Methods of MIMO Decoders for Very High Throughput WLAN IEEE802.11ac

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***Abstract*— Exponential growing of wireless multimedia communications has forced the IEEE802.11 workgroup to define new standard of WLAN. It is named a Very High Throughput WLAN IEEE 802.11ac which exploits MIMO-OFDM technology to provide up to 6,9Gbps of throughput.**

MIMO decoder is the vital part of WLAN 802.11ac. It decodes the received signals to get back the transmitted information. There are many methods can be implemented in MIMO Decoder. The linear methods, such as Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) are simple but low in performance. At the other side, the well-known non-linear method called Maximum Likelihood Detection (MLD) measures the likelihood of the received signal to all symbol candidates. It gives an optimum performance by the cost of very high complexity. Between them, there are some sub-optimal methods, such as K-best, Trellis, and Sphere Detection. These three methods are low in complexity but give performance close to optimum. This paper is adressed to compare the performance and complexity of above methods as MIMO decoders for 8x8 WLAN 802.11ac. Observation is conducted under small room channel model.

***Keywords*—WLAN 802.11ac, MIMO, OFDM, MLD, Trellis, K-best, Sphere, Decoder.**

I. INTRODUCTION

Exponential growing of wireless multimedia communication has sued IEEE-SA (Standard Association) to determine a new WLAN, i.e. 802.11ac. It is able to give maximum 6,9 Gbps of throughput. For providing such very high throughput in very good performance, the 802.11ac exploits MIMO - OFDM (Multiple Input Multiple Output – Orthogonal Frequency Division Multiplexing) technolgy. It combines parallel streaming up to 16 antennas with 160 MHz bandwidth and high-order modulation, i.e. 256-QAM. [1]

MIMO decoder is the vital part of WLAN 802.11ac. It decodes the received signal to get back the transmitted information. There are many methods can be implemented to do this decoding job. Commonly used methods are linear, such as Zero Forcing (ZF) and Minimum Mean Square Error (MMSE). Both of them are simple but low in performance. At the other side, the well-known non-linear method called Maximum Likelihood Detection (MLD) promises optimum performance. It counts all distances of the received signal to symbol candidates. To do this, MLD needs very high complexity of computation which grows exponentially proportional to the number of transmit antennas and the modulation order [2]. In the middle, there are some methods to lower the complexity of MLD while keeping the performance close to optimum. They are called sub-optimum methods. K-Best, Trellis, and Sphere Detection (SD) are members of them.

Performance of MLD based MIMO Decoder for WLAN 802.11n in 20 MHz and 40 Mhz of bandwidth are reported in [3] and [4], respectively. Implementation of sub-optimum methods, i.e. K-best and Trellis in MIMO decoder for WLAN 802.11n system are presented in [5] and [6], respectively. Further, performance comparison of ZF, MMSE, MLD, K-Best, and Trellis methods to cancel the interferences in 2x2 WLAN 802.11ac are observed in [7].

This paper is addressed to explore the performance and complexity of ZF, MMSE, K-Best, Trellis, SD, and MLD as MIMO decoders for 8x8 WLAN 802.11ac. The observation and analyzing is conducted to achieve BER 10^{-6} under small room channel model.

II. MIMO SYSTEM

Received signal in a MIMO system with *N* transmit and *M* receive antennas is expressed as:

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} \quad (1)$$

where $y=[y_1, y_2, ..., y_M]^T$, **H** is MIMO channel matrix with size $M \times N$, $\mathbf{x} = [x_1, x_2, ..., x_N]^T$ is the transmitted symbol vector, and $\mathbf{n} = [n_1, n_2, ..., n_M]^T$ is the additive white Gaussian noise.

A. MIMO Decoder for VHT WLAN 802.11ac

In VHT WLAN 802.11ac, MIMO decoder is used to get back the transmitted symbol **x** from the received signal **y.** Most of the WLAN devices implement linear methods in MIMO Decoder, such as ZF and MMSE to decode **y**.

i. Linear Zero Forcing Decoding

In ZF decoding, the received signal is equalized by the inverse of estimated channel matrix, **W.**

$$\mathbf{W} = \left(\mathbf{H}^{H}\mathbf{H}\right)^{-1}\mathbf{H}^{H} \tag{2}$$

where superscript ^{H} is transpose-conjugate of the matrix. No noise is considered here. The information is obtained by:

$$\begin{aligned}\hat{\mathbf{x}} &= \mathbf{W}\mathbf{y}\\ \hat{\mathbf{x}} &= \mathbf{W}\left(\mathbf{H}\mathbf{x} + \mathbf{n}\right)\\ \hat{\mathbf{x}} &= \mathbf{x} + \mathbf{W}\mathbf{n}\end{aligned} \tag{3}$$

ii. Linear Minimum Mean Square Error Decoding

Differs from ZF, MMSE takes the noise into part of **W**, as:

$$\mathbf{W} = \left(\mathbf{H}^{H}\mathbf{H} + \mathbf{n}\mathbf{I}\right)^{-1}\mathbf{H}^{H} \tag{4}$$

where **I** is matrix identity. It is easy to verify that MMSE is just the same as ZF when no noise is considered. Complexity of these linear decoding methods are proportional to the number of transmit antennas, as [5]:

$$O = N + N^2 \tag{5}$$

iii. Non-Linear-Optimal Maximum Likelihood Decoding

MLD compares the Euclidean distance of the received signal to all possible symbol candidates. It then searches the minimum distance of them, as the following equation:

$$\hat{\mathbf{x}} = \arg\min\left\|\mathbf{y} - \mathbf{H}\mathbf{x}\right\|^2 \tag{6}$$

Number of computation needed by MLD is:

$$O = L^M \tag{7}$$

where M is number of receive antenna and L is the modulation order, i.e L=1 for BPSK, L =2 for QPSK, L =4 for 16-QAM, L =6 for 64-QAM, and L=8 for 256-QAM.

iv. Non-Linear-Sub-Optimal *K*-Best Decoding

After decomposing the channel matrix **H** into **Q** and **R** matrices using QR decomposition such that **H = QR** [7, 8], equation (6) can be stated as:

$$\hat{\mathbf{x}} = \arg\min\left\|\hat{\mathbf{y}} - \mathbf{R}\mathbf{x}\right\|^2 \tag{8}$$

where $\hat{\mathbf{y}} = \mathbf{Q}^{H}\mathbf{y}$. **Q** is a unitary matrix which size is M x N and $\mathbf{QQ}^H = \mathbf{I}$, while **R** is an upper triangular matrix which size is N x N.

Involving N transmit antenna into (8), yields:

$$\hat{\mathbf{x}} = \arg\min\sum_{i=1}^{N}\left|\hat{\mathbf{y}} - \sum_{j=1}^{N}\mathbf{R}_{ij}\mathbf{x}_j\right| \tag{9}$$

For $i = 1, 2, ..., N$, (9) is obtained by:

$$T_i\left(\mathbf{P}_i\right) = T_{i+1}\left(\mathbf{P}_{i+1}\right) + \left|e_i\left(\mathbf{P}_i\right)\right| \tag{10}$$

where $T_{N+1}(\mathbf{P}_{N+1}) = 0$; $T_i(\mathbf{P}_i) > T_{i+1}(\mathbf{P}_{i+1})$; and

$$e_i\left(\mathbf{P}_i\right) = \hat{y} - \sum_{j=1}^{N} R_{ij}x_j \tag{11}$$

$\mathbf{P}_i = [s_i, s_{i+1}, ..., s_N]^T$ is called the *Partial Symbol Vector* and $T_i(\mathbf{s}_i)$ is *Partial Euclidean Distance* (PED). In *K*-Best decoding method, a breadth-first tree is conducted to search for solution of (9). It checks all siblings of a node before proceeds to the next level. The best K node that have the smallest accumulated PEDs is kept. Every path corresponds to a transmitted information **x**. Complexity of *K*-Best method is

$$O = K^M \tag{12}$$

The value of K which is $\leq L$ is choosen as the trade-off between performance and computational complexity. At the first antenna stage, the value of K is set to be 64 and then it is kept to be 16 until the 8-th antenna stage.

v. Non-Linear-Sub-Optimal Trellis Decoding

In Trellis method, after the channel matrix **H** is decomposed into **Q** and **R** matrices, the received signal can be restated as:

$$\begin{aligned}\mathbf{y} &= \mathbf{QR}\,\mathbf{x} + \mathbf{N_0}\\ \mathbf{Q}^H\mathbf{y} &= \mathbf{Q}^H\left(\mathbf{QR}\,\mathbf{x} + \mathbf{N_0}\right)\\ \mathbf{Q}^H\mathbf{y} &= \mathbf{R}\mathbf{x} + \mathbf{Q}^H\mathbf{N_0}\end{aligned} \tag{13}$$

For instance, in M x N MIMO system, to get back the transmitted symbol **x**, Euclidean distance ($\mathbf{\Lambda}$) on each received signal **y** is calculated as:

$$\mathbf{\Lambda} = \left\|\begin{bmatrix}\hat{y}_1\\ \hat{y}_2\\ \vdots\\ \hat{y}_M\end{bmatrix} - \begin{bmatrix}R_{11} & R_{12} & \cdots & R_{1N}\\ 0 & R_{22} & \cdots & R_{2N}\\ \vdots & 0 & \ddots & \vdots\\ 0 & \cdots & 0 & R_{MN}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ \vdots\\ x_N\end{bmatrix}\right\|^2 \tag{14}$$

where $\hat{\mathbf{y}} = \mathbf{Q}^H\mathbf{y}$. $\mathbf{\Lambda}$ can be splitted into:

$$\mathbf{\Lambda} = \omega^{(1)} + \omega^{(2)} + ... + \omega^{(N)} \tag{15}$$

where $\omega^{(t)}$ is *1-D* Euclidean distance for t-th antenna. In case of four transmit and receive antennas, we get:

$$\begin{aligned}\omega^{(1)} &= \left\|\hat{y}_4 - R_{44}x_4\right\|^2\\ \omega^{(2)} &= \left\|\hat{y}_3 - \left(R_{33}x_3 + R_{34}x_4\right)\right\|^2\\ \omega^{(3)} &= \left\|\hat{y}_2 - \left(R_{22}x_2 + ... + R_{24}x_4\right)\right\|^2\\ \omega^{(4)} &= \left\|\hat{y}_1 - \left(R_{11}x_1 + ... + R_{14}x_4\right)\right\|^2\end{aligned} \tag{16}$$

In trellis method, the number of *Partial Euclidean Distance (PED)* is L^2P on each antenna stage, so the complexity is:

$$O = N\,L^2\,P \tag{13}$$

with P is the number of path with minimum weight chosen in each node [11]. In this case, P is 1.

vi. Non-Linear-Sub-Optimal Sphere Decoding

To solve MLD equation in (6), Sphere decoding (SD) calculates all vector of $\mathbf{x}$ that satisfies

$$\|\mathbf{y}-\mathbf{Rx}\|^2 < \mathbf{Z}^2 \qquad (13)$$

where $\mathbf{Z}$ is the *Sphere*'s radius. Choosing value of $\mathbf{Z}$ is an important problem to determine the complexity and performance of SD. When the value of $\mathbf{Z}$ is big, SD will have big number of hypothesis of symbol candidates. In this case, SD requires high complexity and give high error performance. Consequently, if the value of $\mathbf{Z}$ is small, SD will have empty hypothesis. No symbol candidates to be calculated in euclidean distance to the received signal which lead to error. When this happen, the searching have to be repeated by incrasing the *Sphere* radius. Searching process to satisfy equation (13) can be solved using back-substitution algorithm. The complexity of Sphere decoding can be found by: [12].

$$O = N^2 + \sum_{i=1}^{N}\left((i-1)S_{i-1} + 2 + S_i\right) \qquad (14)$$

where S_i is the number of symbol candidates within radius. In the simulation S_i for first stage is 64 and then the value is kept to be 16 until the 8-th antenna stage.

III. SIMULATION AND DISCUSSION

The VHT WLAN 802.11ac can be set depend on need. Simple representation of setting is called the Modulation and Coding Scheme (MCS). It defines the constellation type, coding rate, and the throughput. For example, when number of spatial stream is eight with 40 MHz of bandwidth, MCS 7 of 802.11ac means the system is set to 64-QAM and coding rate 5/6. With 800ns of guard interval length, VHT WLAN 802.11ac provides 1,08 Gbps of data rate. With 400ns of guard interval length, VHT WLAN 802.11ac provides 1,2 Gbps of data rate. All simulations are conducted under small room channel model or channel model B of IEEE TGn. Simulation parameters are listed in Table 1 and performance comparison of all methods implemented as MIMO decoders in BER and PER are shown in Fig. 1 and Fig. 2, respectively.

TABLE I. SIMULATION PARAMETERS

Parameters	Value	
Antenna configuration	8 x 8	
Bandwidth	40 MHz	
Modulation Coding Scheme (MCS)	MCS 7 of 802.11ac VHT	
Subcarrier modulation	64-QAM	
Coding rate	5/4	
Number of packet	1000 packets	
Number of data per packet	1000 octets	
Channel Model	B of IEEE TGn	
Guard Interval Length	800 ns	400 ns
Data rate	1.080 Gbps	1.2 Gbps
MIMO decoder method	ZF, MMSE, MLD, Trellis, *K*-best, Sphere	

A. Run Test Results

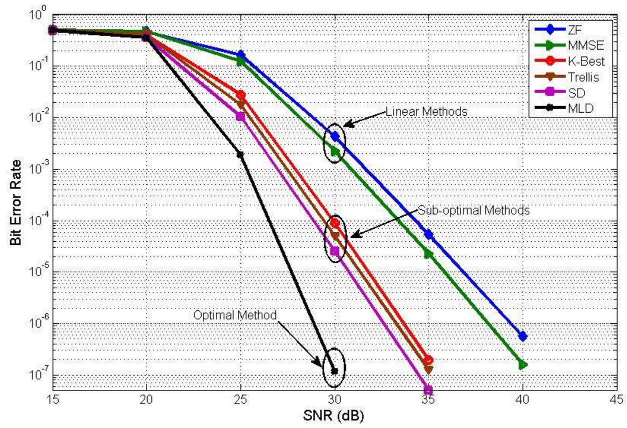

Fig. 1. Performance comparison of methods used as MIMO decoder for VHT WLAN 802.11ac in Bit Error Rate versus SNR (dB). The linear methods (ZF and MMSE) are simple but low performance. Sub-optimal methods (K-Best, Trellis, and SD) give better performance compared to linear ones with lower complexity compared to the optimal method (MLD). 5 dB performance improvement due to better decoding methods is boosted by the use of 8x8 MIMO configuration which contributes high diversity gain.

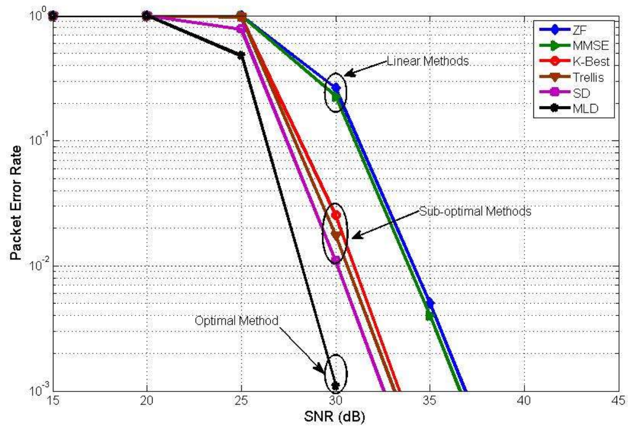

Fig. 2. Performance comparison of methods used as MIMO decoder for VHT WLAN 802.11ac in Packet Error Rate versus SNR (dB). The linear methods (ZF and MMSE) are simple but low performance. Sub-optimal methods (K-Best, Trellis, and SD) give better performance compared to linear ones with lower complexity compared to the optimal method (MLD). 3 dB performance improvement due to better decoding methods is boosted by the use of 8x8 MIMO configuration which contributes high diversity gain.

B. Complexity Analysis

The complexity comparison of the discussed methods as MIMO decoder is listed in Table II.

TABLE II. COMPLEXITY COMPARISON OF MIMO DECODERS METHODS FOR 8X8, 40 MHS, IN MCS 7 OF 802.11AC

N	Complexity				
	ZF & MMSE	MLD	Trellis	K-best	Sphere
1	2	64	64	64	67
2	6	64^2	$2x64^2$	64x16	152
3	12	64^3	$3x64^2$	$64x16^2$	191
4	20	64^4	$4x64^2$	$64x16^3$	232
8	72	64^8	$8x64^2$	$64x16^7$	416

As mentioned in the previous section, it can be verified that the linear method ZF and MMSE have the lowest complexity. Then gradually the complexity is increasing for Sphere, Trellis, and *K*-Best methods. MLD has the highest complexity, especially in the case of number of transmit antenna $N = 8$.

Implementation of the non-linear-sub-optimal methods is expected to give significant improvement of performance. However in the results, they only contribute 3-5 dB better performance compared to linear ones. This situation can be understood, since the use of 8x8 MIMO antenna configuration already boosted the performance of all methods by it's high diversity gain.

IV. CONCLUSION

We have presented the exploration of several methods for MIMO decoder for next generation very high throughput (VHT) WLAN 802.11ac in 8x8 antenna configuration and 40MHz bandwidth. The common linear methods i.e ZF and MMSE are the lowest in complexity but the worst in performance. The non-linear-sub-optimum methods, i.e. Trellis *K*-best, and Sphere demonstrate better performance compared to the existing linear methods with the cost of higher complexity. The non-linear-optimum method MLD shows the best performance with the highest complexity. The use of 8x8 antenna configuration indeed contributes significant performance improvement due to high diversity gain. This is the reason why the non-linear methods only give 3 to 5 dB performance improvement.

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