Validation of a Green Wireless Communication System with ICA Based Semi-Blind Equalization

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Abstract— **In this paper, we validate a green wireless communication system with the independent component analysis (ICA) based and precoding aided semi-blind equalization, on a testbed which consist of a pair of Keithley signal generator and signal analyzer connected to antennas. The implemented system requires only a small amount of side information to be transmitted to the receiver, therefore achieves energy- and spectrum-efficient green communications. The system performance is measured in different wireless channels and compared with simulation results. Compared with training data based channel equalization with overhead of 3.6%, precoding ICA equalization has a better BER performance, which gives a good tradeoff between bandwidth and energy requirement. The impact of precoding weight constant on the BER performance is showed and optimal constant value is found. The impact of frame length on the performance of ICA based equalization is also evaluated.**

Key words— **green communications, independent component analysis, orthogonal frequency division multiplexing, equalization, signal generator, signal analyzer.**

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) [1] is a promising technical candidate for green wireless communication systems. In particular, a lot of wireless standards (IEEE802.11a, LTE and Wi-Max) have adopted OFDM technology [13] as a method to improve wireless communication in the future. By dividing wideband frequency selective fading channel into parallel narrowband flat fading sub-channels, OFDM can effectively combat frequency selective fading or time dispersive channels in a broadband communication channel. OFDM employs cyclic prefix (CP) to mitigate the effect of inter-symbol interference (ISI). In wireless OFDM communication systems [1], channel estimation and equalization are two significant technologies at receiver.

In practical communication system, the receiver does not know the exact information of the wireless channel. Therefore, the estimation method to get channel state information (CSI) [2] is important, which directly affects channel equalization. Blind channel estimation and equalization technology can acquire the CSI or equalizer coefficients straightforwardly from the statistics and structure of received signals. Besides, without increasing extra bandwidth, it improves the spectral efficiency.

Among the approaches of blind channel estimation and equalization, independent component analysis (ICA) is considered as an efficient higher order statistics (HOS) based blind source separation technique [3][4][5]. Without requiring the accurate CSI, ICA is an effective solution to recover transmitted data directly from the statistics of the received signal by maximizing non-Gaussianity of the ICA output signal. A blind receiver structure [8] was proposed to avoid error propagation across subcarriers. By the means of using a pre-filter at transmitter, the correlation between reference subcarrier and other subcarriers is introduced to resolve this error problem. Simulation results demonstrate that pre-filter structure is a robust scaling process against error propagation at receiver. However, for higher order modulation schemes, the performance of this method is degraded.

Ambiguity problem is considered as one of the drawbacks in ICA equalized signal. In blind estimation method, the ambiguity on all signal subcarriers is as same as that on the reference subcarrier [8]. In [9] [10], the training information added before transmission can be used to conquer the ambiguity, but reference and training symbols consume some subcarriers, which will reduce the spectral efficiency of the system. In [6], a reference data is applied to each subcarrier of the source data during the process of precoding in order to eliminate the ambiguity without consuming extra bandwidth. However, all of the aforementioned work is based on simulation only. Although there exist randomness in their channel matrices, it is still different from the wireless communication channel in real life.

In this paper, we use a pair of Keithley signal generator and signal analyzer, which are connected to antennas, to validate the ICA based and precoding aided approach in [6] in real wireless communication channels. Our work is different in the following aspects. Firstly, we evaluate the system performance in practical environment and compare the measured results with simulated results. Secondly, we use reference symbol sub-block formed by constant amplitude zero autocorrelation (CAZAC) sequences [7] for synchronization in order to find out the best start point of the received signal sequence. Thirdly, we use compensation symbol sub-blocks to compensate for the local oscillator drift. In real-time transmission with communication instruments, delay caused by multipath and phase drift always happen, so synchronization and drift compensation are necessary. It is showed that the measured results match the simulated results that is the implemented of wireless communication system performs well.

The system model is presented in Section II. We describe the ICA based and precoding aided semi-blind equalization in Section III. The measured results and their analysis are given in Section IV. Finally in Section V, conclusion is drawn.

II. SYSTEM MODEL

We consider a WiFi system [11] operating at 2.45 GHz. The systems and algorithms of this paper are developed by using MATLAB and implemented on the Keithley 2920 RF Signal Generator (V2920A) and Keithley 2820 RF Vector Signal Analyzer (V2820A) respectively. Connected to a pair of antennas developed in [12], the signal generator V2920A generates and transmits time domain signal to the receiver V2820A through wireless multipath channel in any environment where they are located. We establish a connection between the MATLAB in the personal computer (PC) and the two instruments. This is to control the instruments through MATLAB so that the communication (sending and receiving data) between the MATLAB and the instruments can be performed.

A. *System Setup Requirement:*

Hardware

a) Two communication instruments named V2920A (signal generator and transmitter) and V2820A (signal receiver and analyzer).
b) A pair of antennas operating at 2.45GHz central frequency. The antennas are designed with a novel dual-feed Planar Inverted-F [12] for radio communication systems at 2.45 GHz. The antennas have innovation that it contains only one radiating plate with a pair of matched and isolated port in order to reduce the mutual coupling and achieving a good isolation.
c) A computer/PC which the instruments will be linked to and controlled from.
d) An Ethernet/local area network (LAN) box or router with at least three sockets.
e) Three Ethernet/LAN cables.

Software

a) Some software is required to be download from the official website. They are “IviSharedComponents” and “IviVisaSharedComponents”. The respective software need to be installed before the installation of MATLAB and IVI instrument drivers. More information and help can be obtained from the file “Using IVI with MATLAB”.
b) MATLAB software with the version of 2009 or newer is necessary.
c) IVI instrument driver of the specific instrument is to be downloaded from its official website or from cd of the instrument.
d) The latest version of ‘Agilent IO Libraries suite’ to be downloaded from Agilent website. Here in our project, we use the version 16.1.

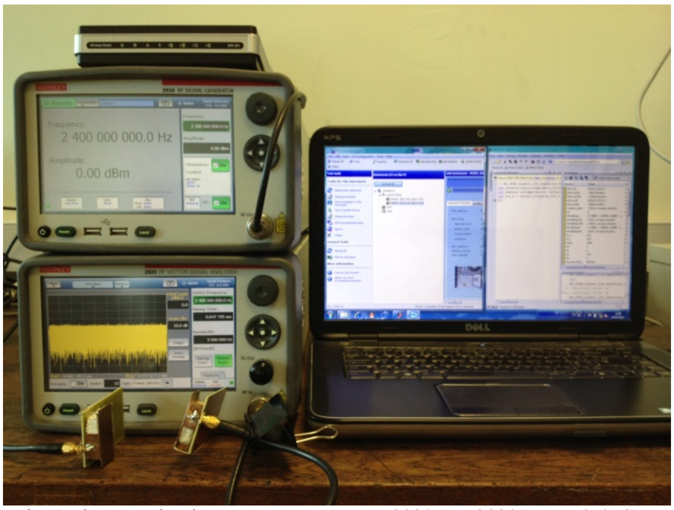

Fig. 1 The setup hardware system: router, V2920A, V2820A, two 2.45GHz antennas and computer/PC

B. *System Setup Procedure*

a) The software of IviSharedComponents and IviVisaSharedComponents are installed on the PC. Then the IVI instrument drivers of the instruments V2820A and V2920A are installed on the PC. After that, MATLAB is installed on the PC. The MATLAB must contain the instrument control box which is used to connect and control the instrument through MATLAB. Finally, the Agilent IO Libraries suit is installed on the PC.
b) The antennas are connected to V2920A and V2820A respectively with cable.
c) The two instruments are physically connected to the PC through the Ethernet/LAN box or router. Turn on the instruments. Then detecting the instruments through the PC.
d) This step is to connect/interface the instruments to MATLAB through the PC so that the instruments may be controlled from MATLAB.

C. *Frame Structure*

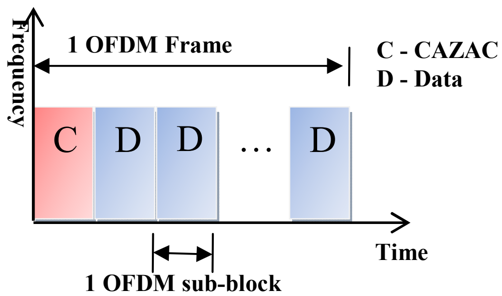

Fig. 2 Precoding aided transmit signal frame structure

In the software level system of this paper, we consider OFDM system. In this paper, an OFDM frame is a combination of OFDM sub-blocks. One frame consists of *M*

($32 \le M \le 200$) OFDM sub-blocks, and each sub-block has N ($64 \le N \le 256$) sub-carriers. Frame is the unit of transmission between V2920A and V2820A, which is to say, at each transmission, V2920A transmits one OFDM frame to V2820A. Figure 2 shows an example of ICA based precoding aided OFDM frame structure. C means CAZAC sequence composes the first sub-block, and D means that the sub-block is formed by the source data.

In real time signal transmission, an OFDM frame will experience some delays caused by multipath before reaching the receiver. In our measurement, the receiver V2820A needs to know where the starting point is in each OFDM frame. To achieve this target, the cross correlation between the received OFDM frame and the CAZAC reference symbol is used. Since the real-time multipath channel is varying and subject to random fading, the synchronization point of each OFDM frame is dynamic. Therefore, a synchronization span is needed to detect the best starting point.

At receiver, the first V (1<V<20) sub-blocks of the received signal frame are used as compensation symbol blocks to compensate the drift. That is to say, precoding based method will not introduce any redundant data or consume extra bandwidth, and it will have a good BER performance.

D. Precoding aided system model

For precoding aided method, antenna of V2920A transmits one frame in each transmission time span. In the frame, let $s_m(n)$ denotes the signal on subcarrier n (*n=1, ..., N*) of the m-th (*m=1, ..., M*) sub-block, then the m-th sub-block is formed as $S_m = [s_m(1), \dots, s_m(N)]$. So an OFDM frame can be written as $S = [S_1, \dots, S_M]$. In order to eliminate the ambiguity caused by ICA based equalization, precoding is introduced to get the correlation between the reference data and received source data. We employ precoding on each subcarrier before transmission, so the original source data can be transformed by the following

$$\hat{S}_m(n) = \frac{1}{\sqrt{1+a^2}}\left[S_m(\mathrm{n}) + \mathrm{a}S_{ref,m}(\mathrm{n})\right] \quad (1)$$

where a ($0 \le \mathrm{a} \le 1$) is precoding weight constant. It can give a tradeoff on the transmitted power allocation between the original source data stream $S_m(\mathrm{n})$ and the reference data $S_{ref,m}(\mathrm{n})$. Reference data $S_{ref,m}(\mathrm{n})$ is well known by both transmitter and receiver.

Before each transmission, we apply inverse discrete Fourier transform (IDFT) to the source data stream transforming them from frequency domain to time domain, and add a cyclic prefix (CP) with length L_{cp} (we set $L_{cp} = \frac{N}{8}$ in this paper) to each symbol sub-block. CP is used to avoid the effect of inter-block interference (IBI) and will be removed at the receiver. Therefore, the received signal $Y_m(n)$ on subcarrier n within m-th sub-block can be written as

$$Y_m(n) = H_m(n)\hat{S}_m(n) + N_m(n) \quad (2)$$

Where $H_m(n)$ with length of N is channel frequency response on n-th subcarrier within the m-th sub-block, and $N_m(n)$ is additive white Gaussian noise (AWGN) vector (Since we did this project by using the instrument, the channel and AWGN are unknown to us, here in the equation (2) $H_m(n)$ and $N_m(n)$ are assumed vectors).

According to [6], ICA based equalization can be used directly to the received signal Y to recover the transmitted signals on each subcarrier. However, ICA will introduce different permutation and phase shifts to the equalized data compared with the original data stream. So we also apply de-rotation and phase shifting to the ICA equalized signal to eliminate the ambiguity.

Before transmission of the signal, a CAZAC sequence data is pre-pended to the frame. This will help to find out best synchronization point at the receiver by using the cross correlation between the CAZAC sequence data and received delayed data. By finding the maximum value of the correlation results, we can get the starting point of the received signal, and then remove CAZAC symbol block.

After synchronization detection, we are going to compensate local oscillator drift caused by the instruments. For precoding aided method, we set the first V received sub-blocks as training blocks, and use them to do the compensation. This will not introduce any extra redundant or disturb the received signals.

$$\tilde{Y}_m(n) = \mu_m(n)H_m(n)S_m(n) + \mu_m(n)N_m(n) \quad (3)$$

In equation (3), $\mu_m(n)$ is the compensation factor on n-th subcarrier within the m-th sub-block. With the local oscillator drift corrected, we can see the compensated received signal sequence $\tilde{Y}_m(n)$ which is related to $\widetilde{H}_m(n)$ and $\widetilde{N}_m(n)$, as it is shown in equation (4).

$$\tilde{Y}_m(n) = \widetilde{H}_m(n)S_m(n) + \widetilde{N}_m(n) \quad (4)$$

Now we have determined the exact starting point and removed the drift inside the received signal, the next step we have to do is ICA based semi-blind equalization. Figure 3 shows the entire communication OFDM system model blocks.

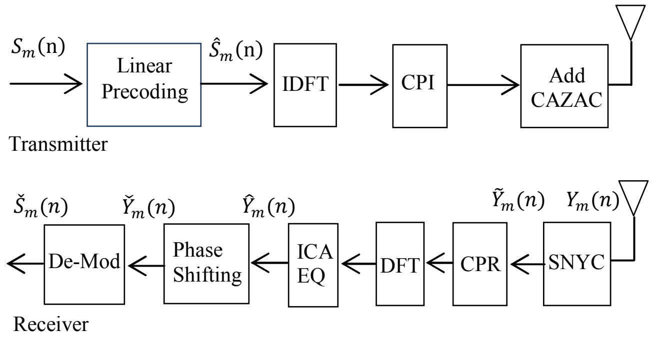

Fig. 3 Block model of precoding aided OFDM system with ICA based equalization with frame index m, subcarrier index n (CPI: cyclic prefix insert, SNYC: synchronization, CPR: cyclic prefix remove, EQ: equalization, De-Mod: demodulation)

III. ICA Based Semi-Blind Equalization

There is various numbers of algorithms for ICA [3], and JADE [4] is well established and widely used. The channel equalization is applied to each subcarrier within every sub-block, which is to say, ICA equalize the received signal based on subcarrier. However, this will introduce phase ambiguity problem. Phase shift is used to resolve this problem. Then ICA equalized signal can be written as

$$\hat{Y}_m(n) = P_m(n)S_m(n) \qquad (5)$$

where $P_m(n)$ is the phase deviation matrix which is caused by imperfect compensation and noise. This problem can be resolved by using the de-rotation process to the equalized signal $\hat{Y}_m(n)$ as follows:

$$\check{Y}_m(n) = \hat{Y}_m(n)[\delta(n)/|\delta(n)|] \qquad (6)$$

where $\delta(n)$ is phase deviation factor with QPSK modulation derived from $\hat{Y}_m(n)$. $\delta(n)$ can be represented as

$$\delta(n) = \left\{\frac{1}{N}\sum_{n=1}^{N}[\hat{Y}_m(n)]^4\right\}^{-\frac{1}{4}} e^{-j\frac{\pi}{4}}. \qquad (7)$$

However, the process of eliminating phase ambiguity brings phase rotation to $\check{Y}_m(n)$ as

$$\check{Y}_m = Q_m(n)S_m(n) \qquad (8)$$

where $Q_m(n) = qe^{j\theta_\tau(n)}$ is a kind of quadrant ambiguity with four possible phase rotation: $\theta_\tau(n) = \frac{\pi}{2}\gamma$ $(\gamma \in \{0,1,2,3\})$.

To mitigate this quadrant ambiguity, the next step is to do cross correlation and find out the correct phase rotation. The estimated cross correlation within sub-block *m* ban be donated as

$$\beta_m = \frac{1}{N}\sum_{n=1}^{N}\check{Y}_m(n)[S_{ref,m}(\mathrm{n})]^* \qquad (9)$$

where $[S_{ref,m}(\mathrm{n})]^*$ is the complex conjugate of reference data sequence $S_{ref,m}(\mathrm{n})$. We can search for the largest value of β_m to find out the correct phase rotation $\theta_\tau^{cor}(\mathrm{n})$ on the n-th subcarrier.

$$\theta_\tau^{cor}(\mathrm{n}) = \arg\max_{\theta_\tau}\frac{1}{M}\sum_{m=1}^{M}|\beta_m(\mathrm{n})| \qquad (10)$$

By arranging the correct phase rotation sequence, we can get $B_m = [b_m e^{j\theta_\tau^{cor}(1)}, b_m e^{j\theta_\tau^{cor}(2)}, \ldots, b_m e^{j\theta_\tau^{cor}(N)}]$ to recover the received signal in equation (8).

$$\tilde{S}_m = B_m(n)Q_m(n)S_m(n) \qquad (11)$$

After the procedure above, we pass the estimated data sequence $\tilde{S}_m$ to the decision device to obtain the recovered data sequence $\check{S}_m(n)$ of the source data $S_m(n)$. By calculating the difference between recovered data sequence $\check{S}_m(n)$ and original data sequence $S_m(n)$, we get bit error rate.

IV. Results and Analysis

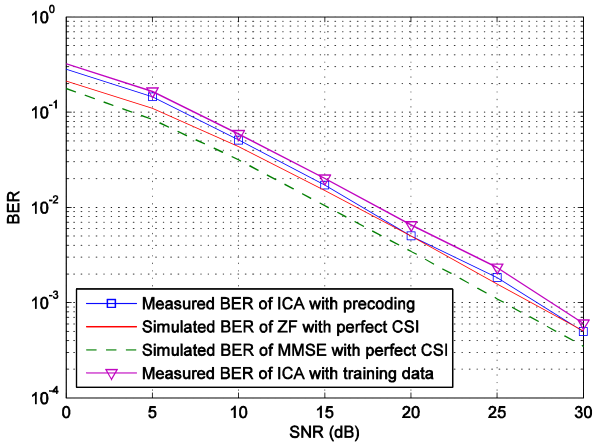

Fig. 4 BER vs SNR (dB) in room area with precoding weight a=0.36, N=512, M=128, L_{cp}=64

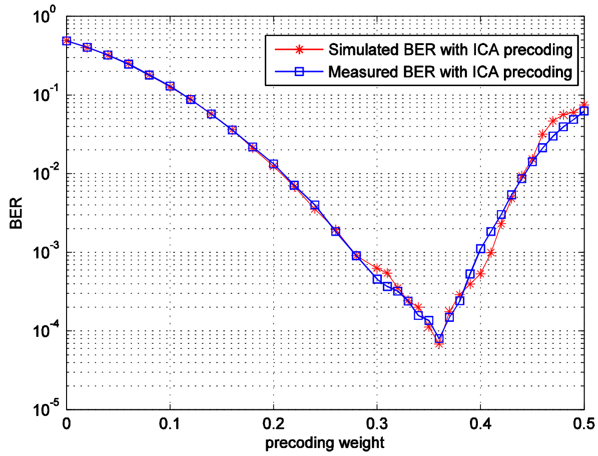

Fig. 5 BER vs precoding weight in room area with SNR (dB)=30dB, N=512, M=128, L_{cp}=64

In this section, we use the measurement results to analyze the performance of ICA based channel equalization with precoding weight. In each sub-block, the number of subcarrier is set as *N*=512, and length of CP $L_{cp} = \frac{N}{8} = 64$. Precoding weight constant is set as a sequence of numbers between 0 and 0.5 in order to find out the best performance point. All of the measurements have been done in a room space with normal temperature 17℃.

In figure 4, we pre-set the precoding weight constant as a=0.36 and measure the bit error rate (BER) performance of ICA based equalization method. QPSK modulation [1] is used. By comparing the measured result and simulated result with zero forcing (ZF) and minimum mean square error (MMSE) equalization, we can see that ICA based measured BER is similar with the results of ZF. We can also see the BER performance of ICA based with training data prefixed before transmitted data. The overhead of the training symbol is 3.6%. With a better BER performance, precoding method gives a good tradeoff between system complexity and bandwidth requirement.

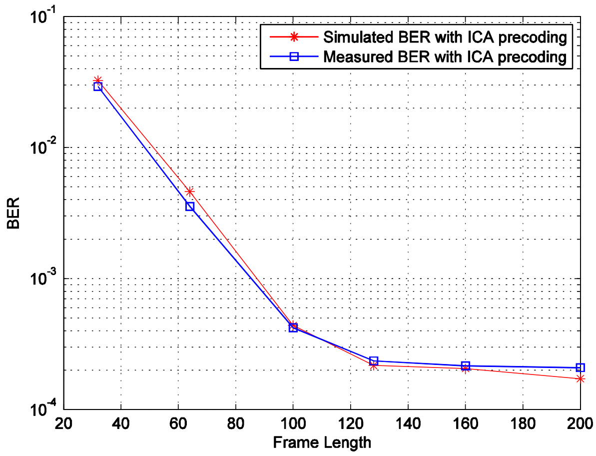

Fig. 6 BER vs frame length in room area with SNR (dB) =30dB, N=512, precoding weight a=0.36

Since the measurement is implemented in real time, the condition outside especially the multipath channel is always changing, and that causes some parameters variable. So we have to test which precoding weight point is the best under room area with temperature of 17°C. In the result shown in figure 5, we set the precoding weight range from 0 to 0.5. By calculating the temperature, the SNR in dB equals 30 dB is assumed. With subcarrier number N=512, frame length M=128 and cyclic prefix length L_{cp}=64, the measurement result provides a BER performance which is close to the optimal case of simulated one. The best precoding weight constant a is 0.36 at that circumstance.

To get how the frame length can affect the ICA based equalization performance, BER performance versus different frame length is measured within room area. Figure 6 demonstrates the measured BER result which is close to the simulated one. A longer frame length will provide a better BER performance which is to say that less bit errors.

V. Conclusions

In this paper, we have validated the precoding aided and ICA based semi-blind equalization [6], by using the real-time testbed composed of the Keithley signal generator and signal analyzer. The reference data for precoding are designed offline with very little complexity, and the precoding constant is chosen to maintain a good BER performance. As showed by the measured results, a precoding weight constant valued between 0.3 and 0.4 generally gives the best BER performance. A frame size of around 120 OFDM symbols, which is reasonable for slow fading channel in WiFi systems, yields a good steady-state performance.

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