Practical Soft Demapper-Based Decoder for Sparse Code Multiple Access

Syed Aamer Hussain
Razak Faculty of Technology and Informatics
Universiti Teknologi Malaysia
Kuala Lumpur, 54100, MALAYSIA
aamerhussain1987@graduate.utm.my

Norulhusna Ahmad
Razak Faculty of Technology and Informatics
Universiti Teknologi Malaysia
Kuala Lumpur, 54100, MALAYSIA
norulhusna.kl@utm.my

Khoirul Anwar
The University Center of Excellence for Advanced Intelligent Communications
School of Electrical Engineering
Telkom University
Bandung, 40257, INDONESIA
anwarkhoirul@telkomuniversity.ac.id

***Abstract*—Existing SCMA systems presented for multiuser detection has high computational complexity. The complexity is a prime concern considering its implementation in a machine-to-machine (M2M) communication involving limited capacity devices. Since these devices have low processing power, so practical implementation of SCMA needs to be optimised for better performance. This paper proposes an SCMA decoder with a soft demapping technique to reduce the computational complexity, providing better performance. To improve the stability of SCMA system for M2M communication, this paper proposes the use of noise variance threshold ψ, to handle the system's stability. Results confirmed that the proposed soft demapper-based SCMA reduced the execution time to 33% and the iteration number to 63% compared to the conventional SCMA scheme deploying message passing algorithm (MPA)-based decoding. The proposed SCMA provides an improvement of 2.5 dB at a BER of 10^{-3} under the block Rayleigh fading channels and an improvement of approximately 1.1 dB at a BER of 10^{-5} dB under the fast Rayleigh fading channels. The improvements come from the fast convergence of iterative decoding using a soft demapper supported by a variance threshold ψ that avoids the duality decision at the border of the decision area.**

***Index Terms*—Soft Demapping Decoder, Practical Implementation, computational Complexity**

I. Introduction

Sparse code multiple access (SCMA) [1] is a code domain non-orthogonal multiple access (NOMA) scheme, which is considered a preferred option for fifth generation telecommunication (5G) and future mobile communication systems [2], [3]. Considering the SCMA scheme for M2M communication like IoT, various challenges are associated with its implementation [8]. The prominent ones are computationally optimised architecture, system stability, and improved multi-device communication. To achieve reduced complexity in the SCMA architecture, it is observed that decoder is the most processing-intensive block in the SCMA architecture.

Literature presents various research approaches for decoder optimisation. Prominent methods presented are, maximum likelihood, MPA, and machine learning. Considering, maximum likelihood (ML), its implementation is limited due to its high computational complexity [9]. In addition, MPA and log-MPA decoders are frequently used in SCMA architecture because of their low complexity, but unlike ML, it induces performance limitations in the system implementation [10]. Modern machine-learning techniques have also been presented to be effective [11]. The multi-classification model adapts according to the deep learning optimisation parameters and performs SCMA decoding. However, such a technique is problematic when the number of users/devices increases. Another study researched the applicability of sphere decoding for SCMA to reduce the receiver's complexity by narrowing the range of believable superposed constellation points [12]. Considering all the cases, the convergence efficiency of existing decoders in SCMA architectures is still low. Soft demapping-based decoding serves as an alternative to achieve higher convergence efficiency. It has been studied as an optimised decoder in [13], where the decision threshold algorithm is used for demapping the data with low computational complexity and high throughput. Alhamdi in [14] also used the optimal soft demand for 5G new radio (NR) wireless communication systems to propose thresholds for practical applications.

Considering the literature and requirements of M2M communication in IoT, a soft demapper is preferred as a computationally better and faster converging decoder. However, the incorporation of a soft demapper-based decoder in the SCMA architecture needs to be researched based on the complexity and BER performance. Unlike [14], this paper covers soft-demapper from the perspective of SCMA rather than 5G-NR domain. Specifically, this study proposes the use of a soft demapper-based MPA decoder in the SCMA architecture to improve the convergence efficiency and computational overhead. The paper also uses log-likelihood ratio (LLR) limiter from [14] and proposes additional noise variance threshold to improve system stability for practical implementation. These additions improve the adaptability of the SCMA system in IoT device communication which is a leading requirement in future communication systems.

This paper consists of five sections . Section 1 gives an introduction of the existing systems. Section 2 provides background of the work already done. Section 3 presents the proposed architecture and system design. Section 4 is the simulation and results section presenting the analysis and significance of the proposed method. The last section provides concluding remarks regarding the effectiveness of the research.

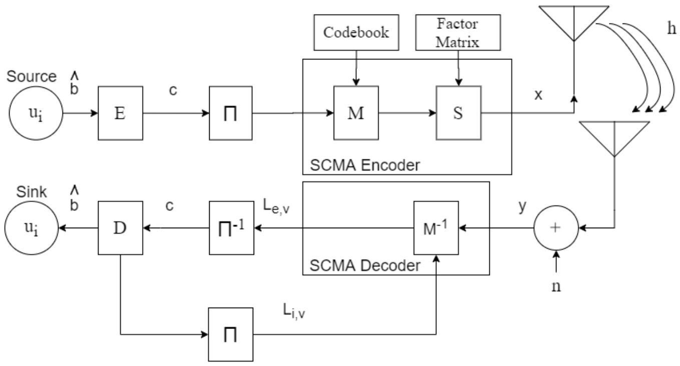

Fig. 1. Structure of the proposed SCMA transmitter and receiver involving iterative decoding.

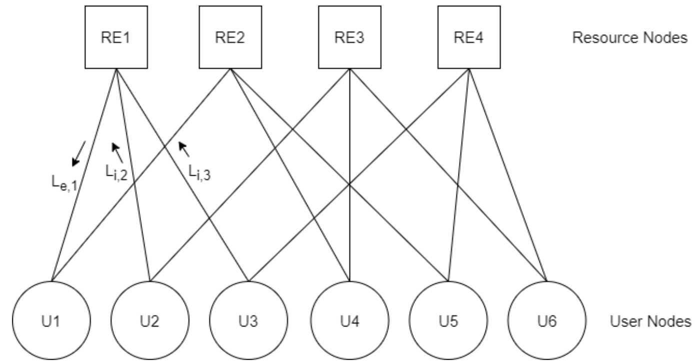

Fig. 2. Resource block data assignment for regular (4 x 6) factor matrix.

II. Conventional SCMA System

Considering the design of conventional SCMA systems, the system is primarily composed of encoding and decoding blocks using the codebook mapping feature. The communication is performed in the form of data frames, where each frame signifies a limited time slot allocated for transmissions. The frame comprises several resource blocks (RBs), the smallest unit of resources that can be allocated to a user. RB represents a slot of a frame composed of multiple frequency sub-carriers, where the spreading of user data is in the more minor resource elements (REs). RE represents a single subcarrier that can be multiplexed with user data. The basic architectural block diagram of the SCMA system for user *v* is shown in Figure 1.

Conventionally, the system input is binary user data $\hat{b} \in B(B = 0, 1)$. The input data are encoded into *c* using the error correction encoder (E). The paper includes repetition coding (RC) as a channel coding scheme with a channel coding rate of *R*. RC has limitations in the form of code rate flexibility and drastic increases in the size of the transmitted data. However, the complexity of coding schemes like convolution codes was considering in choosing RC for the said IoT application. The channel-coded data c is then randomly interleaved (Π) and encoded by the SCMA encoder. The encoder is composed of mapping *M* and spreading the *S* modules. An SCMA encoder maps $log_2 W$ bits to a codebook of size $K \times W \times V$, where *K* is the number of resource elements, *W* signifies the number of codewords in the codebook, and *V* is the number of users. Based on the mapping and spreading, the encoder outputs a sparse matrix with complex data, which is sent throughout the channel represented by *'x'*.

The received signal is given as

$$\boldsymbol{y} = \sum_{(\boldsymbol{v}=\boldsymbol{1})}^{\boldsymbol{V}} \boldsymbol{h_v}.\boldsymbol{x_v} + \boldsymbol{n}, \tag{1}$$

where $h_v = (h_1, h_2, ...h_V)$ represents the channel state, $x_v = (x_1, x_2, ...x_V)^T$ represents the symbol of the v-th user, and n is the additive white Gaussian noise (AWGN) with $[.]^T$ is the transpose operation. The channel will effect the phase of each user transmission but it will be corrected by soft-demapper since it works based on symbols as described in subsequent section.

The received signal *"y"* is initially decoded by the SCMA decoder. As discussed, the decoder (M^{-1}) estimates the soft information from the transmitted bits in the form of an LLR. The processing can be represented by a bipartite graph, as shown in Figure 2. The graph is composed of *V* vector nodes (VN) and *K* function nodes (FN). The degree of VN is equal to d_v, that is, the number of resources (RE) occupied by a single user, while the degree of FN is similar to d_f, which is the number of users multiplexed on a single resource. The formulation of bipartite graph is governed by the factor matrix discussed in the next section.

The LLR for each coded symbol that exists at the VN is deinterleaved (Π^{-1}) and decoded by the FEC decoder *D*. The decoder estimates the bit data $\hat{b}$ from the codewords. The decoder (*D*) as feedback gives the a priori information L_{iv} back to the FN in the SCMA decoder. The subsequent data passing between M^{-1} and *D*, or specifically FN and VN, creates an iterative operation for data processing. The process is iterated until a convergence point is achieved based on either the maximum number of iterations or zero decoding error.

III. Proposed System Design

This paper discusses the optimisations in the main blocks of conventional SCMA architecture, including the SCMA codebook, spreading matrix design, and decoder module.

A. SCMA Codebook

This study uses a codebook containing complex BPSK (CBPSK) modulated mother constellation, which is part of the technical standard for 5G modulation set by the Third Generation Partnership Project (3GPP) [20]. Use of CBPSK avoids dualism in SCMA processing by increasing sparsity among the modulation symbols, thus improving the decoding efficiency. As shown in Figure 3,CBPSK modulation symbols has a comparatively sparse structure. It is advantageous for SCMA, where higher overloading exists, represented by d_f. Therefore, not all users multiplexed on a single resource block have the same symbol, thereby improving decoding. Based on

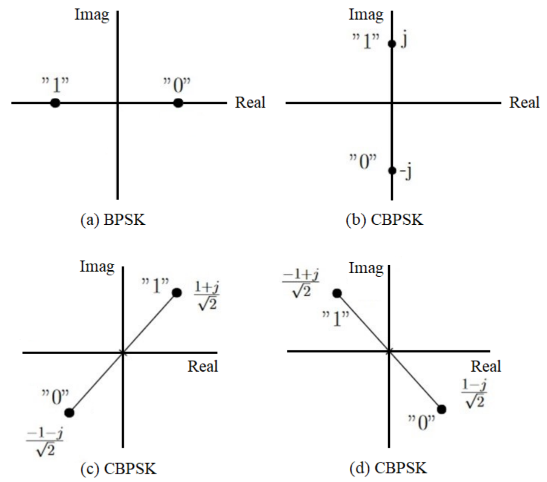

Fig. 3. SCMA mapping symbols.

this condition, the modulated CBPSK can be classified into three types of modulation symbols, as depicted in Figure 3(b), 3(c), and 3(d).

To demonstrate advantages of the proposed method, larger number of signals should be used, for example, 4 codewords per user that is typical in the literature about SCMA. However, in this study the main objective is to highlight the fast convergence of soft-demapper which can be validated for simple codewords. Still, such a complex system can also be realized and developed with the soft-demapper [21].

B. Binary Factor Matrix

SCMA can overload resources by multiplexing more users with fewer resources given by $\lambda = \frac{V}{K}$ where V users are sparsely multiplexed at the K REs and $K < V$. However, overloading creates a challenge in data decoding. To improve decoding for overloaded SCMA systems, sparsity is introduced in data communication. The sparsity is generated by allocating only the d_f number of users to the d_v number of REs, where $d_f << V$ and $d_v << K$. It is represented in the form of a spreading or factor matrix **F** which governs the assignment of a particular user to an RE. For user *v*, this matrix is determined by the nonzero elements of the binary factor vector f_v. Correspondingly, the whole SCMA structure can be represented by a factor matrix $\mathbf{F} = (f_1, \ldots . f_V)$. The factor matrix used in this study for six users sparsely multiplexed on four resources is given as

$$\mathbf{F} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix}. \quad (2)$$

C. Proposed Modules

1) Soft Demapper-based Decoding: In the conventional SCMA systems, the decoding is performed based on the constellation of the received signal derived from individual user codebooks. This paper presents soft demapper-based decoding, which in addition to the received signal constellation, also incorporates the information about the quadrant of the received constellation symbols. Association of a symbol with any quadrant is translated in the form of sign (either positive or negative). It allows better performance and reduced number of iterations *T*. In this case, additional information improves the extrinsic LLR, thereby improving symbols decoding and reducing the iterations T toward the maximum LLR. The use of soft-demapper is also advantageous in case of fading channels where the receiver design becomes complex because signal can spread everywhere compared to AWGN channel where any simple receiver like maximum likelihood receiver can also be implemented.

From Figure 1 the intrinsic information from channel decoder is provided to SCMA decoder as $L_{i,v}$, where based on the constellation each sign combination is fed to the SCMA decoder and value of LLR signifies its effect. The procedure can be viewed from Figure 3, where in the case of resource node 1 the priori LLRs from user node 2 $L_{i,2}$ and 3 $L_{i,3}$ contributes to the extrinsic belief L_{e_1} from resource node 1 to user node 1, given by

$$L_{e_1} = \ln \frac{\sum\limits_{C \in C^{+1}} \exp\left(- \frac{(|r - h_v \cdot c|}{\sigma^2}) + b_2 L_{i,2} + b_3 L_{i,3} \right)}{\sum\limits_{C \in C^{-1}} \exp\left(- \frac{(|r - h_v \cdot c|}{\sigma^2}) + b_2 L_{i,2} + b_3 L_{i,3} \right)}, \quad (3)$$

where *b* signifies the sign information of the LLR, *c* represents the codewords, *r* represents the received signal, h_v shows the channel coefficient, and σ shows the variance.

2) Control Parameters: This paper also includes noise variance threshold (TH) at only the decoding end for the practical implementation of a soft demapper. For this, a threshold for the channel variance σ is proposed, whose numerically optimised value is identified experimentally. TH improves the decoding accuracy, which is hampered at higher SNR when the LLR of the received signal corresponding to different constellation points is equal. A cap on σ creates a mismatch in the LLRs, categorising the signal to one of the constellation points. Such a condition is observed mostly in the case of fading channels at high SNR. The variation in the demapper equation in (3) after introducing the threshold ψ is given by

$$L_{e_1} = \begin{cases} \ln \frac{\sum\limits_{C \in C^{+1}} \exp\left(- \frac{(|r - h_v \cdot c|}{\psi^2}) + b_2 L_{i,2} + b_3 L_{i,3} \right)}{\sum\limits_{C \in C^{-1}} \exp\left(- \frac{(|r - h_v \cdot c|}{\psi^2}) + b_2 L_{i,2} + b_3 L_{i,3} \right)}, & \sigma < \psi \\ \ln \frac{\sum\limits_{C \in C^{+1}} \exp\left(- \frac{(|r - h_v \cdot c|}{\sigma^2}) + b_2 L_{i,2} + b_3 L_{i,3} \right)}{\sum\limits_{C \in C^{-1}} \exp\left(- \frac{(|r - h_v \cdot c|}{\sigma^2}) + b_2 L_{i,2} + b_3 L_{i,3} \right)}, & \text{otherwise} \end{cases} \quad (4)$$

Considering the proposed decoder and parameters, the optimisation criterion is based on determining the average BER

Q_b while keeping the LLR a significant value using TH ψ.

$$\begin{aligned} \min \quad & T, Q_b = f(SNR, \psi) \\ \text{s.t.} \quad & 0 < \psi < 0.7. \end{aligned} \tag{5}$$

The study evaluates the reduction in system computational complexity considering iterations T and optimisation of the system parameter TH ψ, keeping the BER Q_b at a minimum.

IV. Results and Discussion

The section discuss the performance of SCMA soft-demapper for SNR of 2 to 20 dB under block and fast fading channels. The comparison is made with the conventional SCMA based on log-MPA decoder with similar parameters as the soft-demapper based SCMA. The results are bench-marked against the theoretical results extracted from uncoded BPSK scenario (fading theory), which signifies the effect of channel coding and decoder efficiency. From results, average BER of the system is observed to be around $10{-}2$ at lower SNR and $10{-}6$ at higher SNR, similar to other co-existing systems [22]. The study uses repetition codes as the error correction codes. They are considered instead of complex LDPC codes since repetition codes have better performance in multi-user scenario.

A. Parameter Evaluation

It is postulated that the stability and performance of the proposed SCMA are linked to the proposed parameters. This section considers these parameters and investigates the effect of control parameters on the system stability. The parameters can be divided into the control and coding parameters.

1) Control parameter: The proposed control parameter is the threshold on the noise variance of the communication channel. As discussed, this threshold exists only at the decoder end and optimised value is determined experimentally considering results for different SNRs. In the simulation, the optimum threshold value for demapper-based SCMA systems is determined in the block Rayleigh fading channel. The simulation is performed with $R = 1/5$, and $T = 3$. Various threshold values ranging between 0.1 - 0.6 are tested in this simulation. The results in Figure 4 show an optimum threshold of 0.4. For lower thresholds the system average BER goes above the theoretical uncoded BPSK curve, which signifies the importance of the cap on the variance in the decoding sequence.

2) FEC coding parameters: The RC code rates of $R = \{3, 5, 7\}$, and $\{9\}$ are analysed for its impact on the BER to extract the best value based on the BER performance. The simulation is performed with $\psi = 0.4$, and $T = 3$. For block fading, it is observed from Figure 5 that the regular demapper-based SCMA has significant effect on the BER with the variation in the code rate. Correspondingly, repetition codes provides coding gain when the channel gains for all repetitions are not the same as in the case of fast fading. Figure 5 shows the effect of code rate variation in the case of fast fading channel. The effect of channel gain can be observed from the BER curve.

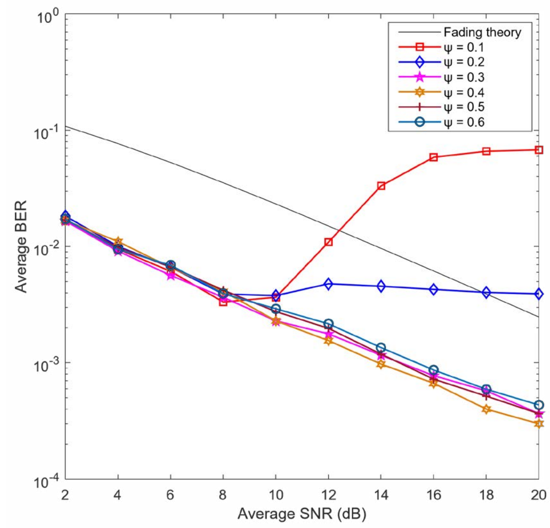

Fig. 4. Threshold variation for regular matrix demapper-based SCMA under block Rayleigh fading channel.

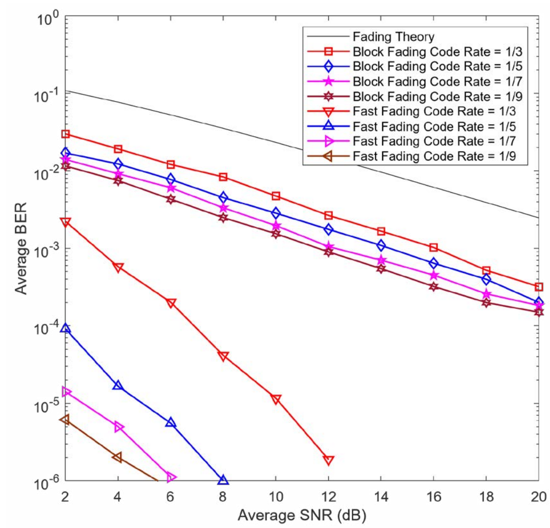

Fig. 5. Demapper-based SCMA code rate variation under block Rayleigh fading channel.

Considering results it is observed that the BER performance is significantly improved as the code rate increases. However, with an increase in the code rate, the system's data rate also decreases, which renders the performance ineffective. Therefore, the preferred code rate choice is kept higher than the minimum performance value of 1/5.

B. Computational Complexity Analysis

Based on the optimised parameters, the demapper-based SCMA system was compared with the conventional SCMA considering their complexity. The analysis is based on reducing the complexity of the system without compromising system performance. This study optimises the variable T and computational overhead of the system.

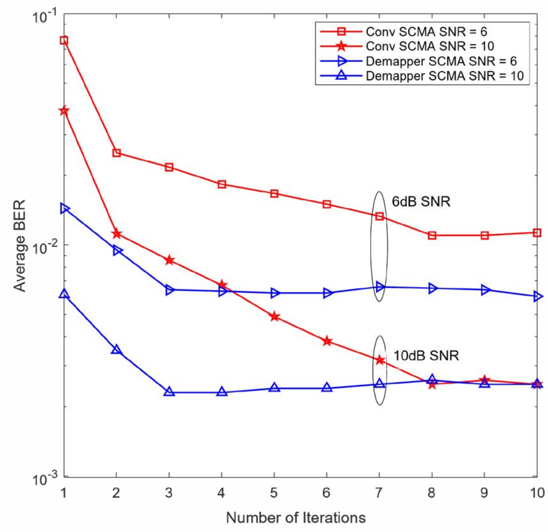

Fig. 6. Convergence comparison between conventional and demapper-based SCMA under block Rayleigh Fading.

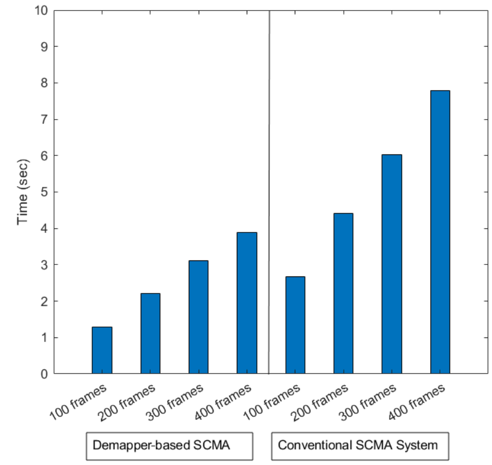

Fig. 7. Conventional and demapper-based SCMA execution time comparison.

1) Decoder Iterations: To investigate the effect of message passing iterations on the SCMA system performance, simulations were performed with SNR of 6 dB and 10 dB while varying the number of iterations and analysing the BER. A simulation with $\psi = 0.4$, and $T = 3$ and $R = 1/5$ was performed. The results show that for conventional SCMA systems, the slope of the BER curve is relatively low, resulting in slow convergence with a high number of iterations, that is, $T = 8$. In the case of demapper-based SCMA, the slope of the BER curve is relatively high, and a fast convergence at a low number of iterations is observed, where $T = 3$.

A comparison of the convergence under a block Rayleigh fading channel is shown in Figure 6. It is evident that even at higher SNR values, the demapper has a fast convergence, achieving a similar BER with fewer iterations while maintaining system stability. For example, at an SNR of 6 dB, the convergence of the proposed decoder requires only three iterations, as compared to conventional SCMA which require eight iterations. The performance is almost identical for higher SNR of 10 dB, where the convergence is achieved at three and eight iterations for demapper and conventional SCMA, respectively. This is because the inclusion of more data from the received signal constellation improves the decoding estimation of the algorithm. Also for both the demapper and conventional SCMA, the convergence point or global minima for the error rate are the same. However, the soft demapper has faster convergence and better performance in achieving minima than conventional SCMA.

2) Computational Complexity: Considering a reduced number of iterations, the number of computations involved in the iterative algorithm is also significantly reduced. The reduction in multiplication and addition counts due to iteration optimisation is helpful in the execution of the algorithm for processing scarce processors with limited high-speed memory. Math Works, Inc. MATLAB Version 2019 profile tool, a comparison of the execution time for the conventional and demapper-based SCMA systems was performed. With parameters similar to those in the decoder iteration test, the simulation execution time is noted for transmission, reception, and decoding of 100, 200, 300, and 400 frames, with each frame having five blocks. Figure 7 shows the results of simulation, where low convergence and high processing requirements left conventional SCMA with a high execution time compared to the demapper-based SCMA system. A comparison of the results shows an approximately 50% improvement in execution time for demapper-based SCMA compared with conventional SCMA.

C. BER Analysis

BER Comparison of proposed soft demapper SCMA with conventional SCMA using optimised parameters identified in the previous sections is performed. The analysis uses RC with a code rate of $R = 1/5$with $\psi = 0.4$ for the proposed decoder-based SCMA.

The proposed decoder includes information about the received signal constellation of the FEC decoder and intrinsic information, as shown in Equation 3. Figure 8 shows the BER comparison of proposed decoder and conventional SCMA, where both techniques use the CBPSK codebook and parameters similar to those in the complexity analysis. For the block Rayleigh fading channel, the conventional SCMA achieved an error rate of 10^{-3} at an SNR of 16.6 dB, while the demapper based system has a similar error rate at an SNR of 14 dB. The same trend is observed in the case of a fast fading channel, where 10^{-5} BER for conventional SCMA is achieved at an SNR of 6.3 dB while for demapper based system at an SNR of 5.2 dB. It shows That the demapper-based SCMA has a gain of 2.5 dB for the block Rayleigh fading channel and 1.1 dB gain for the fast Rayleigh fading channel due to the improved decoding technique of the demapper-based decoder.

As shown in Figure 6, the demapper-based SCMA has a faster convergence with fewer iterations than the conventional

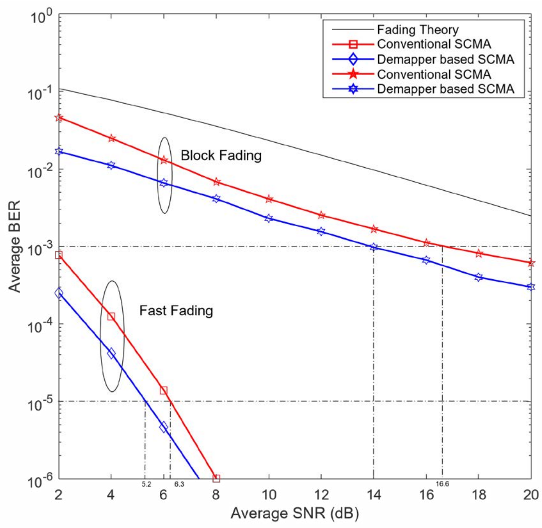

Fig. 8. BER for conventional and soft demapper-based SCMA system for block and fast Rayleigh fading channel.

SCMA. Linking this with the results from Figure 8, it can be observed that even for a fewer number of iterations, the demapper-based SCMA has a much better BER response than the conventional SCMA in the case of both block and fast Rayleigh fading channels.

From Figure 8, it is also evident that fast fading has a better response than the block Rayleigh fading condition . This is mainly due to the increase in diversity which improves the error correction capability of the system because every LLR value is different and is beneficial in decoding and detection.

V. Conclusion

This paper proposes an SCMA decoder with a soft demapping technique that allows the decoder to have less computational complexity and better BER performance. The improvement in the decoder design improves SCMA implementation for M2M IoT communication. This study also presents noise variance threshold ψ for handling SCMA system stability thereby improving SCMA practical implementation. Parameter optimisation allowed better stability and performance even at an SNR of 15–20 dB.

Acknowledgment

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References

[1] H. Nikopour and H. Baligh, "Sparse code multiple access," in Proc. IEEE 24th Int'l. Symp. Personal Indoor & Mobile Radio Commun. (PIMRC), 2013.

[2] Moltafet, M., Yamchi, N. M., Javan, M. R., & Azmi, P. (2017). Comparison study between PD-NOMA and SCMA. IEEE Transactions on Vehicular Technology, 67(2), 1830-1834.

[3] Wang, B., Wang, K., Lu, Z., Xie, T., & Quan, J. (2015, June). Comparison study of non-orthogonal multiple access schemes for 5G. In 2015 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (pp. 1-5). IEEE.

[4] Hussain, S. A., Ahmad, N., Shayea, I., Kaidi, H. M., Abdul, L., Latiff, N. M., & Sam, S. M. (2021). A review of codebook design methods for sparse code multiple access. Indonesian Journal of Electrical Engineering and Computer Science, 22(2), 319-327.

[5] Taherzadeh, M., Nikopour, H., Bayesteh, A., & Baligh, H. (2014, September). SCMA codebook design. In 2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall) (pp. 1-5). IEEE.

[6] Ghaffari, A., Leonardon, M., Cassagne, A., Leroux, C., & Savaria, Y. (2019). Toward high-performance implementation of 5G SCMA algorithms. IEEE Access, 7, 10402-10414.

[7] Luo, F. L., & Zhang, C. J. (Eds.). (2016). Signal processing for 5G: algorithms and implementations. John Wiley & Sons.

[8] Zeng, Jie, Tiejun Lv, Zhipeng Lin, Ren Ping Liu, Jiajia Mei, Wei Ni, and Y. Jay Guo. "Achieving ultrareliable and low-latency communications in IoT by FD-SCMA." IEEE Internet of Things Journal 7, no. 1 (2019): 363-378.

[9] Chen, G., Dai, J., Niu, K. and Dong, C. Optimal receiver design for SCMA system. 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC). IEEE. 2017. 1–6.

[10] Wei, F., & Chen, W. (2017, December). Message passing receiver design for uplink grant-free SCMA. In 2017 IEEE Globecom Workshops (GC Wkshps) (pp. 1-6). IEEE.

[11] C.-P. Wei, H. Yang, C.-P. Li, and Y.-M. Chen, "SCMA Decoding via Deep Learning," IEEE Wireless Communications Letters, 2020.

[12] Yang, L., Ma, X. and Siu, Y. Low complexity MPA detector based on sphere decoding for SCMA. IEEE Communications Letters, 2017. 21(8): 1855– 1858.

[13] I. Ali, U. Wasenmüller, and N. Wehn, "A high throughput architecture for a low complexity soft-output demapping algorithm," Advances in Radio Science, vol. 13, no. C., pp. 73-80, 2015.

[14] A. Syukra, K. Anwar, and D. M. Saputri, "On the Design of Optimal Soft Demapper for 5G NR Wireless Communication Systems," in 2020 10th Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS), 2020, pp. 313-318: IEEE.

[15] Yang, L., Liu, Y., & Siu, Y. (2016). Low complexity message passing algorithm for SCMA system. IEEE Communications Letters, 20(12), 2466-2469.

[16] da Silva, B. F., Le Ruyet, D., & Uchoa-Filho, B. F. (2020). Threshold-based edge selection MPA for SCMA. IEEE Transactions on Vehicular Technology, 69(3), 2957-2966.

[17] Min, B., & Sun, J. (2019, July). Message passing algorithm with dynamic thresholds in SCMA. In 2019 International Conference on Communications, Information System and Computer Engineering (CISCE) (pp. 324-327). IEEE.

[18] Vameghestahbanati, M., Marsland, I. D., Gohary, R. H., & Yanikomeroglu, H. (2019). Multidimensional constellations for uplink SCMA systems—A comparative study. IEEE Communications Surveys & Tutorials, 21(3), 2169-2194.

[19] Yu, L., Lei, X., Fan, P., & Chen, D. (2015, October). An optimized design of SCMA codebook based on star-QAM signaling constellations. In 2015 International Conference on Wireless Communications & Signal Processing (WCSP) (pp. 1-5). IEEE.

[20] 3GPP, "Physical channels and modulation," Tech. Rep., 2018.

[21] Anwar, K., & Matsumoto, T. (2012, May). Iterative spatial demapping for two correlated sources with power control over fading MAC. In 2012 IEEE 75th Vehicular Technology Conference (VTC Spring) (pp. 1-7). IEEE.

[22] Yang, B., Zhang, L., Qiao, D., Zhao, G., & Imran, M. A. (2018, December). Narrowband Internet of Things (NB-IoT) and LTE systems coexistence analysis. In 2018 IEEE Global Communications Conference (GLOBECOM) (pp. 1-6). IEEE.