Reception and Measurement of MIMO-OFDM Signals with a Single Receiver

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***Abstract*— OFDM multi-carrier modulation is expected to be the enabling technology for 4G wireless systems. One of the features that make OFDM the primary choice for 4G is its MIMO compatibility, because MIMO has a very significant potential of enhancing wireless systems for capacity, data rate, and coverage aspects. In this paper, the challenges of MIMO-OFDM measurements are addressed in comparison to SISO, with a special emphasis on WiMAX systems, which employ MIMO-OFDM technology. It is proposed to perform the reception and measurement of MIMO-OFDM signals using a single receiver branch rather than multiple receivers. A complete guide to perform impairment estimation for WiMAX MIMO signals with a single receiver according to the 802.16 standards is also provided.**

I. Introduction

The breathtaking improvements in the wireless communications as well as multimedia applications and hardware have accelerated the emergence of fourth generation (4G) wireless systems. The primary expectation from all future 4G systems is that they provide enormously high data rates to an excessive number of users at the same time. In the wireless community, there is a strong belief that 4G will be based on OFDM. Based on that, WiMAX is considered a suitable candidate for 4G with its potential ability to satisfy very challenging throughput and capacity needs [1]. One of the significant factors leading to this opinion is that the capacity of WiMAX systems can be improved further by adding multiple-input multiple-output (MIMO) feature [2]. Since MIMO can considerably enhance the potential of WiMAX systems, it has been made part of the IEEE 802.16 and 802.16e standards [3], [4].

Systems with MIMO capability operate on a number of parallel channels which leads to a multiplexing gain [5]. In MIMO systems, at the expense of increased hardware and computational complexity, a high spectral efficiency can be achieved. This spectral efficiency, which can be utilized as data rate, capacity, or coverage improvement according to the needs, makes the MIMO technology attractive for bandwidth-greedy wireless applications. Reliable MIMO-OFDM system design requires performing certain MIMO measurements on the system. Optimally, these measurements would be performed either by using multiple vector signal analyzers (VSAs) or a single VSA with multiple input branches. However, it is clear that this kind of a measurement setup would be extremely costly. Hence, in this paper, a much more feasible solution that employs a single receiver is proposed. Regarding this solution, the primary RF front-end impairments are analyzed, and a guide to estimate each of them is provided. The possible reasons for different impairments in different transmitter branches are addressed. It also explained how to examine the constellation diagram of the (combined) received signal in order to have an understanding of the impairment differences between the transmitters. Also, a procedure that explains how to handle WiMAX MIMO signals is provided.

The flow of the paper is as follows. Section II discusses the primary RF front-end impairments. Section III provides a guide to estimate and remove the effects of these impairments. In Section IV, the differences of MIMO measurements from single channel measurements are analyzed in detail. In Section V, it is described how to handle WiMAX MIMO signals. Section VI concludes the paper.

II. Signal Model and the Primary RF Front-end Impairments

In a MIMO-OFDM system, the received signal contains the effects of various RF front-end impairments. These effects have to be determined and removed before making the symbol decisions. The detailed features of RF impairments have been addressed in [6], [7], here, the essential impact of each of them will be summarized so that the reader can follow the MIMO measurement solutions that will be provided.

The received frequency domain signal in a MIMO-OFDM system can be modeled as

$$\begin{aligned} Y_m(k) &= X_m(k - m\gamma - m\omega) \cdot \\ &\quad H_m(k)F(k)e^{jk\rho}e^{jk\omega}e^{j\psi_m}\mu_m(k) + N_m(k) \;, \end{aligned} \tag{1}$$

where m is the OFDM symbol index and k is the subcarrier index. The remainder of the parameters are as follows:

$[\rho]$: The time offset between the transmitter and the receiver. It causes a phase shift that increases linearly over the subcarriers, but does not change from one symbol to another;

$[\gamma]$: The frequency offset between the local oscillators in both sides. It results in a phase shift that changes over symbols rather than subcarriers. Hence, all the subcarriers in the same symbol experience the same amount of phase shift due to the frequency offset;

$[\omega]$: The inaccuracy between the sampling clocks of the transmitter and the receiver. The sampling clock error also causes a phase shift, but, as opposed to the other impairments, this phase shift grows over both subcarriers and symbols;

$[\psi]$: The random phase noise that is caused by the instability of the local oscillator in the transmitter. The random phase noise has a similar effect to the frequency offset. The phase shift it causes is the same for all subcarriers in the same symbol, but the amount of this shift varies between symbols because of the randomness of the phase error;

$[F(k)]$: The frequency response of the analog filters employed in both the transmitter and the receiver;

$[H_m(k)]$: The frequency selectivity and time dependency of the channel. Because of its frequency selectivity, the wireless channel may affect the subcarriers differently. It may also vary over time, especially if the channel is mobile. A time varying channel leads to changes on the same subcarriers from symbol to symbol;

$[X_m(k)]$: The transmitted data; $[N_m(k)]$: Additive noise term;

$[\mu_m(k)]$: The IQ impairments; its effect on $X_m(k)$ can be expressed as

$$\frac{X_m(k)}{2}\left(I_s + Q_s e^{-j\alpha}\right) + \frac{X_m(-k)}{2}\left(I_s - Q_s e^{-j\alpha}\right) \;, \qquad (2)$$

where $[I_s]$ and $[Q_s]$: The in-phase and quadrature components of the transmitted signals. Their ratio yields the IQ imbalance; and $[\alpha]$: The quadrature error. It indicates any deviation from orthogonality between the I and Q components.

III. Estimation and Removal of Impairments in the SISO Case

After having introduced the main factors that lead to impairments in the received signal, in this section it will be addressed how to process the received signal for the single-input single-output (SISO) case. A step-by-step guide that provides the order and short explanations of the necessary impairment estimations is given below. As it will be clear, the order of the estimations is important because each estimation assumes that the other errors that affect the subcarriers in the same way have already been removed. So, after each estimation, the corresponding effect has to be removed from the received signal before proceeding to the next step.

- *Packet Detection:* The beginning and the end of the signal packet is determined by utilizing a simple energy detection method. The threshold may have to be modified adaptively according to the received noise power. This initial step serves as a rough timing estimation.
- *Frequency Offset Estimation (Time Domain):* The time domain signal is correlated with itself. Owing to the pilot subcarriers that are repeated regularly in time, this correlation can be utilized to estimate the frequency offset. Dividing this correlation value by $2\pi D$, where D is the duration between the repeated pilots, yields the frequency offset estimate.
- *Finer Frequency Offset Estimation (Frequency Domain):* After converting the received time signal into the frequency domain, the values of all subcarriers including the pilots become available. Since the frequency offset changes from symbol to symbol, correlating the pilot subcarriers in different symbols yields a finer estimate for the frequency offset.
- *Finer Timing Offset Estimation:* If the received signal contains a preamble (or a midamble) part that has been added to the signal to facilitate synchronization, a finer timing estimation can be done. Since the transmitter generates the preamble according to a certain standard, the same preamble can be generated in the receiver part, as well. Correlating the preamble with the time domain signal yields a very accurate timing estimation.
- *Sampling Clock Error Estimation:* Error in the sampling clock rate adds a phase shift that increases both over symbols and subcarriers. Since the effect of frequency offset (on the symbols) has already been removed, the clock error should be reliably determined by correlating pilots in different symbols.
- *Slope Estimation:* A time offset may still exists at this point, especially if no preamble was sent, since the packet estimation does not very accurately determine the signal starting point. This time offset will indicate itself as an increasing phase slope over subcarriers. Since the impact of the sampling clock error was already canceled in the previous step, it is expected that the phase slope can be estimated by comparing the phases of the subcarriers in the same symbol.
- *Channel Estimation:* Channel estimation is done using again the pilots, which should be now free from all the previously mentioned impairments except the random phase error. The channel estimation can be simply done by interpolating the pilot values in a reasonable way (after removing the pilot power boosting in the downlink (DL)).
- *Random Phase Error Estimation:* The channel estimation is expected to partially take care of the random phase error. For the phase error that still exists, pilots in different symbols have to be correlated. This correlation yields specifically the phase error between the two correlated symbols. Since the amount of error changes randomly from one symbol to another, it has to be determined separately for each symbol. After finding the phase errors for all symbols, the channel estimation should be updated accordingly before making the symbol decisions.

IV. Measurement Challenges in MIMO Compared to SISO

As opposed to systems with a single input, in MIMO systems, the received signal will include the simultaneous transmission of data from multiple transmitter antennas. Therefore, the measured error vector magnitude (EVM) will be based on a combined error vector, which cannot be separated into contributions from separate antennas/transmitter branches. However, under some circumstances, the impairments caused by different branches differ substantially, and a common EVM estimation fails to reflect the error magnitude for all of the branches accurately.

In what follows, the possible factors that lead to different impairment values will be discussed. The MIMO-OFDM system considered here has two transmitter branches and a receiver branch, which can be readily generalized for a higher number of transmitter branches.

1) Time offset between the branches: In order to keep the measurements simple, it would be desired to be able to assume that the signals from the two different transmitter branches are received simultaneously. However, there may be a time offset between the received signals if

- the transmitters are not well synchronized with each other,
- or if the distances from each transmitter to the receiver are considerably different from each other.

In case of a time offset between the transmitter branches, the timing estimation done by the receiver will not be accurate for at least one of the branches.

2) Employing separate clocks: The oscillator that is needed to generate the sampling instants of the DAC can be common to both branches, or each branch can use a separate oscillator. If two separate oscillators are employed by the transmitter branches, serving as sampling clocks, there will be an unavoidable inaccuracy between the sampling periods. This fact will lead to different sampling clock errors for each branch.

Although it is more reasonable to employ a single clock for the entire transceiver, in some cases, the different transmitter branches may run separate clocks. This will be the case if the signals are generated by different sources such as two vector signal generators (VSGs), or two collaboratively operating mobile devices each with a single antenna. Even if there is a single unit with multiple output branches, since each branch will have its own DAC, there will be still two different sampling clock errors, unless the DACs are run by a common external clock input.

3) Using separate IQ modulators: The usage of separate IQ modulators in each transmitter branch has various impacts. One is that it causes the IQ impairments of each branch to be different. Another one is observed on the frequency offset. Since it is certain that the output frequencies of the oscillators in each IQ modulator can never be exactly the same, the signals from each branch have a different frequency offset in the receiver part. The second impact of separate IQ modulators is seen on the random phase error. Most local oscillators display an inconsistent behavior in time in terms of the output frequency, i.e. their frequency makes slight variations in time. This impairment results in phase errors that are random in nature. Therefore, employing two separate local oscillators will lead to two independent phase errors.

4) Using separate RF components: Since each transmitter branch employs its own mixer, analog RF filters, power amplifier, and antenna, the signals from each branch will be modified differently before being radiated into the air. The good thing about the different RF sections is that their effects can be folded into the channel. Therefore, channel estimations can be considered to include the influence of the RF sections on the received signals.

Detecting the Impairment Differences by Examining the Constellation Diagram

When dealing with MIMO signals, having an idea about the potential impairment differences between the transmitter branches can facilitate the measurement of these impairments considerably. Some of these differences can be recognized by investigating the IQ constellation diagram after the removal of offsets from the received combined signal. How the constellation looks for a QPSK modulated space-time transmit diversity (STTD) MIMO signal after the removal of offsets (and before the removal of the channel effects, i.e. equalization) is shown in Fig. 1. Note that there are 16 constellation points (as well as 2 collections of pilot symbols and the point in the middle caused by the non-allocated subcarriers) in the diagram. There are 16 points because each of the 4 constellation points in QPSK are summed vectorially with another 4 points. Two of these quadruples are explicitly indicated with rectangles in Fig. 1.

Simulations have been run aiming to see what kind of effects are observed in the constellation when there are certain differences between the two transmitted signals. For this purpose, various differences were intentionally set between the two signals. When performing the corresponding simulations, it was assumed that one of the signals is not corrupted (does not have an impairment) but the other one does. That means, one of the signals has no IQ imbalance, but the other one has 30% IQ imbalance, *etc.* It should be also noted that only one type of impairment difference is assumed to exist at a time; they have been examined one by one, because it may not be possible to make a reliable guess by simply looking at the constellation if multiple such impairment differences exist at the same time.

In Fig. 2, the effect of $\pi/12$ phase difference between the two transmitted signals is observed. The rotation of the quadruples around their center is apparent. The same effect can be verified by checking the position of the pilots. Fig. 3 shows two signals with 30% IQ imbalance difference. In Fig. 4, the effect of $\pi/12$ quadrature error difference between the signals is shown. Finally, in Fig. 5 two signals with 0.002 radian frequency offset difference are shown. Frequency offset has a similar effect to phase difference in terms of rotation of quadruples. However, since the phase shift caused by the frequency offset increases over symbols, a clear shift is seen in the constellation points. Apparently, each of these impairment differences has a different effect on the constellation diagram, and studying these visual effects, one can make a strong guess about the possible problem with the received MIMO signal by just examining the constellation diagram.

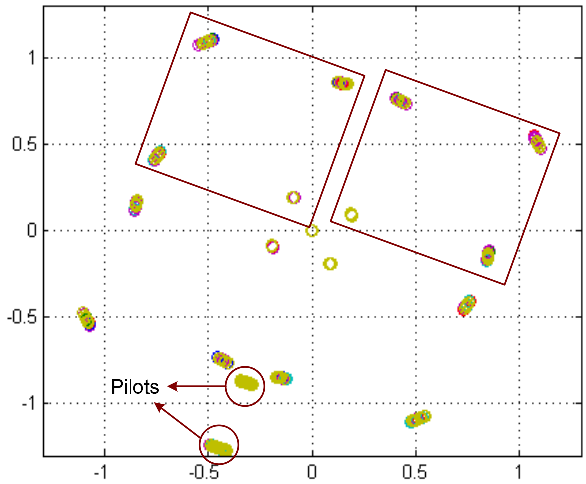

Fig. 1. The constellation for two QPSK modulated STTD signals before equalization.

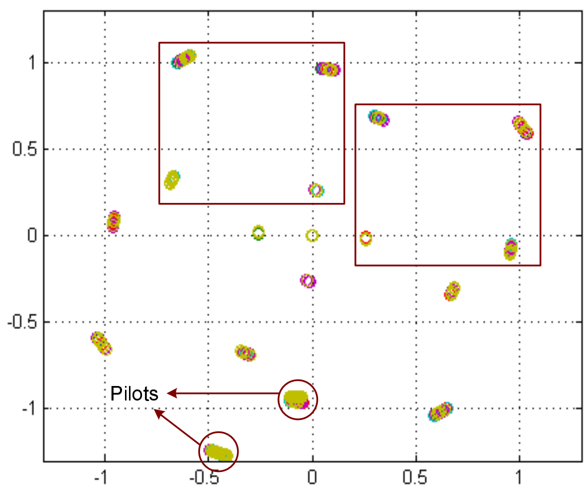

Fig. 2. $\pi/12$ phase difference between the two transmitted signals.

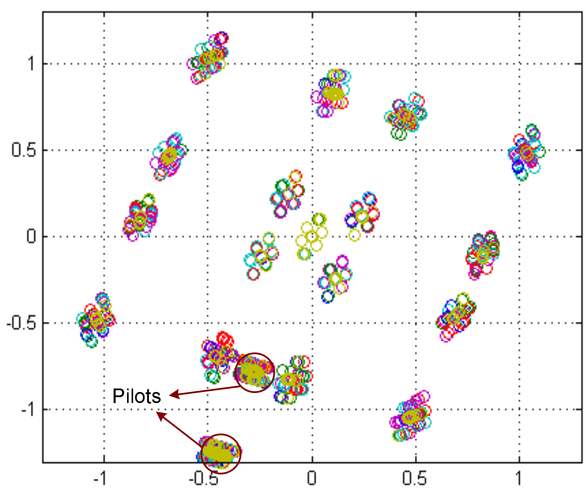

Fig. 3. 30% IQ imbalance difference between the two transmitted signals.

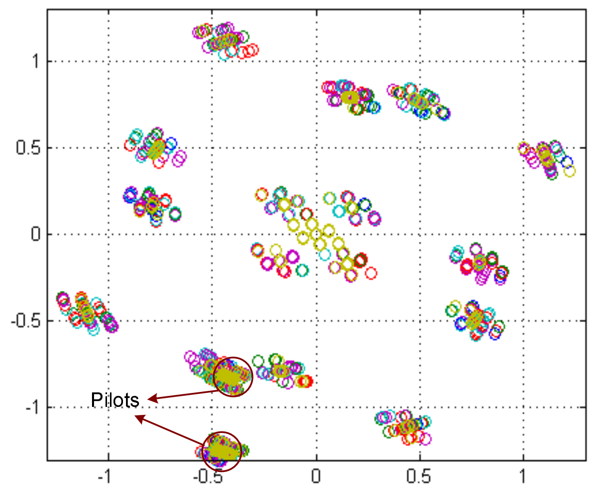

Fig. 4. $\pi/12$ quadrature error difference between the two transmitted signals.

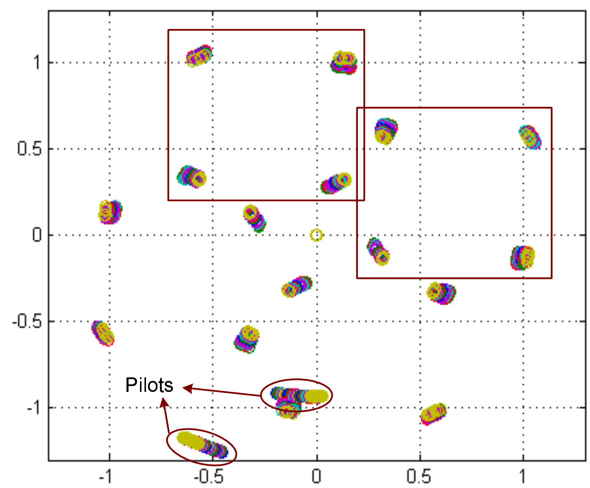

Fig. 5. 0.002 radian frequency offset difference between the two transmitted signals.

V. Procedure to Handle WiMAX MIMO Signals

It is a fundamental issue how to separate the constellations and the contributions to EVM from each transmitter branch when processing MIMO-OFDM signals with a single receiver. In this section, a WiMAX system, which is a recent MIMO-OFDM technology, will be considered. The solution that will be investigated here is based on the use of pilot sequences. To be more specific, space time coded downlink (DL) and uplink (UL) WiMAX signals with PUSC permutation will be analyzed more closely. The (frequency domain) allocations of pilot subcarriers in DL-PUSC and UL-PUSC are shown in Fig. 6 and Fig. 7. In these allocation maps, it is seen clearly that each branch is transmitting a separate set of pilots that are orthogonal to each other either in frequency or in time. Basically, this is the feature that enables separating the impairment contributions from separate branches.

The received time domain signal contains pilot subcarriers from both branches, however, it is not possible to process these pilots separately in time. Therefore, the packet detection

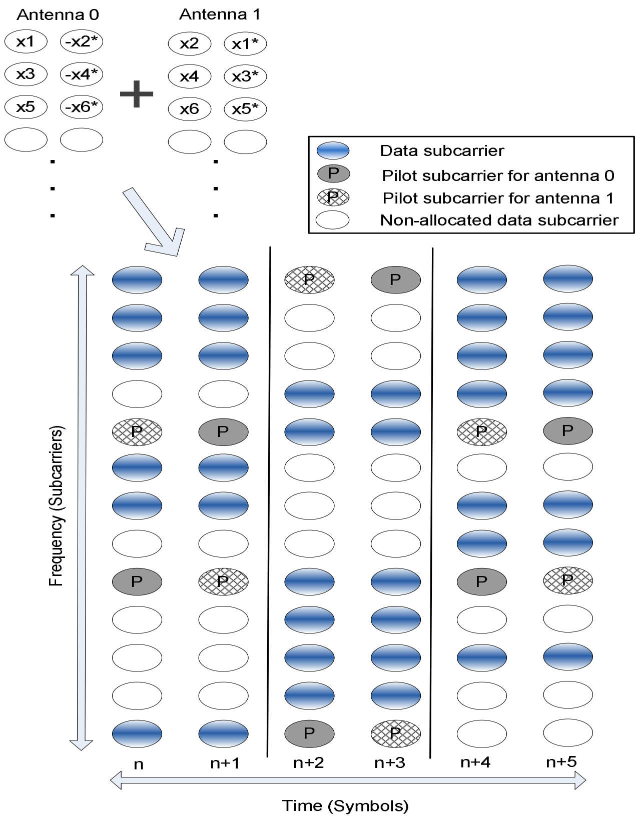

Fig. 6. Allocation of subcarriers in downlink PUSC WiMAX. Implementation of Alamouti (space-time) coding is shown.

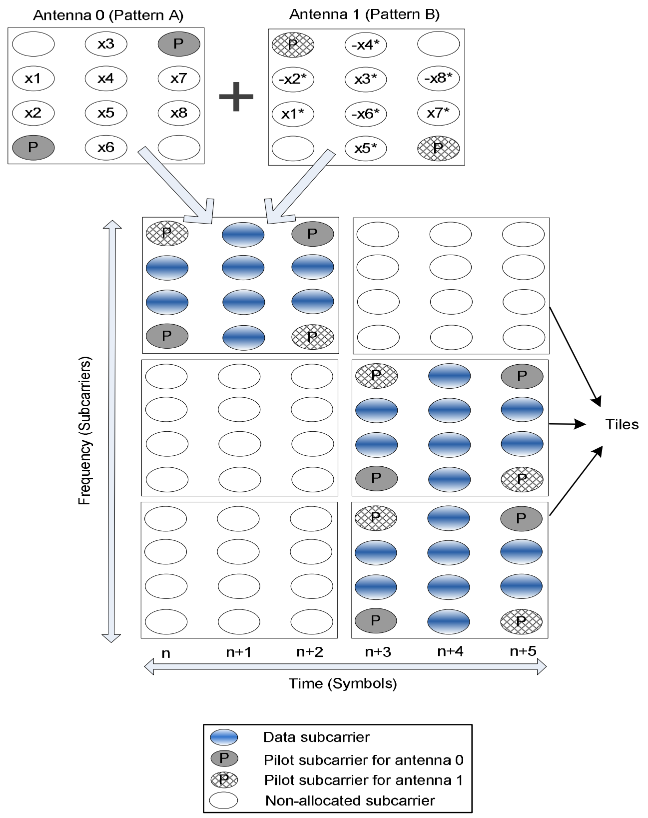

Fig. 7. Allocation of subcarriers in uplink PUSC WiMAX. Implementation of space-frequency coding is shown.

and the time domain based frequency offset estimation can be applicable only if the timing offsets and the frequency offsets from the two branches are close to each other. Otherwise, only after converting the signal to the frequency domain, since pilots from different branches get separated from each other, one can apply the offset estimations (explained in detail for a single channel) to pilots from each branch separately.

In the single channel case, after each estimate the corresponding offset was being removed from the signal. In the MIMO case, however, since each branch has different offsets, it is not useful (nor valid) to remove the offsets from the entire signal. Instead, the estimated offsets are removed from the corresponding set of pilots, only. After determining and removing all the offsets one by one, the channel estimations can be obtained from the pilot sets. Before proceeding to the symbol decision step, the offset estimations obtained for both channels should be incorporated into the corresponding channel estimations.

VI. Conclusion

Parallel to the growing interest towards OFDM and MIMO technologies, the necessity for MIMO-OFDM measurements is increasing. This paper aims at serving as an instructional guide to MIMO measurements using a single receiver instead of multiple receiver branches. In the paper, the main factors resulting in IQ impairments and the way of eliminating their effects are addressed. The measurement challenges that are specific to MIMO scenarios are analyzed in comparison to the single transmitter case. It is explained how to make intelligent guesses about the potential problems in received MIMO signals by examining the constellation diagrams. Also, an instructional procedure to process WiMAX MIMO signals with a single receiver is provided.

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