IEEE P802.22 Wireless RANs

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| MIMO Full Text for the Std.802.22b Standard | | | | |
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Abstract

This document provides the full text referent to transmit diversity in MIMO systems to the 802.22b standard.

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13. Multiple-input, multiple-output (MIMO)

Multiple-input-multiple-output (MIMO) system has attracted a great deal of attention since the mid-1990’s. It consists of multiple antennas at both transmitter and receiver, and are a breakthrough in wireless communication system design. Not limited to time and frequency dimensions, MIMO exploits the spatial dimension created by multiple antennas to achieve improvements in capacity and reliability. Moreover, the improvements come with neither addition of bandwidth nor increment of power, therefore, making MIMO a highly spectral efficient and reliable technique.

The MIMO channel can be made more robust against fading channels than each of its single-input-single-output (SISO) components by exploiting spatial diversity. Furthermore, MIMO channel creates the possibility to increase the transmission rate compared to SISO channel through spatial multiplexing; however, these two features cannot be fully exploited at the same time. A fundamental trade-off between rate increment and robustness against fading exists and must be decided according to the users needs.

In the context of IEEE 802.22b, the MIMO technique described hereafter is more appropriate for the link between base station and relay stations existing in the wireless network backbone of IEEE 802.22b based systems. On the other hand, implementing MIMO on the links between base station and CPEs or relay stations and CPEs is technically more challenging. This is due to the fact that the lower operating frequencies inherent to the TVWS bands require antennas with bigger physical sizes than the ones required by existing wireless communication systems operating at higher parts of the frequency spectrum.

13.1. MIMO channel estimation and synchronization

13.1.1. MIMO pilot allocation

When using MIMO scheme for PHY Mode 2, the data allocation to tile is changed to accommodate multiple antennas transmission for the channel estimation. MIMO pilot allocations for the cases of 2 TX antennas and 4 TX antennas are described in 13.1.1.1 and 13.1.1.2, respectively. Each subsection includes both DS and US pilot allocations for multiple transmit antennas.

13.1.1.1. Pilot allocation for 2 antennas

In the case of two (2) transmit BS antennas, the DS data allocation to tile is changed (Figure 13.1.1.1-1) to accommodate two antennas transmission for channel estimation. Figure 13.1.1.1-1 replaces Figure M1 in 9a.6.1.1 when MIMO is enabled.



Figure 13.1.1.1-1 DS tile structure for 2 TX antennas

In the case of two (2) transmit CPE antennas, the US data allocation to tile is changed (Figure 13.1.1.1-2) to accommodate two antennas transmission for channel estimation. Figure 13.1.1.1-2 replaces Figure N1 in 9a.6.1.2 when MIMO is enabled.



Figure 13.1.1.1-12 US tile structure for 2 TX antennas

13.1.1.2. Pilot allocation for 4 antennas

In the case of four (4) transmit BS antennas, the DS data allocation to tile is changed (Figure 13.1.1.2-1) to accommodate four antennas transmission for channel estimation. Figure 13.1.1.2-1 replaces Figure M1 in 9a.6.1.1 when MIMO is enabled.



Figure 13.1.1.2-1 DS Tile structure for 4 TX antennas

In the case of four (4) transmit CPE antennas, the US data allocation to tile is changed (Figure 13.1.1.2-2) to accommodate four antennas transmission for channel estimation. Figure 13.1.1.2-2 replaces Figure N1 in 9a.6.1.2 when MIMO is enabled.



Figure 13.1.1.2-2 US tile structure for 4 TX antennas

13.2 Space Time Coding (STC)

The MIMO technique described in this section is common to both Mode 1 and PHY Mode 2 of the PHY layer considered in this standard.

13.2.1 Transmit diversity using 2 antennas (Alamouti O-STBC)

Improvement in wireless link robustness against the deleterious effects of fading is achieved by the use of Orthogonal Space-Time Block Codes (O-STBCs) through exploitation of the extra degrees of freedom provided by the multi-input-multi-output (MIMO) channel.

Let us consider a wireless communications system with two antennas at the transmitter side and a single antenna at the receiver side. Additionally, let both transmit antennas, namely antenna one and two, be spaced at least half-wave length from each other and from which two symbols *s1* and *s2* are respectively transmitted (simultaneously) at a given symbol period *T*. If during the following symbol period *-s2\** and *s1\**, where \* represents complex conjugation operation, are now transmitted respectively from antenna one and two, we can represent the encoding scheme in the following manner,

G2 = ,

where the columns of the above encoding matrix represent the transmit antennas, the rows correspond to the symbol periods and *sn* is the symbol taken from a complex constellation *C* with *n* ∈ {1,2}.

Considering that the channel remains constant across two consecutive symbol periods, i.e., a block fading channel, we can write

h1(t) = h1(t+T) = h1,

h2(t) = h2(t+T) = h2,

where *T* is the symbol period, *h1* and *h2* are the channels paths between the transmit antenna and the receive antenna. Thus, received signals are expressed by

r1 = h1s1 + h2s2 + n1,

r2 = -h1s2\* + h2s1\* + n 2.

Here, n1 and n2 are zero-mean white complex Gaussian distributed noise values with variance σ2n /2 per dimension.

After performing the following signal combination at the receiver,

  
,

the estimated symbols are given by

 = s1 (|h1|2+|h2|2) + h1\*n1 + h2n2\*,

= s2 (|h1|2+|h2|2) - h1n2\* + h2\*n1.

The diversity order provided by the Alamouti scheme is the same as the one provided by the maximum ratio combining (MRC) receiver with a single transmit antenna and two receive antennas. However, Alamouti scheme benefits from having the complexity transferred to the transmitter premises where device size is not a major constraint.

13.2.2. Transmit Diversity with Array-Interference Gain

The technique disclosed in this subsection is full rate based on array-interference constructive aggregation. Its objective is to improve the link reliability over conventional transmit diversity, i.e., Space-Time Block Codes (STBC). This technique intentionally creates aligned array interference so as to exploit its energy in the form of added array gain. As a result, the overall gain (diversity gain + array gain) reduces the bit-error probability (BEP) as compared to the diversity gain only yielded by conventional STBCs based systems.

13.2.2.1. Transmit Diversity with Array-Interference Gain for 2 antennas

In this subsection we describe the structure of a 2 transmit (TX) antennas (nt = 2) transmit diversity TDD system exploiting transmit array interference. Since the system is based on TDD, both transmitter and receiver operate in the same frequency channel, however, in different time-slots. In addition, in a TDD communication system, transmitter and receiver alternate their roles, i.e., the transmitter in time “Tn” is the receiver in the consecutive time “Tn+1”. A direct consequence of the aforementioned, is that both transmitter and receiver can estimate the wireless channel **H** during the time in each they are acting as receiver.

The vector **H** = [h1 h2] represents the multiple-input-single-output (MISO) channel between the base station and the single antennae receiver (RX) white space device.In the analyses presented hereafter, **H** is considered to be quasi-static.

Symbols vectors are transmitted through **H** and noise is added at the receiver as shown in Fig. 1. The transmitter is composed of two blocks, namely, ‘array gain maximization’ and ‘transmit vector selector’. On the other hand, the receiver is composed of the blocks “channel estimator”, “combiner”, “array gain maximization” and “ML detection” in order to recover the transmitted symbols, however, with array-interference gain. The aforementioned blocks are described in the following subsections.

In 2 TX antennas systems, a total of two unique transmit vectors Gm, for *m* ∈ {0,1} exists. As it will be explained in the following, each Gm yields a single interference, which is aligned to the original signal thus inproving system robustness towards fading. The total interference has componets coming from all antennas in the array thus it is hereafter called aligned array interference IAm. It should be noted that IAm, where *m* ∈ {0,1}, are functions of the fading channel **H**, and both TX and RX can estimate **H** due to the reciprocity of up-link/down-link. Consequently, IAm can be calculated beforehand and stored in RX device memory.

figure2

**Figure 1.** Transmit Diversity with Array-Interference Gain for 2 TX Antennas.

The ‘channel estimator’ block performs channel estimation based on pilots. The estimation is then provided to the ‘combiner’ block and the ‘array gain maximization’ block.

Both “Array Gain Maximization” blocks in TX and RX, perform



in order to compare all the IAm and selects the one that has the maximum value.

Following, the “array gain maximization” block at the transmitter sends *m* inherent to the maximum array interference to the “transmit vector selector” block, which selects Gm to be transmitted over the channel **H** since Gm will yield the maximum array gain. In addition, “the array gain maximization” block at the receiver sends the index *m*, in binary, to the ‘combiner’ block, which is collocated in the same RX device. For instance, if *m* = ‘1’, the ‘combiner’ block will utilize the weight *w1*, when it receives the signal from TX.

The ‘combiner block’ provides symbol estimate to the ‘maximum likelihood (ML) detector’ block.

##### Array Gain Maximization Block

In the array gain maximization block, the array interference IAm is stored as a function of **H.**

* Array Interference IA0



* Array Interference IA1



In order to select the most aligned interference, the ‘array gain maximization’ block performs



The ‘array gain maximization’ block at the TX directly sends *m* to the collocated ‘transmit vector selector’ while the ‘array gain maximization’ block at the receiver sends *m* to the collocated ‘combiner block’. For the following implementation examples co nsider that *m* is represented by 3 bits.

##### Transmit Vector Selector Block

* Transmit if *m* is ‘000’;



* Transmit if *m* is ‘001’;



where *s* is a symbol taken from a complex constellation *C*.

##### Combiner Block

Let and denotes transpose operation and *n*, the zero-mean additive white Gaussian noise (AWGN).



* If the ‘combiner’ block receives *m = 000* from the ‘array gain maximization’ block, the received signal is

.



The combiner, then, utilizes



for the combination. However, for the specific case of m = 000, multiplying vector *wm* is not necessary and left here for illustration purposes only. The ‘combiner’ block performs the following combination,



,



which is, then, passed to the ML detector to perform the symbol estimation.

* If the ‘combiner’ block receives m = 001, then,



The combiner, then, utilizes



yielding,



This is, then, passed to the ML detector to perform the symbol estimation.

13.2.2.2. Transmit Diversity with Array-Interference Gain for 4 antennas

##### Array Gain Maximization Block

In the case of 4 TX antennas, there are eight unique Gm together with their respective IAm as well as *wm*, m ∈ {0,1,2,3,4,5,6,7}.



In order to select the most aligned interference, the ‘array gain maximization’ block performs,



The ‘array gain maximization’ block at the transmitter sends *m* to the ‘transmit vector selector’ block collocated at the transmitter while the ‘array gain maximization’ block at the receiver sends *m* to the ‘combiner’ block collocated at the receiver.

##### Transmit Vector Selector Block

* Transmit if *m* is ‘000’;



* Transmit if *m* is ‘001’;



* Transmit if *m* is ‘010’;



* Transmit  if *m* is ‘011’;
* Transmit if *m* is ‘100’;



* Transmit if m is ‘101’;



* Transmit if *m* is ‘110’;



* Transmit if *m* is ‘111’;



##### Combiner Block

##### Letand for the sake of simplicity in the example, the channel estimation be perfect, i.e., .



* If the ‘combiner’ block receives m = 000 from the ‘array gain maximization’ block, it utilizes



to perform the combination





which is, then, passed to the ML detector to perform the symbol estimation.

* If the ‘combiner’ block receives m = 001 from the ‘array gain maximization’ block, it utilizes



and performs the following combination,



which is, then, passed to the ML detector to perform the symbol estimation.

* If the ‘combiner’ block receives m = 010 from the ‘array gain maximization’ block, it utilizes



and performs the following combination,



which is, then, passed to the ML detector to perform the symbol estimation.

* If the ‘combiner’ block receives m = 011 from the ‘array gain maximization’ block, it utilizes



and performs the following combination,







which is, then, passed to the ML detector to perform the symbol estimation.

* If the ‘combiner’ block receives m = 100 from the ‘array gain maximization’ block, it utilizes



and performs the following combination,



which is, then, passed to the ML detector to perform the symbol estimation.

* If the ‘combiner’ block receives m = 101 from the ‘array gain maximization’ block, it utilizes



and performs the following combination,



which is, then, passed to the ML detector to perform the symbol estimation.

* If the ‘combiner’ block receives m = 110 from the ‘array gain maximization’ block, it utilizes



and performs the following combination,



which is, then, passed to the ML detector to perform the symbol estimation.

* If the ‘combiner’ block receives m = 111 from the ‘array gain maximization’ block, it utilizes



and performs the following combination,



which is, then, passed to the ML detector to perform the symbol estimation.

The above procedure describes how to obtain diversity added with array gain for systems with multiple antennas at the transmitter, however, with single antenna at the receiver. Bellow, extension to system configuration consisting of multiple receiving antennas is presented.

If more than one antenna is available in the receiver terminal, maximum ratio combining (MRC) can be utilized to significantly enhance link reliability. For simplicity, in the following example consider that the number of antennas available at the receiver is 2. The technique, however, can be utilized for any number of receive antennas.

In order to use MRC, little modification is necessary to what has been presented. The ‘Array Gain Maximization’ block, now, performs



for 2 TX antennas, and



for 4 TX antennas. Here, IAm is the array interference in the first RX antenna, given in the previous sections and I’Am represents the array interferences in the second RX antenna. Since the channel to the second RX antenna is given by **H** = [h3 h4], for two TX antennas, and **H** = [h5 h6 h7 h8], for 4 TX antennas, I’Am becomes





or















.

The ‘array gain maximization’ block at the transmitter sends *m* to the collocated ‘transmit vector selector’ block while the ‘array gain maximization’ block at the receiver sends *m* to the collocated ‘combiner block’. The ‘combiner block’ will combine the received signal, just as described in the previous sections, in order to deliver  to the ML detector. Note that  is given in the previous sections and is given by



with y’ being the signal received by the second RX antenna and **H** = [h3 h4], for 2TX, or **H** = [h5 h6 h7 h8], for 4 TX.

The technique described above is full rate and yields full spatial diversity added to antenna array gain thus yielding better link reliability.

13.3 Spatial Multiplexing

The MIMO technique described in this section is common to both Mode 1 and PHY Mode 2 of the PHY layer considered in this standard.

13.3.1 Spatial Multiplexing using 2 Antennas

Previous sections have described methods to improve wireless link robustness against the deleterious effects of fading. Two spatial diversity techniques were described, namely Alamouti Code and a form of transmit diversity, which exploits the antenna array interference to obtain extra diversity gain. One application example of the aforementioned techniques is link-range extension between IEEE 802.22b CPEs in order to service a wider geographical area. This is fundamental whenever the antennas of both CPEs are positioned relatively low due to the strong signal attenuation characteristic to near ground wave propagation.

This section, however, describes a highly spectral efficient technique that significantly enhances the IEEE 802.22b system throughput. Spatial multiplexing transmits independent and separately encoded signals, i.e. streams, from each transmit antenna, therefore reusing (or multiplexing) the space dimension. In IEEE 802.22b systems, enhanced data-rate enables CPEs with bandwidth-hungry applications, e.g., such as wireless video transmissions for monitoring purposes, or it can increase the density of CPEs with data-rate comparable to legacy IEEE 802.22 standard.

Let us consider the 2x2 wireless communications depicted in Fig. 13.3.1-1. The channel gains between the ith transmit antenna and the jth receive antenna *hj,i* is represented by the MIMO channel matrix

***H*** = .

Additionally, let both transmit antennas, namely antenna one and two, be spaced at least half-wave length from each other and from which two symbols *s1* and *s2*, taken from an arbitrary complex constellation *C*, are simultaneously transmitted. Representing the transmitted symbols by the vector ***s*** *=* [*s1 s2*]*T* and the noise at the receive antennas by ***n*** = [*n1 n2*]*T*, also illustrated in Fig. 13.3.1-1, we can represent the received signals as

= + , **(1)**

or

***y*** *=* ***Hs + n****.*  **(2)**

Here, *nj* is the zero-mean white complex Gaussian distributed noise with variance σ2n/2 per dimension and T denotes transpose operation.



Figure 13.3.1-1 - Schematic Representation of Spatial Multiplexing technique.

Spatial Multiplexing Signal Detection:

Several receiver techniques exist to obtain the estimate of the transmitted symbols and . In this section the linear zero-forcing (ZF) method is described along with its ordered successive interference cancelation (OSIC) variant. Employing the following weight matrix,

***Z = (HHH)-1HH****,* **(3)**

the ZF method intends to cancel the interference between symbols *s1* and *s2* by

**. (4)**

Substituting (2) and (3) into (4), yields

***s* + *(HHH)-1HHn****.* **(5)**

or

= + **(6)**

Obviously, perfect recovery, i.e., nulling of interference, is not achieved due to the presence of an enhanced noise component ***(HHH)-1HHn*** in (5) and (6).

For an improved bit-error-rate (BER) and packet-error-rate (PER) performance, OSIC technique successively cancels components from the received signal until one of the data streams is detected. Although this method leads to increase in complexity, it is however not significant in the face of BER and PER improvements.

From Fig. 13.3.1-2, it can be easily understood the principle of OSIC detection. The symbol, from a parallel stream, which is estimated first, is then subtracted from the originally received signal yielding a reduced interference signal. This reduced interference signal is used in the following stage of the OSIC detection where the other symbol will be estimated. Here, *i* refers to the estimation order which does not necessarily follows the same symbol order, i.e., *si* could be *s2*while *si+1*, *s1*. There are several criteria to select the symbol estimation order, e.g., SNIR-based order, SNR-based order, column norm-based order with the latter being adopted through this section.

In order to determine the estimation order we rewrite (1) as

= + . **(7)**



Figure 13.3.1-2 - Schematic diagram of SM detection based on OSIC technique.

From (7) it is clear that symbols *s1* and *s2* have their magnitude affected by the norm of ||***H:,1***||and||***H:,2***||,denoting first and second columns of ***H***, respectively. It is therefore obvious to estimate the symbols according to the order of the norms of ***H***.

The first symbol *si* is estimated by the ith row of ***Z****,*

**y**,  **(8)**

yielding

,  **(9)**

which is then mapped to the possible transmitted symbol from the constellation *C* with the closest Euclidian distance to it.

Once the first estimation occurs, the mapped is then used in the next stage to estimate ,

.  **(10)**

In the case that is correctly estimated, mapping (10) to the symbol with closest Euclidian distance from *C* yields. For instance, consider that and it was correctly estimated. It can be easily seen that (10) becomes

+  **(11)**

yielding,

+  **(12)**

In the case that is not correctly estimated, error propagation occurs thus compromising BER and PER performances.

13.3.2 Spatial Multiplexing using 4 Antennas

Previous sections have described spatial multiplexing with 2 Tx and 2 Rx antennas. This section illustrates the same technique, however, for 4 Tx and 4 Rx antennas.

Consider a 4x4 wireless communications system. The channel gains between the ith transmit antenna and the jth receive antenna *hj,i* is represented by the MIMO channel matrix

***H*** =

Similarly to the 2x2 case, let all antennas be spaced at least half-wave length from each other from where four symbols *s1*, *s2*, *s3*, *s4*, taken from the arbitrary complex constellation *C* are simultaneously transmitted. The transmitted symbols vector is ***s*** *=* [*s1 s2 s3 s4*]*T* and the noise at the receive antennas is ***n***  = [*w1 w2 w3 w4*]*T* with the received signals also given by ***y*** *=* ***Hs + n****.*

Spatial Multiplexing Signal Detection:

Linear zero-forcing (ZF) method yields the estimated symbols ***s* + *(HHH)-1HHn***due to **,** where ***Z = (HHH)-1HH***, where **H** represents Hermitian operator.

Similarly to the 2x2 case, improved bit-error-rate (BER) and packet-error-rate (PER) performance can be obtained through OSIC technique. Here we detail the OSIC technique applied to a 4x4 SM-MIMO system. The symbol, from a parallel stream, which is estimated first, is then subtracted from the originally received signal yielding a reduced interference signal. This reduced interference signal is used in the following stage of the OSIC detection where another symbol will be estimated and then subtracted from the signal in order to further reduce interference. This procedure is repeated until all symbols are estimated.

Again considering column norm-based order, ||***H:,1***||, ||***H:,2***||, ||***H:,3***|| and||***H:,4***||, and for illustrations purposes, considering that ||***H:,1***|| > ||***H:,2***|| > ||***H:,3***|| >||***H:,4***||, the symbols are estimated in the following order:

The first symbol *s1* is estimated by the 1th row of ***Z****,*

**y**,  **(1)**

yielding

,  **(2)**

which is then mapped to the possible transmitted symbol from the constellation *C* with the closest Euclidian distance to it.

Generating the reduced interference (provided that ) signal,

.  **(3)**

A new MIMO matrix is constructed by deleting the 1st column, i.e.,

,

with  ***= (H)-1H***.

Then, is estimated by

**. (4)**

Again, a further reduced interference signal (provided that ) is generated by

,  **(5)**

along with

and ***= (H)-1H***.

Estimation of follows,

**. (6)**

Finally, the last reduced interference signal (provided that ) is generated by

,  **(7)**

along with

and  ***= (H)-1H***.

The last estimation follows,

**. (8)**

Note that precoder-based spatial multiplexing could be employed by exploiting the channel reciprocity inherent to TDD systems. This is due to the fact that both the down-link (DL) and the up-link (UL) of TDD systems operate in the same frequency however in different time-slots and thus are highly correlated. The channel state information (CSI) can be obtained by the Tx side during (UL) transmissions.

Once CSI is known, the Tx transmits the , where ***W*** is the NtxNs precoding matrix with Nt referring to the number of transmit antennas and Ns to the number of streams. For instance, for the 4x4 SM-MIMO with zero-forcing considered above, **W = αH-1**,

, (9)

due to Tx power constraints and where *Tr* represents the trace of

After dividing the received signal **α,**  it then becomes

**(10)**

or

**(11)**