Code Index Modulation and Spatial Modulation: A New High Rate and Energy Efficient Scheme for MIMO systems

Fatih Çogen*, Erdoğan Aydın*, Nihat Kabaoğlu*, Ertuğrul Başar†, and Haci Ilhan ‡
*Electrical and Electronics Engineering Department, Istanbul Medeniyet University, Istanbul, Turkey
†Electronics and Communication Engineering Department, Istanbul Technical University, Istanbul, Turkey.
‡Electronics and Communication Engineering Department, Yıldız Technical University, Istanbul, Turkey
Email: cogenfatih@gmail.com, {erdogan.aydin, nihat.kabaoglu}@medeniyet.edu.tr, basarer@itu.edu.tr, ilhanh@yildiz.edu.tr

***Abstract*—In this paper, in order to increase data rate, error performance and energy efficiency in wireless communication systems, a new multiple-input multiple-output (MIMO) transmission scheme, called code index modulation and spatial modulation (CIM-SM), is proposed over the Nakagami-m fading channel by combining recently two promising modulation techniques, SM and CIM. In the CIM-SM scheme, incoming data bits specify activated transmit antenna indices, two modulated symbols as well as their corresponding spreading code indices. Therefore, the information bits are conveyed not only by the two modulated symbols but also by the active antenna indices of SM as well as the spreading code indices. Consequently, the proposed CIM-SM scheme spends less transmission power while performing faster data transmission compared with the conventional direct sequence spread spectrum (DS-SS), SM and CIM-SS systems. Our computer simulations show that CIM-SM scheme provides considerably better error performance than DS-SS, SM and CIM-SS systems. In addition, the performance analysis of the proposed system is performed over the Nakagami-m fading channels for BPSK modulation.**

***Keywords*—Spatial modulation, code index modulation, MIMO systems and direct sequance spread spectrum.**

I. Introduction

The demand for high data rates in wireless communication systems, and therefore the need for a high spectrum efficiency, has recently made the emergence of innovative transmission systems compulsory. In this context, multiple-input multiple-output (MIMO) transmission technologies have become the focus of attention by researchers because MIMO systems provide increased performance for wireless channels, which deteriorate the performance due to multipath propagation [1]. Moreover, since MIMO systems use the antenna diversity technique on both transmitter and receiver sides, reliable and robust communication is established between transmitter and receiver terminals. In addition, MIMO systems offer increase in capacity and diversity gain for wireless networks [2].

In recent years, a new high data rate, low complexity transmission technique, known as spatial modulation (SM), has attracted great interest from researchers and has recently been involved in many studies [3]-[6]. In the SM technique, both transmitter and receiver sides are equipped with multiple antennas to obtain the spatial diversity of the rich scattering environment. The SM scheme is introduced by researchers as a low-complexity technique alternative to the conventional MIMO systems since only one of the multiple transmission antennas is always active in each transmission time slot [7]. Thus, SM technique provides higher data rate than traditional single-input multiple-output (SIMO) systems, while reducing complexity. In addition, inter-channel interference (ICI) is completely avoided in SM scheme because this scheme does not need the antenna synchronization due to its nature.

SM, which is a member of the index modulation (IM) is a candidate for 5G and beyond wireless networks, and it is a new generation communication system that researchers have been working on in recent years [8],[9]. In the most general way for the transmission of information in IM, indices of units such as transmitting antennas, sub-carriers, time intervals, spreading codes and pre-coding matrces etc. are considered as an additional information. In this scheme, the indices carry extra information. Thus, little or no energy is spent for additional information carried in the indices. As a result, IM provides both energy efficiency and spectral efficiency [10].

On the other hand, a new IM technique, called CIM-SS, considers the indices of spreading codes to convey extra information in addition to the transmitted symbols. Specifically, in CIM-SS scheme some of the information bits are used to modulate the symbol to be transmitted, while others are used to select the spreading code to be activated. Thus, additional information is loaded into the indices of the spreading code. At the receiver side, the spreading code is first detected to recover the mapped bit, then the received symbol is demodulated. With this rational order, just like the SM technique, only a part of the bits are physically transmitted over the channel, while the other part is loaded into the spreader code indices. For this reason, the CIM-SS system increases the efficiency and data rate of the communication system while reducing energy consumption [11], [12].

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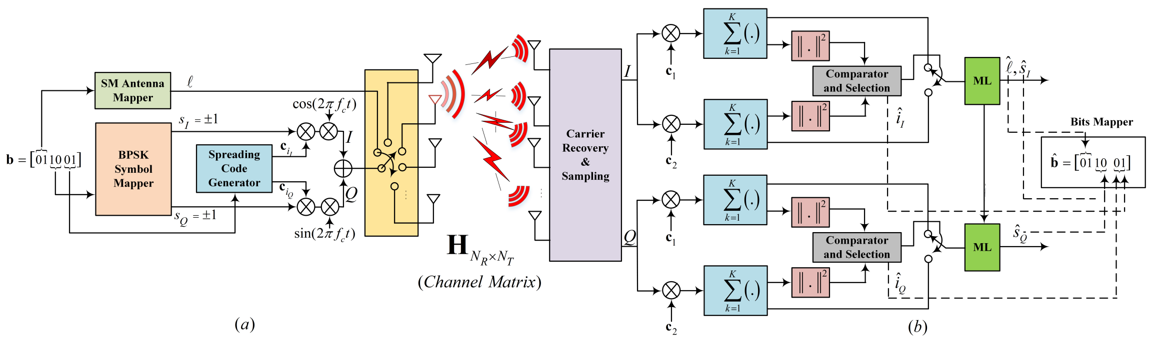

Fig. 1. CIM-SM system model, (a) transmitter structure, (b) receiver structure.

In this study, we propose a new MIMO transmission system with high energy-efficiency, high data rate and better error performance, called CIM-SM, by combining SM and CIM techniques, which are two promising techniques for next generation communication systems. It has been shown via computer simulation results that the proposed system provides better error performance than DS-SS, SM and CIM-SS systems while consumes less transmission energy. Performance analysis of the proposed CIM-SM is evaluated over Nakagami-m fading channels since Nakagami-m distribution has become the focus of attention due to the ability to model much more extensive channel conditions, characterize the envelope distribution and adapt experimental data.

The paper is organized as follows: In section II, we introduce the general CIM-SM scheme. In Section III, throughput, data rate and energy efficiency are presented. Simulation results and performance comparisons are given in Section IV. Finally, Section V concludes the paper.

II. System Model

The general structure of the proposed CIM-SM scheme is depicted in Fig. 1, where N_T and N_R are denote the number of transmit and receive antennas at the transmitter and receiver sides, respectively. Two different Walsh Hadamard spreading codes, i.e., $\mathbf{c}_i = [c_{i,1}, c_{i,2}, \ldots, c_{i,K}]^T$, $i \in \{1, 2\}$ are used for i_I and i_Q, also each of spreading codes consists of a K chips. In-phase (I) and quadrature (Q) channel components are considered both in the transmitter and receiver sides. In addition to this, BPSK modulation is used and $\{\pm 1\}$ symbols are transmitted. Finally, the proposed system structure is designed by adapting SM, CIM techniques and BPSK modulation.

Considering the transmitter structure of the CIM-SM system shown in Fig. 1 (a), **b** is the incoming binary information bits to be transmitted along one symbol period (T_s). In the CIM-SM transmitter scheme, **b** is divided into $\log_2(N_T)$, $\log_2(2M)$ and $\log_2(2L)$ sub-vector groups, where M and L are defined as modulation order and numbers of different spreading code sequence, respectively. The first, second and third sub-block groups of bits are conveyed in the antenna indices of SM, BPSK symbols and indices of spreading codes, respectively. Thus, $2(\log_2(M) + \log_2(L))$ bits are transmitted in I and Q components through both BPSK symbols and spreading code indices. As a result, the BPSK symbol sequences spread by the spreading code are transmitted from the single antenna activated by SM technique by means of the I and Q components.

The noisy and faded received signal of CIM-SM can be expressed as follows:

$$\begin{aligned} y(t) &= \sum_{k=1}^{K} \Big(s_I\, c_{i_I,k}\, p\big(t - kT_c\big) \cos(2\pi f_c t) \\ &+ s_Q\, c_{i_Q,k}\, p\big(t - kT_c\big) \sin(2\pi f_c t) \Big) h(t) + n(t), \quad (1) \end{aligned}$$

where, s_I, $s_Q \in \{\pm 1\}$ are the BPSK symbols transmitted in I and Q channels, respectively. $p(t)$ is a unit rectangular pulse shaping filter on $[0, T_c]$, where T_c is the period for the spreading code and f_c is the carrier frequency. $n(t) \sim C(0, N_0)$ is a complex Gaussian random process with zero mean and variance of N_0. $h(t)$ represents the Nakagami-m fading channel. The Nakagami-m fading channels are completely modelled as $h(t) = \sqrt{\sum_{q=1}^{m} |h(t)_{q,R}|^2} + j\sqrt{\sum_{q=1}^{m} |h(t)_{q,I}|^2}$ [13], where the samples taken from $h(t)_{q,R}$ and $h(t)_{q,I}$ identical and independently distributed Gaussian random variables, with zero mean and $\sigma_h^2 = 1/(2m)$ variance. The probability distribution function (PDF) of envelope and phase of the Nakagami-m fading channels are respectively written as $f(\nu) = \frac{2\nu^{2m-1} m^m}{\Gamma(m)} e^{-m\nu^2}$, $f(\theta) = \frac{\Gamma(m) |\sin(2\theta)|^{m-1}}{\Gamma^2(m/2) 2^m}$ [13], where $\Gamma(m)$ is the Gamma function. When $f(\theta)$ is considered, the phase distribution is not uniformly distributed if $m \neq 1$.

Since the I and Q components of (1) have a similar structure, the signal model can be rewritten only for the in-phase part. Thus, at the receiver after the perfect carrier estimation, the baseband expression of the component I is given by:

$$y_I(t) = \sum_{k=1}^{K} s_I\, c_{i_I,k}\, p\big(t - kT_c\big) h(t) + n_I(t), \quad (2)$$

where, $n_I(t)$ denotes the AWGN component. After sampling of the baseband signal, the k^{th} noisy chip signal received by r^{th} receive antenna can be rewritten as:

$$y_{i,r}^k = s_I\, c_{i,k}\, h_r + n_{i,r}^k, \quad r = 1, 2, \ldots, N_R \quad (3)$$

where i denotes the code index. For clarity of presentation, the index I is dropped from y and n. First, the spreading code index is detected from the sampled signal by using a correlator. For this reason, the vector $\mathbf{y}_{i,r} = [y_{i,r}^1, y_{i,r}^2, \ldots, y_{i,r}^K]^T$ is multiplied by the corresponding $\mathbf{c}_i$ spreading code in each branch and summed over the period $T_s = KT_c$. Thus, the despreaded output of the correlator can be expressed as

$$\begin{aligned} y_{i,r} &= \sum_{k=1}^{K} c_{i,k}\, y_{i,r}^{k} = \sum_{k=1}^{K} c_{i,k} \left(s_I\, c_{i,k}\, h_r + n_{i,r}^{k} \right) \\ &= E_s\, s_I\, h_r + \tilde{n}_r, \quad r = 1, 2, \ldots, N_T,\ i = 1, 2 \end{aligned} \quad (4)$$

where, E_s denotes the average energy transmitted per symbol and is expressed as $E_s = \sum_{k=1}^{K} c_{i,k}^2$. $\tilde{n}_r = \sum_{k=1}^{K} c_{i,k} n_{i,r}$ is the AWGN term multiplied by the Walsh Hadamard code. When despreading operation is performed, the resulting vector set can be expressed as:

$$\mathcal{Y} = \left\{ \mathbf{y}_1, \mathbf{y}_2 \right\}. \quad (5)$$

As shown in Fig. 1 (b), I and Q branches are used to obtain the spreading code index, the active antenna index and the transmitted symbol sequence, i.e., $\left(\hat{i}_I, \hat{i}_Q, \hat{\ell}, \hat{s}_I, \hat{s}_Q\right)$. In order to reduce the complexity of the CIM-SM system, firstly the code indices $\left(\hat{i}_I, \hat{i}_Q\right)$ are detected, then $\hat{\ell}$ and $\left(\hat{s}_I, \hat{s}_Q\right)$ will be estimated. Therefore, the obtained $\left(\hat{i}_I, \hat{i}_Q\right)$ indices are reported back to the despreading vector set, and then the $\mathbf{y}_{\hat{i}}$ despreading data associated with the $\left(\hat{i}_I, \hat{i}_Q\right)$ is only applied to the input of the maximum likelihood estimator. By this way, the complexity of the system is greatly reduced.

To estimate the code index, first of all, the norm square of the $\mathcal{Y}$ is calculated, then, the index of the maximum element of the set $||\mathcal{Y}||^2$ is determined. Since the Walsh codes are orthogonal to each other, the largest valued element of the normed vector equals the despreaded element over the same index. That is, $\sum_{k=1}^{K} c_{i,k}\, c_{j,k} = \begin{cases} 1, & \text{if } i = j \\ 0, & \text{if } i \neq j \end{cases}$. Thus, code index is detected using the index of the maximum element of the normed vector set as follows:

$$\hat{i}_I = \arg\max \left\{ \left|\left| \mathcal{Y} \right|\right|^2 \right\} = \arg\max \left\{ \left|\left| \mathbf{y}_1 \right|\right|^2, \left|\left| \mathbf{y}_2 \right|\right|^2 \right\}. (6)$$

Finally, the ML estimator detects a estimation of $\hat{\ell}$ and $\hat{s}_I$ by testing all combinations of $\left(\ell, s_I\right)$ over $\mathbf{y}_{\hat{i}}$. Thus, the ML estimation of the $\left(\ell, s_I\right)$ parameters for the in-phase component of the proposed system can be expressed as:

$$\left(\hat{\ell}, \hat{s}_I\right) = \underset{\substack{\ell \in \{1, 2, \ldots, N_T\} \\ s_I \in \{+1, -1\}}}{\arg\min} \left\{ \left|\left| \mathbf{y}_{\hat{i}_I} - E_s\, s_I \mathbf{h}_\ell \right|\right|^2 \right\}, \quad (7)$$

where, the vector $\mathbf{h}_\ell$ has $(N_R \times 1)$ dimensions and refers to the ℓ^{th} column of the $\mathbf{H}$ channel matrix. The rows of the matrix $\mathbf{H}$ carry the information of the receiving antenna index whereas the columns of the matrix $\mathbf{H}$ carry the information of the transmitting antenna index. The channel matrix can be expressed as $\mathbf{H} = \left[\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_{N_T}\right]$.

In addition, for the Q branch, the CIM-SM system receiver uses the $\hat{\ell}$ obtained from the I branch at the same time to reduce the complexity of proposed system. Thus, the ML estimation of the Q component can be simplified as follows:

$$\hat{s}_Q = \underset{s_Q \in \{+1, -1\}}{\arg\min} \left\{ \left|\left| \mathbf{y}_{\hat{i}_Q} - E_s\, s_Q \mathbf{h}_{\hat{\ell}} \right|\right|^2 \right\}. \quad (8)$$

Finally, with the bit-back matching technique using the obtained $\left(\hat{i}_I, \hat{i}_Q, \hat{\ell}, \hat{s}_I, \hat{s}_Q\right)$ values, the transmitted bit sequence $\hat{\mathbf{b}}$ is obtained at the receiver.

III. Throughput, Data Rate and Energy Efficiency Analyses of the CIM-SM System

In this section, the proposed CIM-SM scheme will be compared to SM, CIM-SS and conventional DS-SS methods in terms of throughput, data rate and energy efficiency.

A. Throughput Analysis and Data Rate

In general, the throughput of a system is defined as the number of correct bits that a terminal has obtained per unit time. Therefore, the throughput of a system can be defined as follows [14]:

$$R_t = \frac{(1 - P_\varepsilon)}{T_s} \Big(\log_2(2M) + \log_2 N_T + \log_2(2L) \Big), \quad (9)$$

where, while P_ε indicates the total error probability of the system, $(1 - P_\varepsilon)$ indicates the correct bits received during time T_s.

CIM-SM, SM, CIM-SS and DS-SS systems have the same $T_s = KT_c$ symbol duration. Therefore, the throughput comparisons can be done fairly. During the same symbol time and while $N_T = 4, M = 2$ ve $L = 2$, the SM technique transmits 3 bits, the CIM-SS technique transmits 4 bits, the SS-QAM signal transmits 1 bit, on the other hand, the CIM-SM system transmits 6 bits. The CIM-SS system carries 2 bits in I component and another 2 bits in Q component. However, the proposed CIM-SM scheme carries 2 bits in the I component, another 2 bits in the Q component in addition to the 2 bits in the index of the active transmission antenna. Thus, the amount of bits transmitted in the CIM-SM system through the T_s symbol period is $\chi = \log_2(2M) + \log_2 N_T + \log_2(2L)$.

B. Energy Efficiency

In the CIM-SM system, the $\log_2(2M)$ bits are transmitted through the modulated symbol directly whereas the $\log_2(2L)$ bits are carried in the index of the Walsh Hadamard code and the $\log_2(N_T)$ bits are conveyed in the index of active antenna. Therefore, $\chi' = \log_2(2L) + \log_2(N_T)$ bits transmission energy is conserved because the transmission energy is not spent by the system but is carried in the indices. For example, since SS-QAM carries 2 bits while $M = 4$, the CIM-SS system maintains $\%50$ of the total used energy compared to the DS-SS system. Also, while $N_T = 4, M = 2$ and $L = 2$, the CIM-SM system maintains $\%33.3$ of the total energy compared to the CIM-SS system.

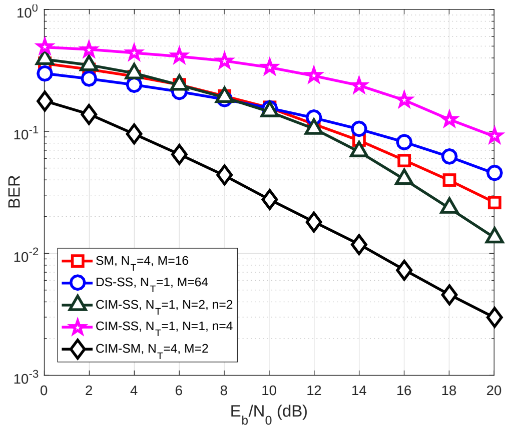

Fig. 2. Performance comparison of CIM-SM, SM, CIM-SS and DS-SS systems for $N_R = 1$ and $m = 1$.

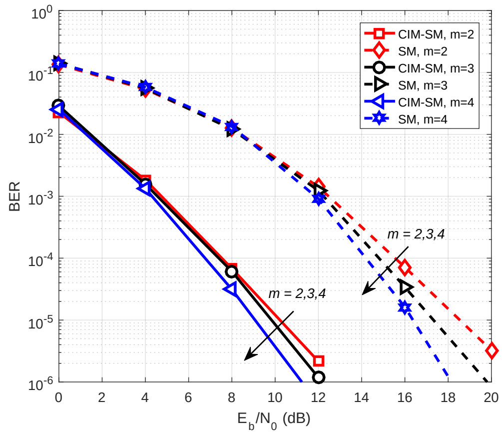

Fig. 3. Performance comparison of CIM-SM and SMsystems for $N_T = N_R = 4$ and $m = 2, 3, 4$.

IV. Simulation Results

In this section, computer simulation results are presented for BPSK modulation over Nakagami-m fading channels. In the receiver, the ML detection technique is used to estimate the transmitted symbols and indices. Average BER performances were obtained by the Monte Carlo simulation method. SNR is defined as $\mathrm{SNR(dB)} = 10\log_{10}(E_b/N_0)$, where $E_b = \frac{1}{\chi}\sum_{k=1}^{K}\left(\frac{c_{i,k}}{\sqrt{K}}\right)^2$ is the average bit energy and χ is the number of bits for one symbol. In addition, the spreading code is normalized with $\sqrt{K}$ for the transmission power to remain constant and $K = 64$ is considered for simulation. SM, CIM-SS [12] and DS-SS methods were used as reference for the simulation results.

BER performance curves of CIM-SM, SM, CIM-SS and DS-SS methods for $\chi = 6$ bits are presented when $N_R = 1$ and $m = 1$ in Fig. 2. The CIM-SM technique transmits 6 bits by 2 bits with antenna index, 2 bits with spreading code index, 2 bits with BPSK symbol through I and Q components. The SM technique carries 6 bits: 2 bit antenna index and 4 bits with a 16-PSK modulated symbol. In the CIM-SS method, two conditions have been considered. In the first scenario ($N = 2, n = 2$), 4 bits are transmitted in spreading code indices and 2 bits are transmitted with 4-PSK modulation; in the second scenario ($N = 1, n = 4$), 2 bits are transmitted in spreading code indices and 4 bits are transmitted with 16-PSK modulation. In the DS-SS method, all 6 bits are carried on a 64-PSK modulated symbol.

Fig. 2 shows the average BER performance comparison curves of the CIM-SM and SM techniques curves for $\chi = 6$ bits and different values of fading parameter, i.e., $m = 2, 3, 4$ when $N_T = N_R = 4$. Considering Figs. 2 and 3, it is observed that the proposed method has a considerable SNR gain compared to other methods.

V. Conclusion

In this paper, a new MIMO transmission system with high energy-efficiency, high data rate and better error performance, called CIM-SM has been proposed by combining SM and CIM techniques ,which are promising techniques for next generation communication systems. It has been shown via computer simulation results that the proposed system provides better error performance than DS-SS, SM and CIM-SS systems while consuming less transmission energy. Performance of the proposed CIM-SM is evaluated over Nakagami-m fading channels.

References

[1] J. N. Laneman, D. N. C. Tse and G. W. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *IEEE Trans.Inf. Theory*, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[2] I. Emre Telatar, “Capacity of multi-antenna Gaussian channels,” *European Trans. Telecommun.*, vol. 10, no. 6, pp. 585-595., November 1999.

[3] R. Y. Mesleh, H. Haas, C. W. Ahn and S. Yun, “Spatial modulation - A new low complexity spectral efficiency enhancing technique,” *2006 First International Conference on Communications and Networking*, pp. 1-5, Beijing, China, 2006.

[4] R. Y. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn and S. Yun, “Spatial modulation,” *IEEE Trans Veh. Technol.*, vol. 57, no. 4, pp. 2228-2241, July 2008.

[5] J. Jeganathan, A. Ghrayeb, L. Szczecinski and A. Ceron, “Space shift keying modulation for MIMO channels,” *Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3692-3703, July 2009.

[6] S. Sugiura, S. Chen and L. Hanzo, “Coherent and differential space-time shift keying: A dispersion matrix approach,” *IEEE Transactions on Communications*, vol. 58, no. 11, pp. 3219-3230, Nov. 2010.

[7] M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura and L. Hanzo, “Spatial modulation for generalized MIMO: Challenges, opportunities, and implementation,” *Proc. IEEE*, vol. 102, no. 1, pp. 56-103, Jan. 2014.

[8] E. Aydin and H. Ilhan, “A Novel SM-Based MIMO System With Index Modulation, *IEEE Commun. Lett.*, vol. 20, no. 2, pp. 244-247, Dec. 2016.

[9] E. Basar, M. Wen, R. Mesleh, M. Di Renzo, Y. Xiao, and H. Haas, “Index modulation techniques for next-generation wireless networks, *IEEE Access*, vol. 5, pp. 1669316746, Sep. 2017.

[10] E. Basar, “Index modulation techniques for 5G wireless networks, *IEEE Commun. Mag.*, vol. 54, no. 7, pp. 168175, Jul. 2016.

[11] G. Kaddoum, M. F. A. Ahmed and Y. Nijsure, “Code index modulation: A high data rate and energy efficient communication system,” *IEEE Commun. Lett.*, vol. 19, no. 2, pp. 175-178, Feb. 2015.

[12] G. Kaddoum, Y. Nijsure and H. Tran, “Generalized code index modulation technique for high-data-rate communication systems,” *IEEE Trans Veh. Technol.*, vol. 65, no. 9, pp. 7000-7009, Sept. 2016.

[13] M. Yacoub, G. Fraidenraich, and J. Santos Filho, “Nakagami-m phase-envelope joint distribution, *Electron. Lett.*, vol. 41, no. 5, pp. 259-261, Mar. 2005.

[14] D. Tse and P. Viswanath, “Fundamentals of wireless communication,” *Cambridge university press*, 2005.