MIMO-OFDMA Measurements; Reception, Testing, and Evaluation of WiMAX-MIMO Signals with a Single Channel Receiver

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Abstract— **The number of MIMO-OFDMA systems is expected to increase sharply in the near future. Engineers who need to test these systems face two difficulties. First, the lack of descriptive instructions to conduct reliable measurements. Second, the increased hardware cost due to the need for multiple transmitters and receivers. This paper first introduces all measurable parameters of MIMO-OFDMA systems and provides a clear guide to perform the measurements specific to various parts of the system. Then, it proposes to implement reception of MIMO-OFDMA signals using a single receiver rather than multiple receivers. For this purpose, impairments related to each of the RF front-end components are investigated. Challenges of MIMO-OFDMA measurements are addressed in comparison with SISO. A complete procedure is provided to receive and do impairment estimation for WiMAX MIMO signals using a single receiver according to the IEEE 802.16 standards.**

Index Terms— **WiMAX, 4G, MIMO-OFDMA measurements, RF front-end impairments, impairment estimation, space-time transmit diversity, spatial multiplexing, joint demodulation**

I. Introduction

Orthogonal frequency division multiple accessing (OFDMA) is expected to be the enabling technology for the fourth generation (4G) wireless communication systems. One of the features that make OFDMA the primary choice for 4G is its compatibility with the multiple input multiple output (MIMO) technology [1], [2], because MIMO has a very significant potential for enhancing wireless systems in capacity, data rate, and coverage aspects.

MIMO adds the multiplexing gain to the proven transmit or receive diversity gains of single input multiple output (SIMO) and MISO systems as a result of operating on a number of parallel channels [3]. It can achieve the high spectral efficiency desired by future bandwidth-greedy wireless systems at the expense of increased hardware and computational complexity. MIMO is especially important for OFDMA based WiMAX systems because it is a part of the IEEE 802.16 and 802.16e standards [4], [5], which are considered suitable candidates for 4G [6], [7].

Reliable MIMO implementation in WiMAX systems as well as other OFDMA technologies requires performing certain MIMO measurements on the system. Considering this need, in this paper, it is aimed to introduce all the measurable parameters of MIMO-OFDMA systems, to explain how to perform the measurements for different system components, and to discuss the challenges specific to some measurements along with some possible solutions.

Optimally, MIMO measurements and signal reception are performed either by using multiple vector signal analyzers (VSAs) or a VSA with multiple RF front-ends. Needless to say, this kind of a measurement setup is extremely costly. Therefore, in this paper, a much more feasible solution is proposed, which employs a single receiver. Considering a WiMAX MIMO system, 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. Furthermore, a complete procedure that explains how to process WiMAX MIMO signals with a single receiver is given. The procedure handles the signal from its reception up to the symbol decision stage.

The flow of the paper is as follows. In Section II, various measurable MIMO-OFDMA parameters are investigated. Section III introduces a number of device under test options. Section IV provides practical MIMO measurement results for antenna transmission and RF combining cases. Section V discusses the primary RF front-end impairments. Section VI provides a guide to estimate and remove the effects of RF front-end impairments. Section VII analyzes the differences of MIMO measurements from single channel measurements in detail. Section VIII describes how to handle WiMAX MIMO signals. Section IX provides the details about combining the transmitted WiMAX MIMO signals from two transmitter branches. Section X concludes the paper.

II. Measurable MIMO Parameters

The set of measurable parameters in MIMO systems comprise all parameters in SISO systems such as IQ impairments, spectral flatness, frequency offset, and phase offset. In this section, rather than these well known parameters, the ones that are the most critical for MIMO implementation will be addressed.

A. Antenna Correlation

The correlation between the antennas of a MIMO system is of vital importance for the system performance. A high correlation may substantially ruin the diversity and multiplexing gains targeted by using multiple antennas [8]. Antenna

Manuscript received June 30, 2007.

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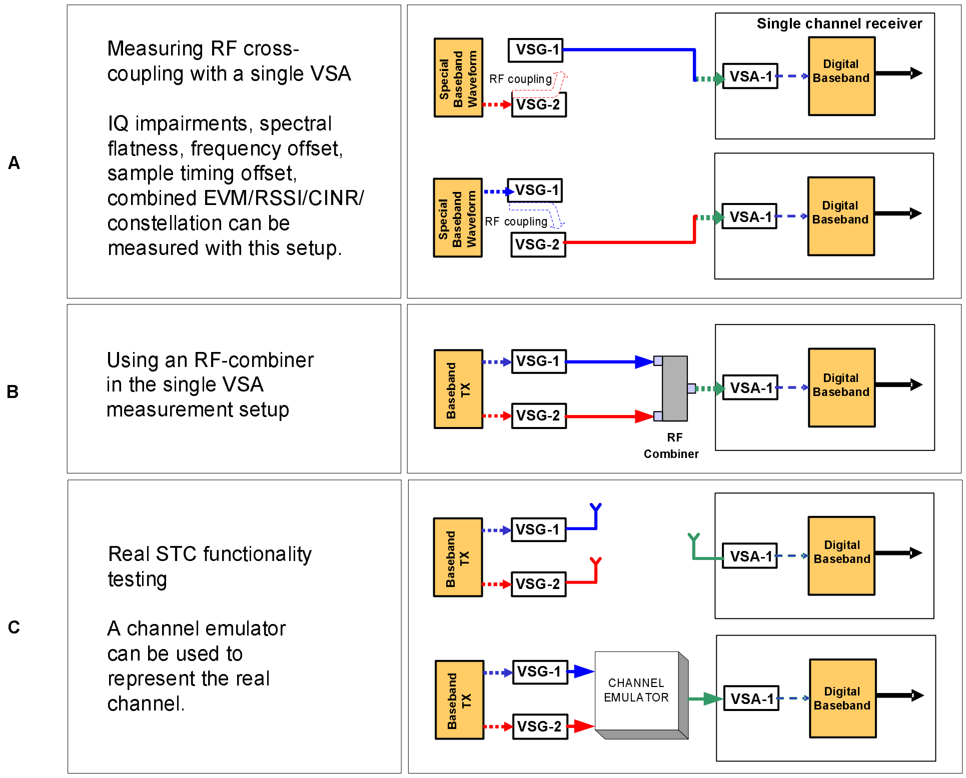

Fig. 1. Measuring RF cross-coupling with a single VSA. EVM/CCDF/Constellation/CINR/RSSI can be measured with this setup.

correlation can vary depending on the antenna separation and the angular spread of the incoming wave [9].

Because of its significance on the achievable gains, antenna correlation has to be quantified while doing a system performance analysis. The correlation between the receiver (Rx) antennas can be measured with a simple setup. In the transmitter (Tx) side, only one branch is allowed to be active, whose signals are captured by all receiver antennas. By recording and correlating the signals received by each of the antennas, the receiver antenna correlations can be determined.

If the complex correlation coefficient is higher than 0.7, a significant reduction in the targeted gains should be expected [2]. In such a case, the most reasonable solution would be to increase the distance between the antennas if it is possible.

B. RF Cross-Coupling

In general, the cross-coupling between the RF front-ends of separate branches of a MIMO system is not taken as seriously as the antenna correlation. However, signals at different front-ends may become correlated to each other because of the coupling between the front-ends. Hence, the negative effect of RF cross-coupling on the system performance can be significant, and it might be necessary to quantitatively measure it.

The setup to measure the RF cross-coupling between the two transmitter branches using a single VSA is shown in Fig. 1-a. Two separate measurements are done. In each measurement a known signal is transmitted from one of the branches while the inactive branch is directly connected to the VSA in the receiver part via a cable. The cross-coupling can be measured in this simple way also when the number of branches is more than two.

C. Error Vector Magnitude and Constellation Parameters

Error vector magnitude (EVM) can be defined as the vector difference between the ideal points in a constellation diagram and the decision points based on the received signal measurements [10]. Since the EVM measurements include both amplitude and phase errors, they are a direct indicator of the received signal quality.

EVM and constellation measurements are the most commonly used, and hence, the most important measurements. The setup for these measurements, which can also be used to obtain the complementary cumulative distribution function (CCDF), carrier-to-interference-plus-noise-ratio (CINR), and the received signal strength indicator(RSSI), is illustrated in Fig. 1-a. This setup requires each transmitter branch to quantify the coupling from other branches. The coupling effects from all other active branches have to be canceled while performing measurements on each branch. Cable connection rather than wireless transmission/reception is preferred in order to eliminate the effects of the channel. In this setup, the measurement has to be repeated as many times as the number of transmitter branches in order to obtain all system parameters. Alternatively, an RF combiner with known characteristics can be utilized in order to be able to measure the parameters of all branches simultaneously as shown in Fig. 1-b.

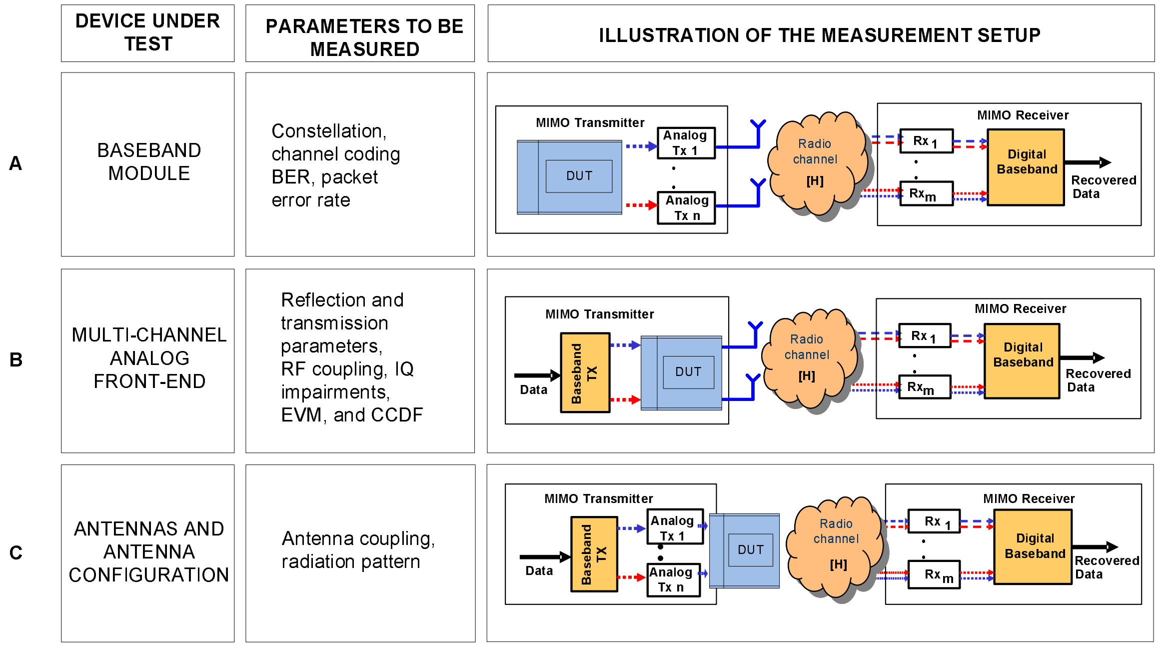

Fig. 2. Various device under test options for MIMO OFDMA measurements.

D. Channel Parameters

The measurement of the channel parameters constitutes an important initial step in the MIMO implementation [11]. A reliable separation of the signals received at each branch depends on correctly determining the channel fading coefficients. The other important channel parameters to be measured are the channel delay spread, channel coherence time, and the noise level in the channel. In order to get reliable statistics of channel parameters, the same measurements have to be repeated extensively, which constitutes the tough part of channel measurements.

The method of performing channel estimation can vary from system to system. Channel estimation in WiMAX MIMO systems is done by making use of orthogonal sets of pilots, one set for each transmitter antenna. The pilots are periodically repeated both in frequency and time.

Once the channel parameters are determined, the real radio channel environment can be simulated in an RF test lab by using a channel emulator whose parameters are set according to the channel measurements. The usage of the channel emulator is illustrated in Fig. 1-c. The use of a channel emulator can enable testing various channel conditions very conveniently, however this component considerably increases the hardware cost.

III. MIMO Transmitter Measurement Options

The MIMO OFDMA transmitter measurements can be various according to the part of the system to be tested. The device under test (DUT) can be almost every single component or group of components in the system. Possible DUTs include the baseband transmitter, the analog RF front-end, the antennas, the radio channel, and several combinations of these components.

The bottom-line of the transmitter measurements is to ensure that the effects of all the system components except the device under test are known accurately, and these effects are calibrated while doing the necessary measurements on the DUT. In the remainder of this section, each of the widely necessitated DUT options will be investigated. As a visual help, these measurements are illustrated in Fig. 2. Because of the reciprocity between the transmitter and receiver parts of the system, only the transmitter components will be considered here.

A. Baseband Module

Baseband module can be the DUT if the parameters of the RF front-end, the antennas and the radio channel are available. In this configuration, the analog front-end is the vector signal generator (VSG) with multiple branches. The connection between the transmitter and receiver sides can be done via a direct cable, via actual antennas and the radio channel, or a channel emulator.

There are various measurements that can be performed on the baseband module. The accuracy of the constellation points, which are generated by digital means in the baseband, may be investigated. The efficiency of the forward error correction (FEC) coding algorithms implemented in the baseband can also be determined. The indicators of the channel coding efficiency are the packet error rate (PER) and the bit error rate (BER) parameters.

B. Analog RF Front-end

The analog RF front-end may considerably change the transmitted signal. Therefore, it might be necessary to measure its effects on the signal. The reflection and transmission parameters of the RF front-end can be very useful. Also, the cross-coupling between the multiple front ends that constitute the transmitter part of a MIMO system is a very fundamental parameter to measure. Another quantity to determine related to the RF front-end is the IQ impairments [12]. The IQ impairments are caused by the inconsistency of the I and Q branches of the IQ modulator. The limited accuracy of the local oscillator leads to a frequency offset, which is also an IQ impairment. The IQ impairments are reflected in the EVM.

C. Antennas

The reflection and transmission parameters are among the measurable quantities for antennas as in the case of the RF front-end. Beside these, the radiation pattern of the antennas according to changing antenna configurations can be measured. When doing the measurements on the analog RF front-end and the antennas, these two system components can be considered separately, or it is also possible to consider them as a whole along with the baseband module to obtain transmitter parameters.

D. Radio Channel

The radio channel can also be considered as a DUT. By doing measurements on the radio channel, various antenna separations and radio environments can be tested to obtain the proper channel models. As it was mentioned in Section II, measurable channel related parameters include fading coefficients, channel delay spread, channel coherence time, and the noise level.

IV. Measurement Results

Most of the information presented so far is obtained while performing extensive measurements on WiMAX MIMO systems. In this section, two of these measurements will be investigated in detail in order to provide a solid example of what to measure on MIMO systems and what to expect to see according to the specific measurement setup.

A. Measurement Setup

In the first setup that will be under focus, Tx and Rx antennas are used, whereas in the second one transmitter signals are combined with an RF combiner and fed to the receiver. The second setup is shown in Fig. 3. The WiMAX MIMO system settings, which are common to both setups, are given in Table I. In these 1024 FFT scenarios, there are 840 subcarriers left after removing the guard bands.

B. Discussion of Measurement Results

The measurements performed on the WiMAX MIMO signals include spectral flatness, CCDF, RSSI, constellation, and EVM measurements. In the following, the results obtained for each of these measurements will be displayed and discussed.

The first plot on Fig. 4 shows the spectral flatness of the measured channel. For both antenna transmission and RF combining cases, the curve for only one of the channels is plotted. As expected, the wireless channel displays a strongly

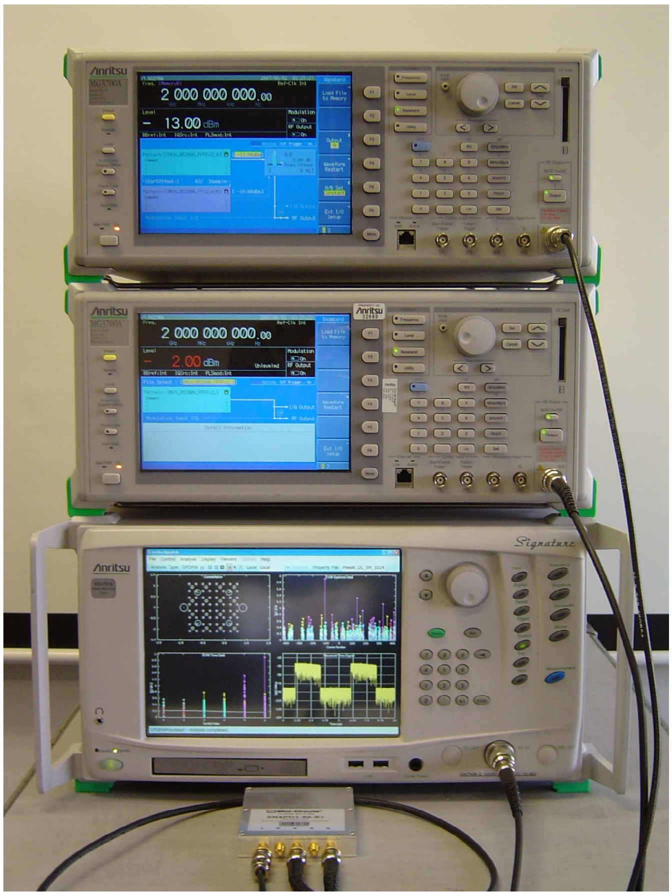

Fig. 3. The 2x1 measurement setup. The outputs of the transmitters are combined with an RF combiner and provided to a single receiver.

TABLE I
WiMAX MIMO System Settings

Parameter	Value
DL / UL	Downlink
Number of transmitters	2
Number of receivers	1
MIMO type	Matrix B (SMUX)
Permutation	PUSC
FFT Size	1024
Number of symbols	14
Bandwidth	10 MHz
Modulations	16QAM & 64QAM
Coding Rates	1/2 & 1/2

frequency selective behavior. In the second setup, however, the channel that is composed of the RF combiner and the cables that are used for connection has a rather flat frequency response. The second plot on Fig. 4 shows the CCDF curves obtained for both setups. The difference in the distribution of received powers clearly indicates the energy loss in the antenna transmission case. This fact is also verified by the RSSI values determined, which are -25.46dBm and -47.55dBm, respectively.

The constellations of the received signals are shown in Fig. 5. The signals of both 16QAM and 64QAM bursts are plotted on the same constellation map. The wider clouds around the constellation points in the first map indicate the effect of

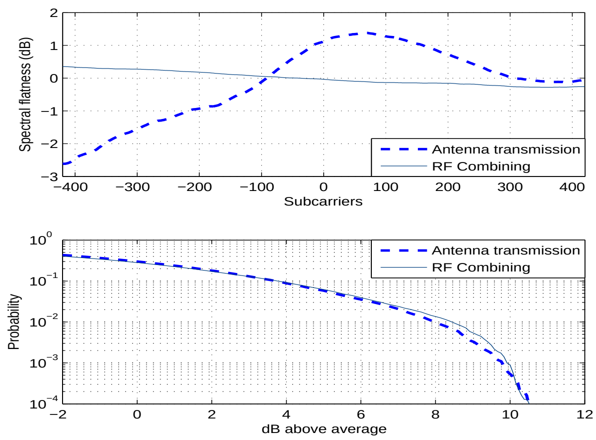

Fig. 4. Spectral flatness and CCDF measurements for the antenna transmission and RF combining cases.

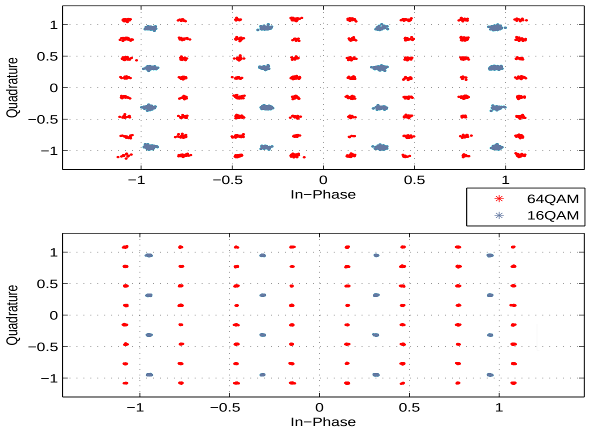

Fig. 5. a. Constellation diagram for the antenna transmission b. Constellation diagram for the RF combining case.

the wireless channel on the MIMO signals in the antenna transmission case. A similar conclusion can be reached by looking at the EVM values demonstrated in Fig. 6. These values are computed symbol by symbol for both setups. The first four symbols belong to 64QAM data bursts, whereas the last four are 16QAM signals. The comparison of the EVMs shows that there is a difference that reaches 10% between the two setups. Also note that the EVM values are generally higher for 64QAM signals compared to the 16QAM.

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

In a MIMO-OFDMA 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 [13] and [14]; here, the essential impact of each of them will be summarized so that the reader can follow the MIMO measurement solutions that will be presented.

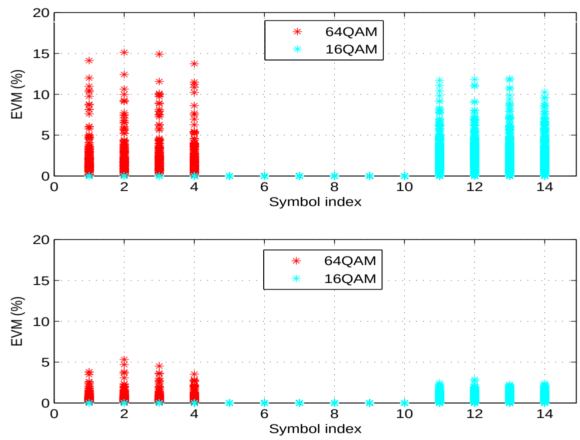

Fig. 6. a. EVM values for the antenna transmission b. EVM values for the RF combining case.

If $X_m(k)$ is the transmitted OFDMA signal in the frequency domain, then, ignoring the inter-carrier interference (ICI) effects, the received signal can be modeled as [15]

$$\begin{aligned} Y_m(k) \; = \; & X_m(k)H_m(k)F(k)\, \exp(-j2\pi k\tau/N) \\ & \times\, \exp(j2\pi m\varepsilon(1+T_{\mathrm{CP}}))\, \exp(j\pi\varepsilon)\mathrm{sinc}(\pi\varepsilon) \\ & \times\, \exp(j2\pi mk\delta(1+T_{\mathrm{CP}}))\, \exp(j\pi k\delta)\mathrm{sinc}(\pi k\delta) \\ & \times\, \exp(j\Phi_m) + N_m(k), \qquad (1) \end{aligned}$$

where m is the symbol index, k is the subcarrier index, T is the symbol duration, T_{CP} is the length of the cyclic prefix, N is the FFT size, and $f_s = N/T$ is the sampling frequency. The remainder of the parameters and their effects are as follows:

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

$[\varepsilon]$: The frequency offset between the oscillators in both sides normalized to the subcarrier spacing $(1/T)$. It results in a drift that increases with time. All subcarriers in the same symbol experience the same amount of shift due to the frequency offset;

$[\delta]$: The inaccuracy between the sampling clocks of the transmitter and receiver normalized to the sampling frequency (f_s). The sampling clock error causes a phase shift in frequency, which grows both with time and with frequency;

$[\Phi_m]$: Random phase noise, which is caused by the instability of oscillators. It leads to a phase shift that 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 effective combined frequency response of the analog filters employed in both the transmitter and the receiver;

$[H_m(k)]$: Frequency selectivity and time dependency of the channel. Because of its frequency selectivity, the channel affects the subcarriers differently. It may also vary over time, especially if a mobile channel is considered;

$[N_m(k)]$: Complex additive white Gaussian noise (AWGN).

VI. Estimation and Removal of Impairments in the SISO Case

The main factors that lead to impairments in the received signal were introduced in the previous section. In the following, processing the received signal in the SISO case will be addressed. 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 impairment estimation, the corresponding effect has to be removed from the received signal before proceeding to the next step.

1) *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.
2) *Frequency Offset Estimation (Time Domain):* The received time domain signal $Y(n)$ is correlated with $Y(n+MD)$
$$\begin{aligned} Z(n) &= \sum_n Y^*(n)Y(n+MD) \\ &= \exp(j2\pi\varepsilon MD)\sum_n \left|Y(n)\right|^2 , \end{aligned} \quad (2)$$
where M is the number of symbols in between, and $D = T + T_{CP}$. Owing to the pilot subcarriers that are repeated regularly in time, $Z(n)$ can be utilized to obtain the frequency offset by computing $\varepsilon = \angle Z(n)/2\pi MD$.
3) *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 effect of frequency offset changes from symbol to symbol, a finer estimate for ε can be obtained by correlating the pilots in two different symbols separated by M symbols $\big(Y_m(k)$ and $Y_{m+M}(k)\big)$
$$\begin{aligned} Z(k) &= \sum_k Y_m^*(k)Y_{m+M}(k) \\ &= \exp(j2\pi\varepsilon MD)\sum_k \left|Y_m(k)\right|^2 , \end{aligned} \quad (3)$$
and then computing $\varepsilon = \angle Z(k)/2\pi MD$.
4) *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.
5) *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.
6) *Slope Estimation:* A time offset may still exists at this point, especially if no preamble was sent, since the packet estimation does not determine the signal starting point very accurately. This time offset will indicate itself as a phase shift that increases with a certain slope over subcarriers. Since the impact of the sampling clock error was already canceled in the previous step, this slope can be estimated by comparing the phases of the subcarriers in the same symbol.
7) *Random Phase Error Estimation:* To determine the random phase error, pilots in different symbols have to be correlated. This correlation yields 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.
8) *Channel Estimation:* Channel estimation is done using again the pilots, which should be now free from all the impairments mentioned so far. The channel estimates for the subcarriers between the pilots are obtained by interpolating the pilot values in a reasonable way.

VII. Measurement Challenges in MIMO Compared to SISO

As opposed to systems with a single input, in MIMO systems, the received signal includes simultaneously transmitted data from multiple transmitter antennas. Therefore, the measured error vector magnitude is 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-OFDMA system considered here has two transmitter branches and one receiver branch.

1) Time offset between the branches: In order to keep the measurements simple, it is desirable to assume that signals from the two 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 digital-to-analog converter (DAC) may be common to both branches, or each branch can use a separate oscillator. If two separate oscillators are employed 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, 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 use 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. Another effect 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 reflect the effect of the RF sections on the received signals.

VIII. Procedure to Handle WiMAX MIMO Signals

Although the term MIMO implies usage of multiple receivers, it is possible to process MIMO signals with a single receiver if there is a solution to the fundamental issue how to separate the constellations and the EVM contributions of each transmitter branch. In the remainder of this paper, a WiMAX system will be considered as an example to MIMO systems using OFDMA. To be more specific, space time coded (STC) downlink (DL) and uplink (UL) WiMAX signals with PUSC permutation will be analyzed more closely. The solution that will be investigated here is based on the use of pilot sequences. In WiMAX, each Tx branch is transmitting a separate set of pilots that are orthogonal to each other according to their subcarrier allocation maps. 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 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 impairment estimation the corresponding effect was being removed from the signal. In the MIMO case, however, since each branch has different impairments, it is not valid to remove the effects from the received signal. Instead, the estimated effects are removed from the corresponding set of pilots, only. After determining and removing all the effects one by one, the channel estimations $H(k)$ can be obtained from the pilot sets. Before proceeding to the symbol decision step, the impairment estimations obtained for both channels should be applied to the corresponding channel estimations as follows

$$\begin{aligned}\hat{H}_m(k) &= H_m(k)\,\exp(-j2\pi k\tau/N)\,\exp(j2\pi m\varepsilon(1+T_{\mathrm{CP}})) \\ &\times \exp(j2\pi mk\delta(1+T_{\mathrm{CP}}))\,\exp(j\Phi_m). \end{aligned} \tag{4}$$

IX. Combining the MIMO Signals From Two Transmitter Branches

The two MIMO options that are considered in the 802.16 standard for WiMAX systems are the space-time transmit diversity (STTD) and the spatial multiplexing (SM). In this section, the implementation of these two methods will be shortly explained. The focus will be on how to combine the received MIMO signals in each case.

A. Space-Time Transmit Diversity

In the STTD case, Alamouti encoding [16] is applied to subcarrier pairs, where the same subcarriers of two consecutive OFDMA symbols constitute a pair. In the receiver part, the STTD signals are combined in a special way that will be explained shortly. A single receiver is enough for combining STTD signals, and this is very appropriate for the purpose of employing a single receiver to keep the hardware cost at a minimum.

In the STTD implementation for DL-PUSC WiMAX, the signals of the subcarriers x_1 and x_2, which constitute a subcarrier pair, are transmitted as $[x_1, -x_2^*]$, respectively, from the first antenna, and in the order of $[x_2, x_1^*]$ from the second antenna, according to the Alamouti coding. In the receiver, the signals received at consecutive symbol times on each carrier pair are

$$Y_1(k) = H_1(k)x_1 + H_2(k)x_2 + N_1\ , \tag{5}$$

$$Y_2(k) = -H_1(k)x_2^* + H_2(k)x_1^* + N_2\ , \tag{6}$$

where $H_1(k)$ and $H_2(k)$ are the channel responses, and N_i is noise. These two received signals can be combined in two different ways to yield the transmitted signals as follows

$$\begin{aligned}C_1 &= \hat{H}_1(k)^*Y_1(k) + \hat{H}_2(k)Y_2(k)^* = \\ &x_1(|\hat{H}_1(k)|^2 + |\hat{H}_2(k)|^2) + \hat{H}_1(k)^*N_1 + \hat{H}_2(k)N_2^*,\end{aligned} \tag{7}$$

$$\begin{aligned}C_2 &= \hat{H}_2(k)^*Y_1(k) - \hat{H}_1(k)Y_2(k)^* = \\ &x_2(|\hat{H}_1(k)|^2 + |\hat{H}_2(k)|^2) + \hat{H}_2(k)^*N_1 - \hat{H}_1(k)N_2^*,\end{aligned} \tag{8}$$

where $\hat{H}_m(k)$ are the channel estimations. Assuming that noise has a limited effect, a reliable estimation for x_1

and x_2 can be obtained by $C_1/(|\hat{H}_1(k)|^2 + |\hat{H}_2(k)|^2)$ and $C_2/(|\hat{H}_1(k)|^2 + |\hat{H}_2(k)|^2)$, respectively.

In UL-PUSC WiMAX, on the other hand, the implementation of STTD is different. Alamouti coding is applied to adjacent subcarriers in the same symbol (rather than the same subcarriers in adjacent symbols). Therefore, it is more like space-frequency coding rather than space-time coding. In the receiver, the signals received at consecutive subcarrier locations are

$$Y_1(k) = H_1(k)x_1 - H_2(k)x_2^* + N_1 \ , \qquad (9)$$
$$Y_1(k+1) = H_1(k+1)x_2 + H_2(k+1)x_1^* + N_2 \ , \qquad (10)$$

These signals are combined as follows

$$C_1 = \hat{H}_1^* Y_1(k) + \hat{H}_2 Y_1(k+1)^* \ , \qquad (11)$$
$$C_2 = \hat{H}_1^* Y_1(k+1) - \hat{H}_2 Y_1(k)^* \ , \qquad (12)$$

and the transmitted signals x_1 and x_2 can be obtained as in the case of space-time coding.

B. Spatial Multiplexing

In spatial multiplexing, each branch transmits a different signal. Ideally, there should be N receivers if there are N transmitter branches. This way, N independent copies of each transmit signal is received. By making use of the channel information, these copies are combined to obtain the desired signals. If there is a single receiver available, however, the transmitted signals can only be obtained by doing joint demodulation [17].

In joint demodulation, at every subcarrier each possible IQ signal pair $[x_1, x_2]$ is considered to be a hypothesis. Each hypothesis is simulated by applying the channel responses, and the best hypothesis is determined in a minimum squared error approach as follows

$$\epsilon(k) = |Y(k) - \hat{H}_1(k)x_1 - \hat{H}_2(k)x_2|^2 \ , \qquad (13)$$

where $Y(k)$ is the received signal, x_1 and x_2 are the two signals that constitute the hypothesis, and $\hat{H}_1(k)$ and $\hat{H}_2(k)$ are the corresponding channel estimates.

If two transmitter antennas, each transmitting, for example, a QPSK modulated signal, are considered, then there are 4^2 hypotheses to check for each received data subcarrier, which does not pose a serious computational challenge. However, the complexity of this method increases proportional to N^k, where N is the modulation order, and k is the number of transmitter branches. Therefore, for MIMO applications that employ a number of transmitters and use higher order modulations, the computational complexity may set a practical limit to the feasibility of this method. A version of joint demodulation that utilizes multiple receivers can be considered as a solution in such a case.

X. CONCLUSION

Parallel to the growing interest towards OFDMA and MIMO technologies, the necessity for MIMO-OFDMA 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 measurable MIMO parameters are explained in detail, and the possible device under test options are introduced. Practical measurement results are demonstrated and analyzed for a 2x1 system both for antenna transmission and RF combining setups. 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. In the paper, a detailed procedure about receiving and combining WiMAX MIMO signals transmitted from two transmitter branches with a single receiver is also given. This way, a complete solution for receiving, measuring, and evaluating MIMO-OFDMA signals with a single receiver is provided.

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