Performance Analysis of MIMO-OFDM Systems using Indoor Wideband MIMO Channel Measurement Data

Gia Khanh Tran
Department of Electrical and Electronic Engineering
Tokyo Institute of Technology
Email: khanhtg@mobile.ee.titech.ac.jp

Nguyen Dung Dao
Kei Sakaguchi
and Kiyomichi Araki
Graduate School of Science and Engineering
Tokyo Institute of Technology

Hiroshi Iwai
Tsutomu Sakata
and Koichi Ogawa
Network Development Center
Matsushita Electric Industrial Co., Ltd.

Abstract— **In this paper, throughput performance of MIMO-OFDM system in real residential home environment was evaluated by using wideband MIMO channel measurement data. Computer simulations were carried out to compare the performance of MIMO-OFDM systems with various detection methods, i.e. MMSE, VBLAST, QRM-MLD and SVD-MIMO, in addition to that of the SISO-OFDM system. The results showed that the SVD-MIMO transmission can provide the highest average and outage throughput under the assumption of perfect CSI feedback. On the other hand, QRM-MLD yielded the best performance among the systems without CSI available at the transmitter. It was also found that the outage throughput performance of MMSE and VBLAST degrades severely due to the existence of spatial correlation in the real home environment.**

I. Introduction

The MIMO-OFDM transmission system combining the conventional Orthogonal Frequency Division Multiplexing (OFDM) with the Multiple-Input Multiple-Output (MIMO) system is the most promissing candidate for the next generation wireless communication system[1]. By exploiting multiple antennas at both the transmitter (Tx) and the receiver (Rx), the MIMO system can greatly increase the channel capacity at a given bandwidth and power.

When the Channel State Information (CSI) is available both at the Tx and Rx, the singular value decomposition (SVD) based spatial multiplexing called SVD-MIMO is known to maximize the channel capacity[2]. In the MIMO system without CSI feedback, there are linear detection methods, such as Minimum-Mean-Square-Error (MMSE), and non-linear algorithm such as decision feedback based Vertical Bell Labs Layered Space-Time (VBLAST)[3] and QRM-MLD which is a low complexity version of Maximum Likelihood Detection using QR decomposition and M-algorithm[4]. Most of the research in current literature focus on the system design aspects of MIMO-OFDM system while the performance in the real environment is seldom considered. Only a few simulation or experiment based performance analysis can be found e.g. in [5] and [6]. Unrealistic simulation conditions or insufficient sample points in these literature are the main limitations in evaluating the performance of the MIMO-OFDM system over large dynamic channel variations common in the real environment.

In this paper, using more than 50,000 spatial samples of channel measurement in a real residential home environment described in [7], computer simulations were performed to compare the performance of MIMO-OFDM systems with various detection methods, i.e. MMSE, VBLAST, QRM-MLD and SVD-MIMO, in addition to that of the Single-Input Single-Output (SISO) system. As a result, SVD-MIMO transmission was found to provide the highest average and outage throughput under the assumption of perfect CSI feedback. It was also found that QRM-MLD, which significantly reduces computational complexity compared to the conventional MLD, can be considered the most preferable alternative detection method in the case where CSI is not available at the Tx. Furthermore, it was also found that the outage throughput performance of MMSE and VBLAST degrades severely due to the existence of spatial correlation in the real home environment.

The rest of this paper is organized as follows. In Section II, analysis methods including the channel measurement and simulation method will be described. Results of analysis are provided in Section III, and some discussions about the results will be given in Section IV. Finally, Section V concludes the paper.

II. Analysis Method

A. Channel Measurement

Wideband channel measurements were carried out in the residential home environment within an area of 15m by 10m including two rooms, a hallway, living and dining areas. The layout of the house with the location of transmit antennas and measurement areas are shown in Fig. 1. The receiver was located on a mobile scanner to obtain spatial samples. The rooms were equipped with furniture such as beds, tables and chairs. Measurement areas in the living room where the transmit antenna was located were mostly Line-of-Sight (LOS) environment, while measurement areas in the hallway, bedroom and Japanese room were non-Light-of-Sight (NLOS) environment due to walls, doors and furniture between transmit and receive antennas. Measurement system parameters are listed in Table I.

The whole home environment was divided into 53 small areas of 60cm$\times$60cm. In these small areas, 961 channel measurements were performed with a step of 2cm in each direction, yielding a total of $50,933$ measurement points. Measurement results showed that the average path loss in the living room, hallway, bedroom and Japanese room were -53dB, -70dB, -81dB, and -84dB respectively. The spatial

TABLE I

MEASUREMENT SYSTEM PARAMETERS.

MIMO configuration	4(Tx) × 4(Rx)
Array configuration	Half a wavelength spacing ULA
Center frequency	5.06GHz
Bandwidth	20MHz
Transmit signal	IEEE 802.11a modified
Training length	64 OFDM symbols
# of measurement points	50, 933

samples of channel matrices obtained above were used for the performance analysis simulation.

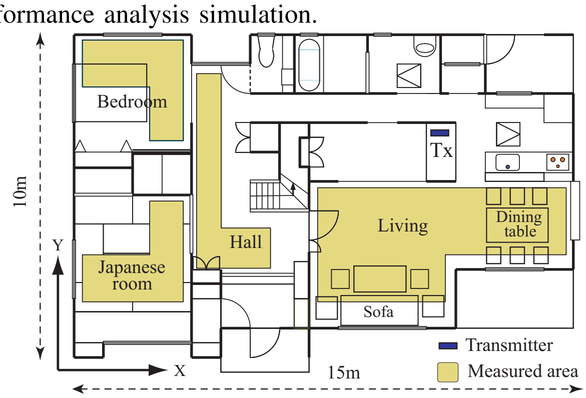


Fig. 1. Overview of measurement environment.

B. Simulation Method

The signal processing model of the simulation is shown in Fig. 2 and simulation parameters are summarized in Table II. Because the measured channel data are in frequency domain, simulation was performed with complex base band signals for each subcarrier. It means that IFFT and FFT described in Fig. 2 are omitted in the simulation. At the Tx, after the binary input data are mapped to complex quadrature amplitude modulation (QAM) constellations, the complex signal is sent through a subcarrier in frequency domain. At the Rx, a MIMO detection will be chosen to detect the received signals. The QAM demapper then converts the detected complex symbols to binary data. In the simulation, the Tx and Rx are perfectly synchronized and channel estimation is perfect. The channel is assumed to be quasi-static, which means the channel responses do not change during each transmission. Total transmit power is divided equally among the transmit antennas.

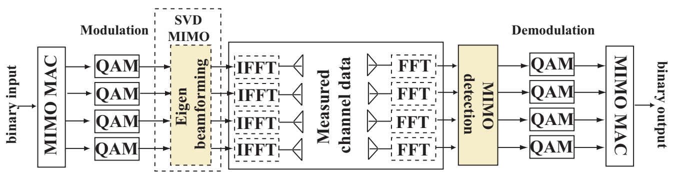


Fig. 2. System model for simulation.

For the assumption that CSI is not available at Tx, we focused on three types of open loop detection methods, i.e. MMSE, VBLAST with MMSE nulling, and QRM-MLD. Diversity order of each detection method increases in this order however so does the computational complexity. In open loop

TABLE II

SIMULATION PARAMETERS.

Total transmit power	0dBm
Noise power	−92dBm (NF = 7dB)
System configuration	SISO-OFDM, 4 × 4 MIMO-OFDM
OFDM configuration	IEEE 802.11a standard
MIMO scheme	MMSE, VBLAST(MMSE) QRM-MLD, SVD-MIMO
Modulation	Adaptive modulation M-ary QAM (M-ary = 2, 4, 16, 64)
Packet length	60 bytes

transmission, throughput was maximized by applying a search algorithm on all signal constellations as follows,

$$T = m_t \max_{M} \log_2(M)(1 - PER(M)), \tag{1}$$

where m_t denotes the number of transmit antennas, PER denotes the packet error rate calculated by comparing the final binary output data stream from all substreams and subcarriers with its original input and M represents the QAM constellation size which is kept unchanged for all subcarriers and antennas in each transmission .

Closed loop simulation of SVD-MIMO is performed with the assumption that CSI is fed back perfectly to the Tx. Left singular eigenvector and right singular eigenvector used for the beamforming at Rx and Tx respectively can be obtained by performing a SVD of the channel matrix. SVD-MIMO is known for its high diversity order and most of the computional complexity depends on that of the SVD. In the simulation with SVD-MIMO, adaptive modulation algorithm was performed for each substream across all subcarriers. Throughput was calculated from the summation of adaptive throughput of each substream in the following way,

$$T = \sum_{i=1}^{m} \max_{M_i} \log_2(M_i)(1 - PER_i(M_i)), \tag{2}$$

where i represents the substream index, m is the rank of channel matrix. M_i and PER_i denote the constellation size and the packet error rate of the ith substream respectively. Adaptive modulation was not performed on each subcarrier due to the small delay spread (high frequency correlation) observed from the propagation result in the model house.

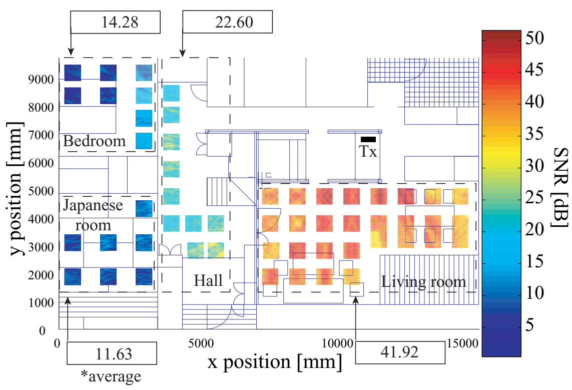


Fig. 3. SNR distribution.

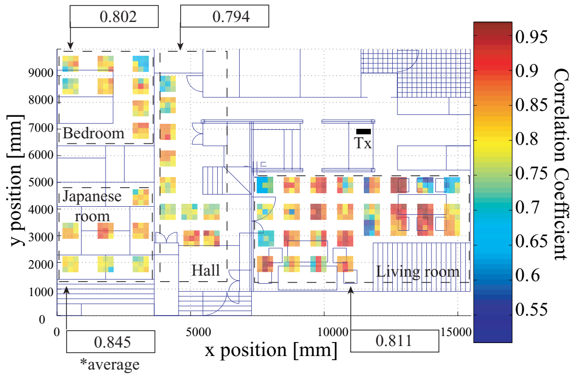


Fig. 4. Spatial correlation distribution at the Rx.

III. Results of Analysis

A. SNR and Spatial Correlation

SNR distribution for the whole house surface with average value for each area is shown in Fig. 3. The number indicated in the small rectangular with an arrow pointing towards a specific room in the map is the average SNR of the corresponding area. The same interpretation can be applied for other distribution maps in this paper. The figure shows that SNR is rather high in the living room and gradually decreases as the distance from the Tx increases. The decrease can be explained by the shadowing and penetration loss due to the presence of obstacles and walls in the house in addition to the free space path loss.

Figure 4 shows the spatial correlation coefficients between the adjacent antenna elements at the Rx side. The result of analysis shows that the spatial correlation both at the Tx and Rx are almost the same. The spatial correlation is found to be high with an average of about 0.7 to 0.8 depending on the rooms. The influence of such high correlation values is significant to the performance of MIMO systems.

B. Instantaneous Throughput Distribution

Instantaneous throughput distributions for SISO, MMSE, VBLAST, QRM-MLD and SVD-MIMO are shown from Fig. 5 to Fig. 9 respectively. It can be observed from the maps that the room-average throughput is highest in the living room and decreases in the hallway, the bedroom and the Japanese room sequentially in accordance with the average SNR distribution. Depending on the MIMO schemes the throughput of MIMO system in the living room with high SNR is about 2 to 3.5 times that of the SISO system. This fact can be explained by the benefit of spatial multiplexing. However, in the bedroom and Japanese room with lower SNR, throughput of the MIMO schemes seems to be worse than that of SISO except for the SVD-MIMO.

C. Statistical Throughput Performance

For further analysis, the distance and SNR dependency of the throughput with various schemes will be studied in this subsection. Due to the fading characteristics of the wireless channel, a statistical value of throughput is required for a more concise throughput performance evaluation. In this paper, the statistical values of throughput are calculated from the samples $\mathbf{T}$ of instantaneous throughput from a 20cm×20cm area where the wide sense stationary is assumed to be satisfied. The average throughput $T_\mu = E[T \in \mathbf{T}]$ and the 1% outage throughput T_o satisfying $\Pr(T \leq T_o \in \mathbf{T}) = 1\%$ are used in the analysis. Figures 10(a) and 11(a) show average and 1% outage thoughput versus distance calculated from the Tx to the center of the 20cm squared area and the corresponding average SNR respectively.

From Fig. 10, it can be seen that among the three schemes without CSI at the Tx side, QRM-MLD provides best performance while MMSE performs badly particularly in areas far from the Tx and VBLAST holds the second place. It is also found that throughput achieved by MIMO system with different detection methods are 2 to 3.5 times that of SISO in LOS environment with high SNR. However, this benefit of spatial multiplexing decreases with increasing distance from the Tx and particularly, performance of MMSE is worse than that of SISO for distances farther than 6.5m from the Tx or at the SNR lower than 28dB. The fact can be explained by the effect of spatial correlation and will be discussed in next section.

On the other hand, SVD-MIMO seems to outperform the other methods with a 3 times benefit in throughput compared to SISO maintained even in low SNR areas of the bedroom and Japanese room. It is also found that the throughput performance of SVD-MIMO in high SNR areas of the living room is slightly inferior to that of QRM-MLD. It can be explained by the limitation of the constellation size in the simulation which is unable to maximally utilize the benefit of strong eigenbeam gains, e.g. of the 1^{st} and 2^{nd} substreams.

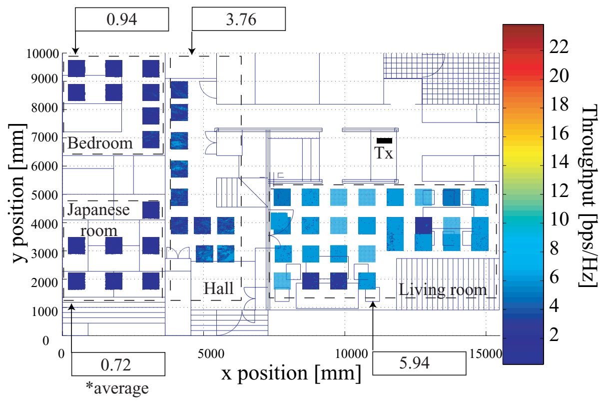


Fig. 5. SISO throughput distribution.

Furthermore, the stability of system performance can be studied by comparing the 1% outage throughput in Fig. 11 with the average throughput in Fig. 10. It can be seen that QRM-MLD and SVD-MIMO are very robust schemes to the wireless link fluctuation showing very small variation between the average and outage throughput. Meanwhile, the large difference of these two statistical values in the performance of MMSE implies that MIMO with MMSE detector seems not to be a high reliability transmission method. In a realistically reasonable area of SNR ranging from 15dB to 30dB, the throughput performance can be ranked as follows: SVD-MIMO, QRM-MLD, VBLAST, SISO, MMSE. This order is due to the diversity order of the decoding schemes.

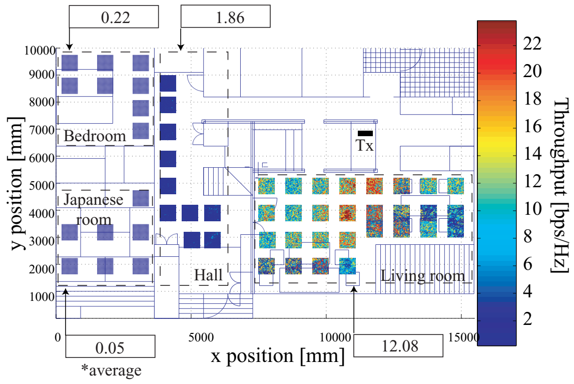


Fig. 6. MMSE throughput distribution.

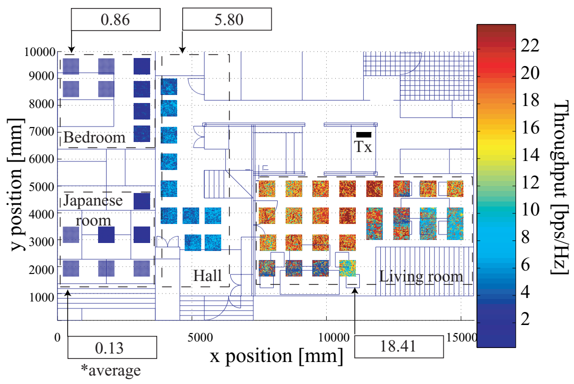


Fig. 7. VBLAST throughput distribution.

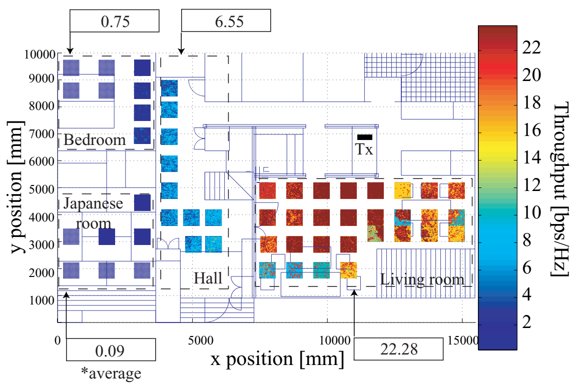


Fig. 8. QRM-MLD throughput distribution.

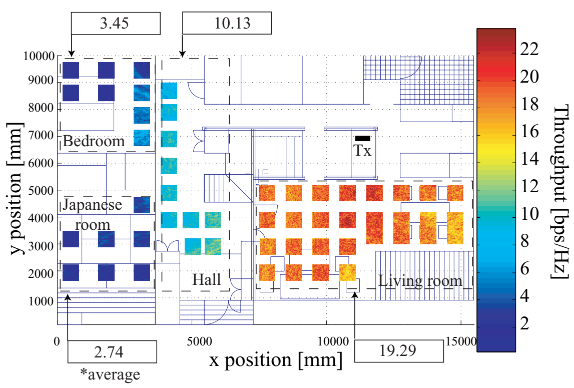


Fig. 9. SVD-MIMO throughput distribution.

IV. Discussion

The channel measurement in real residential home environment proved that the benefit of MIMO system in increasing channel capacity can be obtained both in LOS and NLOS environment[7]. However, from the results above, the throughput of spatial multiplexing, such as MMSE, VBLAST and QRM-MLD were found to be worse than that of SISO in the far areas, e.g. the bedroom and Japanese rooms. In order to understand the effect of spatial correlation on throughput performance, a numerical simulation using flat Rayleigh fading channel with spatial correlation at both the Tx and Rx was carried out. In the simulation, the channel matrix $\mathbf{H}$ of the 4×4 MIMO system was generated by using the Kronecker model [8] as follows,

$$\mathbf{H} = \sqrt{\mathbf{R}_r}\mathbf{G}\sqrt{\mathbf{R}_t}^T, \qquad (3)$$

where $\mathbf{G} \in \mathcal{C}^{4\times4}$ is an independent identically distributed (i.i.d.) zero-mean and unit variance elements complex Gaussian matrix, $\mathbf{R}_t \in \mathcal{C}^{4\times4}$ and $\mathbf{R}_r \in \mathcal{C}^{4\times4}$ denote the correlation matrices observed at the Tx and Rx respectively, and $[\cdot]^T$ denotes the transpose operator. In this simulation, it is assumed that $\mathbf{R}_t = \mathbf{R}_r = \mathbf{R}$ and the exponential correlation matrix shown in (4) was applied on both sides of the MIMO channel

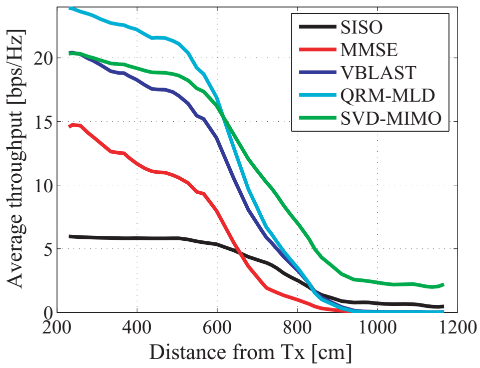
$$\mathbf{R} = \begin{pmatrix} 1 & r & r^2 & r^3 \\ r & 1 & r & r^2 \\ r^2 & r & 1 & r \\ r^3 & r^2 & r & 1 \end{pmatrix}, \qquad (4)$$

where $r \in [0, 1]$ denotes the correlation coefficient between the two adjacent antenna elements.

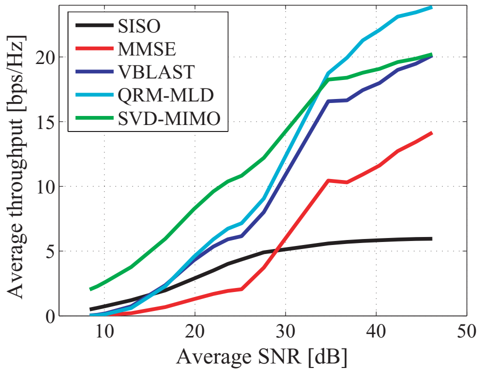
Figure 12 shows the relation between average throughput and SNR with $r = 0$ and $r = 0.8$. The value $r = 0.8$ was chosen in accordance with the average spatial correlation in the low SNR areas of the bedroom and Japanese room as shown in Fig. 4. From the figure it can be seen that when the antenna elements are completely uncorrelated ($r = 0$), throughput performances of all MIMO schemes are better than that of SISO. However, when spatial correlation exists, the degradation in performance of all schemes with respect to SISO becomes obvious, especially in MMSE case. Furthermore, result shown in Fig. 12 matches well with the experimental result in Fig. 10(b) in the SNR region from 5dB to 30dB, which reveals that the bad performance of spatial multiplexing in low SNR areas is due to the effect of spatial correlation.

Because the effect of spatial correlation in the real life environment cannot be neglected, not all methods of MIMO schemes result in a good performance compared to the conventional SISO system. MMSE performance is found to be the worst and should be left out. Now we compare the performance of the remaining three MIMO schemes: VBLAST, QRM-MLD and SVD-MIMO.

Firstly, it can be seen clearly that SVD-MIMO can provide the best average and outage throughput performance. However, the requirement for a feedback channel as well as a good feedback algorithm can be seen as a challenge for a realization of SVD-MIMO.



(a) Distance dependency.



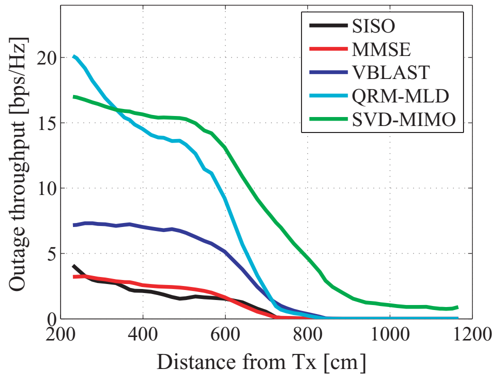
(b) SNR dependency.

Fig. 10. Average throughput performance.

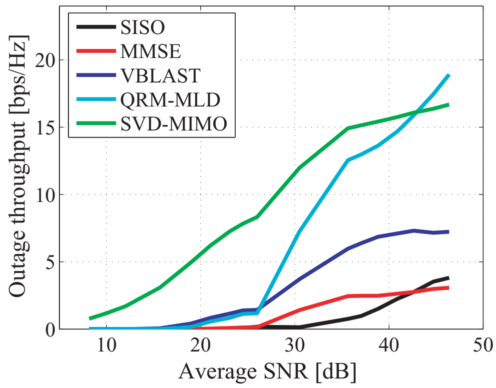
On the other hand, QRM-MLD may be regarded as the next alternative candidate ensuring high data rate transmission in the case that CSI is not available at the Tx. Although the QRM-MLD and VBLAST have almost the same computational complexity up to 16QAM modulation order, it can be seen that the QRM-MLD has better tolerance against spatial correlation.

V. Conclusion

In this paper, performance of MIMO-OFDM system in a real residential home environment was evaluated by using wideband channel measurement data. From the results, it can be concluded that SVD-MIMO scheme can provide the highest throughput performance and system reliability under the assumption of perfect CSI feedback. It was also found that QRM-MLD can be considered to be the most preferable alternative detection method in the case where CSI is not available at the Tx. Furthermore, the outage throughput performance of MMSE and VBLAST were found to degrade severely due to the existence of spatial correlation in the real home environment.



(a) Distance dependency.



(b) SNR dependency.

Fig. 11. 1% outage throughput performance.

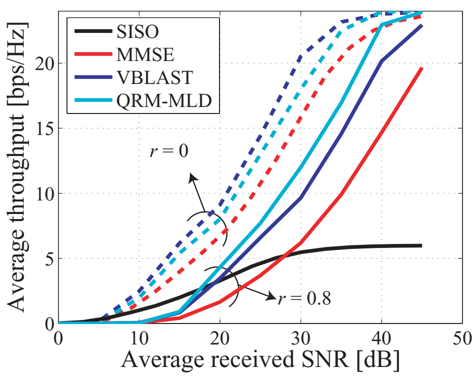


Fig. 12. Effect of spatial correlation on throughput performance.

References

[1] H. Bölcskei, D. Gesbert, and A.J. Paulraj, "On the capacity of OFDM-based multi-antenna systems," *IEEE Trans. Commun.*, vol. 50, no. 2, pp. 225-234, Feb. 2002.

[2] I.E. Telatar, "Capacity of multi-antenna gaussian channels," Eur. Trans. Telecommun., vol. 10, no. 6, pp. 585-595, 1999.

[3] G.J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," *Bell. Labs. Tech. J.*, vol. 1, no. 2, pp. 41-59, 1996.

[4] K.J Kim and J. Yue, "Joint channel estimation and data detection algorithms for MIMO-OFDM systems,"*Proc. 36th Asilomar Conference*, vol. 2, pp. 1857-1861, Nov. 2002.

[5] X. Zhu and R.D. Murch, "Performance analysis of maximum likelihood detection in a MIMO antenna system" *IEEE Trans. Commun.*, vol. 50, no. 2, pp. 187-191, Feb. 2002.

[6] T.C.W. Schenk, G. Dolmans and I. Modonesi, "Throughput of a MIMO OFDM based WLAN system,"*Proc. IEEE 11th Symposium on Communications and Vehicular Technology*, Nov. 2004.

[7] D.D. Nguyen, H.Y.E. Chua, K. Sakaguchi, K. Araki, H. Iwai, T. Sakata and K. Ogawa, "Measurements on area coverage of 5GHz band MIMO-OFDM system in residential home environment,"*Proc. 16th PIMRC*, Sep. 2005.

[8] J.P. Kermoal, L. Schumacher, K.I. Pedersen, P.E. Mogensen and F. Frederiksen, "A stochastic MIMO radio channel model with experimental validation,"*IEEE J. Sel. Areas Commun.*, vol. 20, no. 6, pp. 1211-1226, Aug. 2002.