A Novel Multi Stream Superposition Multi Rate Coded Modulation (MS-SMRCM)

Ahmed E. Zein Eldin, Esam A.A. Hagras, Hala Mansour Abdel-Kader

Abstract—This paper is concerned with the design of a wireless data transmission which provides Un-equal Error Protection (UEP). A Multi Stream Superposition Multi Rate Coded Modulation (MS-SMRCM) system has been introduced. In the proposed MS-SMRCM, each user data bit stream can be divided into two bit streams. The first bit stream represents the region of high priority, while the second represents the region of low priority. These two bit streams are encoded, spread and interleaved separately. The resultant chip interleaved sequences are modulated and superimposed together to achieve UEP at the receiver side. A simple Chip-By-Chip (CBC) iterative Multi User Detection (MUD) strategy is used. In AWGN channel, the proposed MS-SMRCM in case of eight users input, the performance of single user is better than eight users by 2.2 dB at $\mathrm{BER} = 10^{-4}$. The performance is investigated over AWGN and Rayleigf fading channels in the presence of High Power Amplifier (HPA).

Index Terms— CBC Iterative MUD, HPA, MS-SMRCM, UEP, AWGN, Rayleigh Fading Channel.

◆

1 INTRODUCTION

ANY communication channel is characterized by a so-called channel capacity. Operating near capacity implies power efficiency and simultaneously bandwidth efficiency. Obviously, there is a trade-off between power and bandwidth efficiency. Therefore, achieving power and bandwidth efficiency simultaneously is a challenging task [1], as well as, in future Broadband Wireless Access systems; the main challenge is to transmit an error sensitive application data with a higher bit rate efficiently over error prone wireless channels.

Error performance of communication channels is usually poor without error control due to channel imperfections and the inherent additive noise. Using error control coding will cause bandwidth expansion, which is not desirable, where; the limitation and higher cost of spectrum occupation are among the most important challenges in wireless communication systems. In order to overcome this drawback, such coding and modulation should be integrated to match the channel situation, Coded Modulation (CM) schemes are used to achieve both power and bandwidth efficient communication by mapping information sequences onto an expanded set of channel signals with the help of error correcting codes [1-3].

In such Equal Error Protection (EEP) systems, a fixed code is constructed for the worst case of average channel/source conditions, this result in the waste of resource for the protection of the least sensitive bits, since they are assigned the same protection level as the most sensitive bits.

A classic technique that used for maximizing error control performance while limiting the required redundancy is to apply Unequal Error Protection (UEP) [4]. Codes that are designed to provide different levels of data protection are known as UEP codes, the term UEP implies that the resources available to provide protection to the various bit streams are not equally distributed, but instead, each bit stream may be protected so that it withstands a different level of channel noise.

Simply, different levels of protection are provided for different parts of the data according to their degrees of importance, UEP receiver matches the protection level according to the system requirement, and thus can save the system resources. For example, in packet communications, the header must be protected more than the payload, because in the worst case, if the destination address is lost, the entire packet will be lost. A multilevel encoder in [5] is considered an UEP system, the information sequence is divided into parallel sequences in decreasing order of importance, and the encoding process consists of the different rate encoders to create the desired UEP characteristics. Specific examples include practically all digital speech and image transmission systems.

Superposition Coded Modulation (SCM) implies transmission of different symbol streams on the same modulation interval, it is a powerful modulation technique that is being considered in many emerging broadband communication systems. SCM has been studied as an alternative scheme for high throughput transmission [6-7]; it has several advantages over conventional CM schemes. One interesting feature of SCM is that, the transmitted signal exhibits an approximately Gaussian distribution since it is a linear superposition of several independent code words (each referred to as a layer). Superposition coding is conceptually simpler and has lower encoding complexity. Another feature of superposition coding is that it can be treated as a perfectly cooperating multiple access system by viewing one layer as one user. Hence, the low cost CBC iterative decoding techniques developed in [8] can be employed.

The most common types of power amplifiers used in communication systems are Travelling Wave Tubes Amplifiers (TWTA) and Solid State Power Amplifiers (SSPA). Obviously HPAs are a part of almost all communication links and due to

---

- *Ahmed E. Zein Eldin is currently pursuing PhD degree program in Electronics and Communications Department, Faculty of Engineering at Shoubra, Benha University. E-mail: a3hzein@hotmail.com*
- *Esam A. A. Hagras, Electronics and Communications Departmen, Technical Research Center, E-mail: esamhagras_2006@yahoo.com*
- *Hala Mansour Abd-Elkader, Prof. Electronics Electronics and Communications Department, Faculty of Engineering at Shoubra, Benha University. E-mail: hala.abdelkader@gmail.com*

the non-linear nature of the electronic components that they are made of, their conversion characteristics are non-linear.

In general, two major classes defining the time behavior of HPA; HPA models with memory and memory-less HPA models. The word memory-less implies not only an instantaneous relationship between input and output, but also implies that the device does not exhibit frequency selective behavior over the bandwidth of operation. In addition to amplify the signal, the non-linear amplifier generates non-linear distortion in both amplitude and phase which causes the loss of system reliability resulting in a higher BER [9,10].

In this paper, a multi user (multi stream) MS-SMRCM system is introduced, the coding scheme is designed in such a way that, for each user, the most important information bits result in a better error rate than other information bits using different rate convolutional encoders. All of the layers employ a common spreading sequence, the interleaving index sequences is considered as a code to distinguish layers. Binary Phase Shift Keying (BPSK) signaling is considered over a time-invariant single path channel with equal power allocation in the presence of non-linear HPA Rapp model [10], considering both AWGN and Rayleigh fading channels. CBC iterative MUD strategy is applied.

This paper is organized as follows, a transmitter structure for the proposed MS-SMRCM in the presence of non-linear HPA is presented in section 2, section 3, introduces a CBC iterative MUD, the proposed MS-SMRCM system performance evaluation is investigated in section 4, the conclusions are presented in Section 5.

2 MS-SMRCM TRANSMITTER STRUCTURE

SCM has been investigated by many authors [1-3], [11,12]. SCM consists of transmitting both bit streams in all available modulation intervals using superposition of channel codes in the modulation space. The transmitter of the proposed system is depicted in Fig. 1.

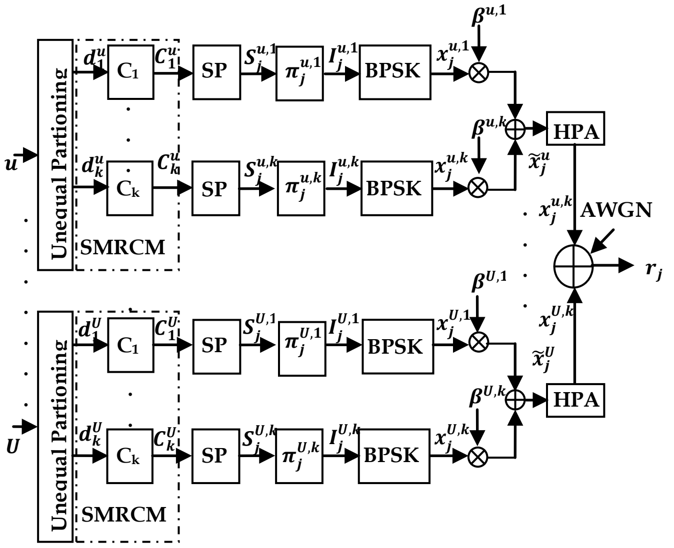

Fig. 1. Transmitter structures of the proposed MS-MRCM

BPSK signaling is considered over a time invariant single path channel. A multi user $u, \{u = 1,2, \dots, U\}$, each user data input, $d^u \in \{+1, -1\}$, is un-equally partioned based on data priority into k sub-sequences $\{d_k^u = d_1^u, \dots, d_k^u, k = 1,2, \dots, K\}$, the k^{th} sub-sequence is encoded using different rate convolutional encoders (used as component codes) at the k^{th} level [13].

Convolutional encoders transform a whole sequence of information bits into a sequence of encoded bits by convolving the information bits with a set of generator coefficients, resulting in coded sub-sequences [15], $\{C_1^u, \dots, C_k^u\}$, C_k^u, are spread using a length S spreading sequences $S^k \in \{+1, -1\}$, the same composite spreading sequence is applied to all layers. The encoded chip sequence obtaining after spreading is written as, $\{S_j^{u,k}, j = 1,2, \dots, J\}$, where, $J = N \times S$ is the chip length.

In contrast to Code Division Multiple Access (CDMA), specific spreading codes are used for layers separation. Interleaving is essential for system performance, as it reduces the mutual dependence among superimposed chips. A specific distinct chip layered random interleavers are employed as layer specific interleavers for layer separation, $\{\pi_j^{u,k}, k = 1,2, \dots, K\}$, to produce interleaved chip layered data sequences, $\{I_j^{u,k}, k = 1,2, \dots, K\}$, the interleaved chips layered data sequences are mapped onto the modulated symbols, $\{x_j^{u,1}, \dots, x_j^{u,k}\}$, which are elements of a BPSK constellation.

Afterward, the modulated symbols are weighted, this weighting corresponds to power and phase allocation and is crucial for the performance of SM, to simplify discussion, the weighting factor $\{\beta^{u,k}\}$ is assumed to be real constant weighting factor, i.e., the magnitudes of chips are all identical and set to 1, the weighted symbols are superimposed together to produce the SMRCM signal sequence $\tilde{x}_j^u$.

$$\tilde{x}_j^u = \sum_{u=1,k=1}^{U,K} \beta^{u,k} x_j^{u,k} \tag{1}$$

$\tilde{x}_j^u$, is fed to the HPA, non-linearly amplified, as given in [9], Rapp model is used for modeling memory-less SSPA behavior models for the proposed SMRCM system, the output of HPA, x_j^u, is given by:

$$\tilde{x}_j^u(t) = A(t)\, cos\, (\omega_c\, t + \varphi(t)) \tag{2}$$

$$x_j^u(t) = F[A(t)]\, cos\, [\omega_c\, t + \varphi(t)\, \Psi(A(t))] \tag{3}$$

Where, $F[A(t)], \Psi[A(t)]$ are the gain distortion function that represents the Amplitude to Amplitude transfer characteristics (AM/AM), and the phase distortion function that represents Amplitude to Phase transfer characteristics (AM/PM), of the SSPA non-linearity Rapp model respectively, which are given by:

$$\begin{cases} AM/AM : F\left[\tilde{x}_j^u\right] = x_j^u = \dfrac{\tilde{x}_j^u}{\left(\left(1 + \tilde{x}_j^u / v_{sat}\right)^{2p}\right)^{1/2p}} \\ \\ AM/PM :\ \Psi(A(t)) = 0 \end{cases} \tag{4}$$

$\tilde{x}_j^u, x_j^u$ are the input and output signals voltage, v_{sat} is the amplifier input saturation voltage, p, is called "knee factor", that controls the smoothness of the transition from the linear region to the saturation region (Limiting Region) of characteristic curve. As the value of p, increases, the SSPA model approaches the limiter model [9, 10].

3 MS-SMRCM CBC ITERATIVE RECEIVER STRUCTURE

Generally, the spread information signal looks like random interference to all the other users, increasing the number of users increases the amount of interference, resulting in a degraded system performance, which can be partially suppressed at the receiver while decoding each user signal [14].

The decoding/detection principle discussed below is derived based on the similarity between the superposition coding scheme and the Interleave Division Multiple Access scheme (IDMA) [15]. An iterative CBC-MUD algorithm is exploited to suppress the channel fading and multiple access interference.

The receiver is assumed to have perfect knowledge of the channel state information. The received signal is processed iteratively, since there are large numbers of interference terms, the Gaussian approximation is still valid even after last iteration.

The received signal at time instant j can be written as:

$$r_j = \sum_{u=1}^{U} x_j^u + n_j, j = 1,2,\dots,J \tag{5}$$

Where, x_j denoted the transmitted data symbols for the user at time instant j, and n_j zero mean AWGN with ance $\sigma^2 = N_0/2$.

The CBC iterative receiver, in Fig. 2, consists of an Elementary Signal Estimator (ESE) and a bank of single user A Posteriori Probability (APP) detectors for the De-Spreading operation (DES) working in turbo type manner [16].

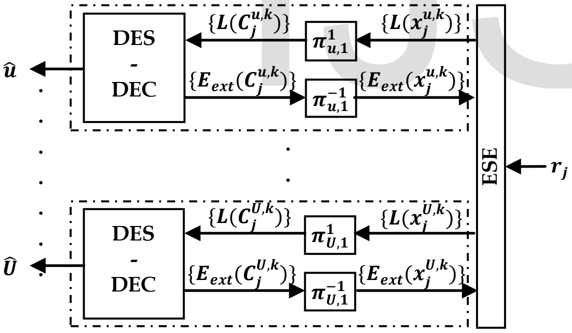

Fig. 2. Receiver structures of the iterative decoding/detection for the proposed MS-SMRCM

The received signal at time instant j can be re-written as:

$$r_j = F\left[\sum_{\substack{k=1\\u=1}}^{K,U} \beta^{u,k}\, x_j^{k,u}\right] + \xi_j^{k,u} \tag{6}$$

Where, $\xi_j^{u,k} = r_j - \beta^{u,k} x_j^{u,k}$, represents a distortion term with respect to $x_j^{u,k}$, $x_j^{u,k}$ is treated as a random variable with mean $E(x_j^{u,k})$ and variance $Var(x_j^{u,k})$. The initial values for both mean $E(x_j^{u,k})$ and variance $Var(x_j^{u,k})$ are "0" and "1" respectively. Then form "(6)," we can write:

$$E(r_j) = \sum_{u=1,k=1}^{U,K} \beta^{u,k}\, E(x_j^{u,k}) \tag{7a}$$

$$Var(r_j) = \sum_{u=1,k=1}^{U,K} |\beta^{u,k}|\, Var(x_j^{u,k}) + \sigma^2 \tag{7b}$$

Using the central limit theorem, $\xi_j^{u,k}$ in "(6)," can be approximated by a Gaussian random variable with:

$$E(\xi_j^{u,k}) = E(r_j) - \beta^{u,k} E(x_j^{u,k}) \tag{8a}$$

$$Var(\xi_j^{u,k}) = Var(r_j) - |\beta^{u,k}|^2 Var(x_j^{u,k}) \tag{8b}$$

The ESE outputs are the Logarithm Likelihood Ratio (LLRs) about $\{x_j^k\}$ computed based on "(7-8)," as:

$$\begin{aligned} L(x_j^{u,k}) &= log\left(\frac{Pr(x_j^{u,k}) = +1|r_j}{Pr(x_j^{u,k}) = -1|r_j}\right) \\ &= log\left(\frac{exp\left(-\dfrac{(r_j - E(\xi_j^{u,k}) - \beta^{u,k})^2}{2Var(\xi_j^{k})}\right)}{exp\left(-\dfrac{(r_j - E(\xi_j^{u,k}) + \beta^{u,k})^2}{2Var(\xi_j^{u,k})}\right)}\right) \\ &= \frac{2\beta^{u,k}(r_j - E(\xi_j^{u,k}))}{Var(\xi_j^{u,k})} \end{aligned} \tag{9}$$

For the layer k, the corresponding ESE outputs $L(x_j^{u,k}, j = 1,2,\dots\dots,J)$, are de-interleaved to form $L(C_j^{u,k}, j = 1,2,\dots\dots,J)$, and delivered to the DSE for layer k.

For simplicity, we focus on the chip related to d_1^u, the first bit of layer k. It is assumed that, $L(C_j^{u,k})$ are uncorrelated due to interleaving [15]. Let the interleaving for layer k be expressed as $\pi_j^{u,k} = j^{`}$, i.e., $C_j^{u,k} = x_{j^{`}}^{u,k}$. Then based on "(9)," the APP detector outputs log-APP ratios, LLR for d_k^u can be computed using $L(C_j^{u,k})$ as:

$$\begin{aligned} L(d_k^u) &= log\left(\frac{Pr(d_k^u) = +1|r}{Pr(d_k^u) = -1|r}\right) \\ &= log\left(\frac{\prod_{j=1}^{S} Pr(C_j^{u,k} = S_j^{u,k}|r_{j^{`}})}{\prod_{j=1}^{S} Pr(C_j^{u,k} = -S_j^{u,k}|r_{j^{`}})}\right) \\ &= \sum_{j=1}^{S} log\frac{Pr(C_j^{u,k} = S_j^{u,k}|r_{j^{`}})}{Pr(C_j^{u,k} = -S_j^{u,k}|r_{j^{`}})} \end{aligned} \tag{10}$$

$$= \sum_{j}^{S} S_j^{u,k}\, L(C_j^{u,k}) \tag{11}$$

Convolutional decoders can easily process soft-decision input (i.e., information on the reliability of the demodulator output) and compute soft-decision output (i.e., information on the reliability of the estimated information bits). A soft value implies a real number such as a probability is used, instead of a binary value which is defined by a hard value [14].

The use of soft-in/soft-out decoding stages [17]:

1. The use of soft a-prior information.
2. Interleaving between chips to remove correlation between them.
3. Iterations to improve previous data estimates.

The Extrinsic LLRs $\{Ext(C_j^{u,k})\}$ form the output of the DES and are fed back to the ESE after interleaving. In the next iteration, $\{Ext(x_j^{u,k})\}$ are used to update $\{E(x_j^{u,k})\}$ and $\{Var(x_j^{u,k})\}$ as [12].

$$E\left(x_j^{u,k}\right) = \left(\frac{exp\left(Ext\left(x_j^{u,k}\right)\right) - 1)\right)}{exp\left(Ext\left(x_j^{u,k}\right)\right) + 1)\right)}\right)$$
$$= tanh\left(\frac{Ext\left(x_j^{u,k}\right)}{2}\right) \qquad (12)$$

$$Var\left(x_j^{u,k}\right) = 1 - E\left(x_j^{u,k}\right)^2 \qquad (13)$$

This iterative process is repeated a preset number of times. The iterative process continues in this manner until further iterations yield little or no significant improvement. In the final iteration the DES produces hard decisions on information bits to re-construct the each user data transmitted.

4 PERFORMANCE EVALUATION

In this section, the simulated results demonstrate the performance of the proposed MS-SMRCM system. Each user data length is assumed to be $(N = 384)$ bit length partioned into two bit streams or two layers $(L = 2)$, based on data priority, the encoding process is applied. The same spreading code is used for all layers, it contains $(S = 16\ or\ 32)$ balanced sequences. The number of iterations in the CBC iterative receiver was set to $(Iter = 3)$.

For the HPA linearity, an ideal amplifier would be a totally linear response device, but real amplifiers are only linear response within certain practical limits, so, the HPA non-linearity behavior can be investigated at different smoothness factors. Fig. 3 shows the relationship between input voltage and output voltage linear response and non-linear response at different HPA smoothness factors $(p = 1,2,3,100)$.

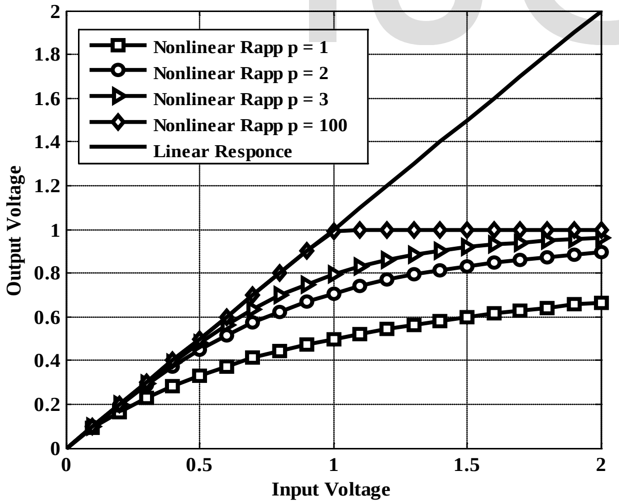

Fig. 3. Relationship between Input voltage and output voltage linear response and non-linear response at $(p = 1,2,3,100)$.

Fig. 4 shows the MS-SMRCM performance for 1,2,4,8 users using spreading length 16, where the single user performance is better than two, four and eight users by 0.1 dB, 0.2 dB and 2.3 dB respectively at BER= 10^{-4} due to the effect of multi user input with different code rates.

Fig. 5 shows the four users performance evaluation in four cases over AWGN channel, the first case is MS-USM, where, each user data length is equally partioned into two bit streams, each one is 192 bit length and no convolutional encoders are used, it can be written in the form MS-USM $(192 - 192)$. The second case is MS-UEP-SCM, where each user data length is un-equally partioned into two layers, the high priority data stream is 128 bit length, convolutionally coded with rate, $(R = 1/2)$, while the low priority data stream is 256 bit length and has no coding, it can be written in the form MS-UEP-SCM$(128, 1/2 - 256)$.

The third case is MS-EEP-SCM, where each user data length is equally partioned into two bit streams, each one has the same priority, using equal error rates convolutional encoders, it can be written in the form, MS-EEP-SCM$(192,1/2 - 192,1/2)$. Finally, the fourth case, Multi Rate input and Multi Rate Coding, where each user data input is un-equally partioned into two layers, high priority data stream is 128 bit length, convolutionally encoded with rate, $(R = 1/3)$, while the low priority is 256 bit length, encoded with rate, $(R = 2/3)$, the resultant symbols can be written in the form MS-SMRCM$(128, 1/3 - 256, 2/3)$, the difference between MS-USM and MS-UEP-SCM is 0.2 dB, while the difference between MS-SMRCM and MS-EEP-SCM is 0.2 dB.

Fig. 6. shows the effect of iteration number in detection process, for iteration=1, at $\mathrm{E_b/N_0} = 8$ dB, BER performance of four users is degraded to 2.4×10^{-3}, while, for iteration=2,3 the performance is improved to be 5.8dB and 5.9dB respectively. Fig. 7 shows the Rayleigh fading channel effect on MS-SMRCM performance at velocity 90 km/hr, the difference between a single user and two users performance is 0.9 dB and while the difference between a single user and four users is 2.8 dB at $\mathrm{E_b/N_0} = 14$ dB. The simulation results for AWGN channel in the presence of non linear HPA are shown in Fig. 8, where the difference between a single user and two users performance is 0.7 dB, while the difference between a single user and four users is 2.6 dB at $\mathrm{E_b/N_0} = 14$ dB. In Fig. 9, the effect of HPA non-linearity behavior over the Rayleigh fading channel is clear, the single user performance is better than two users by 4 dB, while at $\mathrm{E_b/N_0} = 14$ dB, the BER performance of four users is degraded to 3.2×10^{-4}.

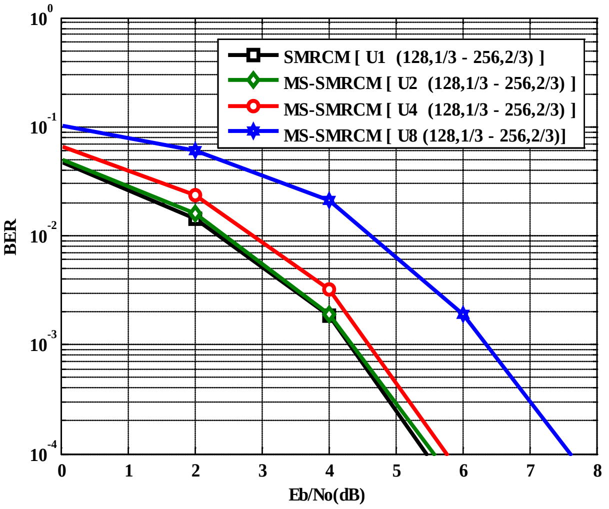

Fig. 4. BER performance of MS-SMRCM using two different rates $(U = 1,2,4,\ N = 384,\ L = 2,\ S = 16,\ Iter = 3)$

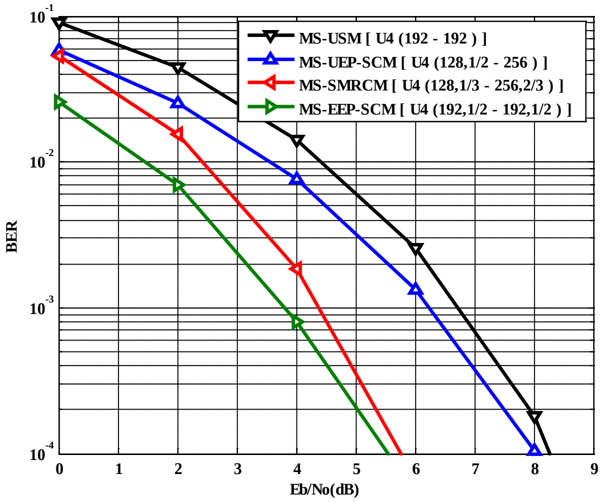

Fig. 5. BER performance of MS-SMRCM using two different rates $(U = 4,\quad N = 384,\quad L = 2,\quad S = 32,\quad Iter = 3)$

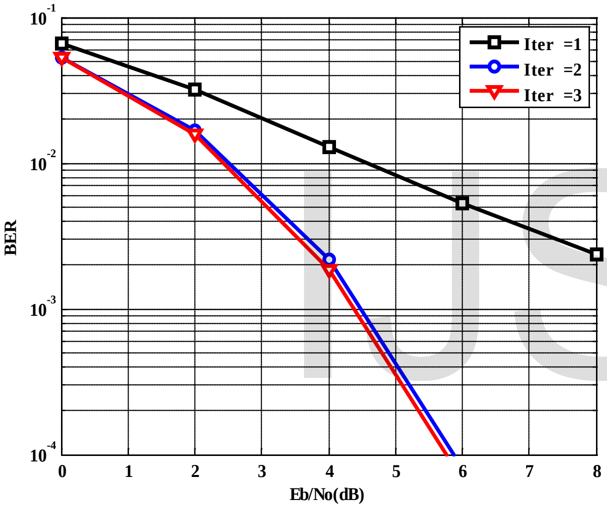

Fig. 6. BER performance of MS-SMRCM using two different rates $(U = 4,\quad N = 384,\quad L = 2,\quad S = 32,\quad Iter = 1,2,3)$

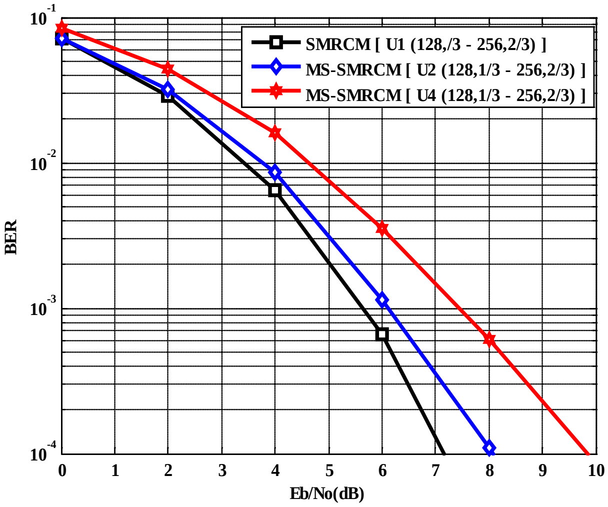

Fig. 7. BER performance of MS-SMRCM using two different rates $(U = 1,2,4,\ N = 384,\ L = 2,\ S = 32,\ Speed = 90\ km/hr,\ Iter = 3)$

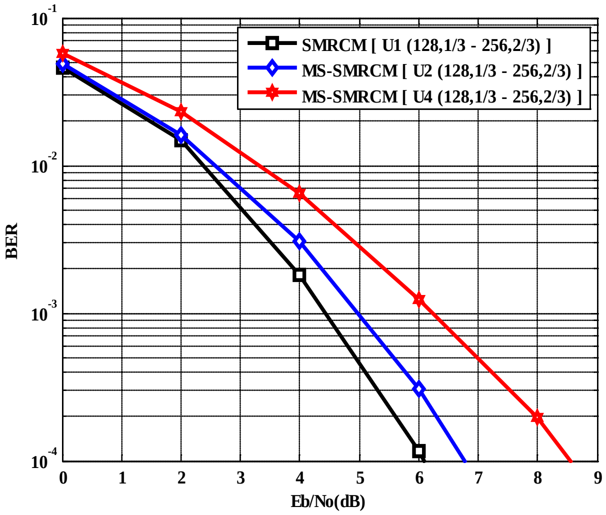

Fig. 8. BER performance of MS-SMRCM using two different rates and HPA Rapp model $(U = 1,2,4,\ N = 384,\ L = 2,\ S = 32,\ p = 3,\ Iter = 3)$

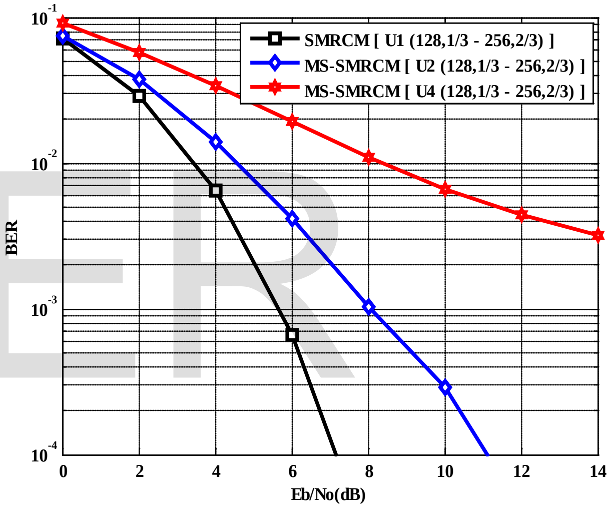

Fig. 9. BER performance of MS-SMRCM using two different rates and HPA Rapp model
$(U = 1,2,4,\ N = 384,\ L = 2,\ S = 32,\ p = 3,\ Speed = 90\ km/hr,\ Iter = 3)$

5 CONCLUSIONS

In this paper, a novel MS-SMRCM communication system has been investigated. In the proposed MS-SMRCM, the user data stream is un-equally partioned based on data priority. Simulation results for the proposed MS-SMRCM are compared with the three systems USM, UEP-SCM and EEP-SCM over AWGN channel. Also, the performances of all users have been studied in the presence of HPA Rapp model and Rayleigh fading channels.

Four users comparison in AWGN channel, the performance of the proposed MS-SMRCM is better than MS-USM by about 2.4 dB. Also, the proposed MS-SMRCM is better than MS-UEP-SCM by 0.2 dB. The performance of the proposed MS-SMRCM is degraded by about 0.2 dB compared with MS-EEP-SCM, All comparisons have been studied at BER $= 10^{-4}$. In HPA, the difference between single user and two and four users is 0.8 dB and 2.6 dB at BER $= 10^{-4}$ respectively. The

Rayleigh fading channel effect at velocity 90 km/hr in the presence of HPA, the difference between single user and two users is 4 dB while, the four users performance is 3.2×10^{-4} at $E_b/N_0 = 14$ dB.

REFERENCES

[1] Hoeher and Peter Adam "Superposition Coded Modulation Myths and Facts," Communications Magazine, IEEE, Vol. 49, pp. 110-116, Dec. 2011.

[2] Karabulut and Güneş Z. "Rate Design Rule for Superposition Coded Modulations," Canadian Conference on Electrical and Computer Engineering, Vol. 1, pp. 365-368, May 2004.

[3] Wang and Xin "Design of Superposition Coded Modulation for Unequal Error Protection," IEEE International Conference on Communications, Vol. 2, pp. 412-416, Jun 2001.

[4] Atungsiri, S. A. , Tateesh, S. T. , Kondoz and Ahmet M. "Multirate Coding for Mobile Communication Link Adaptation," IEE Proceedings Communications, Vol. 144(3), pp. 211-216, 1997.

[5] Imai H, Hirakawa S. "A New Multilevel Coding Method using Error Correcting Codes," IEEE Transactions on Information Theory, Vol. 23(3), pp. 371-377, 1977.

[6] Yang G, Shen D, Victor OK "UEP for Video Transmission in Space-Time Coded OFDM System," IEEE INFOCOM, Vol. 2, pp.1200-1210, 2004.

[7] Tong, Jun , Ping, Li , Ma and Xiao, "Superposition Coding with Peak-Power Limitation," IEEE International Conference on Communications, 2006. ICC '06. Vol. 4, pp. 1718-1723, June 2006.

[8] Tianbin Wo, Meelis Noemm, Dapeng Haoand Peter Adam Hoeher "Iterative Processing for Superposition Mapping," Journal of Electrical and Computer Engineering, Vol. (2010), 13 pages, 2010.

[9] Pavol Pavelka, Jozef Krajňák, Pavol Galajda and Dušan Kocur "Analysis of Non Linear Distortions in MC-CDMA Systems," Acta ElectrotechnicaetInformatica Vol. 7(4), 2007.

[10] Amanjot Singh and Hardeep Kaur, "Non linearity analysis of high power amplifier in OFDM system," nternational Journal of Computer Applications, Vol. 37(2), Jan. 2012.

[11] G. Karabulut and A. Yongacoglu, "Superposition Block Coded Modulation," Canadian Conference on Electrical and Computer Engineering,Vol. 3, pp.1629-1632, May 2003.

[12] X. Ma and L. Ping, "Coded Modulation using Superimposed Binary Codes," IEEE Tran. Inform. Theory, Vol. 50 (12), pp. 3331-3343, Dec. 2004.

[13] Ahmed E. Zein Eldin , Esam A.A. Hagras , Hala Mansour Abdel-Kader, '' A Novel Superposition Multi Rate Coded Modulation (SMRCM)," International Journal of Computer Networks and Wireless Communications (IJCNWC), Vol. (3), no. 2, pp. 190-196, April 2013.

[14] Rolf Johannesson, Kamil Sh. Zigangirov " Fundamental of Convolutional Codes,'' Wiley, John & Sons, Incorporated, March, 1999.

[15] Li Ping, "Interleave Division Multiple Access and Chip By Chip Iterative Multi User Detection," IEEE Communication Magazine, Vol. 43(6), pp. S19-S23, June 2005.

[16] L. H. Liu, J. Tong, and Li Ping, "Analysis and Optimization of CDMA Systems with Chip-Level Interleavers," IEEE J. Select. Areas Comm. Vol. 24(1), pp. 14.

[17] Mark C. Reed, ''Iterative Receiver Techniques for Coded Multiple Access Communication Systems,'', PhD dissertation, Dept. of Division of Information Technology, Engineering and the Environment, School of Physics and Electronic Systems Engineering., University of South Australia 1999, available at, http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.35.2415 (2013)