

Array Antennas Based Joint Beamforming for IEEE 802.11n Wi-Fi

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Abstract—In order to achieve array gain and spatial diversity or multiplexing gain simultaneously, a novel joint beamforming based on MIMO and array antenna techniques, referred to as J-BF, is proposed for the LTE and Wifi downlink. Array gain is achieved from array antenna based beamforming, referred to as AA-BF. Spatial diversity and multiplexing gains are achieved from MIMO based beamforming, referred to as MIMO-BF. To implement J-BF, i.e., joint AA-BF and MIMO-BF, an access point (AP) is equipped with separate array antennas. Before sending any data-frame in the J-BF mode, firstly, based on the estimated omni-directional CSI, the directional beam can be formed by the array antenna, and the array gain is achieved. Secondly, based on the estimated directional CSI, MIMO-BF is implemented to achieve the spatial diversity or multiplexing gain. More importantly, the J-BF algorithm maintains compatibility with 802.11n and there is not any change in terminals. Simulation results show that the proposed scheme can support the joint AA-BF and MIMO-BF effectively and provide much higher array gain or spatial gains than the traditional MIMO or array antenna respectively.

Keywords: *Beamforming; Array Antenna; MIMO*

I. INTRODUCTION

Due to the demand for higher data rates in wireless communications, some key technologies are proposed to enhance the capacity of wireless networks, e.g., LTE/LTE-A and Wi-Fi. MIMO precoding [1] is a very promising technology in LTE and Wifi, which is a multi-stream beamforming (BF) technique and can significantly improve system capacity and diversity gain, referred to as MIMO-BF [2]. MIMO-BF has demonstrated significant capacity improvement in scatter-rich wireless environments, e.g., the Rayleigh independent identically distributed (i.i.d) channel. In order to exploit the diversity or capacity gain in MIMO systems as large as possible, proper transmission precoding has been proved to be very effective under the condition that the channel knowledge information is available at the transmitter side[3]. Nevertheless, if the scattering is not rich enough at all, line-of-sight (LOS) component will be presented with a high probability, which can bring bad influence on MIMO-BF. As we all know, the LOS is a component that exists by virtue of a direct path between the transmitter and the receiver. And the LOS component manifests itself if the separation distance

between antennas is less than the coherent distance of the channel.

In the traditional array antenna based beamforming, referred to as AA-BF [4], the same signal is emitted from each of the transmit antenna arrays with appropriate phase and amplitude so that the signal power is maximized at the receiver. AA-BF can enhance signal quality and increase system capacities without increasing the total transmit power [5]. Compared with MIMO-BF, AA-BF requires the LOS component, and the antenna arrays are closely co-located.

Hence, there is an urgent demand for joint beamforming, referred to as J-BF, to take full advantage of both AA-BF and MIMO-BF simultaneously in variable environments. In this paper, we present a J-BF strategy, i.e., joint MIMO-BF and AA-BF, for the LTE or Wifi downlink, which can provide spatial diversity, multiplexing gain and array gain simultaneously in different wireless environments. Moreover, the J-BF is implemented in the transmitter, i.e., access point (AP), and there is not any change in the receiver, i.e., mobile station (STA). The proposed J-BF is effective in both LTE/LTE-A and Wi-Fi, and for simplicity, we only consider implementing it in Wi-Fi in this paper.

The paper is organized as follows. The system model is introduced in Section II. The joint MIMO-BF and AA-BF algorithm is proposed in Section III. Simulation results are provided in Section IV. In Section V, the conclusion is given.

II. SYSTEM MODEL FOR JOINT BEAMFORMING

A. System Model

To take full advantage of both MIMO-BF and AA-BF simultaneously, each AP is equipped with N_T array antennas, each of which consists of N_a arrays, as shown in Fig. 1. These array antennas are well separated from each other by a distance D_c which exceeds the coherent distance of the channel. Moreover, in order to achieve the array gain as large as possible, the arrays within each antenna are highly close to each other [6]. According to the standard of Wifi, all STAs are equipped with N_R omni-directional antennas.

Consider a signal vector \mathbf{s} of dimensional $N_{SS} \times 1$ where N_{SS} is the number of data streams. The signal vector is multiplied by a matrix for MIMO-BF, $\mathbf{W} \in \mathbb{C}^{N_T \times N_{SS}}$, and a matrix for AA-BF, $\mathbf{V} \in \mathbb{C}^{(N_T \times N_a) \times N_T}$, prior to transmission. So at the receiver, the received signal vector \mathbf{r} of dimensional $N_R \times 1$ is multiplied by the post-processing matrix \mathbf{P} in order to extract the desired signal from the receiver perfectly, which can be expressed as:

$$\tilde{\mathbf{s}} = \mathbf{Pr} = \mathbf{P}(\mathbf{H}\mathbf{V}\mathbf{W}\mathbf{s} + \mathbf{n}) \quad (1)$$

where the channel matrix $\mathbf{H} \in \mathbb{C}^{N_R \times (N_T \times N_a)}$, and the channel noise $\mathbf{n} \in \mathbb{C}^{N_R \times 1}$, which is drawn from an ensemble of i.i.d complex Gaussian random variables with zero mean and variance σ_n^2 .

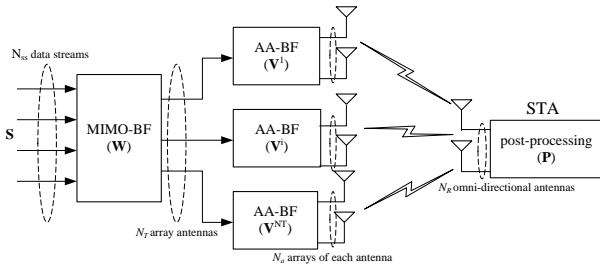


Fig. 1 System model for joint beamforming

The AA-BF matrix \mathbf{V} could be expressed as: $\mathbf{V} = \text{diag}\{\mathbf{v}_{N_a \times 1}^1, \mathbf{v}_{N_a \times 1}^2, \dots, \mathbf{v}_{N_a \times 1}^{N_T}\}$, where $\mathbf{v}_{N_a \times 1}^i$ is the AA-BF vector of the i -th antenna at the transmitter. In order to constrain the total transmit energy, the matrix satisfies $(\mathbf{v}_{N_a \times 1}^i)^H \mathbf{v}_{N_a \times 1}^i = 1$, where $(\)^H$ denotes the conjugate transpose operator.

The channel matrix \mathbf{H} is expressed as: $\mathbf{H} = [\mathbf{H}_{N_R \times N_a}^1, \mathbf{H}_{N_R \times N_a}^2, \dots, \mathbf{H}_{N_R \times N_a}^{N_T}]$, where $\mathbf{H}_{N_R \times N_a}^i$ is the channel matrix from the i -th antenna with N_a arrays at the transmitter to the receiver. For simple analysis, a set of channel models in Wifi [7], is given in Tab. 1.

TAB. 1 CHANNEL MODELS

RMS delay		Environment	Example
Model Spread (ns)			
A	0	N/A	N/A
B	15	Residential	Intra-room, room to room
C	30	Residential/small office	Conference room, classroom
D	50	Typical office	large conference room
E	100	Large office	Multi-story office
F	150	Large space	city square

III. JOINT BEAMFORMING ALGORITHM

At the beginning, the transmitter works in the omni-directional mode as it does not know both the MIMO-BF and

AA-BF matrix (i.e., \mathbf{W} and \mathbf{V}) corresponding to its receivers. Before calculating the two vital matrixes in the J-BF mode, the transmitter has to get the relevant CSI by which the \mathbf{W} and \mathbf{V} can be naturally obtained. The reciprocity between the uplink and downlink channels can be exploited to achieve the CSI [8]. Please note that the required CSI for MIMO-BF and AA-BF is tremendous different.

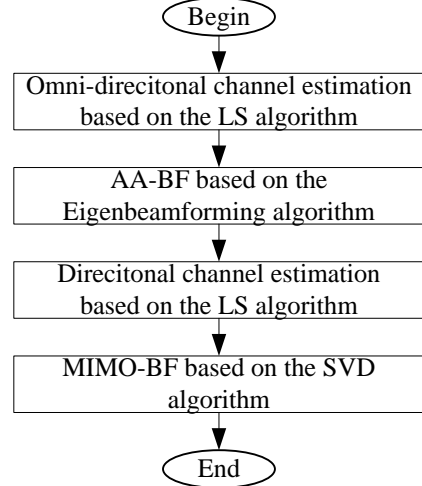


Fig. 2 Flow chart for J-BF

To implement J-BF in the LTE downlink, as shown in Fig. 2, firstly, the AP estimates the CSI of the omni-directional channel through the uplink, and calculates the AA-BF matrix \mathbf{V} based on the estimated omni-directional CSI. Since then, the AP transmits its packets in the AA-BF mode. Secondly, after implementing AA-BF, the AP estimates the CSI of the AA-BF channel through the uplink, and calculates the MIMO-BF matrix \mathbf{W} based on the estimated directional CSI. Finally, the J-BF is implemented and the benefits including diversity, array and multiplexing gains can be obtained through the J-BF mode eventually. The detailed steps are shown in the following:

- Omni-directional channel estimation

Wi-Fi is a typical OFDM-based packet transmission system, which divides the bandwidth into N orthogonal subcarriers. And the training symbols for N subcarriers can be obviously represented by the following diagonal matrix:

$$\mathbf{X} = \begin{bmatrix} X[0] & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & X[N-1] \end{bmatrix} \quad (2)$$

where $X[k]$ represents the training symbols at the k -th subcarrier, $k = 0, 1, 2, \dots, N-1$, with $E\{X[k]\} = 0$ and $\text{Var}\{X[k]\} = \sigma_x^2$.

Given that the channel gain from the STA to the i -th antenna at the AP is $H_{N_a \times N_R}^i[k]$ for the subcarrier k , the received training signal \mathbf{Y} can be expressed as

$$\begin{aligned}
\mathbf{Y} &\triangleq \begin{bmatrix} Y[0] \\ Y[1] \\ \vdots \\ Y[N-1] \end{bmatrix} \\
&= \begin{bmatrix} X[0] & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & X[N-1] \end{bmatrix} \begin{bmatrix} \mathbf{H}_{N_a \times N_R}^i[0] \\ \mathbf{H}_{N_a \times N_R}^i[1] \\ \vdots \\ \mathbf{H}_{N_a \times N_R}^i[N-1] \end{bmatrix} + \begin{bmatrix} Z[0] \\ Z[1] \\ \vdots \\ Z[N-1] \end{bmatrix} \\
&= \mathbf{X} \mathbf{H}_{N_a \times N_R}^i + \mathbf{Z} \quad (3)
\end{aligned}$$

where the channel vector $\mathbf{H}_{N_a \times N_R}^i$ from the STA to the i -th antenna at the AP can be expressed as:

$\mathbf{H}_{N_a \times N_R}^i = [H_{N_a \times N_R}^i[0], H_{N_a \times N_R}^i[1], \dots, H_{N_a \times N_R}^i[N-1]]^T$ and the noise vector $\mathbf{Z} = [Z[0], Z[1], \dots, Z[N-1]]^T$ with $E\{Z[k]\} = 0$ and $Var\{Z[k]\} = \sigma_z^2$.

In the following discussion, we assume that $\hat{\mathbf{H}}$ denotes the estimate values of the channel matrix $\mathbf{H}_{N_a \times N_R}^i$. And the least-square (LS) estimation algorithm is used to get $\hat{\mathbf{H}}$ in such a way that the following cost function is minimized:

$$\begin{aligned}
J(\hat{\mathbf{H}}) &= \|\mathbf{Y} - \mathbf{X}\hat{\mathbf{H}}\|^2 \\
&= (\mathbf{Y} - \mathbf{X}\hat{\mathbf{H}})^H (\mathbf{Y} - \mathbf{X}\hat{\mathbf{H}}) \\
&= \mathbf{Y}^H \mathbf{Y} - \mathbf{Y}^H \mathbf{X} \hat{\mathbf{H}} - \hat{\mathbf{H}}^H \mathbf{X}^H \mathbf{Y} + \hat{\mathbf{H}}^H \mathbf{X}^H \mathbf{X} \hat{\mathbf{H}}
\end{aligned} \quad (4)$$

By setting the derivative of the function with respect to $\hat{\mathbf{H}}$ to zero, we can obtain

$$\frac{\partial J(\hat{\mathbf{H}})}{\partial \hat{\mathbf{H}}} = -2(\mathbf{X}^H \mathbf{Y}) + 2(\mathbf{X}^H \mathbf{X} \hat{\mathbf{H}})^* = 0 \quad (5)$$

Hence, $\mathbf{X}^H \mathbf{X} \hat{\mathbf{H}} = \mathbf{X}^H \mathbf{Y}$, which gives the solution to the LS estimation as

$$\hat{\mathbf{H}} = (\mathbf{X}^H \mathbf{X})^{-1} \mathbf{X}^H \mathbf{Y} = \mathbf{X}^{-1} \mathbf{Y} \quad (6)$$

With respect to the reciprocity between the uplink and downlink channels, the downlink CSI from the i -th antenna at the AP to STA, $\mathbf{H}_{N_R \times N_a}^i$, can be represented as:

$$\mathbf{H}_{N_R \times N_a}^i = (\hat{\mathbf{H}})^T. \quad (7)$$

- Array antenna based beamforming

There have been several effective AA-BF algorithms, e.g., direction-of-arrival (DOA) based beamforming [9] and eigenbeamforming[10], for the AP to get the directional beams based on the estimated omni-directional CSI. Eigenbeamforming takes full advantage of the spatial

correlations by transmitting over the strongest beam to a given user which can increase system capacity and reduce the interference from others, and we take it as the AA-BF algorithm in this paper.

Based on the estimated omni-directional CSI, the spatial correlation matrix between the i -th antenna of the AP and its STA is obtained as follows:

$$\mathbf{C}^i = E\left\{(\mathbf{H}_{N_R \times N_a}^i)^H \mathbf{H}_{N_R \times N_a}^i\right\} \quad i = 1, 2, \dots, N_T \quad (8)$$

The sorted eigenvalue decomposition of the correlation matrix \mathbf{C}^i in the descending order is expressed as:

$$\mathbf{C}^i = \mathbf{D}^i \mathbf{\Lambda}^i (\mathbf{D}^i)^H = \sum_{k=1}^{N_a} \lambda_{k,i} \mathbf{D}_{k,i} (\mathbf{D}_{k,i})^H \quad i = 1, 2, \dots, N_T \quad (9)$$

where $\mathbf{D}_{1,i}$ corresponding to the largest eigenvalue $\lambda_{1,i}$, is the principal eigenvector of \mathbf{C}^i .

In eigenbeamforming, the AA-BF vector of the i -th transmitter antenna at the AP, $\mathbf{v}^i = \mathbf{D}_{1,i}$.

- Directional channel estimation

Obviously, after implementing AA-BF, the channel has been changed seriously, which is not the initial omni-directional channel. So we have to estimate the CSI of the directional channel, referred to as \mathbf{H}_{AA-BF} , again. Similarly, it is easy to estimate the AA-BF channel based on the LS algorithm as shown in the first step.

- MIMO based beamforming

Several effective MIMO-BF algorithms have been studied, e.g., Singular Value Decomposition (SVD) [11], Geometric Mean Decomposition (GMD) [12], etc. In this paper, we just take SVD into consideration.

The SVD of \mathbf{H}_{AA-BF} can be expressed as:

$$\mathbf{H}_{AA-BF} = \mathbf{U} \mathbf{\Sigma} \mathbf{W}^H \quad (10)$$

where \mathbf{U} and \mathbf{W} are unitary matrices; $\mathbf{\Sigma}$ is a diagonal matrix of the singular values of \mathbf{H}_{AA-BF} in the descending order. The MIMO-BF matrix \mathbf{W} is achieved now.

Up to now, the AP has got the AA-BF and MIMO-BF matrix, and then sends its packets in the J-BF mode.

- Decoding

In order to decode the desired signal from each antenna at the STA, the received signal \mathbf{r} should be multiplied by a weight matrix \mathbf{P} such that

$$\tilde{\mathbf{s}} = \mathbf{P} \mathbf{r} \quad (11)$$

Some popular decoding methods can be exploited to calculate \mathbf{P} , e.g., the zero-forcing (ZF) and minimum mean square error (MMSE) algorithm recommended. In order to maintain compatible with 802.11n without any change in STA, the ZF is taken into account.

The ZF technique nullifies the interference by the following matrix:

$$\mathbf{P} = \left((\mathbf{H}\mathbf{V}\mathbf{W})^H \mathbf{H}\mathbf{V}\mathbf{W} \right)^{-1} (\mathbf{H}\mathbf{V}\mathbf{W})^H \quad (12)$$

where $()^H$ denotes the Hermitian transpose operation. That is to say, it inverts the effect of channel as

$$\tilde{\mathbf{s}} = \mathbf{P}\mathbf{r} = \mathbf{s} + \tilde{\mathbf{n}} \quad (13)$$

where $\tilde{\mathbf{n}} = \mathbf{P}\mathbf{n} = \left((\mathbf{H}\mathbf{V}\mathbf{W})^H \mathbf{H}\mathbf{V}\mathbf{W} \right)^{-1} (\mathbf{H}\mathbf{V}\mathbf{W})^H \mathbf{n}$.

IV. SIMULATION RESULTS

In order to evaluate the proposed joint beamforming algorithm, the following simulations are performed under the indoor channel model D [13]. The values of the parameters used to obtain numerical results for simulations are specified in Wi-Fi, and some of the main parameters are given in Tab. 2. The distance between antennas at the AP is 0.5λ and that between arrays in an antenna is 0.25λ . For comparison, both the $N_T \times N_a \times N_R$ J-BF system and $N_T \times N_R$ MIMO system are evaluated under the same scenarios. For simplicity, we assume that both the AP and STA have the perfect CSI.

TAB. 2 SIMULATION PARAMETERS

Parameter	Value
Frequency	2.4GHz
Bandwidth	20MHz
Spatial data stream	1, 2, 3, 4
OFDM Symbol Length	4us
CP Length	0.8us
FFT Size	64
Modulation Scheme	64QAM
Channel model	D
AA-BF algorithm	Eigenbeamforming
MIMO-BF algorithm	SVD
Decoding	ZF

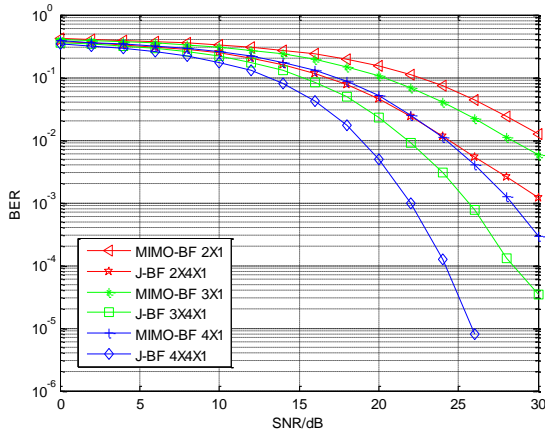


Fig. 3 BER performance of J-BF with variable N_T

The performance of J-BF using variable number of antennas at the AP is examined in Fig. 3, where the number of independent data streams is fixed at one. Obviously, the BER performance of J-BF increases with the increasing transmit antennas as it provides a larger diversity order of N_T . Unfortunately, due to only one antenna at the receiver, we cannot get any spatial multiplex gain under this scenario. On

the other hand, the performance of the $N_T \times N_a \times N_R$ J-BF is much better than that of the $N_T \times N_R$ MIMO-BF as J-BF can obtain array gain to improve the link quality.

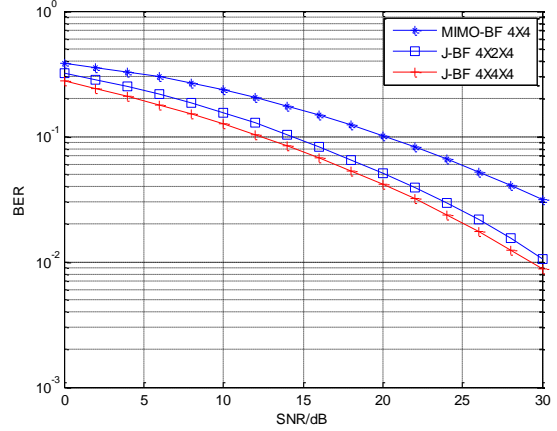


Fig. 4 BER performance of J-BF with variable N_a

Fig. 4 shows that the performance of 4x2x4 and 4x4x4 J-BF is much better than that of 4x4 MIMO-BF as J-BF can achieve array gains by means of AA-BF. Moreover, the 4x2x4 J-BF scheme is 2 dB inferior to the 4x4x4 J-BF scheme as the latter one can obtain a greater array gain with a larger number of arrays. Compared with Fig.3, the number of independent data streams is 4 as $N_R=4$ in Fig.4.

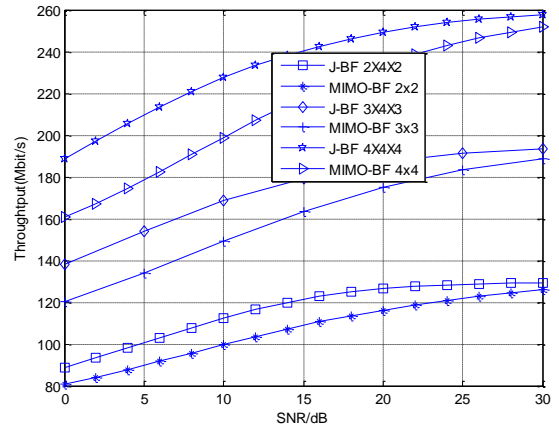


Fig. 5 Throughput of J-BF with variable N_R

Fig. 5 shows that system throughput of the 4x4x4 J-BF scheme is much higher than that of the 3x4x3 or 2x4x2 J-BF scheme as it achieves a greater spatial multiplex gain and can support up to 4 independent spatial data streams while the latter two schemes only support 2 and 3 spatial data streams, respectively. Moreover, system throughput of the 4x4x4 J-BF scheme is higher than that of the 4x4 MIMO-BF as J-BF can achieve array gains.

V. CONCLUSIONS

In this paper, in order to achieve both array gain and spatial diversity or multiplexing gain, a joint AA-BF and MIMO-BF, called J-BF, is presented. Firstly, the AP estimates the CSI of

the omni-directional channel in the uplink, and calculates the AA-BF matrix based on the estimated omni-directional CSI. Since then, the AP transmits its packets in the AA-BF mode. Secondly, after implementing AA-BF, the AP estimates the CSI of the AA-BF channel in the uplink, and calculates the MIMO-BF matrix based on the estimated directional CSI. Hence, the J-BF algorithm is implemented, which is compatible with 802.11n. Simulation results show that after taking full advantage of both array antennas and MIMO, J-BF can provide a much lower BER than the conventional AA-BF and MIMO-BF respectively.

Currently, we are carrying out the following two researches. Firstly, we are researching adaptive beam-forming algorithms based on joint AA-BF and MIMO-BF. Secondly, in order to introduce the joint beamforming, we are researching enhanced SDMA protocols for 802.11n.

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REFERENCES

- [1] H. K. Jayesh, K. B. Huang, *MIMO precoding enable spatial multiplexing, power allocation and adaptive modulation and coding*[p], US 7,702,029 B2, Apr. 20, 2010.
- [2] Y. P. Wu, C. K. Wen, C. S. Xiao, X. Q. Gao, R. Schober, Linear MIMO precoding in jointly-correlated fading multiple access channels with finite alphabet signaling, *IEEE International Conference on Communications (ICC)*, pp. 5306-5311, 2014.
- [3] D. R. Qin, Z. Ding, S. Dasgupta, On Forward Channel Estimation for MIMO Precoding in Cooperative Relay Wireless Transmission Systems, *IEEE transaction on Signal Processing*, pp. 1265-1278, 2014.
- [4] X. R. Wang, E. Aboutanios, M. Trinkle, M. G. Amin, Reconfigurable Adaptive Array Beamforming by Antenna Selection, *IEEE Transactions on Signal Processing*, pp. 2385-2396, 2014.
- [5] J. Singh, S. Ramakrishna, On the feasibility of beamforming in millimeter wave communication systems with multiple antenna arrays, *IEEE transactions on Wireless Communications*, pp. 1, 2015.
- [6] R. A. Soni, R. M. Buehrer and R. D. Benning, "Intelligent antenna system for cdma2000," in *IEEE Signal Processing Magazine*, vol. 19, no. 4, pp. 54-67, 2002.
- [7] A. Stephens, B. Bjerke, et al. (2004). *Usage Models*, IEEE 802.11-03/802r23.
- [8] T. Luo, A. Damnjanovic, Malladi, *channel estimation for wireless communication*[p], US 2011/006653 A1, Feb. 3, 2001.
- [9] D. J. Yeom, S. H. Park, et al. Performance analysis of beamspace MUSIC with beamforming angle, *International Conference on Signal Processing and Communication Systems (ICSPCS)*, pp. 1-5, 2014.
- [10] J. Choi, On Coding and Beamforming for Large Antenna Arrays in mm-Wave Systems, *IEEE Wireless Communications Letters*, pp. 193-196, 2014.
- [11] H. Busche, A. Vanaev and H. Rohling, "SVD-based MIMO precoding and equalization schemes for realistic channel knowledge: Design criteria and performance evaluation," in *Wireless Personal Communications*, vol. 48, no. 3, pp. 347-359, 2009.
- [12] Y. Jiang, J. Li and W. W. Hager, "Joint transceiver design for MIMO communications using geometric mean decomposition," *IEEE Trans. Signal Processing*, vol. 53, no. 10, pp. 3791-3803, 2005.
- [13] V. Erceg, L. Schumacher, et al. (2004). *TGn Channel Models*, IEEE 802.11-03/940r4.