FPGA PROTOTYPING OF MIMO DETECTOR FOR OVER-1GBPS WIRELESS TRANSMISSIONS

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ABSTRACT

We developed two types of practical maximum-likelihood detectors (MLD) for multiple-input multiple-output (MIMO) multiplexing systems with a capability of 1 Gbps-class real-time processing speed, using a field programmable gate array (FPGA) device. We introduce two simplified metrics for implementations; referred to as a Manhattan metric and a correlation metric. In using the Manhattan metric, the detector needs no multiplication operations, at the cost of slight performance degradation within 1 dB. By using the correlation metric, the MIMO-MLD can significantly reduce the complexity in both multiplications and additions without any performance degradation. This paper demonstrates the BER performance of these MLD prototypes through the use of an all-digital baseband 4×4 MIMO testbed integrated on the same FPGA chip.

INTRODUCTION

An MIMO wireless communication system, which exploits multiple antennas at both transmitter and receiver sides, has been a promising technique to achieve high speed transmission and high spectrum-efficiency. There have been a number of researches and developments working toward practical use of the MIMO technique to achieve over 100 Mbps or 1 Gbps transmissions.

In MIMO systems, an MLD scheme offers excellent performance. Since the receiver estimates the most-likely signals among all the possible transmitting signals, the computational complexity of distance metric calculations becomes extremely high in general. Consequently, some computationally efficient schemes have been studied. As a kind of low-complexity detectors, we can employ a spatial filter based on the minimum mean-square error (MMSE) criterion and an ordered successive detection (OSD), that performs successive replica subtractions to improve the MMSE detector. More recently, the so-called sphere decoding (SD) [1, 2] has been proposed for low-complexity MIMO-MLD. The SD approach efficiently searches the ML estimate by exploiting the QR decomposition.

Since the MMSE, OSD and QR-SD receivers require large bit-width computations in multiplications to maintain precision for the matrix inversion or the QR decomposition, they are not always efficient for practical implementation [3]. In this paper, we propose practical ML detectors introducing simplified metrics; hereinafter referred to as a Manhattan metric and a correlation metric. The Manhattan metric can eliminate the use of arithmetic multiplications at the receiver with a slight performance degradation. The correlation metric can considerably reduce the number of multiplications and the number of metrics to compute without any performance degradation. By making use of an FPGA, we developed 1 Gbps-order real-time MIMO-MLD prototypes using these simplified metrics. Along with the MLD prototypes, we implemented a digital baseband 4×4 MIMO testbed in the same FPGA device for performance evaluation of our designed MLDs.

MLD FOR MIMO SYSTEMS

Signal Model

We consider a QPSK 4×4 MIMO system, where $M = 4$ transmitting antennas and $N = 4$ receiving antennas are used. Throughout this paper, we use the discrete-time and baseband-equivalent signal model. The transmitter side spatially multiplexes QPSK signals $\boldsymbol{x} \in \{\exp(\mathrm{j}\,2\pi l/L) \mid l = 0, 1, \ldots, L-1\}^M$, where $L = 4$ is the modulation level. Under a frequency-flat fading channel, the received signals vector $\boldsymbol{y} \in \mathbb{C}^{N\times 1}$ is expressed as

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{w}, \tag{1}$$

where $\boldsymbol{H} \in \mathbb{C}^{N\times M}$ and $\boldsymbol{w} \in \mathbb{C}^{N\times 1}$ denote discrete samples of a channel matrix and an additive white Gaussian noise (AWGN) vector with a variance of σ^2, respectively. The notations $[\cdot]^{\mathrm{T}}$ and $\mathbb{C}$ are the transpose and the field of complex numbers, respectively.

Euclidean Metric

Among the candidates of the transmitting signals, the most-likely estimate is a candidate $\hat{\boldsymbol{x}}$ such that the corresponding replica of the received signal $\hat{\boldsymbol{y}} \triangleq \hat{\boldsymbol{H}}\hat{\boldsymbol{x}}$ is closest to the received signal $\boldsymbol{y}$, resulting in the minimum magnitude of an error signal $\boldsymbol{e} \triangleq \boldsymbol{y} - \hat{\boldsymbol{y}} \in \mathbb{C}^{N\times 1}$.

Here, $\hat{\boldsymbol{H}} \triangleq \left[\hat{\boldsymbol{h}}_1, \hat{\boldsymbol{h}}_2, \ldots, \hat{\boldsymbol{h}}_M\right] \in \mathbb{C}^{N\times M}$ stands for the estimated channel matrix corresponding to $\boldsymbol{H}$. Accordingly, the MIMO-MLD searches a candidate $\hat{\boldsymbol{x}}$ that minimizes the squared Euclidean distance between $\boldsymbol{y}$ and $\hat{\boldsymbol{y}}$, that is referred to as the Euclidean metric μ_{E}:

$$\mu_{\mathrm{E}} \triangleq \|\boldsymbol{e}\|^2 = \|\boldsymbol{y} - \hat{\boldsymbol{H}}\hat{\boldsymbol{x}}\|^2 \tag{2}$$

$$= \sum_{n=1}^{N} \Big(\big|\Re[e_n]\big|^2 + \big|\Im[e_n]\big|^2 \Big), \tag{3}$$

where $\|\cdot\|$, $\Re[\cdot]$ and $\Im[\cdot]$ denote the Euclidean norm, the real-part and imaginary-part operations, respectively. Since $2NL^M = 2{,}048$ real multiplications are required in general to compute all of the Euclidean metrics, the hardware implementation is often infeasible due to a logic resource limitation of the target device. Therefore, we adopt two practical metrics: the Manhattan metric and the correlation metric.

Manhattan Metric

In order to avoid the use of arithmetic multiplications, we replace the squared Euclidean distance with the Manhattan distance. Since the Manhattan distance is computed by adding absolute values of the real and imaginary parts of the error signals vector $\boldsymbol{e}$ for every dimension, the metric computation may be easy to implement. In this alternative MLD, a Manhattan metric μ_{M} is given by

$$\mu_{\mathrm{M}} \triangleq \sum_{n=1}^{N} \Big(\big|\,\Re[e_n]\,\big| + \big|\,\Im[e_n]\,\big| \Big). \tag{4}$$

Although the use of the Manhattan metric may cause a performance degradation (in actual within 1 dB), the fact that multiplication operations are not required is still useful for practical hardware implementations. Also, the replica calculation does not require the multiplications in QPSK transmissions.

Correlation Metric

While the Manhattan metric eliminates the use of multiplications, it degrades the BER performance and cannot reduce the number of addition operations. In order to jointly achieve the ML performance and a manageable-level low complexity in both multiplications and additions, we introduce the correlation metric. Letting g_m and $a_{i,j}$ be spatial correlation values as defined by

$$g_m \triangleq \hat{\boldsymbol{h}}_m^\dagger \boldsymbol{y}, \qquad a_{i,j} \triangleq \hat{\boldsymbol{h}}_i^\dagger \hat{\boldsymbol{h}}_j, \tag{5}$$

the correlation metric μ_{C} is represented as follows:

$$\mu_{\mathrm{C}} \triangleq \Re\Big[\boldsymbol{g}^\dagger \hat{\boldsymbol{x}} - \sum_{i=1}^{M-1} \sum_{j=i+1}^{M} a_{i,j}\, b_{i,j}\Big], \tag{6}$$

where $\boldsymbol{g} \triangleq [g_1, g_2, \ldots, g_M]^{\mathrm{T}} \in \mathbb{C}^{M\times 1}$ and $b_{i,j} \triangleq \hat{x}_i^* \hat{x}_j$. The superscripts $[\cdot]^\dagger$ and $[\cdot]^*$ designate the Hermitian transpose and the complex conjugate, respectively. Since the Euclidean metric can be written by

$$\mu_{\mathrm{E}} = \underbrace{\big\|\boldsymbol{y}\big\|^2 + \sum_{m=1}^{M} \big\|\hat{\boldsymbol{h}}_m\big\|^2 |\hat{x}_m|^2}_{\text{constant}} - 2\,\mu_{\mathrm{C}}, \tag{7}$$

the minimization of μ_{E} coincides with the maximization of μ_{C} under PSK transmissions. Although we should employ multiplications to get $\boldsymbol{g}$ and $a_{i,j}$, the number of multiplications can be reduced to $4MN + 2(M-1)MN = 160$ from $2NL^M = 2{,}048$ in comparison with the Euclidean metric, more remarkably, without any performance degradation. Other terms $\boldsymbol{g}^\dagger\hat{\boldsymbol{x}}$, $\sum a_{i,j}b_{i,j}$ and $b_{i,j}$ do not use multiplications to be calculated owing to the constellation symmetry of QPSK.

To further reduce the operations in additions, we use the phase characteristics of the correlation metric. The number of the possible values of the term $\sum a_{i,j}\, b_{i,j}$ is L^{M-1} (not L^M), and that of the term $\boldsymbol{g}^\dagger\hat{\boldsymbol{x}}$ is also L^{M-1} without phase rotation of $\hat{x}_1$. The optimum phase of $\hat{x}_1$ can be decided by observing the real and imaginary parts of $\boldsymbol{g}^\dagger\hat{\boldsymbol{x}}$. Subsequently, the number of metrics to be searched can be reduced to 64 from 256 with no degradation.

ONE-CHIP FPGA TESTBED DESIGN

Using an FPGA device with approximately two million gates, we implemented the above-mentioned simplified MLD schemes. Along with 79,040 logic elements, the FPGA device has about 7 Mbit built-in memory and 176 dedicated blocks for 9-bit multiplications. In addition to the MLD implementation, an all-digital baseband MIMO testbed was integrated in the same FPGA chip for performance evaluations of the implemented receiving algorithms. The hardware description language (HDL) is Verilog-HDL. Altera Quartus II v4.0 was used to perform the HDL compilations and the FPGA configurations. In the design, fixed-point arithmetic operations are employed. The block diagram of the overall one-chip MIMO testbed is shown in Fig. 1. The testbed consists of an MIMO received signal generator (RSG), a digital automatic gain controller (AGC), an MIMO detector (MLD in this paper) and a bit-error-rate (BER) counter.

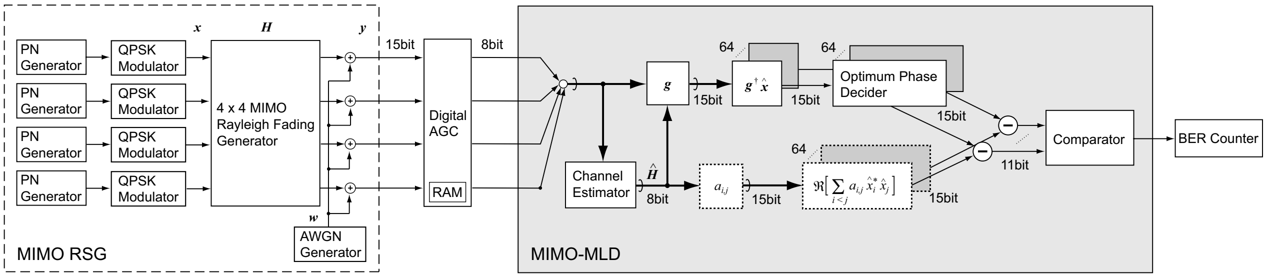

Fig. 1. Block diagram of digital baseband MIMO testbed and MIMO-MLD using correlation metric integrated in single FPGA chip.

MIMO Received Signal Generator and Digital AGC

As addressed in [4], the 4×4 MIMO RSG has four major components: four pseudo-random noise (PN) binary sequence generators, four QPSK modulators, sixteen Rayleigh fading generators and four AWGN generators. We use a transmission frame format consisting of a forty-symbol information sequence preceded by an orthogonal training sequence with eight symbols long. The PN generator works during an information period.

We assume a quasi-static Rayleigh fading channel, in which the channel response is in-variant during a transmission frame. Therefore, our Rayleigh fading generator does not require a Jakes model based fading fluctuation as presented in [4] and [5], where fading signals are generated by looking up a triangular function table with various cyclic counters emulating a Doppler phase shift. Regarding a Rayleigh fading as a multiplicative Gaussian noise, both of the AWGN generator and the Rayleigh fading generator can be implemented in a similar manner. In this paper, we construct white Gaussian noise on the basis of the central limit theorem, by adding up some uniform-random numbers.

When an integer number is given by an N_{G}-bit tuple of successive N_{G} values from an M-sequence, the number becomes a uniform-random integer. Here, a summed number of L_{G} random integers generated by the M-sequence can approach the Gaussian distribution as L_{G} is sufficiently large. In this MIMO testbed design, we set $N_{\mathrm{G}} = 9$, $L_{\mathrm{G}} = 8$ and use a 20-stage M-sequence for Rayleigh fading generators with different initial states, whereas $N_{\mathrm{G}} = 9$, $L_{\mathrm{G}} = 16$ and four M-sequences with a stage of 39, 41, 47 and 49 for AWGN generators. For simple implementation avoiding multiplications, E_{b}/N_0 per antenna can be set some values out of 0.0, 2.5, 6.0, 8.5 and ∞ dB, by employing bit-shift operations and additions.

The digital AGC selects appropriate 8 bits of each 15-bit received signals after buffering every transmission frame and detecting maximum amplitude. Hence, the AGC uses memory area on the FPGA to store one-frame Rx signals. Through computer simulations, we confirmed that the truncation of 8-bit width for the AGC output could occur almost no performance degradation of the MIMO-MLD. The BER counter displays the number of error bits for $2^{11} = 2{,}048$ frames by using an LED on the board. Except for the MIMO detector part, the implemented testbed does not use multiplication operations.

MLD Signal Processing

In a training period, the channel estimator performs correlation operations between the Rx signal sequences and the training sequences to achieve sixteen complex-valued channel coefficients based on the least-squares (LS) estimation. Thanks to the orthogonality of the training sequences, multiplication operations are not necessary even for the LS channel estimation.

In the MLD with the Manhattan metric, 8-bit truncated replica signals are computed by 64 replica generators in parallel (with no need of multiplications). Using these replica signals and four rotated Rx signals, 256 error signals vectors $\boldsymbol{e}$ and the corresponding Manhattan metrics μ_{M} are calculated. The metrics are fed into an 8-bit comparator to detect the smallest one. Although the Manhattan metric may incur a performance degradation, the MIMO detector does not require the use of multiplications which occupies typically numerous logic elements.

The MLD design using the correlation metric calculates ten correlation values (g_1, g_2, g_3, g_4, $a_{1,2}$, $a_{1,3}$, $a_{1,4}$, $a_{2,3}$, $a_{2,4}$, $a_{3,4}$) from an estimated channel matrix and a received signals vector. Since each of them requires $N = 4$ complex multiplications, $10 \cdot 4N = 160$ real multiplications (8-bit width) are used in total. After computing these correlation values, 64 patterns of $\boldsymbol{g}^{\dagger}\hat{\boldsymbol{x}}$ ($\hat{x}_1 = 1$) and $\sum a_{i,j}\, \hat{x}_i^* \hat{x}_j$ are calculated without multiplications. An optimum phase decider determines a phase index l that maximizes $\Re[\boldsymbol{g}^{\dagger}\hat{\boldsymbol{x}} \exp(\mathrm{j}\, 2\pi l/L)]$, and the maximum value subtracted by $\Re[\sum a_{i,j}\, \hat{x}_i^* \hat{x}_j]$ is fed into an 11-bit comparator to detect the largest one among 64 candidates. Note that, at the optimum phase decider, arithmetic operations except for comparisons are not needed.

IMPLEMENTATION RESULTS AND PERFORMANCE EVALUATIONS

First of all, we show the used logic resources for implementation of the MIMO testbed except the MLD part in Table 1. The MIMO-RSG, digital AGC and BER counter consume about 9,500, 490 and 150 logic elements, respectively; totally $12.7\,\%$ logic elements on the used FPGA device. The digital AGC uses 7,680 memory bits ($0.1\,\%$ internal memory on the FPGA).

Table 2 shows the result of our implemented MLD design specifications. The MLDs using the Manhattan metric and the correlation metric require about 50,800 and 12,700 logic elements, respectively. When we do not use 160 embedded blocks for multiplications in the FPGA, the MLD using the correlation metric consumes around 32,700 logic elements ($41.4\,\%$ of the FPGA). Because the

Table 1. Used logic resource except for MLD part

MIMO-RSG	9,441 LE	(11.9 %)
AGC	485 LE	(0.6 %)
	7,680 memory bits	(0.1 %)
BER counter	149 LE	(0.2 %)

LE: Logic element

Table 2. Implemented MLD design specifications

	Manhattan metric	Correlation metric
Used logic elements	50,806 LE	12,742 LE + 160 EB (32,748 LE)
Max clock frequency	116.3 MHz	139.9 MHz
Max data rate	930 Mbps	1,119 Mbps

EB: Embedded block for multiplications

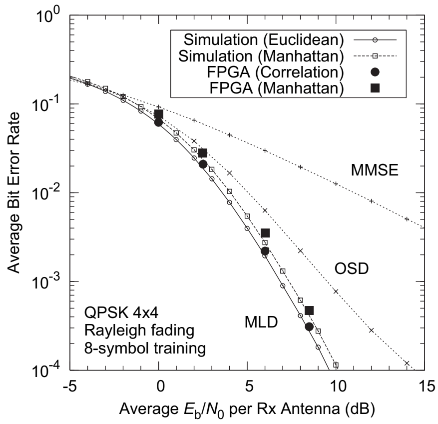

Fig. 2. Average BER performance as a function of average E_b/N_0 per receiving antenna over Rayleigh fading 4×4 MIMO channels.

correlation metric can reduce the number of metrics to 64 from 256, the used resource area is less than that of the MLD using the Manhattan metric in spite of the use of multiplications. The respective MLDs can work at a processing speed of 116 MHz and 140 MHz; corresponding to the maximum data rate of 930 Mbps and 1,119 Mbps because of the real-time 8-bit detection per clock in information periods.

Fig. 2 shows the BER performance of our implemented MLDs as a function of average E_b/N_0 per receiving antenna, obtained by the use of one-chip FPGA MIMO testbed. The clock frequency is set to be the respective maximum frequency shown in Table 2. For comparison, we also present computer simulation results of MLDs using the Euclidean metric and the Manhattan metric, OSD and MMSE detectors. Here, the OSD is based on the MMSE criterion and employs a post-detection signal-to-interference-plus-noise ratio (SINR) ordering. As observed in the figure, the performance degradation due to the use of the Manhattan metric is within 0.7 dB compared to the Euclidean metric. The two types of the simplified MLD outperform MMSE and V-BLAST detectors significantly. It should be noticed that the performances of the implemented ML detectors agree well to the simulation results in spite that fixed-point arithmetic operations and bit-width limitations are employed in the FPGA implementation.

CONCLUSIONS

In this paper, we developed two ML detectors for 4×4 MIMO systems with a capability of 1 Gbps-order real-time processing. For practical implementation, we proposed MIMO-MLD introducing two simplified metrics: the Manhattan and correlation metrics. The Manhattan metric does not require the multiplication operations, at the cost of a slight performance degradation of about 0.7 dB. In the correlation metric, the detector can significantly reduce the computational complexity without performance degradation, leading to offer a better benchmark in the implementation compared to the Manhattan metric. These MLD prototypes were evaluated through an MIMO testbed integrated in the same FPGA chip. We confirmed that overall MIMO testbed including MLD can be implemented on one-chip FPGA device with a logic element of two million gates. The advantage of the use of the correlation metric can be held even in QAM transmissions since the QAM can be regarded as a constellation multiplexed by multiple QPSK signals.

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References

[1] E. Viterbo and J. Boutros, "A universal lattice code decoder for fading channels," *IEEE Trans. IT*, vol. 45, no. 5, pp. 1639–1642, Jun. 1999.

[2] M. O. Damen, K. Abed-Meaim, and J. C. Belfiore, "Generalised sphere decoder for asymmetrical space-time communication architecture," *Electron. Lett.*, vol. 36, pp. 166-167, Jan. 2000.

[3] A. Adjoudani, E. C. Beck, A. P. Burg, G. M. Djuknic, T. G. Gvoth, D. Haessig, S. Manji, M. A. Milbrodt, M. Rupp, D. Samardzija, A. B. Siegel, T. Sizer, II, C. Tran, S. Walker, S. A. Wilkus, and P. W. Wolniansky, "Prototype experience for MIMO BLAST over third-generation wireless system," *IEEE JSAC*, vol. 21, no. 3, Apr. 2003.

[4] M. Cui, H. Murata, and K. Araki, "Real-time MIMO received signal generator for spatial multiplexing systems," *Proc. IEEE VTC Fall*, Oct. 2004.

[5] S. Tsukamoto, T. Sasau, T. Sakashi, H. Yoshino, and T. Matsumoto, "Complex baseband array response simulator," *IEICE Tech. Rep.*, RCS98-206, pp. 67–73, Feb. 1999. (in Japanese)