Reduction of Computational Complexity in Multistage DS-CDMA System

J. RAVINDRABABU[1], DASI SWATHI[1], J. V. RAVI TEJA[2], J. V. RAVI CHANDRA[3], S. PUJITHA BHAVANI[1], S. SWEEKAR[1], A. NAGA SREEJA[1]
[1]E.C.E. Department, P.V.P. Siddhartha Institute of Technology,
Vijayawada,
INDIA

[2]Software Engineer-1, FactSet Systems Pvt. Ltd,
Hyderabad,
INDIA

[3]C.S.E. Department, V. R. Siddhartha Engineering College,
Vijayawada, Andhra Pradesh,
INDIA

Abstract: - Multiple Access Interference (MAI) is one of the major problems that limit the system capacity of Direct Sequence-Code Division Multiple Access (DS-CDMA) Wireless Communication Systems. The reduction of MAI to improve system capacity without increasing computational Complexity is the motivation to do this work. The objective of this paper is to develop efficient multiuser detection algorithms that improve the DS-CDMA system performance i.e., to achieve a low Bit Error Rate (BER) and high Signal to Noise Ratio (SNR) with less computational complexity. The BER performance of the multistage multiuser detection schemes using Kasami spreading sequences and MMSE detector is found to be better than that of a conventional Matched Filter detector in a single-stage multiuser detection scheme but the Computational Complexity increases with the number of stages and the number of users. The BER performance of the multistage multiuser PIC detection scheme is found to be better than that of a single-stage multiuser PIC detection scheme but at the cost of computational complexity increasing with a number of stages and users. It is found that the BER performance of the multistage multiuser PPIC detection scheme is better than that of the multistage multiuser PIC detection scheme but the computational complexity increases. Though the computational complexity is found reduced in the multistage multiuser DPIC when compared to the multistage multiuser PIC, the BER performance remains almost the same as that in multistage multiuser PIC.

Key-Words: - Multiuser Detection, MAI, PIC, PPIC, DPIC, Computational Complexity.

Received: August 29, 2023. Revised: July 15, 2024. Accepted: August 21, 2024. Published: September 5, 2024.

1 Introduction

As limited bandwidth is allocated for various wireless services and as many users as possible are required to be accommodated which has to be achieved by effectively sharing the allotted bandwidth, multiple access techniques need to be used in the field of communications for a minimum degradation in the system performance, [1], [2], [3], [4]. Since the spectrum utilization in Frequency Division Multiple Access (FDMA) is not efficient and exact synchronization is needed in Time Division Multiple Access (TDMA), one has to go in for a Code Division Multiple Access (CDMA) technique. In this users can occupy the entire channel at all times unlike in FDMA and TDMA and the users are recognized by their a-priori codes assigned uniquely. The users can be recognized at the receiver by using a correlator treating the remaining users' signal energies as noise. The CDMA has more spectral efficiency and user capacity when compared to FDMA and TDMA. CDMA uses a "spread spectrum" technology where in a large bandwidth spreading signal multiplies the narrowband message signal and the users are differentiated by their unique codes, [5], [6], [7], [8], [9], [10].

In a perfect synchronous DS-CDMA transmission, the spreading codes retain their orthogonality whereas in the asynchronous case they exhibit non-zero off peak auto-correlation and cross-correlation values. However a perfect synchronous DS-CDMA system may not be possible to realize in practice and thus suffers from MAI as well as from near-far effects, [11], [12], [13], [14], [15].

In a mobile environment, MAI can exist in a single-user conventional detection at the receiver even though mutually orthogonal codes are employed for all the users at the transmitter end. The single-user conventional detector can also suffer from near-far effect in practice. The received signal contains the desired signal, thermal noise, and the MAI. In a single-user conventional detector, the signal from each user at the receiver end is demodulated independently of other users whereas in MAI is treated as additional noise adding to thermal noise and hence limiting the system capacity, [16], [17], [18].

In a multiuser detection scheme, the received signals from all the users with the presence of MAI are demodulated simultaneously and hence also known as joint detection. The receiver has a priori knowledge of the spreading codes of each user and MAI is not treated as additional noise in multiuser detection. When optimum MUD systems are used no power control is required but the computational complexity increases. Hence, sub-optimum approaches are being sought, [19].

2 Literature Review

[20], a low-complexity hybrid analog-digital signal detector for uplink multiuser massive multiple-input multiple-output (MIMO) systems. In particular, both the hardware cost and computation load can be reduced.

[21], Sparse-aware (SA) detectors have attracted a lot of attention due to their significant performance and low complexity, in particular for large-scale multiple-input multiple-output (MIMO) systems. Similar to the conventional multiuser detectors, the nonlinear or compressive sensing-based SA detectors provide better performance but are not appropriate for the over-determined multiuser MIMO systems in the sense of power and time consumption. The linear SA detector provides a more elegant tradeoff between performance and complexity compared to the nonlinear ones.

After the review of the existing relevant literature, the following observations are being made:

i. The overall BER performance among all the multi-user detectors was found better in the maximum likelihood detector/the optimum detector at the cost of very high computational complexity and thus not realistic for implementation.
ii. Reduced computational complexity exists in decorrelating detectors and MMSE detectors. However in these linear detectors, the calculation of the inverse cross-correlation matrix is difficult.
iii. The computational complexity increases linearly with the number of users in SIC, PIC, HIC, and PPIC techniques. Each type of interference cancellation detector has its level of complexity, processing time, and BER performance.

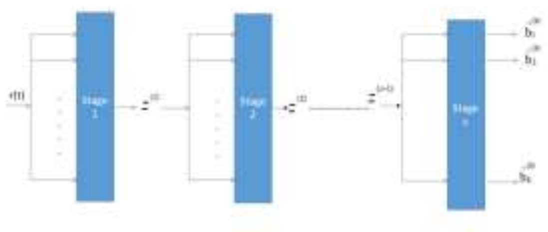
Given the above observations, there exists a need to make studies to enhance visual DS-CDMA system performance and reduce the difficulty of computing. Further, interference cancellation methods other than the existing ones are to be explored for DS-CDMA systems.

The CDMA signal and channel model are covered in the following chapter. Standard single-user and multiuser detection methods are covered in Section 3. The fourth section describes multiple phases of detection techniques and noise. Simulation results on the performance comparison of several multistage multiuser identification approaches are presented in Section 5. An overview of the results is provided in Chapter 6's results.

3 Multistage Multiuser Detection Techniques

3.1 Multistage Multiuser PIC with MMSE Detector

Data bit estimation and interference cancellation need to be done for each user at every stage in multistage PIC schemes. The MMSE detector estimates data bits and subtracts interference from the first stage onwards in this Multistage Multiuser PIC scheme. The Multistage Multiuser PIC with MMSE Detector is shown in Figure 1.



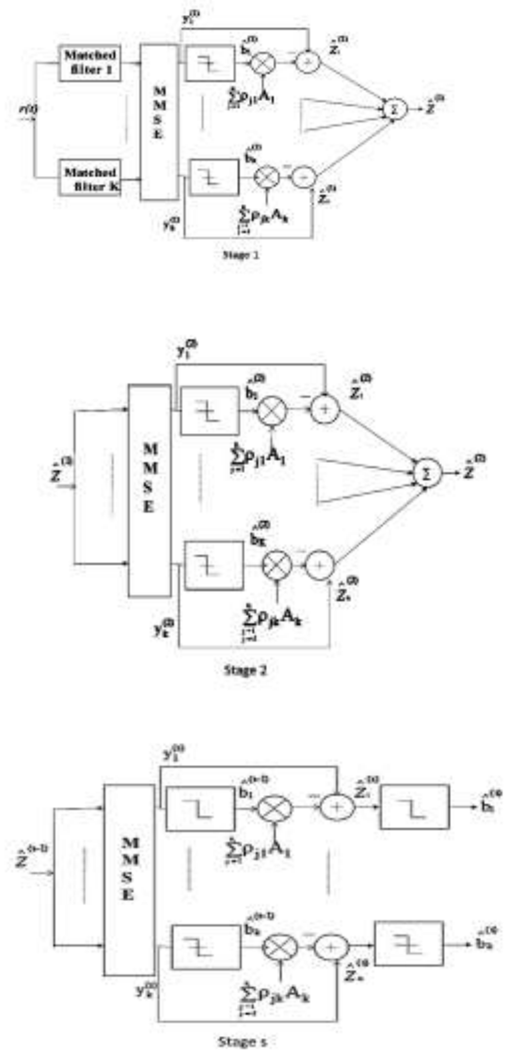


Fig. 1: Multistage Multiuser PIC with MMSE Detector

- **Algorithm for Multistage Multiuser PIC with MMSE detector:**

$$\hat{b}_1^{(1)} = \text{sgn}(y_{mmse})$$

For s=2 to S %/ Cancellation of Interference s-1 stages/

For k=1 to K %/ The interference is subtracted from every user signal at each stage /

$$Z_k^{(s-1)} = y_{mmse} - \sum_{\substack{j=1 \\ j\neq k}}^{K} A_j \rho_{jk} \hat{b}_j^{(s)}$$

where

$$\rho_{kj} = R_{kj} - \text{diag}(R_{kj})$$

$$z_k^{(s-1)} = y_{mmse} - \sum_{\substack{j=1 \\ j\neq k}}^{K} A_j (R_{kj} - \text{diag}(R_{kj})) \hat{b}_j^{(s)}$$

End

$$\hat{b}_k^{(s)} = \text{sgn}(z_k^{(s-1)}) \quad \text{%/ Decision /}$$

End

3.2 Computational Complexity of PIC

Computational Complexity involves the amount of time taken to accomplish the multiuser detection starting from the time of arrival of the transmitted signal at the first stage of the detector of the receiver. Therefore, the time required to perform the number of multiplications and the wide variety of additions in the detection process need to be calculated to arrive at the computational complexity.

The cancellation of MAI from the stronger user every time until the closing user requires the multiplication of two matrices. To accomplish the multiplication of an ($A_1 \times B_1$) matrix with a ($B_1 \times C_1$) matrix, $A_1B_1C_1$ multiplications and A_1B_1C additions are needed.

Therefore, assuming K users in the system wherein the transmission is a burst waveform, each user transmits D data symbols in the burst, B represents the number of chips in the spreading code for every user, and U is the complicated matrix which includes the factors that describe the channel impulse response, then one needs DB instances of multiplications and DB instances of additions for each user for one data symbol in a single path burst. If the bursts arrive along L multi-path channels, then the receiver would require DBL instances of multiplications and DBL instances of addition for one data symbol. Combine the D symbols transmitted from the dispersive paths, requires in addition DL instances of multiplications and DL instances of additions. Therefore, DBL+DL times of multiplications and DBL+DL times of additions are required to get the data estimates from the receiver. In the signal reconstruction process, the data estimates need to be respread with the spreading code first and then convolved with the corresponding channel impulse response, which leads to DBL multiplications and (DB+U−1) additions. To get the data estimate for every user, the effects of remaining users need to be subtracted. To cancel one user's MAI, it needs (DB+U−1) subtractions. Therefore, for every user, (K−1)(DB+U−1) subtractions are needed. For a system supporting K users, the whole number of mathematical operations are S_{PIC1} = K [DBL+DL+DBL+DL+DBN+DBL+DB+U-1+(K-1)(DB+D-1)]

= K [3DBL+2DL+DB+K(DB+U-1)] for first stage

Therefore, for two-stage,
S_{PIC2} = 2 K [3DBL+2DL+DB+K(DB+U-1)]
Therefore, the number of operations needed by the two-stage PIC detector for every one symbol is

$$S_{PIC2\,/symbol} = S_{PIC2} / KD$$

3.3 Multistage Multiuser PPIC with MMSE Detector

In this scheme, the MAI Cancellation is implemented using a weight factor at every stage to decide about the amount of cancellation to be implemented, [14], [15], [16].

In a Multistage Multiuser PPIC scheme, the weight factor used for interference cancellation affects a biased selection statistic. The bias has its strongest effect on the first stage of interference cancellation. In the subsequent stages, its effect decreases. However, if the biased selection statistic is unfair at the first stage leading to a wrong cancellation, then the effects of these errors can escalate in the subsequent stages, [13], [14], [16].

One way to mitigate the effect of the biased selection statistic to enhance the overall performance of multistage PPIC is to multiply the amplitude estimates with a partial cancellation factor, $C_K^{(s)}$ lying between 0 and 1 [i.e., $0 \le \overset{(s)}{C_K} \le 1$] which varies with the stage of cancellation 's' and the number of users 'K'.

In this scheme also, various stages are involved for interference estimation and cancellation. The MMSE is used in the first stage to estimate the information bits whereas the subsequent stages also use MMSE detectors. The signal reconstruction and subtraction of the predicted interference from other users obtained by weighting the estimates of the information bit of the user in question is carried out at all stages . The multistage multiuser PPIC with MMSE detector is shown in Figure 2.

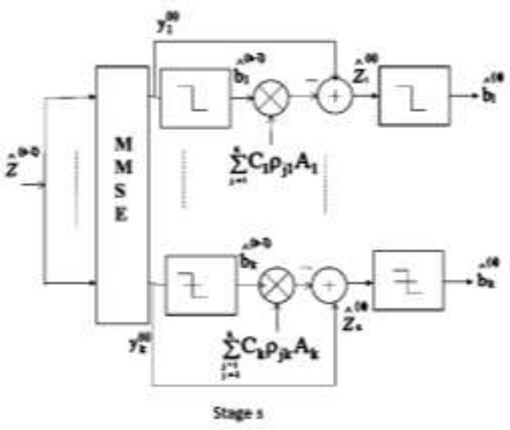


Fig. 2: Partial PIC detector

- **Algorithm for Multistage Multiuser PPIC with MMSE detector:**

$$\overset{\wedge(1)}{b_1} = \text{sgn}(y_{mmse})$$

For s=2 to S %/ Cancellation of Interference s-1 stages /

For k=1 to K %/ The interference is subtracted from every user signal at each stage /

$$z_k^{(s-1)} = y_{mmse} - \sum_{\substack{j=1 \\ j\neq k}}^{K} c_k^{(s)} A_j \rho_{kj} \overset{\wedge(s)}{b_j}$$

where $\rho_{kj} = R_{ij} - diag(R_{ij})$

$$z_k^{(s-1)} = y_{mmse} - \sum_{\substack{j=1 \\ j\neq k}}^{K} c_k^{(s)} A_j (R_{ij} - \text{diag}(R_{ij})) \overset{\wedge(s)}{b_j}$$

End

$$\overset{\wedge(s)}{b_k} = \text{sgn}(z_k^{(s-1)})$$ %/ Decision /

End

3.4 Computational Complexity of PPIC:

For this case, assuming K users in the system where the transmission is a burst waveform, each user transmits D data symbols in the burst, n represents the number of chips in the spreading code for every user, C represents the partial cancellation factor and U is the complicated matrix which includes the factors that describe the channel impulse response, then one needs CDBinstances of multiplications and CDB instances of additions for each user for one data symbol in a single path burst. If the bursts arrive along L multi-path channels, then the receiver would require CDBL instances of multiplications and CDBL instances of additions for one data symbol. Combining the q symbols transmitted from the dispersive paths requires CDL instances of multiplications and CDL instances of additions. Therefore, to get the data estimates from the receiver, CDBL+CDL times of multiplications and CDBL+CDL times of additions are required. In the signal reconstruction part, the detected data have to be re-spread with the spreading code first leading to CDB instances of multiplications and then convolve with the corresponding channel impulse response resulting in DBL times of multiplications and C(DB+U−1) times of additions. To get the estimate for every user, all of the different users' affects need to be subtracted. To cancel one user's MAI, it will need C(DB+U−1) instances of subtraction. Therefore, for every user, (K−1)C(DB+U−1) instances of subtractions are needed. For a system supporting K users, the whole number of mathematical operations are

S_{PPIC1} = KC [DBL+DL+DBL+DL+DB+DBL+DB+U-1+(K-1)(DB+U-1)]
= KC [3DBL+2DL+DB+K(DB+U-1)] for first stage

Therefore, for two-stage,
S_{PPIC2} = 2 KC [3DBL+2DL+DB+K(DB+U-1)]

Therefore, the number of operations needed by the two-stage PIC detectors for every symbol is

$$S_{PPIC2\,/symbol} = S_{PPIC2}/\,KD\,.$$

3.5 Multistage Multiuser Differencing PIC with MMSE Detector

In PIC schemes, the component of MAI from different users is eliminated from the acquired signal to get a higher-anticipated signal for a specific user in parallel. As the exact bit statistics for any user are not known, the anticipated bits are made use of at each stage . As this process is iterative, it's highly possible to have $b_k^{(s)}=b_k^{(s-1)}$ after s^th iteration. Instead of managing with an estimated bit vector $b_k^{(s)}$ at each stage s, one can calculate the difference of the estimated bits in two consecutive stages. Then input at each stage s becomes $e_k^{(s)} = \hat{b}_k^{(s)} - \hat{b}_k^{(s-1)}$ and is called the differencing technique.

The multistage multiuser DPIC with MMSE detector is shown in Figure 3.

The first stage of this DPIC scheme remains the same as in DPIC with an MMSE detector. This scheme makes use of an MMSE detector from the second stage onwards also wherein the preceding estimations from stage-1 are utilized to generate a new vector of signals. Then sum up all the interfering users and subtract them from the MMSE output signal.

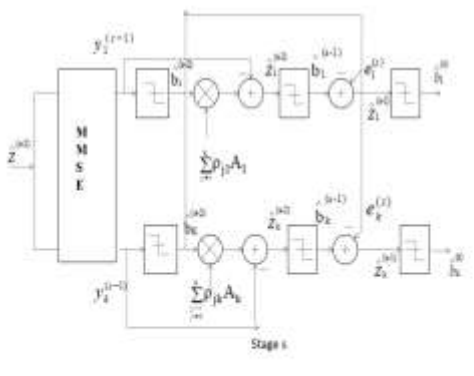


Fig. 3: Difference PIC detector using MMSE

The first stage of this DPIC scheme remains the same as that in DPIC with an MMSE detector. This scheme makes use of MMSE detector from the second stage onwards also wherein the preceding estimations from stage-1 are utilized to generate a new vector of signals. Then sum up all the interfering users and subtract them from the MMSE output signal.

Algorithm for Multistage Multiuser DPIC with MMSE detector:

$\hat{b}_1^{(1)} = \text{sgn}(y_{mmse})$

For k=1 to K %/Interference is subtracted from each user at every stage /

$$z_k^{(2)} = y_{mmse} - \sum_{\substack{j=1\\ j\neq k}}^{K} A_j (R_{ij} - diag(R_{ij}))\,\hat{b}^{(1)}$$

End

$\hat{b}_1^{(2)} = \text{sgn}(Z_1^{(2)})$

%detection/

For s = 2 to S %/ second and next stages: Subtracting multistage

For k = 1 to K

$$z_k^{(s-1)} = z_k^{(s)} - \sum_{\substack{j=1\\ j\neq k}}^{K} A_j (R_{kj} - diag(R_{kj}))\,\hat{e}_j^{(s)}$$

where $e_j^{(s)} = b_j^{(s)} - b_j^{(s-1)}$

End

$\hat{b}_1^{(s)} = \text{sgn}(Z_k^{(s-1)})$ %/decision/

End

3.6 Computational Complexity of DPIC

The computational complexity of this DPIC system can be arrived at on similar lines to that for PIC and PPIC as discussed respectively in sections 3.3 and 3.4 previously. That is, it is based on the total number of multiplications and additions involved in this scheme. The procedure is similar to that in the first stage of PIC except only DB times more additions are required in differencing PIC. Since for a PIC system supporting K users, the total number of mathematical operations are

S_{PIC}= K [DBL +DL+ DBL +DL+DN+ DBL +DB+U-1+(K-1)(DB+U-1)]
=K[3DBL+2DL+DB+K(DB+U-1)] for first stage of PIC.

Therefore, for a single-stage DPIC,
S_{DPIC1} = K[3DBL+2DL+DB+K(DB+U-1)] + DB

Therefore, the number of operations needed by the single-stage DPIC detector for every symbol is

$S_{DPIC1/symbol} = S_{DPIC1} / KD$

Similarly, for a two-stage DPIC

$S_{DPIC2} = 2\{K[3DBL+2DL+DB+K(DB+U-1)] + DB\}$

and the number of operations needed by the two-stage DPIC detector for every symbol is

$$S_{DPIC2/symbol} = S_{DPIC2} / KD$$

4 Simulation Results

The DS-CDMA basic multistage multiuser discrete time paradigm was applied. The customer's data is disseminated via BPSK modulation and Kasami odd spreading sequence.

It is evident from the below simulation results that with an increasing number of stages, the system's overall BER performance is improved as PIC with MMSE detector. However, the computational complexity also increases. The BER performance did not alternate dramatically beyond 4thstage (not shown here). Three stages are only considered for simplicity. BER performance is better at the 3rdstage when compared to that at the 1ststage and 2nd stage for all the cases like PIC, PPIC, and DPIC from Figure 4, Figure 7 and Figure 10 for clarity.

It is evident from the simulation results shown in Figure 5, Figure 8 and Figure 11, that the BER performance degrades with an increasing number of users. But at the same time, the computational complexity increases with an increasing number of users as shown in Figure 6, Figure 9 and Figure 12.

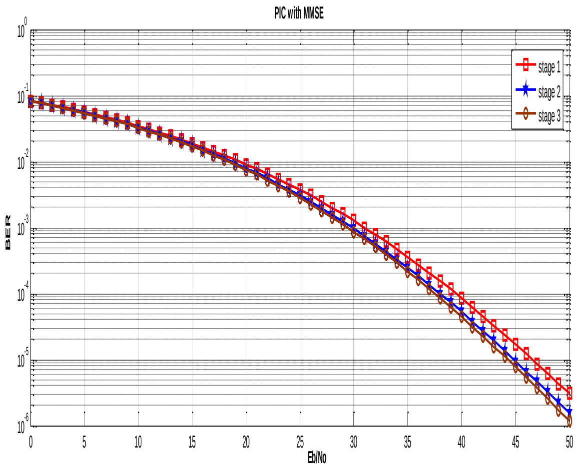


Fig. 4: Bit-Error-Rate performance of PIC with MMSE for K=10 users

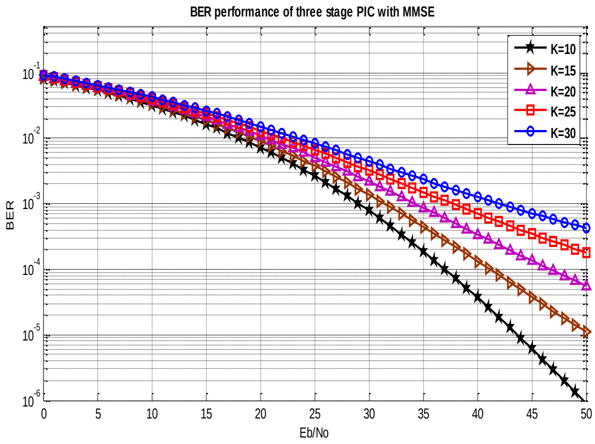


Fig. 5: Bit-Error-Rate performance of three-stage PIC with MMSE different users

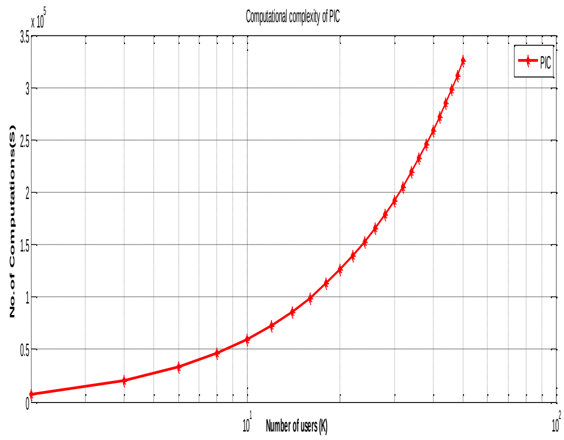


Fig. 6: Computational complexity of PIC

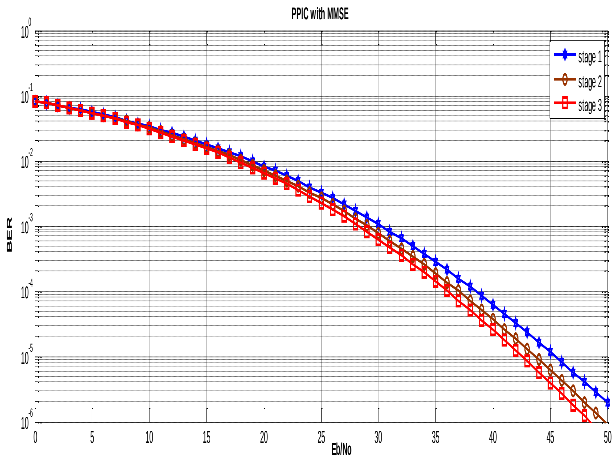


Fig. 7: Bit-Error-Rate performance of PPIC with MMSE for K=10

J. Ravindrababu, Dasi Swathi, J. V. Ravi Teja,
J. V. Ravi Chandra, S. Pujitha Bhavani,
S. Sweekar, A. Naga Sreeja

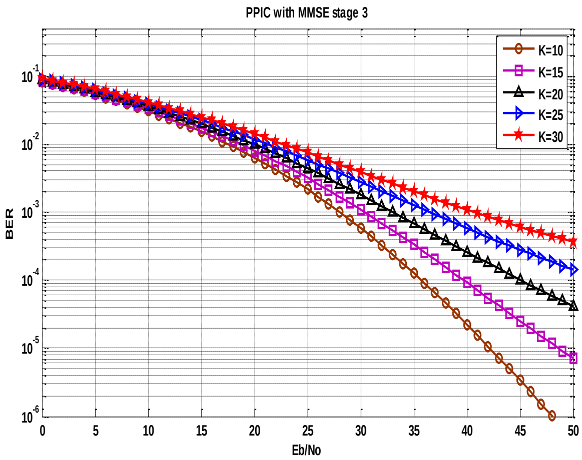


Fig. 8: Bit-Error-Rate performance of PPIC with MMSE for K=No.of users

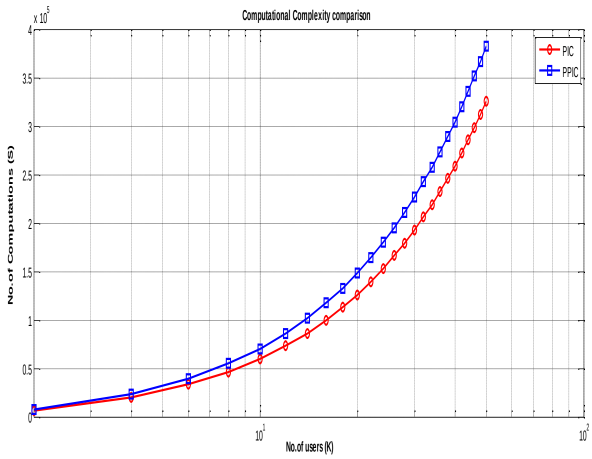


Fig. 9: Computational complexity of PIC and PPIC

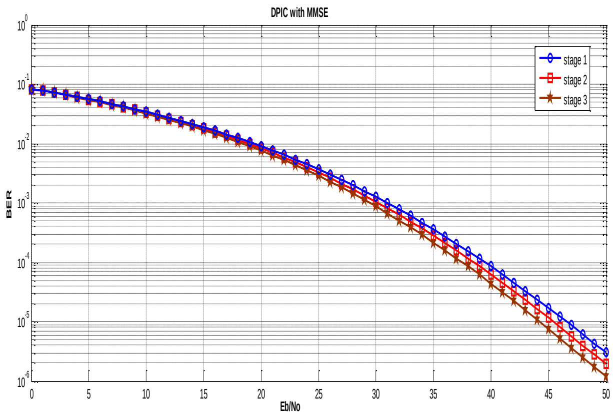


Fig. 10: Bit-Error-Rate performance of DPIC with MMSE for K=10

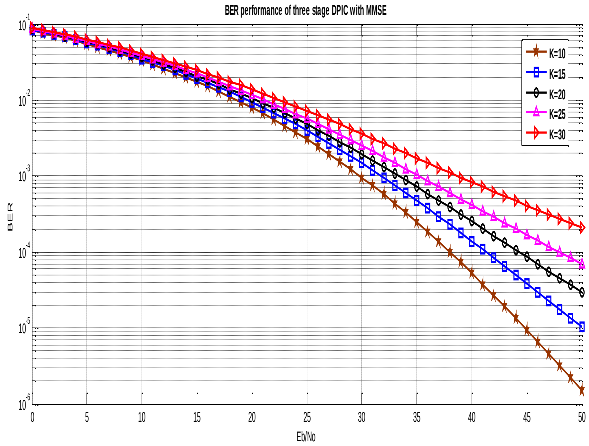


Fig. 11: Bit-Error-Rate performance of DPIC with for MMSE K=No.of users

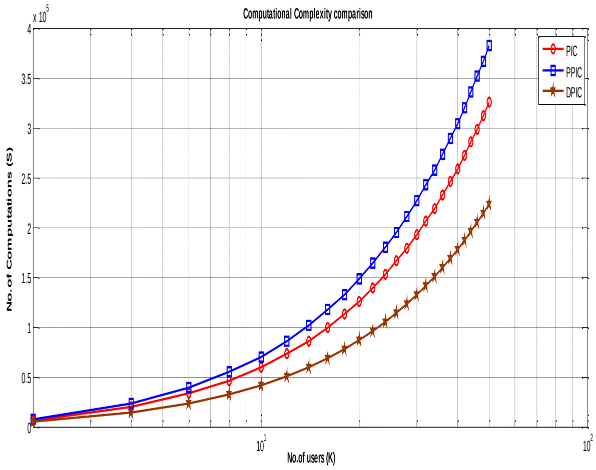


Fig. 12: Computational complexity of PIC, PPIC & DPIC

5 Conclusions

Employing multiple-stage multiuser approaches in DS-CDMA systems can also minimize the complexity of computation and Multiple Access Interference. In the multistage PIC approach, bit error rate (BER) drops and detection becomes more dependable as the number of stages rises. The ability to increase in subsequent phases cannot be guaranteed by the PIC. In a DS-CDMA system, the effectiveness of the Partial Parallel Interference Cancellation (PPIC) technique is assessed. However there is no improvement in computational complexity. The computational complexity decreased by using DPIC. Ultimately, it may be concluded that DPIC outperforms PIC and PPIC.

References:

[1] J. Viterbi. CDMA, *"Principles of Spread Spectrum Communication"*. Addison-Wesley Wireless Communications, 1995.
[2] R.A. Scholtz, "The Origins of Spread-Spectrum Communications". *IEEE Transactions on Communications*, Vol. No 30(5), May 1982, pp.822–854.
[3] S. Verdu, *"Multiuser Detection"*, Cambridge University Press, Cambridge, UK, ISBN: 0521593735, 1998.
[4] L.Vanderdorpe, "Multitone spread spectrum multiple access communications systems in a multipath Rician fading channel," *IEEE Transactions on Vehicular Technology*, Vol. 44, May 1995, pp.327-337.
[5] B. Dhammika and T.Aulin, "Multiuser detection for continuous phase modulation over Rayleigh fading channels," *IEEE Communication letters*, Vol. No.9, October2005, pp..906-908.
[6] Zhao Zhijin, and Zhao Zhidong "Discrete Shuffled Frog Leaping Algorithm for Multi-user Detection in DS-CDMA Communication System" *IEEE international conference on communication technology proceedings*, 2008, pp.421-444. Hangzhou, China.
[7] M. K. Varanasi and B. Aazhang, "Near optimum demodulators for coherent communications in asynchronous Gaussian CDMA channels," in *Proc. 22nd conf. on Information Sciences and Systems*, March 1998, Tainan, Taiwan, pp.832-839.
[8] S. Gray. "Multiuser detection in mismatched multiple access channels," *IEEE Transactions on Communications*, Vol. 43, December 1995, pp.3080-3089.
[9] M. Latva-aho, e "Parallel interference cancellation receiver for DS-CDMA systems in fading channels," in *Proc. IEEE Int. Symp. Personal, Indoor and Mobile Radio Communications (PIMRC)*, 1997, pp.559-564. Helsinki, Finland.
[10] Zhendong Yin, "A complexity-performance-balanced multiuser detector based on artificial fish swarm algorithm for DS-UWB systems in the AWGN and multipath environments" *EURASIP Journal on Advances in Signal Processing*, 2012: Vol. 229, pp.1-13.
[11] Yao Xie, "Reduced-Dimension Multiuser Detection" *IEEE Transactions on Information Theory*, Vol. 59, June 2013, pp.3858-3874.
[12] Bo Ma, "GMM-MUD: An Effective Multiuser Detection Algorithm for DS-UWB-Based Space Formation Flying Systems" *Hindawi Mathematical Problems in Engineering*, 2019, Vol. 5, pp.1-10.
[13] SaifHikmatMousa,"Effective Wide Spectrum Sharing Techniques Relying on CR Technology toward 5G": *A Survey Journal of Communications*, Vol. 15, February 2020, pp.122-147.
[14] SmritiSachan, Performance Analysis of BER in CDMA using Various Coding & Simulation Techniques", *International Journal on Recent and Innovation Trends in Computing and Communication*, Vol. 4, Issue 3, pp.37-42.
[15] Ghani, B., Launay, F., Pousset, Y. . Low-complexity hybrid interference cancellation for sparse code multiple access. *J. Wireless Com. Network* 2022, 95 (2022). https://doi.org/10.1186/s13638-022-02162-y.
[16] J. Ravindrababu and E. V. KrishnaRao, "Interference Reduction in fading environment using Multistage Multiuser Detection Techniques", *WSEAS Transactions on Signal Processing*, Vol. 15, August 2019, pp.36-46.
[17] Daniele Angelosante, Ezio Biglieri, Marco Lops, "Low-complexity receivers for multiuser detection with an unknown number of active users" *Signal Processing*, Vol. 90, 2010, pp.1486-1495.
[18] Linglong Dai, Xinyu Gao, Shuangfeng Han "Low-Complexity Soft-Output Signal Detection Based on Gauss–Seidel Method for Uplink MultiuserLarge-Scale MIMO Systems" *IEEE Transactions on Vehicular Technology*, vol. 64, No. 10, October 2015, pp.4839-4845.
[19] Yang Du, Binhong Dong "Low-Complexity Detector in Sparse Code Multiple Access Systems" IEEE Communications Letters, vol. 20, No. 9, September 2016, pp.1812-1815.
[20] Yinman Lee, Meng-Wei Liang, "Low-Complexity Hybrid Analog-Digital Signal Detector for Uplink Multiuser Massive MIMO Systems" *2019 IEEE 8th Global Conference on Consumer Electronics (GCCE)*, Nara, Japan, pp.415-417.
[21] Rong Ran, and Hayoung Oh, "Low‑complexity sparse‑aware multiuser detection for large‑scale MIMO systems" EURASIP *Journal on Wireless Communications and Networking*, Vol. 58, 2021, pp.1-15.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- J Ravindra Babu, D. Swathi Identified the problem statement and done the mathematical Analysis.
- J V Ravi Teja,J V Ravi Chandra have implemented the Algorithms in section 3.
- S.Pujitha Bhavani, S.Sweekar A.Naga Sreeja carried out the simulation in section 5 using MATLAB.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.