all antennas at bad locations is significantly lower as the number of antennas increases. Link budget improvement refers to the fact that the signals from the various antennas can be combined to form a signal stronger than any of the individual signals [1].

2. MIMO Technology

MIMO technology leverages multipath behaviour by using multiple, transmitters and receivers with an added spatial dimension to dramatically increase performance and range [6]. MIMO allows multiple antennas to send and receive multiple spatial streams at the same time. Communication in wireless channel is impaired predominantly by multipath fading. Multipath is the arrival of the transmitting signal at an intended receiver through differing angles and or differing time delays and or differing frequency shifts due to scattering of electromagnetic waves in the environment. This random fluctuation in signal level known as fading can severely affect the quality and reliability of wireless communication. But MIMO technology takes the advantage of random fading and possible delay spread to multiply transfer rates. MIMO makes antennas work smarter by enabling them to combine data streams arriving from different paths and at different times to effectively increase receiver signal-capturing power. MIMO system with multiple transmitting and receiving antennas is shown in fig.1.

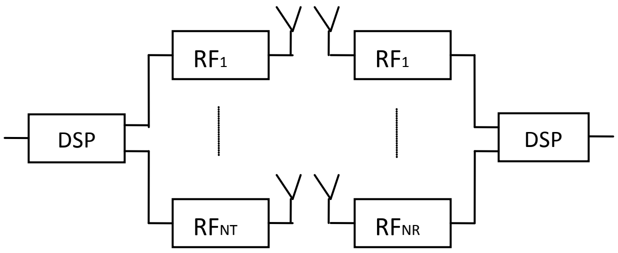

Figure.1 MIMO wireless system [2]

If each multipath route could be treated as a separate channel, it would be as if each route were a separate virtual wire. A channel with multipath then would be like a bundle of virtual wires. MIMO encodes a high-speed data stream across multiple antennas. Each antenna carries a separate, lower-speed stream. Multipath virtual wires are utilized to send the lower-speed streams simultaneously. MIMO is that signals are sampled in the spatial domain at both ends are combined in such a way that they either create effective multiple parallel spatial data pipes therefore increasing the data rate and or add diversity to improve the quality of the communication.

3. Functions of MIMO

There are three main functions of MIMO namely precoding, spatial multiplexing or SM, and diversity coding[6].

3.1. Precoding

It is multi-stream beamforming, in the narrowest definition. In more general terms, it is considered to be all spatial processing that occurs at the transmitter. In beamforming, the same signal is emitted from each of the transmit antennas with appropriate phase weighting such that the signal power is maximized at the receiver input. The benefits of beamforming are to increase the received signal gain, by making signals emitted from different antennas add up constructively, and to reduce the multipath fading effect. In the absence of scattering, beamforming results in a well defined directional pattern, but in typical cellular conventional beams are not a good analogy. When the receiver has multiple antennas, the transmit beamforming cannot simultaneously maximize the signal level at all of the receive antennas, and precoding with multiple streams is used. Note that precoding requires knowledge of channel state information (CSI) at the transmitter.

3.2. Spatial multiplexing

It requires MIMO antenna configuration. In spatial multiplexing, a high rate signal is split into multiple lower rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel. If these signals arrive at the receiver antenna array with sufficiently different spatial signatures, the receiver can separate these streams into parallel channels. Spatial multiplexing is a very powerful technique for increasing channel capacity at higher signal-to-noise ratios. The maximum number of spatial streams is limited by the lesser in the number of antennas at the transmitter or receiver. Spatial multiplexing can be used with or without transmit channel knowledge. Spatial multiplexing can also be used for simultaneous transmission to multiple receivers, known as space-division multiple accesses. By scheduling receivers with different spatial signatures, good separability can be assured.

3.3. Diversity coding

Diversity Coding techniques are used when there is no channel knowledge at the transmitter. In diversity methods, a single stream is transmitted, but the signal is coded using techniques called space-time coding. The signal is emitted from each of the transmit antennas with full or near orthogonal coding. Diversity coding exploits the independent fading in the multiple antenna links to enhance signal diversity. Because there is no channel knowledge, there is no beamforming or array gain from diversity coding.

4. MIMO reference model

Consider a system where the transmitter has N_T antennas, and the receiver has N_R antennas as shown in fig. 2.

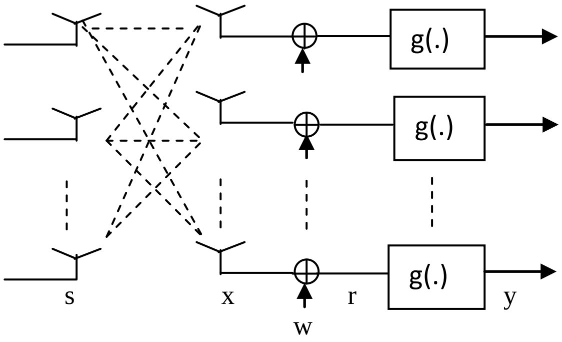

Figure 2. MIMO reference model [3]

We assume that the bandwidth of the transmitted signal is so small that no intersymbol interference occurs, or equivalently, that each signal path can be represented by a complex ~~gain~~ factor. For practical purposes, it is common to model the channel as frequency flat whenever the bandwidth of the system is smaller than the inverse of the delay spread of the channel; hence a wideband system operating where the delay spread is fairly small may sometimes also be considered as frequency flat.

The transmitter emits the signal $s \in C^{NT}$ over stationary memory less flat fading channel $H \in C^{NR \times NT}$ with tap-gain h_{ij} from the j^{th} transmit to the i^{th} receive antenna. Block fading model is used for the channel H. The channel remains constant for some period, long enough to allow for accurate estimation, and changes to an independent realization in the next block. This can be achieved with a sufficiently long interleaver. The received vector $x \in C^{NR}$ is perturbed by a zero mean circularly symmetric Gaussian noise vector $w \in C^{NR}$. A function $g(\cdot)$ acts on every antenna, producing the output vector

$$y = g(r) = g(x + w) \qquad \text{-(1)}$$

The function g(.) maps the complex valued received signal r from the complex plane into one real dimension, element-wise on every antenna. The detector has access only to *y* [3].

Let, h_{mn} be a complex number corresponding to the channel gain between transmit antenna n and receive antenna m. If at a certain time instant the complex signals $\{x_1, \ldots, x_{nt}\}$ are transmitted via the N_T antennas, respectively, the received signal at antenna m can be expressed as

$$y_m = \sum_{n=1}^{N_T} h_{mn} + w_m \qquad \text{-(2)}$$

Where, w_m is a noise term.

The above relation can be easily expressed in a matrix framework. Let x and y be N_T and N_R vectors containing the transmitted and received data, respectively. Define the following $N_T \times N_R$ channel gain matrix [7]:

$$H = \begin{bmatrix} h_{1,1} & h_{1,NT} \\ h_{NR,1} & h_{N_R,N_T} \end{bmatrix}$$

Then, the received signal can be written as

$$\mathbf{y = Hx + w} \qquad \text{-(3)}$$

where $w = [w_1 \cdots w_{NR}]^T$ is a vector of noise samples.

If several consecutive vectors $\{x_1, \ldots, x_N\}$ are transmitted, the corresponding received data can be arranged in a matrix

$$Y = [y_1 \cdots y_N] \qquad \text{-(4)}$$

and written as follows:

$$Y = HX + W \qquad \text{-(5)}$$

Where, $X = [x_1 \cdots x_N]$ and $W = [w_1 \cdots w_N]$.

Then the equation of received signal y can be written in the following equivalent model of vector:

$$y = (x^T \otimes I)h + w \qquad \text{-(6)}$$

Where, y = vec(Y), h = vec(H) and w = vec(W). This expression will be useful for performance analysis purposes.

5. Classification of MIMO

Depending upon the nature of signal MIMO system is broadly classified into two categories.

5.1. Linear MIMO

In linear MIMO systems, the following simple linear input- output relationship is used:

$$y = r = Hs + w \qquad \text{-(7)}$$

The above relation shows that the function g(.) does not modify the received signal. In other words g(.) = r. The linearity enables easy mathematical manipulation and analysis. However, this simple system model neglects several sources of imperfection which exists in real communication systems, such as amplifier nonlinearities, phase noise and other RF imperfections.

5.1. Nonlinear MIMO

In nonlinear MIMO the function g(.) maps the complex valued received signal from the complex plane into one real dimension,

$$g(.) : C^{NR} \longrightarrow R^{NR} \qquad \text{-(8)}$$

The input output relationship for nonlinear MIMO is given by,

$$y = g(r) = g(x + w) = g(Hs + w) \qquad \text{-(9)}$$

This nonlinear processing allows for a very simplified receiver structure, which consumes significantly less power compared to a linear MIMO. The nonlinear detector operates element wise on the perturbed vector r and extract either the amplitude or the phase of the complex signal,

$$y_{i,\,ampl} = g_{ampl}(r_i) = \sqrt{R\{ri\}^2 + J\{ri\}^2} \qquad \text{-(10)}$$

$$y_{i,\,phase} = g_{phase}(r_i) = \arg(r_i) = \tan^{-1}\left(\frac{J\{ri\}}{R\{ri\}}\right) \qquad \text{-(11)}$$

Where, i=1, 2… NR for amplitude and phase detection. The inverse tangent in phase equation considers the quadrant where r_i lies in. In both cases the main characteristics is that the signal y is missing half the dimensions after processing with the function g(.).

6. Channel capacity of MIMO

Channel capacity is the maximum information rate that can be transmitted and received with arbitrarily low probability of error at the receiver. A common representation of the channel capacity is within a unit bandwidth of the channel and can be expressed in bps/Hz. This representation is also known as spectral (bandwidth) efficiency. MIMO channel capacity depends heavily on the statistical properties and antenna element correlations of the channel. Representing the input and output of a memory less channel with the random variables X and Y respectively, the channel capacity is defined as the maximum of the mutual information between X and Y :

$$c = \max p(x) I(x;y) \qquad \text{-(12)}$$

A channel is said to memory less if the probability distribution of the output depends only on the input at that time and is conditionally independent of previous channel inputs or outputs. $p(x)$ is the probability distribution function (pdf) of the input symbols X. For the MIMO system, it is assumed that M antennas at transmitter and N antennas at receiver. The capacity of MIMO channel can be analysed by two cases as follows.

6.1. Transmission of signal

6.1.1. Same signal transmitted by each antenna.

In this case, the MIMO system can be view in effect as a combination of the SIMO and MISO channels. The signal to noise ratio is given by

$$\mathrm{SNR} = \frac{N^2.M^2.\mathrm{signalpower}}{N.M.\mathrm{noise}} = M.N.\mathrm{SNR} \qquad \text{-(13)}$$

So the capacity of MIMO channels in this case is:

$$C_{MIMO} = B.\log_2[1 + M.N.\mathrm{SNR}](BPS/Hz) \qquad \text{-(14)}$$

Thus, we can see that the channel capacity for the MIMO systems is higher than that of SIMO and MIMO system. But in this case, the capacity is increasing inside the log function. This means that trying to increase the data rate by simply transmitting more power is extremely costly [8].

6.1.2. Differnet signal transmitted by each antenna. The big idea in MIMO is that we can send different signals using the same bandwidth and still be able to decode correctly at the receiver. Thus, it is like we are creating a channel for each one of the transmitters. The capacity of each one of these channels is roughly equal to:

$$C_{MIMO} = B.\log_2[1 + \frac{N}{M}.\mathrm{SNR}](BPS/Hz) \qquad \text{-(15)}$$

But we have M_T of these channels, so the total capacity of the system is:

$$C_{MIMO} = M.B.\log_2[1 + \frac{N}{M}.\mathrm{SNR}](BPS/Hz) \qquad \text{-(16)}$$

So, with N≥M, the capacity of MIMO channels is equal to:

$$C_{MIMO} = M.B.\log_2[1 + \mathrm{SNR}](BPS/Hz) \qquad \text{-(17)}$$

Thus, we can get linear increase in capacity of the MIMO channels with respect to the number of transmitting antennas. So, the key principle at work here is that it is more beneficial to transmit data using many different low-powered channels than using one single, high-powered channel. In the practical case of time-varying and randomly fading wireless channel, it shown that the capacity of MxN MIMO system for known channel is

$$C_{MIMO} = B.\log 2\left|\det[I_N + \frac{\mathrm{SNR}}{M} HH^*]\right|(BPS/Hz) \qquad \text{-(18)}$$

Therefore, the capacity increases linearly with the number of transmit antennas.

$$C_{MIMO} = M.B.\log_2[1 + \mathrm{SNR}](BPS/Hz) \qquad \text{-(19)}$$

The capacity of the channel also depends on the channel state information. Hence, there are two cases of analysis of channel capacity that is in perfect CSI and noisy CSI[8].

6.2. Channel state information

6.2.1. Perfect CSI. It is assumed that the receiver has perfect knowledge of the channel realization H at any time for computation of achievable rate of MIMO system. This assumption is not realistic, but it is very important from system analysis point of view.

For a stationary memory less channel the ergodic capacity of linear MIMO system with a total transmit power constraint p and perfect receive CSI is given by

$$\mathrm{Clin} = E_H[\log|\det(I_{NR} + \frac{\mathrm{SNR}}{NT} HH^T)|] \qquad \text{-(20)}$$

In case of nonlinear MIMO, as it is assumed that the channel H is memory less the capacity is given by the mutual information between the channel input s and the detector output y. since H is known to the receiver, the channel output is the pair(y,H).The mutual information can be written as

$$I(s;y,H) = E_H[I(s;y|\mathbf{H} = H] \qquad \text{-(22)}$$

Where, s and H are statistically independent.
From the chain rule for mutual information, the information can be written as follows where, x is the noiseless received signal. s , x, y forms Markov chain

$$s \longrightarrow x \longrightarrow y$$

$$\begin{aligned} I(s,x;y|\mathbf{H}=H) &= I(x;y|\mathbf{H}=H) + I(s;y|x,\mathbf{H}=H) \\ I(s,x;y|\mathbf{H}=H) &= I(s;y|\mathbf{H}=H) + I(x;y|s,\mathbf{H}=H) \end{aligned} \qquad \text{-(23)}$$

The rate can be evaluated, using the monte carlo integration and the fact that the conditional probabilities are known, both for amplitude and phase detection:

$$f(y|x) = \prod_{i=1}^{N_R} f(y_i|x_i) \qquad \text{-(24)}$$

$$f_{ampl}(y_i|x_i) = \frac{2y_i}{\sigma_w^2} e^{\frac{-y_i^2+|x_i|^2}{\sigma_w^2}} I_0\left(\frac{2y_i|x_i|}{\sigma_w^2}\right), \qquad \text{-(25)}$$

$$f_{phase}(\Delta\phi_i|x_i) = \frac{e^{-\rho_i}}{2\pi} + \sqrt{\rho_i/4\pi}.e^{-\rho_i \sin^2 \Delta\phi_i}$$
$$.\cos\Delta\phi_i \operatorname{erfc}(\sqrt{-\rho_i}\cos\Delta\phi_i \qquad \text{-(26)}$$

Where, $\rho_i = |x_i|/\sigma_w^2$

$$\Delta\phi_i = y_{i,\,phase} - \arg(x_i) \in [0,2\pi]$$

I_0 (.) is the zeroth order modified Bessel function of first kind ercf(.) is the complementary error function [3].

6.2.2. Noisy CSI. Now consider the more realistic scenario, where channel knowledge is imperfect, as a result of practical channel estimation. A nonlinear MIMO sensor node can perform channel estimation, but the estimation model would presumably not be linear in that case. For the sake of simplicity it is assume that the receiver has knowledge of a linear minimum mean square error estimate $\hat{H}$ of H.

$$H = \hat{H} + E \qquad \text{-(27)}$$

The capacity of a linear MIMO system with noisy $\hat{H}$ channel estimation is not known. Only upper and lower bounds on the mutual information are given as follows.

A lower bound on the mutual information is given by

$$I_{lower}(s;y|\hat{H}) = E_{\hat{H}}[\log\left|I_{N_R} + \frac{SNR}{1+\sigma_e^2 SNR}\frac{1}{N_T}\hat{H}\hat{H}^H\right|] \text{-(28)}$$

An upper bound can be computed as a function of the lower bound as follows:

$$I_{upper}(s;y|\hat{H}) = I_{lower}(s;y|\hat{H}) + N_R.E_s[\log\left|\frac{1+\sigma_e^2 SNR}{1+\sigma_e^2\|s\|^2}\right|] \qquad \text{-(29)}$$

However, these bounds are tight only for small values of σ_e^2 and are not suited as reference curves for larger values of σ_e^2.

In the case of nonlinear MIMO, due to the effect of noisy channel the input output relation can be written as

$$y = g(\hat{H}s + Es + w) \qquad \text{-(30)}$$

The mutual information between s and y with a noisy channel estimation is given by

$$I(s;y,\hat{H}) = E_{\hat{H}}(I(s;y|\hat{H} = \hat{\mathbf{H}}) \qquad \text{-(31)}$$

The values are computed again with Monte carlo integration as follows

$$f(y_i|s,\hat{H} = \hat{\mathbf{H}} = \int f(s)(f(y_i|s,\hat{H} = \hat{\mathbf{H}})ds$$
$$\cong \frac{1}{M}\sum_{j=1}^{M} f(y_i|s = s_j,\hat{H} = \hat{\mathbf{H}}) \qquad \text{-(32)}$$

Where, sj are M samples of s, normally distributed and generated independent of yi [4].

7. Coclusion

MIMO exhibits increases speed, range, reliability and spectral efficiency for wireless systems. Channel capacity of MIMO is greater than other antenna systems and it increases as number of antenna increases. Nonlinear MIMO systems are by design characterized by low power consumption, fast start up times and high (relatively) rates.

Although the performance of nonlinear MIMO is inferior to linear detection, the nonlinear techniques unexpectedly exploit additional receive antennas to achieve higher spatial multiplexing gains. MIMO technology has attracted attention in wireless communications. It empowers engineers to work in multiple dimensions. By multiplying spectral efficiency, MIMO opens the door to a variety of new applications. Today, MIMO wireless is widely recognized as one of the key technology in the forthcoming high-speed, high-spectrum efficiency wireless networks.

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