MIMO | Signal Detection | Interference Cancellation

Technology Reports

Special Articles on Multi-dimensional MIMO Transmission Technology ― The Challenge to Create the Future ―

Successive Interference Cancelling MIMO Signal Detection Method Using Dynamic Multi-trace-likelihood Ordering Detection

Combining interference cancelling MIMO detection with multi-trace-likelihood detection can provide detection performance near that of MLD, while requiring less computation than MLD. Furthermore, it can be extended easily to requirements for different numbers or complexities of antennas. We have created a testbed for this method and verified its performance. The research described in the paper has received the "Best Paper Award" at APCC2008.

DOCOMO Beijing Communications Laboratories Co.,Ltd.

Jianping Chen

Zhan Zhang

Hidetoshi Kayama

1. Introduction

In the past decade, Multiple Input Multiple Output (MIMO)*1 technology has achieved extremely high growth due to its ability to substantially increase transmission capacity. Generally speaking, MIMO can be used for diversity gain using time (frequency) and spatial coding, for higher transmission rates via spatial multiplexing, for enhanced link quality or system efficiency through beam forming*2, or for multiplexing multiple users. Among these, spatial multiplexing can dramatically increase user transmission bandwidth efficiency, is already being used in existing wireless LAN technology, and is becoming the most important technology for future systems such as Long Term Evolution (LTE) -Advanced*3.

With MIMO spatial multiplexing, multiple data streams are transmitted at the same time using the same frequency, so at the receiving end, these streams must be separated. Many methods have been proposed for doing this, but for all of these methods, there is a trade-off between computational complexity and the accuracy of MIMO signal detection. In other words, there are two directions in MIMO signal-detection research: decreasing the complexity of the algorithm while maintaining high-accuracy detection, and increasing detection accuracy while minimizing any increase in complexity.

Among MIMO signal detection methods, the Zero Forcing (ZF)*4 and Minimum Mean Squared Error (MMSE)*5 methods have low complexity, but they have relatively high required Signal to Noise Ratio (SNR)*6 and a MIMO channel that is not ill-conditioned to achieve adequate performance. This can be a problem in practice.

Conversely, Maximum Likelihood Detection (MLD) is a method which selects the most likely received-signal pattern from all possible combinations of signal patterns, and it has the highest

*1 **MIMO**: A signal transmission technology that uses multiple antennas at both the transmitter and receiver to perform spatial multiplexing and improve communication quality and spectral efficiency.

*2 **Beam forming**: A method for improving signal separation performance at the receiving side by doing precoding on the transmitting side based on channel data or other feedback.

performance of all of the methods. However, the computational complexity increases exponentially with an increase in the number of antennas, or the multiplicity of modulation points, making it difficult to apply the approach directly in practical high-dimension MIMO systems. Given these facts, at NTT DOCOMO, we have proposed an MLD method with adjusted search scope, achieving highly-accurate detection with low computational cost [1], and we are studying and seeking advances with this method.

Other detection algorithms, using Successive Interference Cancellation (SIC), have even lower complexity than MLD, and higher detection accuracy than methods using ZF or MMSE nulling. In these methods, at each step (layer) of the signal-separation processes, the signal transmitted from each antenna is detected. Each layer of signal is eliminated from the original received signal, and the result is passed to the next step. This process is repeated until the signals from all of the layers have been detected.

However, if a detection error occurs in an intermediate layer in SIC, the error propagates to later layers, and can have a significant effect on the overall result. A technique has been proposed which can minimize this effect by proceeding in order, from the most reliable layer to less reliable layers [2], but this method is not optimized with respect to two points. The first point is that, for all of these methods, sorting is required in the SIC processing steps. To optimize and actually perform the SIC process in order of reliability of the antennas, it is most desirable to evaluate the reliability of each antenna at each layer of the process. The second point is that the sorted order determined by statistics such as the layer's Signal to Interference plus Noise Ratio (SINR) does not necessarily reflect a sort in order of reliability of each symbol. To take this perspective into consideration, the Dynamic Nulling and Cancelling (DNC) method has been proposed [3][4], which uses instantaneous signal values as well as statistical information to sort signal layers for detection and cancellation. By applying this ordering prudently, the probability of incorrect detections is reduced. To enhance this ordering concept, we extend the ordering scheme by a multi-trace-likelihood method, which is more accurate in estimating the layer's likelihood, so it further reduces the detection error propogation. Thus, in the packet radio transmission project, we have proposed a multi-trace likelihood based ordering method called Dynamic Ordering M-paths MIMO detection (DOM) [5]. DOM increases freedom in the tradeoff between complexity and detection accuracy.

In this article, we give an overview of this DOM algorithm, which uses multiple search paths and performs signal detection and cancellation in order of estimated reliability of the layers. We also describe implementation of this algorithm in hardware, and discuss the results of a performance evaluation.

2. DOM Algorithm

2.1 MIMO System Model

We assume a Single-User (SU)-MIMO spatial multiplexing model as shown in **Figure 1**. Here N_T is the number of transmitting antennas, N_R is the number of receiving antennas, $x=(x_1, \ldots, x_{N_T})^T$ is the transmission signal, H is the $N_R \times N_T$ channel matrix, $r=(r_1, \ldots, r_{N_R})^T$ is the received signal, and $n=(n_1, \ldots, n_{N_R})^T$ is white noise*7. Then we have the relationship given in Equation (1).

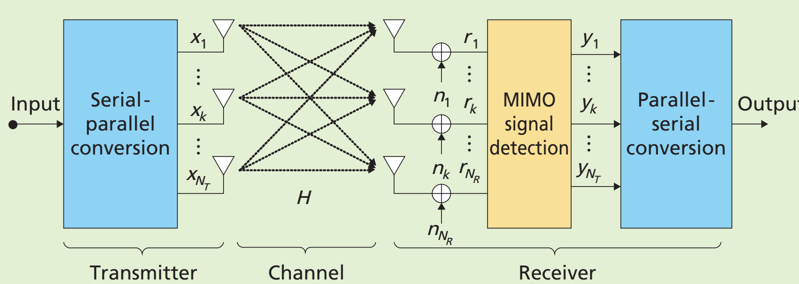

Figure 1 SU-MIMO space multiplexing model

*3 **LTE-Advanced**: The name for IMT-Advanced in 3GPP. IMT-Advanced is the successor to the IMT-2000 Third-Generation mobile communication system.

*4 **ZF**: A detection method that multiplies the received signal by the inverse of the wireless channel matrix.

*5 **MMSE**: A method for signal computation that minimizes mean square error.

*6 **Required SNR**: The minimum value of SNR required for performing MIMO signal separation to obtain a predetermined error rate or better.

*7 **White noise**: Noise which is made up of all frequencies, each having the same average amplitude. In this article, we use it to indicate thermal noise.

$$r = Hx + n \quad (1)$$

2.2 DOM Algorithm Overview

The overall DOM algorithm is composed of three stages: pre-processing, layer processing, and a post processing. Among these, layer processing is repeated by the number of transmission layers (transmission antennas for a direct spatial multiplexing system) that must be separated, and the signal from a single transmit antenna is detected and cancelled from the received signals. The algorithm also maintains information for M search paths for ordering calculation at a time. An example of detection using the DOM algorithm with $N_T = 4$ and $M = 2$ is shown in **Figure 2**, and an overview of each processing step is described below.

1) Pre-processing

MMSE and/or ZF nulling is applied to the received signals, and a coarse detection is done for the signal at each later layer-ordering metric[*8] calculation stage. In other words, for each layer's ordering calculation, MMSE and ZF nulling is repeated before calculating each layer's metric with the remaining signal values after cancelling the previous layers' components;

2) Layer Ordering Metric Calculation

The reliabilities of the estimated symbols are computed based on two parameters: the SINRs from the coarsely detected signal from each transmitter antenna, and the ratio of Euclidean distances[*9] of that layer's estimated symbol value to the two closest symbol points in the constellation[*10].

For Layer 1 of this part of the process, these metrics are accumulated through each layer of the process. For Layer 2 and above, for each of the M symbols selected at the previous layer, the metric is computed for each of the $M \times C$ search paths (C is the modulation multiplicity) for each possible next layer, and the M paths with the smallest metric values are retained as the surviving paths. In Fig. 2, the paths shown with red and blue arrows are the surviving paths.

In the calculation of each layer's likelihood metric, an interference replica[*11] for each of the selected surviving paths is generated, and is cancelled from the received signal before being passed to the next layer.

3) After Ordering Post Processing

From the M paths that survive through the layer ordering calculation, the trace with the smallest metric value is selected as the detection result. In Fig. 2, the symbol shown with a red star at each level is the symbol finally detected.

2.3 Extended Algorithm (DOM-R)

Conventional separation algorithms all handle the signal in the complex number domain. However, by separating the reception points into real and imaginary parts in the complex plane, Quadrature Amplitude Modulation (QAM)[*12] can be separated in to two independent Pulse Amplitude Modulation (PAM)[*13] signals. As a result, the

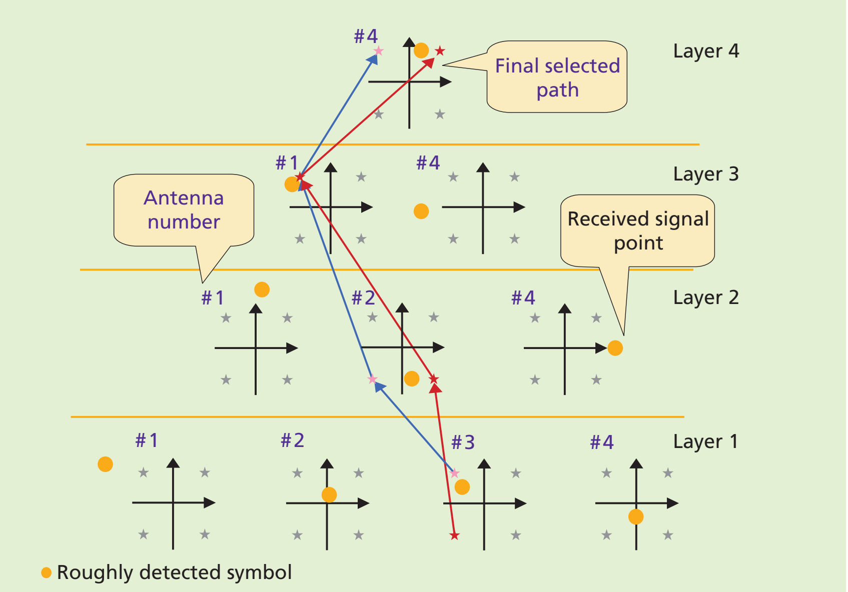

Figure 2 Example of DOM detection with $M = 2$

*8 **Metric**: In this article, we use the accumulated Euclidean distance between the received signal and the estimated value. The smaller this value is, the more likely that the estimated value is correct.

*9 **Euclidean distance**: The shortest distance between two points on a plane or in space.

*10 **Constellation**: The digitally modulated symbol pattern, usually represented in a two-dimensional plane with the X axis for the in-phase component and the Y axis for the orthogonal (Quadrature phase) component.

*11 **Replica**: A regeneration of the received signal using predicted values for the transmitted signal.

real and imaginary parts of the received signal can be evaluated and cancelled out independently, allowing error propagation to be reduced and thus improving reliability. This concept was the basis for the following extension to the DOM algorithm. **Figure 3** shows a comparison between the DOM algorithm that handles the signal as complex values (DOM-C) and the extended algorithm, that handles values as two independent real values (DOM-R).

As shown in Fig. 3, the signal from antenna #2 is determined first, but with DOM-R, the signals are determined and interference is cancelled in order of the real part from antenna #1, followed by the real and imaginary parts from antenna #2, and finally the imaginary part from antenna #1.

2.4 Computational Cost Comparison

The computational cost for DOM is mainly due to the pre-processing part and the layer processing part. The costs for each of DOM-C and DOM-R are shown in **Table 1**. Compared to DOM-C, DOM-R handles twice the data flow, but the number of constellation points considered at each layer is the square root of that for DOM-C. For example, for 64QAM, DOM-C must perform computations for a 64-point constellation, but with DOM-R, only 8-point constellations for each of the real and imaginary parts need to be considered.

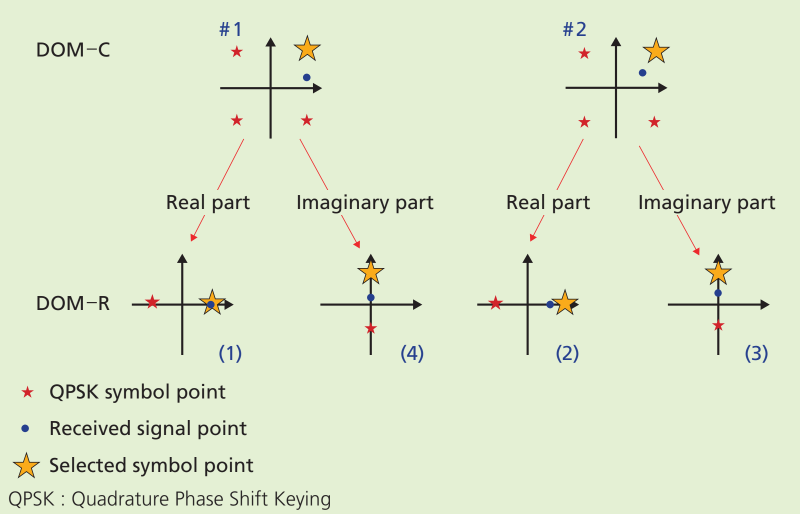

Figure 3 Comparison of DOM-C and DOM-R

Table 1 Complexity analysis of DOM Algorithms

	DOM-C	DOM-R
Pre-processing	$2N_T^3$	$2N_T^3$
Layer processing	$\frac{1}{3}N_T^3+\frac{1}{2}(M+\lvert C\rvert)\cdot N_T^2$	$\frac{2}{3}N_T^3+\frac{1}{2}(M+\sqrt{\lvert C\rvert})\cdot N_T^2$
Pre-processing and layer processing	$\frac{7}{3}N_T^3+\frac{1}{2}(M+\lvert C\rvert)\cdot N_T^2$	$\frac{8}{3}N_T^3+\frac{1}{2}(M+\sqrt{\lvert C\rvert})\cdot N_T^2$

3. Hardware Implementation

The simulation provides an evaluation under a modeled environment, but a realistic experiment using real-time hardware is needed to verify a) that the actual computational load can be implemented with standard hardware, b) what effects it has in an overall system from transmission to reception, and c) under what conditions its real characteristics are as close as those predicted by simulation. In this chapter we describe some key points related to the implementation of a testbed for demonstrating DOM-C and DOM-R.

- Floating-point operations

  For the matrix inversion done in the pre-processing module, over-flow/under-flow[*14] could result from using general fixed-point operations, so we designed a specialized floating-point-operation module to make high-precision, low-computational-cost matrix inversions possible.

- Noise power setting

  To reduce the level of noise increase in the preprocessing stage, the reversion matrix was regularized by a fixed average noise power value. This setting resulted in almost no performance degradation

*12 **QAM**: A digital method of modulating the amplitude and phase of a wave according to a series of data bits. There are several types, according to number of patterns, with names like 16QAM and 64QAM.

*13 **PAM**: A modulation method in which the input signal amplitude is modulated according to a series of pulse amplitudes.

*14 **Over-flow/under-flow**: When performing numeric operations and a correct results cannot be obtained because it exceeds the largest or smallest value that can be represented in the computation.

in observed experimental results .

- Module pipeline structure

The modules that make up DOM are arranged in an overall pipeline structure[*15] (**Figure 4**). Here $H^{\dagger}$ represents the transpose complex conjugate of the channel matrix, H. As shown in the figure, the signal is sampled, input in order from the left, and processed, passing through each module. Enabling the time-sequence data to be processed in a parallel way increases processing throughput.

4. Evaluation of DOM Algorithm Performance

4.1 Computational Simulation

Here we present the results of evaluating the detection performance of both DOM-C and DOM-R by computational simulation.

1) Comparing Performance of DOM-C and DOM-R

The Bit Error Rate (BER) characteristics for DOM-C and DOM-R are shown in **Figure 5**. Here four antennas were used for both transmitting and receiving, 16QAM modulation was used, and the single-path fading channel model was used. From the figure, we see that the DOM-R characteristic was better than the DOM-C characteristic for the same number of surviving traces for ordering, M. Also, the DOM-R characteristic for $M = 2$ is almost the same as the DOM-C characteristic for $M = 4$, and DOM-R for $M = 4$ approaches the performance of Maximum Likelihood (ML) detection, differing by only about 0.2 dB. We obtained almost the same results even when changing the number of antennas or the modulation method, indicating that DOM-R works well generally, for $M \leqq 4$.

2) Effects of Dynamic Sorting

As described earlier, one of the strengths of the DOM algorithm is the dynamic ordering of layered processing, which selects a layer and detects and cancels the signal at each processing layer. This allows the antennas to be selected according to the estimated reliability of their layers, and as a result, propagation of errors through the layers can be suppressed. To verify this effect, we evaluated the characteristics of DOM, with dynamic ordering of the processing, against a Non-DOM (NDOM) method that performs signal detection and decides layer detection order in the preprocessing stage only. The comparison for $M = 2$ is shown in **Figure 6**, while the $M = 4$ case is shown in **Figure 7**.

The figures show that the characteristics were greatly improved by the dynamic multi-trace-likelihood ordering. Further, without it, applying the extended real-number field algorithm resulted in no significant improvement. This shows that unless dynamic ordering of the processing is used, no substantial amount of improvement is possible. This indicates that the proposed scheme is essential for improving detection performance of interference-cancelling MIMO signal detectors.

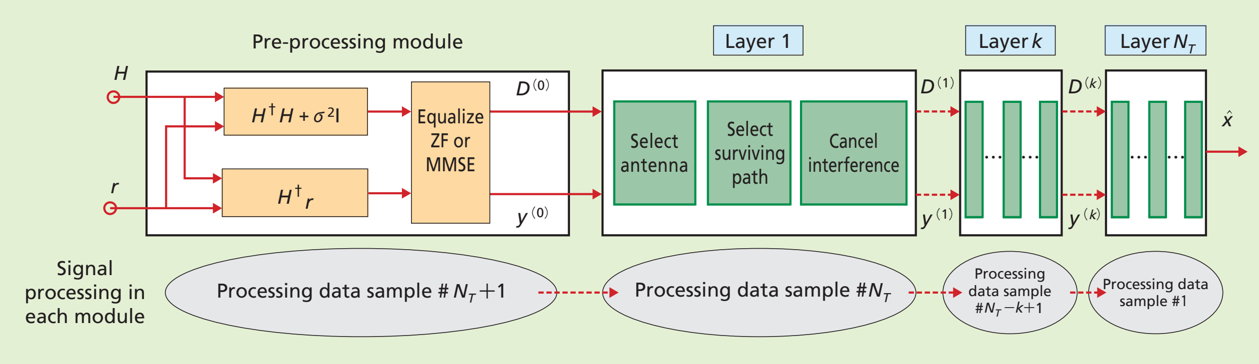

Figure 4 Block diagram of DOM algorithm hardware implementation (pipeline structure)

*15 **Pipeline structure**: A structure that allows parallel processing for efficient use of multiple processing units by each unit successively working as a pipeline in each clock cycle. That allows more efficient use of hardware resources and improved processing throughput.

4.2 Measured Performance Using the Testbed

Figures 8 to 10 show a comparison of simulation results with DOM-R performance evaluation test results from the testbed. Here the 3GPP TR25.996 channel model*16 was set for the PrompSim C8@ channel simulator evaluating for 3 km/h, 30 km/h and 120 km/h cases. The characteristics for MMSE and ML are also shown for comparison.

The results show that in all cases, DOM-R achieved much better performance than MMSE, and achieved performance approaching that of ML. Note that in the experimental results, an error floor occurs in areas of high SNR, but this is due to round-off error in the hardware.

5. Conclusions

In this article, we have described the DOM detection method, which is based on a dynamic multi-trace-likelihood based ordering. Using this method, we have been able to improve detection performance by suppressing propagation of error between layers, which is the main cause of degradation in MIMO signal detection methods using SIC. We also verified that DOM-R achieves performance very close to that of ML through simulation and experiments using a testbed. In the future we will continue to study and evaluate the method for cases of even more antennas.

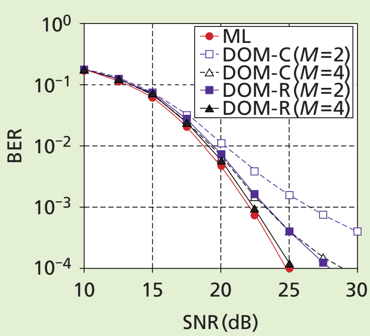

Figure 5 Comparison of DOM algorithms

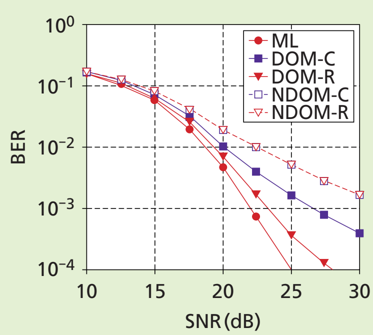

Figure 6 Comparison of dynamic/static ordering algorithm performance ($M=2$)

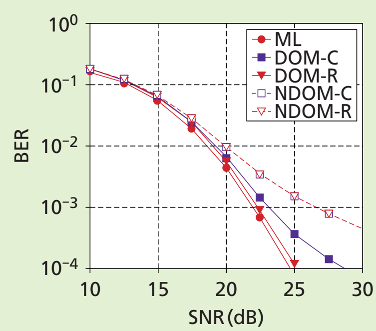

Figure 7 Comparison of dynamic/static ordering algorithm performance ($M=4$)

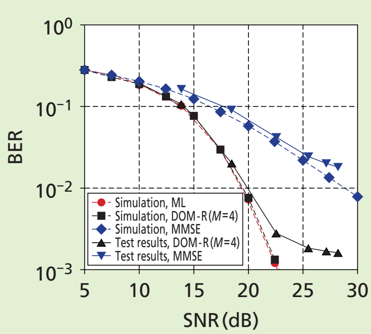

Figure 8 DOM-R test results (3 km/h)

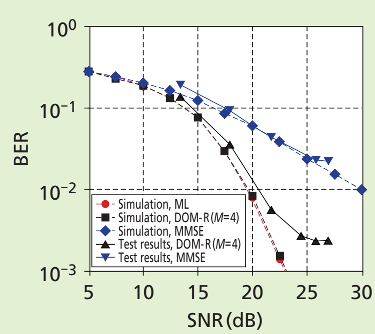

Figure 9 DOM-R test results (30 km/h)

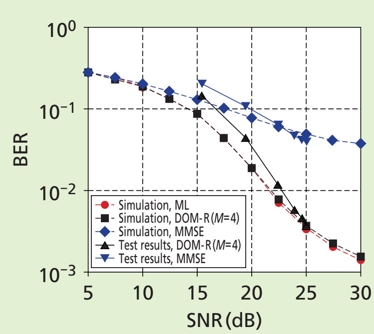

Figure 10 DOM-R test results (120 km/h)

*16 **3GPP TR25.996 channel model**: A wireless channel model specified in 3GPP document number TR25.996 and used for evaluating systems. Four patterns are regulated, according to factors like mobility speed and multipath.

References

[1] K. Higuchi, H. Kawai, N. Maeda and M. Sawahashi: "Adaptive Selection of Surviving Symbol Replica Candidates Based on Maximum Reliability in QRM-MLD for OFCDM MIMO Multiplexing," in Proc. IEEE GLOBECOM 2004, Nov. 2004.

[2] Y. Dai, S. Sun and Z. Lei: "A Comparative Study of QRD-M Detection and Sphere Decoding for MIMO-OFDM Systems," in Proc. IEEE 16th International Symposium on PIMRC 2005, S. Sun, Ed., Vol. 1, pp. 186-190, 2005.

[3] D. Seethaler, H. Artés F. Hlawatsch: "Dynamic nulling-and-cancelling with near-ml performance for MIMO communication systems," in Proc. IEEE ICASSP, '04, H. Artés , Ed., Vol. 4, pp. 777-780, 2004.

[4] D. Seethaler, H. Artés and F. Hlawatsch: "Dynamic Nulling-and-Canceling for Efficient Near-ML Decoding of MIMO Systems," in Proc. IEEE Trans. on Signal Processing, Vol.54, pp.4741-4752, 2006.

[5] J. Chen, Z. Zhang and H. Kayama: "A Dynamic Layer Ordering M-paths MIMO Detection Algorithm and its Implementation," in Proc. APCC 2008.