Paper

Phased array antennas in MIMO receiver

Sebastian Kozłowski, Yevhen Yashchyshyn, and Józef Modelski

Abstract— In this paper, a computer simulation of a MIMO system comprising phased array antennas (PAA) in all receiving branches is presented. In order to examine the system performance under relatively realistic conditions, a ray-tracing simulator was applied to generate a baseband channel impulse response matrix *H*. A bit error rate (BER) of two systems utilizing different detection methods: V-BLAST and simple matrix inversion was examined in order to determine phased array antennas applicability. Results of an attempt to determine relationship between BER and properties of particular matrix *H* realization are also provided.

Keywords— MIMO systems, phased array antennas.

1. Introduction

Telecommunications require increasing amount of data to be transferred as well as increasing bit rates. That, in turn, causes the need for developing the data transfer methods and systems utilizing frequency band in a highly effective way. Consequently, researches on radiocommunication systems with transmitters and receivers provided with more than one antenna, so called MIMO (multiple input multiple output) systems, have been intensified in recent years. The base for this approach is to utilize a space as an additional dimension, what enables establishing several orthogonal subchannels simultaneously in the same frequency band. Such subchannels may carry either independent data streams, what means increase of system capacity [1, 2], or the same data reducing the bit error rate (BER) in the radiolink [3].

Phased array antennas (PAA) have been extensively investigated and have already been widely used, for instance in radars and satellite communications. In personal communications they may be applied in order to mitigate interference caused by other users or systems, mitigate intersymbol interference, or to direct the beam toward terminal. Application of phased array antennas in MIMO receivers and transmitters was also considered. In papers [5–7] such antennas were used in order to improve the performance of MIMO system exposed to the interferences. Phased array antennas can also bring benefit to the system utilizing Alamouti scheme [3] by causing significant signal to noise ratio (SNR) increase [4]. Current paper presents possibility of BER reduction by means of PAAs application in every branch of a MIMO receiver, in the system utilizing orthogonal subchannels for transferring independent data streams.

2. MIMO system model

General block diagram of a MIMO system is shown in Fig. 1. Presented model of the system is valid under following assumptions. Transmitted signals have narrow frequency band, and consequently the radio channel is characterized by flat fading, so there is no intersymbol interference. Vector $x_{[Nt,1]}(t_n)$ of complex symbols selected from the predefined constellation is transmitted and vector $y_{[Nr,1]}(t_n)$ of complex signals is received in every time moment t_n (the dimension of the matrix or vector is enclosed within square brackets). The baseband channel impulse response matrix $H_{[Nr,Nt]}$ is precisely determined and does not change during the transmission of the burst comprising large number of symbols. Every element h_{ij} of the matrix H represents the transmission from the jth transmitter to the ith receiver. Operation of the system can be described by means of formula (1):

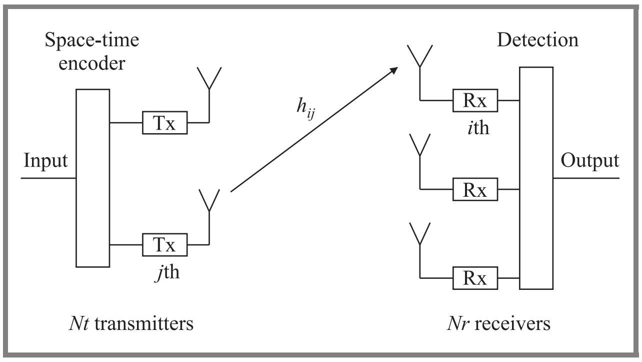

Fig. 1. Block diagram of MIMO system.

$$y(t_n) = H \cdot x(t_n) + n(t_n), \tag{1}$$

where $n_{[Nr,1]}(t_n)$ is the vector of noise samples.

It should be stressed that the useful signal detection (determination of x from the Eq. (1)) is possible only if the matrix H is well conditioned. This is usually satisfied if there is no line of sight (LOS) between the transmitter and receiver and the propagation takes place in the rich scattering environment. Resulting Rayleigh fading, which is harmful to the classical radio systems, is in case of MIMO systems highly desirable since it assures low correlation between different subchannels.

3. Simulation of MIMO system incorporating phased array antennas

A MIMO system comprising two transmitting and two receiving antennas was simulated as an example. Every receiving antenna was realized as 2-element phased array controlled by the tunable (0–360 degrees) lossless phase shifter (Fig. 2). Radiation pattern of a single radiating element is assumed to be omnidirectional and no coupling between any elements is concerned. Radiolink is supposed to be characterized by following parameters: central frequency: 2 GHz, bandwidth: 0.2 MHz, single transmitter output power: 0 dBm, modulation: quadrature phase shift keying (QPSK). Additionally, every element of phased array antenna receives useful signal as well as the noise of given mean power. Each noise sample is a realization of variate described by Eq. (2):

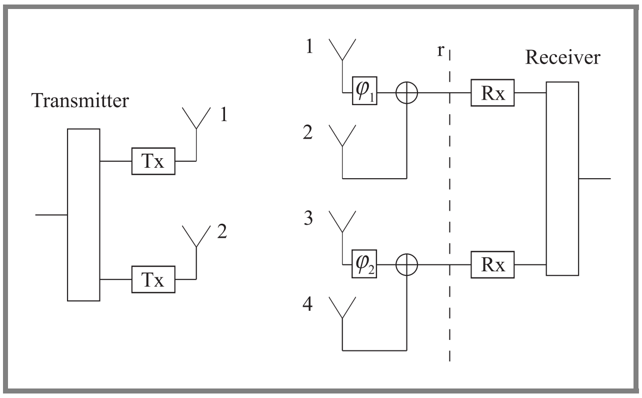

Fig. 2. MIMO system incorporating phased array antennas in each receiver branch (φ – phase shifter, antenna spacing: λ in transmitter, $\lambda/2$ in receiver).

$$n = N(0,\rho^2) + j \cdot N(0,\rho^2), \tag{2}$$

where $N(x,y)$ means normal distribution with mean value x and variance y.
System presented in Fig. 2 can be described by formula analogous to (1):

$$y_{[4,1]}(t_n) = H_{[4,2]} \cdot x_{[2,1]}(t_n) + n_{[4,1]}(t_n). \tag{3}$$

System description can be moved to the "r" plane by means of appropriate processing, involving multiplication by weights and summing:

$$y_{r[2,1]}(t_n) = H_{r[2,2]} \cdot x_{[2,1]}(t_n) \tag{4}$$

while H_r and y_r depend on the phase shifters settings. Please notice that in real system only values of the H_r and y_r are known, as opposed to the values of y and H.
Matrix $H_{[4,2]}$ was generated by means of electromagnetic waves propagation simulator employing ray-tracing 2.5D method. The environment was simulated as the interior and the neighbourhood of the building made of various components and materials (walls, doors, windows) characterized by different permittivity and losses. Figure 3 shows field distribution in small fragment of propagation environment. Two curves are presented, each one corresponds to power level of a signal from one transmitter. Two facts can be deduced from the figure. Firstly, the power level of signals from different transmitters are very different when reaching the receiving antenna located at fixed position. Secondly, because of interference of a number of reflected waves, power level of aforementioned signals changes rapidly when receiving antenna is being moved. The conclusion is that assumed propagation environment satisfies the conditions under which MIMO transmission is possible.

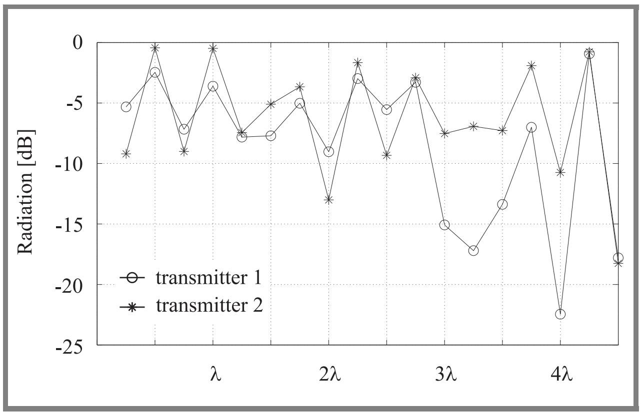

Fig. 3. Field distribution in assumed propagation environment.

Receivers were subsequently positioned in 25 random locations. A transmission of 10 000 symbols (two simultaneous independent streams, 5 000 symbols each) was simulated for every receiver location and for various phase shifters settings. Two detection methods were applied. First was the V-BLAST algorithm [2] and the second, denoted in this paper as INV, consisted in solving the Eq. (4) by simple matrix H_r inversion operation. Results of the experiment are shown in Fig. 4. Particular columns represent BER obtained for the V-BLAST and INV detection for two cases of receiver configuration, first, a receiver provided with two omnidirectional radiators (marked as "2×2" and a dark bar in Fig. 4), and second, a receiver provided with PAAs (marked as "2×4" and a white bar). For the latter case only the lowest BER level has been presented, obtained for the best set of weights. Phase shifters were switched at 2 degrees intervals, noise power level was chosen for every receiver so as to obtain average SNR equal to 10 dB. Results show that application of PAA in every MIMO receiver's branch can provide significant BER reduction – up to ten times.
Testing BER for every set of weights is time-consuming during the simulation and impossible to realize in practice. Consequently determination of the relationship between BER and matrix H_r is more than desirable. Concerning the fact that $|h_{ij}|$ represent the attenuation of the transmitted signal, it seems obvious that they should be as high as possible. For the given noise power level, the higher they are, the greater SNR in receiver's branches is.

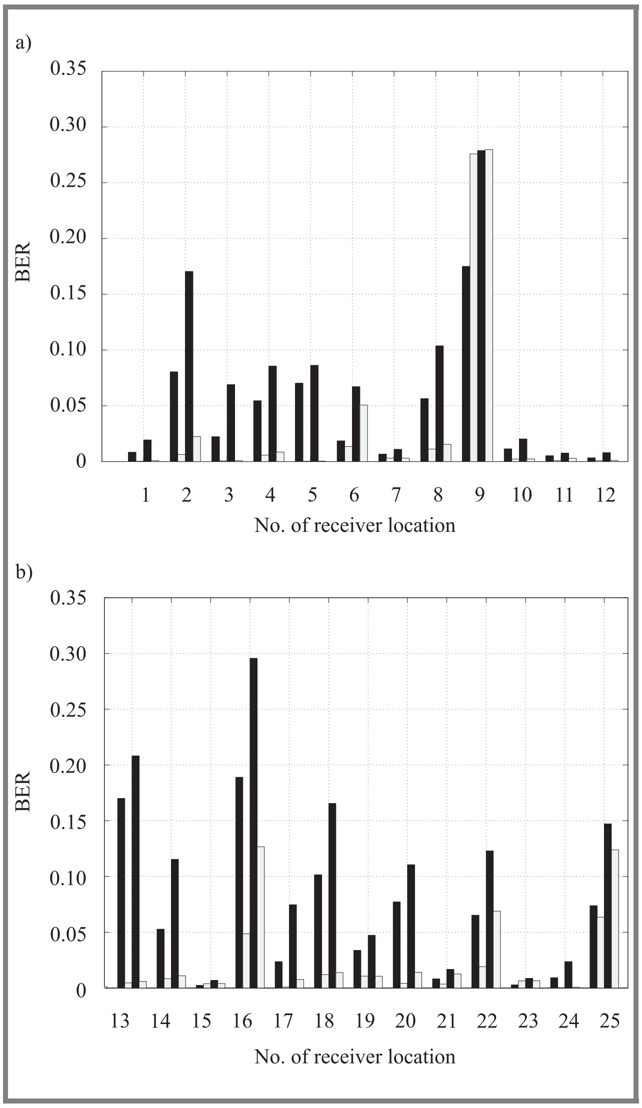

Fig. 4. BER for different receiver locations and: (a) V-BLAST 2×2 (dark bar), V-BLAST 2×4 (white bar); (b) INV 2×2 (dark bar), INV 2×4 (white bar).

However, it should be noticed that during the detection process matrix H_r is subjected to inversion or pseudoinversion operation, so its condition number (ratio of the largest and smallest singular value) $cond(H_r)$ is of great importance. An attempt to find the qualitative relationship enabling to determine which of the given matrix H_r realisation is better concerning the BER has been undertaken. It has been assumed that this relationship can be described as formula with two arguments: $||H_r||^2$ and $cond(H_r)^{-1}$, where $||X||$ means Frobenius norm of the matrix X. It can be easily shown that when the noise with constant power level described by formula (2) is present, then $||H_r||^2$ is proportional to the average SNR measured at the "r" plane. Consequently, if other conditions are unchanged, then increase of $||H_r||^2$ causes better system performance. The better is matrix conditioned, the higher is $cond(H_r)^{-1}$, which reaches its maximum equal to 1 for the identity matrix. Lines of constant BER on the plane $[cond(H_r)^{-1}, ||H_r||^q]$ are shown in Fig. 5. Parameter $q > 0$ is a number empirically determined to be equal to 1.1.

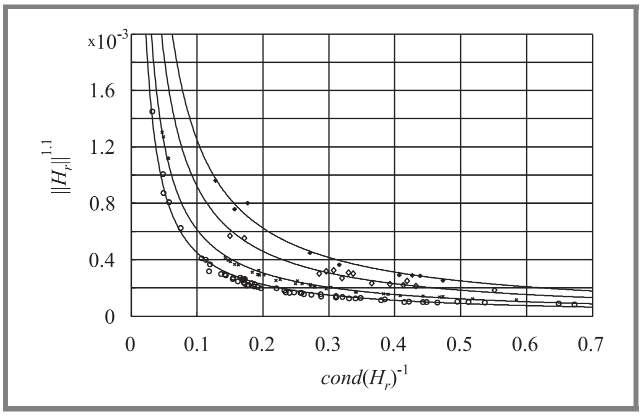

Fig. 5. Constant BER lines for V-BLAST detection.

Lines presented in Fig. 5 correspond to the approximation of simulation results by means of hyperbolas described by equation:

$$F[BER] = ||H_r||^q \cdot cond(H_r)^{-1}, \qquad (5)$$

where $F[BER]$ is a certain unknown, but decreasing function of BER. It means that the most advantageous for the system performance should be such matrix H_r for which the right side of Eq. (5) reaches maximum. The problem of choosing appropriate exponent q remains unsolved and will be investigated in future research.

4. Conclusion

Phased array antenna in each branch of receiver has been proposed to decrease BER of MIMO system utilising two subchannels in order to transmit two independent data streams. It has been shown that application of phase shifters only (neither amplifiers nor attenuators) can improve significantly the system performance. Preliminary results of an approach to evaluate BER on a base of current realization of baseband channel impulse response matrix have been also provided. Performance of narrowband MIMO system depends on many factors. In particular, if matrix H is badly conditioned, then system will not operate properly, no matter how high SNR is.

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Sebastian Kozłowski was born in Warsaw, Poland, in 1980. He received M.Sc. degree in radioelectronics engineering from the Warsaw University of Technology (WUT), Poland, in 2004. His thesis concerned wideband phase shifters and multiport systems for measurements of scattering parameters. Since 2004 he is Ph.D. student at Institute of Radioelectronics, WUT. His current research interests include antenna techniques and MIMO systems.

e-mail: S.Kozlowski@ire.pw.edu.pl
Institute of Radioelectronics
Warsaw University of Technology
Nowowiejska st 15/19
00-665 Warsaw, Poland

Yevhen Yashchyshyn was born in Lviv, Ukraine, in 1957. He received his M.Sc., Ph.D. and D.Sc. degrees in radioelectronics and telecommunications from Lviv University of Technology in 1979 (Ukraine), Moscow Institute of the Electronic Machine Building (MIEM) in 1986 (Russia) and Warsaw University of Technology (WUT) in 2006 (Poland), respectively. In 1991 he obtained the Senior Scientist title. Until 1999 he worked at Lviv Polytechnic National University. Since 1999 he has been with the Institute of Radioelectronics, WUT, as an Associated Professor. His research interests are in the areas of antenna theory and technique, smart beamforming and design of communications antennas. He has published 2 monographs, over 150 technical papers and has obtained 6 patents.

e-mail: E.Jaszczyszyn@ire.pw.edu.pl
Institute of Radioelectronics
Warsaw University of Technology
Nowowiejska st 15/19
00-665 Warsaw, Poland

Józef W. Modelski was born in 1949 in Poland. He received M.Sc. in 1973, Ph.D. in 1978 and D.Sc. in 1987, respectively, all in electronics, at the Warsaw University of Technology (WUT), Poland. He received State Professor's title in technical sciences in 1994. Since 1973 Professor Modelski has been with the Institute of Radioelectronics, Warsaw University of Technology, holding in sequence all academic positions from teaching/research assistant to tenured professor. Since 1996 he has been Director of the Institute. In 1976/77 he spent one year in the USA as a Fulbright grantee. In 1986 for two years he joined the Braunschweig Technical University as a senior scientist. His research interests include the area of: microwave modulators and shifters with semiconductor and ferrite elements, dielectric resonators and their applications, ferroelectric and smart antennas for communication systems. He is the author of 4 monographs, over 250 technical papers. He acts as a consultant to industry and Polish government agencies. J. Modelski has been Senior Member of IEEE since 1990 and Fellow Member since 2001, a Member of MTT-S, AP-S and AES-S. Member of AdCom MTT since 2000, a member of Technical Committees MTT-17 and MTT-20. He was elected 2007 MTT-S President-Elect. He has been a member of the TPCs of MTT-S International Microwave Symposium and the European Microwave Conference since 1996; since 1995 he has been Chair of the International Conference on Microwaves, Radar and Wireless Communications MIKON. He is a member of numerous local conferences in Europe. He received many distinctions in Poland, including Awards of the Minister of National Education and the Minister of Science; he was also the recipient of IEEE Third Millennium Medal and the Walter Cox Award.

e-mail: J.Modelski@ire.pw.edu.pl
Institute of Radioelectronics
Warsaw University of Technology
Nowowiejska st 15/19
00-665 Warsaw, Poland