

Soft values based detector for bit interleaved coded modulation multi input multi output systems

Amjad N. Jabir, Atyaf Sami Noori

Department of Computer Engineering, Dijlah University College, Baghdad, Iraq

Article Info

Article history:

Received Jun 29, 2022

Revised Jul 30, 2022

Accepted Aug 20, 2022

Keywords:

BICM

LLR

LSD

MIMO

ABSTRACT

With the advantages of spatial multiplexing multi input multi output (MIMO) systems in terms of high transmission capacity, the high complexity of the detector at the receiver side of such systems is a major issue. Performance, in terms of bit error rate (BER) is studied for bit interleaved coded modulation (BICM) MIMO systems. List based generation of (bits) soft values is considered for 2 by 2, 4 by 4 systems with 16,64 quadrature amplitude modulation (QAM) and different list sizes utilizing a non systematic convolutional code. Using a sphere detector partial tree search, a scheme is suggested and shown to be more computationally efficient (in terms of the average number of scanned nodes) than a reported alternative for block, flat fading channels. Simulation results reveal that performance in terms of BER can still be maintained.

This is an open access article under the [CC BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.



Corresponding Author:

Amjad N. Jabir

Department of Computer Engineering, Dijlah University College

AlMasafi St, Baghdad 00964, Iraq

Email: amjad.najim@duc.edu.iq

1. INTRODUCTION

The idea of bit interleaved coded modulation (BICM) was first introduced in [1] for the case of a single antenna and 8PSK modulation. A bit-wise interleaver at a binary convolutional encoder output was used with a soft input Viterbi decoder fed by soft bit metrics. It was shown to give a good coding gain over Rayleigh fading channels [1], [2]-[6]. BICM approach was extended to a multi input multi output (MIMO) system setup [7], [8]. It is an attractive solution since the modulation and coding schemes are selected separately rather than dependently as in trellis coded modulation (TCM) of [9]. Muller-Weinfurter [10], it has been shown that the BICM is superior to the space time trellis coded MIMO system of [11], [12] (in fast fading channels). The capacity aspect of such BICM systems was studied in [13]. An adaptive BICM variant was suggested in [14]. BICM system with spatial component interleaver was proposed in [15]. Various approaches were suggested for detection in such systems [16]-[18]. Meeting the requirements of today's and future wide range of data services relies on the design and implementation of reliable, reduced complexity MIMO receivers to utilize the available system resources efficiently.

The focus of this paper is the design of a soft detector in a BICM spatial multiplexing MIMO system. We propose a simple partial tree search based soft detector. This work is organized as follows. Section 2 presents the system model. Section 3 details the generation of bits log likelihood ratios (LLR's). Simulation results with discussion and the conclusion are in sections 4 and 5, respectively.

2. SYSTEM MODEL

The BICM MIMO system is shown in Figure 1, a block (or packet) of source data bits is fed to a standard convolutional encoder with code rate R and then interleaved before being mapped to complex

symbols by a quadrature amplitude modulation (QAM) modulator. A demultiplexer then splits the symbols stream into m branches to be sent by the m transmitter antennas. The n received signals are first processed by a soft output MIMO detector that generates soft bits values or *LLR*'s that are combined together into one stream by the multiplexer. The original order is retrieved by a deinterleaver that feeds soft input Viterbi decoder. The complex baseband, flat fading equation at any time instant is [19]:

$$r = Hs + n \quad (1)$$

with r as the $n \times 1$ received vector, s as the $m \times 1$ transmitted vector, H as $n \times m$ MIMO channel matrix with elements $H_{i,j}$ as the complex channel gains between receiver antenna i and the transmitter antenna j that are assumed to be independently and identically distributed (iid) with real and imaginary components as Gaussian random variables with zero mean and variance of 0.5.

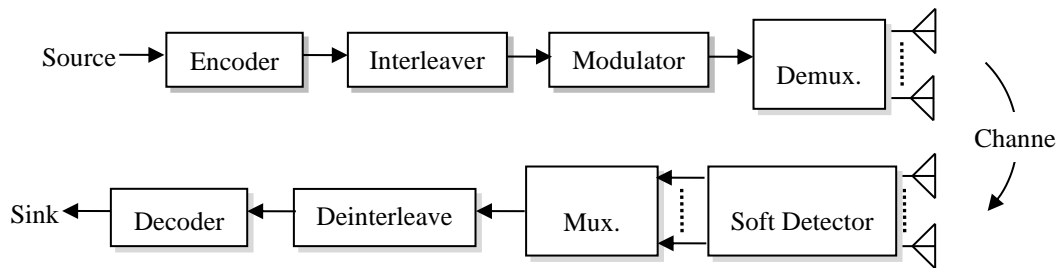


Figure 1. Bit interleaved coded modulation MIMO system setup

The $n \times 1$ complex noise vector n is also assumed to have iid elements of zero mean and variance σ^2 and a covariance matrix of $E(nn') = \sigma^2 I_n$, where E is the expectation operator, $(\)'$ is the conjugated transposition of $(\)$ and I_n is the $n \times n$ identity matrix. Elements of the vector s are assumed to be independently drawn from a gray mapped constellation and scaled to have a unit average power, i.e., $E(ss') = I_m$. The constellation size is α and the possible transmitted vector combinations are $\Omega = \alpha^m$.

3. METHOD

The sphere detector (SD) [20] is an efficient, depth first, tree search based method to find the transmitted vector s that satisfies the condition of:

$$\min_{s \in \Omega} \|r - Hs\|^2$$

it examines a limited search space of all the Hs points lying inside a sphere of radius r centered at the received vector r . Using the structure of the upper triangular matrix R of the QR decomposition of the channel matrix H [16]:

$$\sum_{i=1}^m |r'_i - \sum_{j=i}^m R_{i,j} s_j|^2 \leq r^2 \quad (2)$$

$r' = Q'r$, $Q'Q = QQ' = I_m$ and the multiplication by the unitary matrix Q' does not change the norm value of the distance $\|r - Hs\|^2$. The algorithm begins at the top level, m of the tree in Figure 2, with the selection of the candidate symbol, s_m , that should satisfy the condition:

$$|r'_m - R_{m,m} s_m|^2 \leq r^2$$

once such a symbol is found, s_m will be set to it and the search moves down to level $m-1$, where the condition for the selection of the symbol s_{m-1} , is:

$$|r'_m - R_{m,m} s_m|^2 + \left| r'_{m-1} - \sum_{j=m-1}^m R_{m-1,j} s_j \right|^2 \leq r^2$$

Again, with the first symbol value found to satisfy that condition, s_{m-1} will be set accordingly and search continues downward until the bottom or leaves level of the tree is reached with the constraint:

$$\sum_{i=2}^m \left| r'_i - \sum_{j=i}^m R_{i,j} s_j \right|^2 + \left| r'_1 - \sum_{k=1}^m R_{1,k} s_k \right|^2 \leq r^2$$

it is seen from the above that search radius constraint becomes tighter as it scans the tree in downward direction since all the terms are larger than zero. The above search can be expressed in term of the branch and path metrics; at the top level m , they are the same:

$$P_m = B_m$$

at any other (lower) level, i :

$$P_i = P_{i+1} + B_i$$

the path metric, P_i , at the i^{th} level is the accumulated path metric starting from the top level until the level i (included) and it equals the path metric of the parent branch, P_{i+1} plus the branch metric at the level i :

$$B_i = \left| r'_i - \sum_{j=i}^m R_{i,j} s_j \right|^2, i = m, m-1, \dots, 1$$

$$P_{i+1} = \sum_{j=i+1}^m B_j$$

Along any path in the search tree, the resulting metrics are interrelated; a symbol selection at any branch (node) will affect all the subsequent metrics. If the path metric at any level i , does not satisfy the radius constraint, that branch will be pruned from the tree and not extended further and another symbol selection for that branch will be tested for the same parent node or branch; once found it will be extended further downward. Once a complete path is found from top to a certain leaf at the bottom, the search radius will be reduced to the total path metric of that leaf and search continues with that reduced radius which greatly reduces the complexity expressed as the average amount of scanned nodes. At any level, when all the possible symbol values (or branches) have been tested for complying with the radius constraint at that level, possibly with some pruned, the Algorithm moves up by one level, shifts right by one position and search is continued. Eventually, the vector with the smallest path length is nominated as the solution. If no such total path is found, the radius is considered to be small; it would be increased and search is restarted.

It is clear that the complexity is critically dependent on radius selection. It is usually selected based on noise properties; since $\|r - Hs\|^2 = \|n\|^2$, and $\|n\|^2$ is a chi square random variable with $2n$ degrees of freedom, each term of which has a variance of $\frac{1}{2}\sigma^2$, the radius is set in [21] as $r^2 = k n \sigma^2, k \geq 1$ where $n \sigma^2$ as the average value of that variable. Using the inverse cumulative distribution function (CDF) of such variable, the radius is selected in [19] as the value that this variable will have (i.e., be smaller than or equal to) with a probability that is to be set high enough. There are two important features in the more efficient implementation of the sphere detector of [22]. Firstly, the entire possible symbol values are checked at each level with the resulting branch lengths (or the partial path metrics) sorted in an ascending order. As such, once a path is found that does not satisfy the radius constraint, it will be excluded from the search tree along with all its subsequent branches at that hierarchy level. Secondly, the algorithm starts with an infinite radius and whenever the point Hs is found to have a path length that is smaller than the radius (including the first point), the radius value will be reduced to that metric and search is continued.

The detector in the non iterative system setup of Figure 1 generates bits LLR 's based on [23]:

$$LLR(c_i|r) = \frac{1}{\sigma^2} \left[\min_{s: c_i=0} \|r - Hs\|^2 - \min_{s: c_i=1} \|r - Hs\|^2 \right] \quad (3)$$

$$i = 1, 2, \dots, mM_c$$

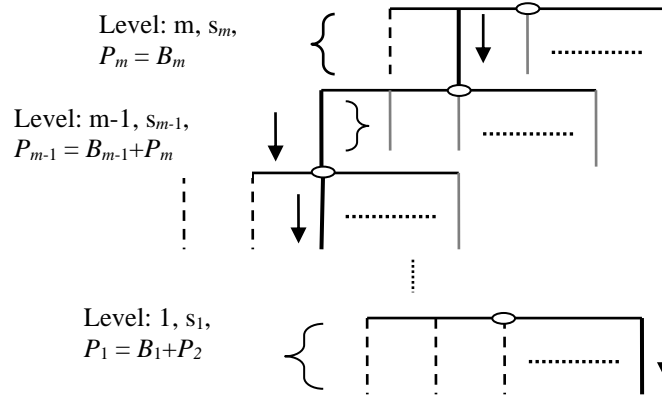


Figure 2. Sphere detector, dashed lines for branches that do not satisfy radius constraint, thin lines for branches yet to be tested, bold lines with arrows indicate one valid complete path

The minimizations in (3) have to be done (per bit) over all the 2^{mM_c-1} possible bit combinations (with the corresponding symbol vector s) that have the bit c_i as 0 or 1. Doing an exhaustive search over such vectors would be highly inefficient and complex. A list sphere detector (LSD) is proposed where a list is constructed that contains the vectors with the least total path metric $\|r - Hs\|^2$ out of an SD that scans the full tree [21]. The list vectors are then used in (3). The list size grows with the number of bits per channel use, mM_c with more reliable LLR value obtained with larger list sizes. Since the LSD has to scan the full tree, it is still complex especially for systems with large dimension of Ω . Here, we modify the SD of [22] to find a limited number of vectors to be used in (3). In this modification, the search radius is selected according to n and the noise variance as in [21]. Since the original algorithm is aimed at finding hard output solution with the minimum of total path metric $\|r - Hs\|^2$, it considers only the first branch at the bottom level since that would be, with sorting, the one with the least metric. We use all the valid branches at that level to construct the list out of a partial tree search and use the first candidate vectors found to satisfy the radius constraint. Radius reduction will be disabled and if the number of found vectors at a certain radius is less than the list size, then the radius is increased just to look for extra ones to fill the list. All the path metrics for the list vectors are fed back to be used for the calculation of the soft values.

4. SIMULATION RESULTS AND DISCUSSION

We used the 64 state, rate $R = \frac{1}{2}$, non systematic convolutional code with octal generator polynomial of (133,171)₈, six bits were used for trellis termination and the decoder trace back length was 35 bits. Block fading model is used where the channel stays unaltered for a number of channel uses and then changes, randomly and independently, from block to another. Figures 3 and 4 show the complexity in terms of the average number of visited nodes with list size $L = 64$ and 128, respectively for a 4×4 system with 16 QAM.

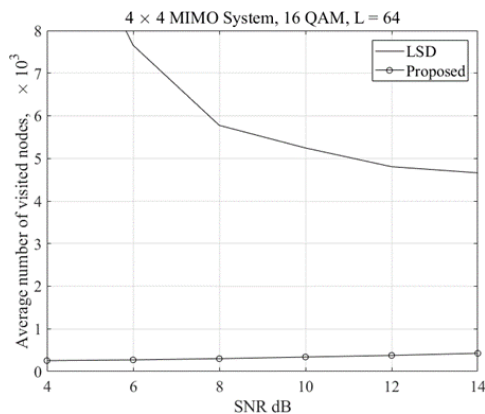


Figure 3. Average number of scanned nodes 4 by 4 system with 16 QAM and $L=64$

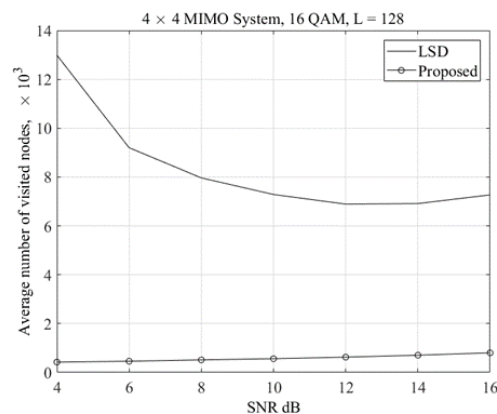


Figure 4. Average number of scanned nodes 4 by 4 system with 16 QAM and $L=128$

Figures 5 and 6 show the corresponding bit error rate (BER) graphs where the mmse and zero forcing (ZF) based detectors refer to those of [23], [24], respectively. Compared with reference LSD method of [21], it is seen that our current suggestion reduces the complexity much further with effectively a very close performance. For that purpose, an extra cost of sorting is required which is in the order of $\mathcal{O}(\alpha \log \alpha)$ of the (quick sort) algorithm of MATLAB [25]. The net effect is a noticeably faster approach.

Figures 7 and 8 present a similar comparison in terms of the BER and complexity for the case of a 2 by 2 system with 64 QAM and $L = 128$. It is to be noted that search tree for this case is considerably smaller than that of Figures 3 and 4; there is $64^2 = 4096$ and $16^4 = 65536$ possible transmitted vector combinations for the first and second cases, respectively. The performances of detectors of [23], [24] have come closer together as shown in Figure 7 (in comparison to that of Figure 5). Figure 5 shows a gap of about 1 dB at $BER = 10^{-3}$ between the tree search based detectors and that of [23].

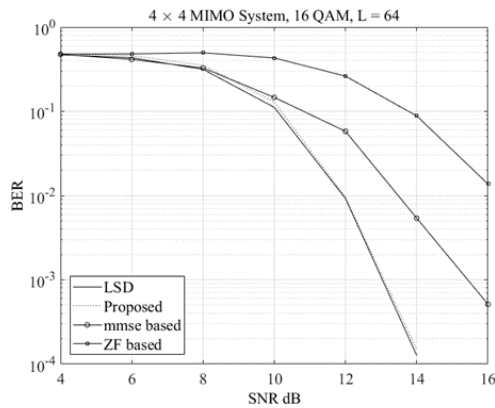


Figure 5. BER vs. SNR for a 4 by 4 system with 16 QAM and $L=64$

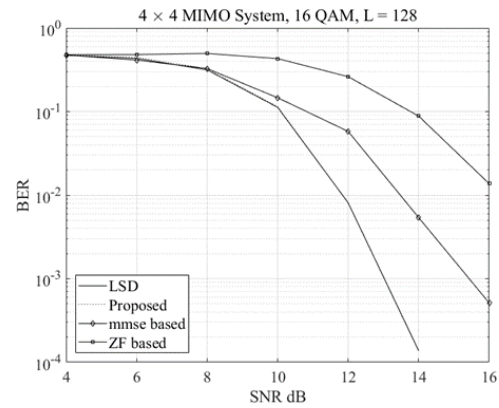


Figure 6. BER vs. SNR for a 4 by 4 system with 16 QAM and $L=128$

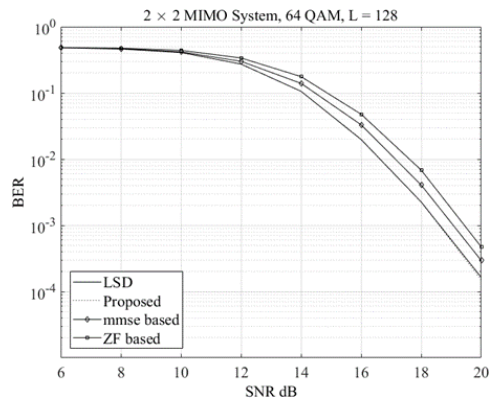


Figure 7. BER vs. SNR for a 2 by 2 system with 64 QAM and $L=128$

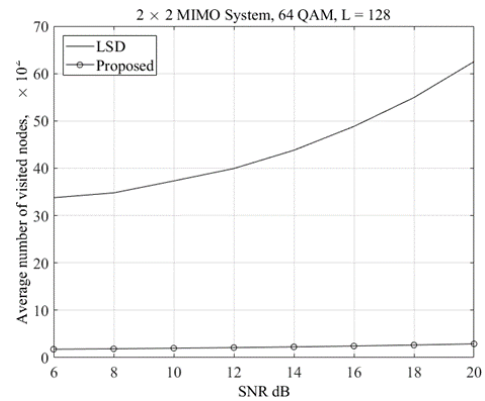


Figure 8. Average number of scanned nodes 2 by 2 System with 64 QAM and $L=128$

5. CONCLUSION

An efficient, reduced complexity, partial tree search based soft detector has been suggested for BICM MIMO systems. It is shown by simulations that a very close performance is achieved at a much lower computational effort in terms of the average number of scanned nodes. It is thought that the suggested method is promising to be further utilized in an iterative system setup to be dealt with in a future work.




REFERENCES

- [1] E. Zehavi, "8-PSK trellis codes for a Rayleigh channel," in *IEEE Transactions on Communications*, vol. 40, no. 5, pp. 873-884, May 1992, doi: 10.1109/26.141453.
- [2] E. Akay, E. Sengul, and E. Ayanoglu, "Bit Interleaved coded multiple beamforming," in *IEEE Transactions on Communications*, vol. 55, no. 9, pp. 1802-1811, Sept. 2007, doi: 10.1109/TCOMM.2007.904405.




- [3] H. J. Park and E. Ayanoglu, "Diversity analysis of bit-interleaved coded multiple beamforming," *2009 IEEE International Conference on Communications*, 2009, pp. 1-9, doi: 10.1109/ICC.2009.5198942.
- [4] E. Sengul, H. J. Park, and E. Ayanoglu, "Bit-interleaved coded multiple beamforming with imperfect CSIT," in *IEEE Transactions on Communications*, vol. 57, no. 5, pp. 1505-1513, May 2009, doi: 10.1109/TCOMM.2009.05.070237.
- [5] P. Elia, B. A. Sethuraman, and P. V. Kumar, "Perfect space-time codes with minimum and non-minimum delay for any number of antennas," *2005 International Conference on Wireless Networks, Communications and Mobile Computing*, vol. 1, pp. 722-727, 2005, doi: 10.1109/WIRLES.2005.1549496.
- [6] G. Caire, G. Taricco, and E. Biglieri, "Bit-interleaved coded modulation," in *IEEE Transactions on Information Theory*, vol. 44, no. 3, pp. 927-946, May 1998, doi: 10.1109/18.669123.
- [7] E. Biglieri, G. Caire, and G. Taricco, "Recent results on coding for multiple-antenna transmission systems," *2000 IEEE Sixth International Symposium on Spread Spectrum Techniques and Applications. 2000. Proceedings*, 2000, pp. 117-121, doi: 10.1109/ISSSTA.2000.878093.
- [8] J. J. Boutros, F. Boixadera, and C. Lamy, "Bit-interleaved coded modulations for multiple-input multiple-output channels," *2000 IEEE Sixth International Symposium on Spread Spectrum Techniques and Applications. ISSSTA 2000. Proceedings (Cat. No.00TH8536)*, vol. 1, pp. 123-126, 2000, doi: 10.1109/ISSSTA.2000.878095.
- [9] G. Ungerboeck, "Channel coding with multilevel/phase signals," in *IEEE Transactions on Information Theory*, vol. 28, no. 1, pp. 55-67, Jan. 1982, doi: 10.1109/TIT.1982.1056454.
- [10] S. H. Muller-Weinfurter, "Coding approaches for multiple antenna transmission in fast fading and OFDM," in *IEEE Transactions on Signal Processing*, vol. 50, no. 10, pp. 2442-2450, Oct. 2002, doi: 10.1109/TSP.2002.803351.
- [11] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction," in *IEEE Transactions on Information Theory*, vol. 44, no. 2, pp. 744-765, Mar. 1998, doi: 10.1109/18.661517.
- [12] A. F. Naguib, V. Tarokh, N. Seshadri, and A. R. Calderbank, "A space-time coding modem for high-data-rate wireless communications," in *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1459-1478, Oct. 1998, doi: 10.1109/49.730454.
- [13] A. Alvarado, F. Brannstrom, and E. Agrell, "A simple approximation for the bit-interleaved coded modulation capacity," in *IEEE Communications Letters*, vol. 18, no. 3, pp. 495-498, Mar. 2014, doi: 10.1109/LCOMM.2014.011314.132633.
- [14] Z. Zhou, B. Vucetic, and Z. Chen, "Adaptive bit-interleaved coded modulation MIMO system with near full multiplexing gain," *2007 IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications*, 2007, pp. 1-5, doi: 10.1109/PIMRC.2007.4394470.
- [15] X. Gao and Z. Wu, "Precoded spatial multiplexing MIMO system with spatial component interleaver," *EURASIP journal on wireless communications and networking*, vol. 1, pp. 1-15, 2016, doi: 10.1186/s13638-016-0558-8.
- [16] G. D. Golden, C. J. Foschini, R. A. Valenzuela, and P. W. Wolniansky, "Detection algorithm and initial laboratory results using V-BLAST space-time communication architecture," in *Electronics Letters*, vol. 35, no. 1, pp. 14-16, Jan. 1999, doi: 10.1049/el:19990058.
- [17] H. Artes, D. Seethaler, and F. Hlawatsch, "Efficient detection algorithms for MIMO channels: a geometrical approach to approximate ML detection," in *IEEE Transactions on Signal Processing*, vol. 51, no. 11, pp. 2808-2820, Nov. 2003, doi: 10.1109/TSP.2003.818210.
- [18] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, "V-BLAST: an architecture for realizing very high data rates over the rich-scattering wireless channel," *1998 URSI International Symposium on Signals, Systems, and Electronics. Conference Proceedings (Cat. No.98EX167)*, 1998, pp. 295-300, doi: 10.1109/ISSSE.1998.738086.
- [19] H. Vikalo, B. Hassibi and T. Kailath, "Iterative decoding for MIMO channels via modified sphere decoding," in *IEEE Transactions on Wireless Communications*, vol. 3, no. 6, pp. 2299-2311, Nov. 2004, doi: 10.1109/TWC.2004.837271.
- [20] U. Fincke and M. Pohst, "Improved methods for calculating vectors of short length in a lattice, including a complexity analysis," in *Mathematics of Computation*, vol. 44, no. 170, pp. 463-71, 1985, doi: 10.2307/2007966.
- [21] B. M. Hochwald and S. T. Brink, "Achieving near-capacity on a multiple-antenna channel," in *IEEE Transactions on Communications*, vol. 51, no. 3, pp. 389-399, Mar. 2003, doi: 10.1109/TCOMM.2003.809789.
- [22] C. P. Schnorr and M. Euchner, "Lattice basis reduction: Improved practical algorithms and solving subset sum problems," in *Mathematical Programming*, vol. 66, pp. 181-199, 1994, doi: 10.1007/BF01581144.
- [23] D. Seethaler, G. Matz, and F. Hlawatsch, "An efficient MMSE-based demodulator for MIMO bit-interleaved coded modulation," *IEEE Global Telecommunications Conference, 2004. GLOBECOM '04*, vol. 4, pp. 2455-2459, 2004, doi: 10.1109/GLOCOM.2004.1378448.
- [24] M. R. G. Butler, and I. B. Collings, "A zero-forcing approximate log-likelihood receiver for MIMO bit-interleaved coded modulation," in *IEEE Communications Letters*, vol. 8, no. 2, pp. 105-107, Feb. 2004, doi: 10.1109/LCOMM.2004.823435.
- [25] MATLAB answers, "What type of sort does the SORT function in MATLAB perform?," *MathWorks*. [Online]. Available: www.mathworks.com/support/solutions/en/data/1-15K1B/index.html?product=SL&solution=1-15K1B.

BIOGRAPHIES OF AUTHORS



Amjad N. Jabir    is a lecturer at the Department of Computer Engineering, Dijlah University College, Baghdad, Iraq. His research areas of interest are MIMO communication, DSP and image processing. He holds a Ph.D degree in communication engineering and networking from UPM University, Malaysia. He can be contacted at email: amjad.najim@duc.edu.iq.



Atyaf Sami Noori    is currently a lecturer at the Department of Computer Engineering, Dijlah University College, Baghdad, Iraq. Her research areas of interest are information systems, image processing and neural networks applications. She holds a PhD degree in Information technology from UUM University, Malaysia. She can be contacted at email atyaf.sami@duc.edu.iq.