

Responses to reviewers' comments

Deep Learning Based Cooperative MIMO Systems for Wireless Body Area Networks

Dear Editor and Reviewers,

We would like to express our sincere thanks to the editor and anonymous reviewers for their time in evaluating our manuscript and providing us with various constructive comments that help us to improve the presentation of our manuscript.

We have carefully addressed all the editor and reviewers' comments and provided a point-by-point reply. The comments of the Editor and Reviewers are typeset in *italic font* and our responses are written in blue color plain font. Additionally, in the revised manuscript, explanations and justifications according to reviewers' comments have been highlighted in *italic font*. Other minor corrections and rearrangements have not been highlighted.

Yours sincerely,

1 Responses to the comments of Editor

Comment of Editor: *The research results reported are too premature for publication. More work is needed to substantiate the conclusions in your manuscript. The reviewers suggested some substantial revisions, which I hope you will consider and address.*

Reply: We would like to thank you for giving us opportunity to revise our manuscript. Following your comments, we have revised our manuscript accordingly and provided our detailed responses to your comments as follows.

We hope that the editor satisfies our response. Again, thank you very much for your helpful comment.

2 Responses to the comments of Reviewer 1

We would like to thank you for reading our manuscript and providing us with various constructive comments. Following your comments, we have revised our manuscript accordingly and provided our detailed responses to your comments as follows.

- 2.1.** *In this manuscript, a approach using deep learning-based cooperative Multiple-Input Multiple-Output systems with the autoencoder technique has been investigated. My comments are as follows: Is the training procedure practical in the real communication system? The overhead should be further discussed.*

Reply: We are grateful for your suggestion. In the revised manuscript, We provide further details about the practical training procedure of the proposed systems. Specifically, the proposed systems use three datasets, $\mathbf{b}$, $\mathbf{z}$, and $\mathbf{H}$, to train within a range of SNR as described in Algorithms 1 and 2. To achieve the best performance for the system, the dataset for channel $\mathbf{z}$ and $\mathbf{H}$, should closely resemble the practical realizations, ideally measured on an actual channel [R1], [R2]. However, these methods require a significant amount of time and complexity. Therefore, to facilitate the evaluation of the proposed solution in research, datasets are often generated using computer simulations such as Matlab, GNURadio, or Python.

Furthermore, compared to baseline systems, proposed systems require additional offline training time to obtain optimal parameter sets. However, once trained on a sufficiently large dataset, the system can operate without needing to be retrained [R3] or undergo additional transfer learning phase to improve its performance [R4].

[R1] Aoudia, Fay & Hoydis, Jakob. (2019). Model-Free Training of End-to-End Communication Systems. *IEEE Journal on Selected Areas in Communications*. PP. 1-1. 10.1109/JSAC.2019.2933891.

[R2] Cammerer, Sebastian et al. "Trainable Communication Systems: Concepts and Prototype." *IEEE Transactions on Communications* 68 (2019): 5489-5503.

[R3] T. O'Shea and J. Hoydis, "An Introduction to Deep Learning for the Physical Layer," in *IEEE Transactions on Cognitive Communications and Networking*, vol. 3, no. 4, pp. 563-575, Dec. 2017.

[R4] S. Dörner, S. Cammerer, J. Hoydis and S. t. Brink, "Deep Learning Based Communication Over the Air," in *IEEE Journal of Selected Topics in Signal Processing*, vol. 12, no. 1, pp. 132-143, Feb. 2018.

Revision: We have added to line 428 of page 18 in the revised manuscript.

"To achieve the best performance for the system, the dataset for channel $\mathbf{z}$ and $\mathbf{H}$, should closely resemble the practical realizations, ideally measured on an actual channel [R1], [R2]. However, these methods require a significant amount of time and complexity. Therefore, to facilitate the evaluation of the proposed solution in research, datasets are often generated using Python simulation. The realizations of $\mathbf{H}$ is generated with a Rayleigh distribution, and the dataset $\mathbf{z}$ consists of Gaussian random variables with a variance of sigma and a mean value of 0."

we have added to line 526 of page 24 in the revised manuscript.

"To attain the optimum performance for the system, the channel datasets, $\mathbf{z}$ and $\mathbf{H}$, should closely mirror the practical realizations, ideally measured on a real-world channel. However, to ease the evaluation of the suggested approach, datasets, $\mathbf{H}$ and $\mathbf{z}$, with Rayleigh and Gaussian distributions, respectively, are generated using Python simulation.

We further discuss the overhead of the proposed algorithm in the conclusion section, at line 731 of page 34 in the revised manuscript.

“Additionally, compared to baseline systems, proposed systems require additional offline training time to obtain optimal parameter sets.

- 2.2.** *The computation complexity and the energy consumption of the proposed system should be analyzed since there are many limitations for nodes in WBAN.*

Reply: We sincerely thank you for your suggestion. In order to compare the computational complexity between baseline and proposed systems, We represent mathematical transformations from the source node to the destination node using the number of floating-point operations (flops) [R5].

In the context of proposed systems using autoencoder (AE) techniques, the computational complexity is calculated as the sum of operations on each fully connected (FC) layer. The activation functions do not significantly increase the complexity of the system [R6]. In the la -th layer, if the numbers of input nodes and output nodes are respectively N_{la-1} and N_{la} , then the complexity is calculated as follows [R6]:

$$C_{la} = 2N_{la-1}N_{la} + N_{la}$$

The computational complexity of a feedforward neural network (FNN) with La hidden layers is calculated using the expression:

$$C_{FNN} = 2N_{in}N_1 + N_1 + \sum_{la=2}^{La-1} (2N_{la-1}N_{la} + N_{la}) + 2N_{La}N_{out}$$

where N_{in} and N_{out} are the number of neurons at the input and the output layers of the FNN network, respectively.

First, we calculate the complexity of the AE-AF-MMSE system. At the source node of AE-AF-MMSE system, The AE system uses bit-labeling method, where $P = Nk$ and the label is encoded into a transmitted signal by an encoder. Total computational complexity is $128Nk + 258N + 16576$.

At the relay node of AE-AF-MMSE system, the relay node amplifies the signal $\mathbf{y}_{sr}^{am}$ by utilizing the amplification matrix $\mathbf{F}$, as follows: $\mathbf{F}\mathbf{y}_{sr}^{am}$, where $\mathbf{F} = \text{diag}\{f_1, f_2, \dots, f_{2N}\}$, and f_i is calculated in (8). Total computational complexity is $4N^2 + 9N$.

At the destination node, the received signals are detected and decoded following equations (11) - (13), and computational complexity is $48N^3 + 26N^2 + 129Nk + 128NR - N + 16576$ with R is the number of relay nodes. The computational complexity of AE-AF-MMSE is detail listed in Table 1.

Then, the computational complexity of the baseline and the proposed systems in the case of one direct path and one relay path is listed in Table 2.

In the AF-MMSE system, the modulation and DEMUX at the source node have a complexity of Nk flops with $k = \log_2(M)$; at the destination node, the demodulation and MUX have a complexity of Nk flops. The complexity of the transformations at the relay node and signal detector at the destination node is calculated as in the AE-AF-MMSE system.

Table 1: The neural network architecture and computational complexity of the AE-AF-MMSE System

	Layer $\times$ layer No.	Activation function	Output neurons	Computational complexity (flops)
Source node (TxS)				$128Nk + 258N + 16576$
Encoder (Enc)	input	-	P	0
	FC $\times 3$	relu	64	$128Nk + 16576$
	FC	linear	$2N$	$258N$
	Normalization	-	$2N$	0
Channel	Rayleigh	-	$2NN$	0
Relay	Amplify	-	$2N$	$4N^2 + 9N$
Destination node (RxD)				$48N^3 + 26N^2 + 129Nk + 128NR - N + 16576$
Detector	MMSE	-	$2N$	$48N^3 + 26N^2 - N$
Decoder (Dec)	FC $\times 3$	relu	64	$128NR + 16576$
	FC	sigmoid	P	$129Nk$

Table 2: Compare the computational complexity of the base systems and the proposed systems

	Source	Relay	Destination	Sum of complexity
AF-MMSE	Nk	$4N^2 + 9N$	$48N^3 + 26N^2 + Nk - N$	$48N^3 + 30N^2 + 2Nk + 8N$
AE-AF-MMSE	$128Nk + 258N + 16576$	$4N^2 + 9N$	$48N^3 + 26N^2 + 128NR$ $129Nk - N + 16576$	$48N^3 + 30N^2 + 128NR +$ $257Nk + 266N + 33152$
AE-AF-RTN	$128Nk + 258N + 16576$	0	$272N^2 + 128NR + 129Nk +$ $512N + 49728$	$272N^2 + 128NR + 257Nk +$ $770N + 66304$
DF-ZF	Nk	$24N^3 + 6N^2 + 2Nk - 2N$	$24N^3 + 6N^2 + Nk - 2N$	$48N^3 + 12N^2 + 4Nk - 4N$
DF-MMSE	Nk	$24N^3 + 12N^2 + 2Nk - N$	$48N^3 + 26N^2 + Nk - N$	$72N^3 + 38N^2 + 4Nk - 2N$
AE-DF-MMSE	$128Nk + 258N + 16576$	$24N^3 + 12N^2 + 128NR +$ $257Nk + 257N + 33152$	$48N^3 + 26N^2 + 128NR +$ $129Nk - N + 16576$	$72N^3 + 38N^2 + 256NR +$ $514Nk + 514N + 66304$
AE-DF-RTN	$128Nk + 258N + 16576$	$136N^2 + 128NR + 257Nk +$ $514N + 49728$	$272N^2 + 128NR + 129Nk +$ $512N + 49728$	$408N^2 + 256NR + 514Nk +$ $1284N + 116032$

Table 3: Compare the computational complexity of the base systems and the proposed systems with $k = 1$ for Figure 7, Figure 8, Figure 10 and Figure 11 in our manuscript

	$N = 2$	$N = 3$	$N = 4$
AF-MMSE	524	1596	3592
AE-AF-MMSE	34958	36671	39308
AE-AF-RTN	69702	72217	75276
DF-ZF	432	1404	3264
DF-MMSE	732	2292	5224
AE-DF-MMSE	69600	72442	76656
AE-DF-RTN	121772	125866	130776

Table 4: Compare the computational complexity of the base systems and the proposed systems for Figure 9 in our manuscript

	complexity	number of flops with $N = 2, k = 1$
AF-MMSE-wdirect	$48N^3 + 30N^2 + 2Nk + 8N$	524
AF-MMSE-1relay	$24N^3 + 16N^2 + 2Nk + 8N$	276
AF-MMSE-2relay	$48N^3 + 34N^2 + 2Nk + 17N$	558
AF-MMSE-3relay	$+ 72N^3 + 96N^2 + 2Nk + 24N$	1012
AE-AF-RTN-wdirect	$272N^2 + 128NR + 257Nk + 770N + 66304$	69702
AE-AF-RTN-1relay	$136N^2 + 128NR + 257Nk + 514N + 49728$	52070
AE-AF-RTN-2relay	$272N^2 + 128NR + 257Nk + 770N + 66304$	69702
AE-AF-RTN-3relay	$408N^2 + 128NR + 257Nk + 1026N + 828804$	87334

Table 5: Compare the computational complexity of the base systems and the proposed systems for Figure 12 in our manuscript

	complexity	flops with $N = 2, k = 1$
DF-MMSE-wdirect	$72N^3 + 38N^2 + 4Nk - 2N$	732
DF-MMSE-1relay	$48N^3 + 24N^2 + 4Nk - 2N$	484
DF-MMSE-2relay	$96N^3 + 50N^2 + 6Nk - 3N$	974
DF-MMSE-3relay	$144N^3 + 120N^2 + 8Nk - 6N$	1636
AE-DF-RTN-wdirect	$408N^2 + 256NR + 514Nk + 1284N + 116032$	121772
AE-DF-RTN-1relay	$272N^2 + 256NR + 514Nk + 1028N + 99456$	104140
AE-DF-RTN-2relay	$544N^2 + 384NR + 771Nk + 1798N + 165760$	173842
AE-DF-RTN-3relay	$816N^2 + 512NR + 1028Nk + 2568N + 232064$	243544

The last column of Tables 2 indicates that, the number of required flops for the baseline systems, including AF-MMSE and DF-MMSE, are approximately $\mathcal{O}(48N^3)$ and $\mathcal{O}(72N^3)$, respectively. Similarly, The number of required flops for the AE-AF-MMSE and AE-DF-MMSE systems are approximately $\mathcal{O}(48N^3)$ and $\mathcal{O}(72N^3)$, respectively. Meanwhile, the AE-AF-RTN and AE-DF-RTN systems require approximately $\mathcal{O}(272N^2)$ and $\mathcal{O}(408N^2)$ flops, respectively.

Observing the computed complexity, as in Table 1-5, and the simulated BER performance results, it is evident that the proposed systems allow for a significant improvement in BER performance but come at the cost of increased computational complexity. However, as listed in Table 2, the

Table 6: Total power consumption of both baseline and the proposed systems in different cases

	w/direct	1relay	2relay	3relay
Number of Node	1 source, 1 relay	1 source, 1 relay	1 source 2 relay	1 source, 3 relay
Total power	2	2	3	4

computational complexity of the proposed systems is primarily due to computations at the destination node (Personal Device). The sensor nodes acting as source and forwarding nodes require fewer FLOPs, which aligns with the compact design requirements of sensors in a WBAN. The significant computational complexity of the proposed systems is also a major limitation, and reducing the computational complexity of these systems is one of the directions that we will continue to investigate in future research studies.

We constrain the simulation conditions by normalizing the transmission power of the source node and the relay nodes to 1 for both baseline and proposed systems. According to this assumption, the total power consumption of the systems listed in Table 6. The system’s power consumption will increase as the number of relay nodes increases. The best-case scenario is the cooperative system consisting of one direct transmission path and one relay path, which offers the best BER performance and the lowest power consumption.

[R5] G. H. Golub and C. F. Van Loan, *Matrix computations*, Johns Hopkins, Dec. 27, 2012.

[R6] Dubey, Shiv Ram and Singh, Satish Kumar and Chaudhuri, Bidyut. *Activation Functions in Deep Learning: A comprehensive Survey and Benchmark*, Neurocomputing. 503. 10.1016/j.neucom.2022.06.111.

[R7] Bhoomi Shah, Hetal Bhavsar, *Time Complexity in Deep Learning Models*, Procedia Computer Science, Volume 215, 2022, Pages 202-210, ISSN 1877-0509.

Revision: We added further description regarding the signal power normalization on line 342 of page 13 of the revised manuscript.

“The transmit vector $\mathbf{x}^{am}$ is power-normalized through the normalization layer in the encoder.

We added additional evaluation of the advantages and limitations of the systems to line 666 of page 31 in the revised manuscript.

“When the systems have the number of relay nodes $L = 1, 2, 3$, respectively, the BER curve gradually decreases, which means the performance of the systems improves. However, the system will have to pay the cost of computational complexity and energy consumption. Assuming that the transmission power of the source node and relay nodes is normalized to 1, the system’s power consumption will increase as the number of relay nodes increases. Table 6 lists the total transmission power of the system in various simulation scenarios. It is clear that the cooperative system with one direct transmission path and one relay path, which provides the best BER performance and the lowest power consumption, is the best-case situation. In the specific case where there is no direct path, depending on the requirements of each application, we choose the system configuration with the most suitable value of L .”

we added additional evaluation to line 711 of page 34 in the revised manuscript.

“The system’s performance is greatly enhanced when numerous relay paths are used. However, as shown in Table 6, the system must pay a price in the form of higher computing complexity and power consumption.”

We included additional evaluation of the complexity in the conclusion section to line 727 of page 34 in the revised manuscript.

“However, it is evident that the proposed systems allow for a significant improvement in BER performance but come at the cost of increased computational complexity. This is a significant limitation of the proposed systems, and reducing the computational complexity of these systems is one of the directions that we will continue to investigate in future research studies.”

2.3. *The relationship among real-valued channel vector, real-valued channel matrices and original channel matrices should be better explained.*

Reply: We sincerely thank you for your suggestion. The rules for transforming equivalent complex vectors and matrices into real-value vectors and matrices are presented in the document [R5]. Accordingly, if $\mathbf{H}^c \in \mathbb{C}^{N \times N}$ and $\mathbf{H} \in \mathbb{R}^{2N \times 2N}$ represent complex channel matrix and real-valued channel matrix, respectively, the relationship between $\mathbf{H}^c$ and $\mathbf{H}$ is as follows:

$$\mathbf{H} = \begin{bmatrix} \text{Re}(\mathbf{H}^c) & -\text{Im}(\mathbf{H}^c) \\ \text{Im}(\mathbf{H}^c) & \text{Re}(\mathbf{H}^c) \end{bmatrix}$$

Similarly, we represent the relationship between complex noise vector $\mathbf{z}^c \in \mathbb{C}^{N \times 1}$ and real-valued noise vector $\mathbf{z} \in \mathbb{R}^{2N \times 1}$ as follows:

$$\mathbf{z} = \begin{bmatrix} \text{Re}(\mathbf{z}^c) \\ \text{Im}(\mathbf{z}^c) \end{bmatrix}$$

Revision: In the revised manuscript, we give a description of the interaction between the complex channel matrix and the real-value channel matrix at line 351 of page 13 in the revised manuscript.

“The relationship between complex channel matrices, noise vectors and real-value channel matrices, noise vectors as follows:

$$\mathbf{H}_{sr} = \begin{bmatrix} \text{Re}(\mathbf{H}_{sr}^c) & -\text{Im}(\mathbf{H}_{sr}^c) \\ \text{Im}(\mathbf{H}_{sr}^c) & \text{Re}(\mathbf{H}_{sr}^c) \end{bmatrix}; \quad \mathbf{H}_{sd} = \begin{bmatrix} \text{Re}(\mathbf{H}_{sd}^c) & -\text{Im}(\mathbf{H}_{sd}^c) \\ \text{Im}(\mathbf{H}_{sd}^c) & \text{Re}(\mathbf{H}_{sd}^c) \end{bmatrix}; \quad \mathbf{z}_{r,1} = \begin{bmatrix} \text{Re}(\mathbf{z}_{r,1}^c) \\ \text{Im}(\mathbf{z}_{r,1}^c) \end{bmatrix}; \quad \mathbf{z}_{d,1} = \begin{bmatrix} \text{Re}(\mathbf{z}_{d,1}^c) \\ \text{Im}(\mathbf{z}_{d,1}^c) \end{bmatrix}$$

”

we add at 362 line of page 14 in the revised manuscript.

$$\text{“where } \mathbf{H}_{rd} = \begin{bmatrix} \text{Re}(\mathbf{H}_{rd}^c) & -\text{Im}(\mathbf{H}_{rd}^c) \\ \text{Im}(\mathbf{H}_{rd}^c) & \text{Re}(\mathbf{H}_{rd}^c) \end{bmatrix}; \mathbf{z}_{d,2} = \begin{bmatrix} \text{Re}(\mathbf{z}_{d,2}^c) \\ \text{Im}(\mathbf{z}_{d,2}^c) \end{bmatrix}; \text{”}$$

2.4. *There are many typos in the manuscript, e.g. symbols below Eq. (5)*

Reply: We sincerely value your careful reading. All typos and grammatical errors have been fixed in the revised version of the manuscript.

We hope that the reviewer satisfies our responses. Again, thank you very much for your helpful comments.

3 Responses to the comments of Reviewer 2

First of all, we would like to thank you for reading our manuscript and providing us with various constructive comments. Following your comments, we have revised our manuscript accordingly and provided our detailed responses to your comments as follows.

General comment: *Author presented "Autoencoder based Amplify forward & Decode forward cooperative algorithm for Body area networks" which is very relevant topic in current days. However the manuscript has several strong as well as weak aspects.*

Reply: We sincerely thank you for your appreciation of the contribution of our paper and your allowance to revise the manuscript. In the following parts, we will address your comment and suggestions.

3.1. *The literature survey to BAN is very restricted, which need to be revised and include more references esp. relating cooperative/MIMO BAN.*

Reply: We would like to thank you for suggestion. We have added studies on MIMO and cooperative MIMO for WBANs. The study [R8], [R9] introduces MIMO antennas designed for the frequency range of 2.4 GHz - 30 GHz and Terahertz, intended for WBAN applications. The research results indicate that the proposed antenna is a good solution for WBAN applications. Additionally, a work [R10] proposes the use of a cooperative sensor scheme employing network coding to create a virtual MIMO system for monitoring sleep apnea. This solution allows for energy efficiency and reduces the impact of phase dispersion. A work [R11] proposes an MIMO system operating in the 5.8 GHz ISM frequency band to mitigate fading. Moreover, a study [R12] proposes the use of a cooperative MIMO system for the body channel. Research results indicate that the proposed scheme reduces energy consumption and enables long-distance transmission compared to a cooperative SISO system.

Revision: We have added studies on MIMO for WBANs to line 102 of page 4 in the revised manuscript.

"The study [R8], [R9] introduces MIMO antennas designed for the frequency range of 2.4 GHz - 30 GHz and Terahertz, intended for WBAN applications. The research results indicate that the proposed antenna is a good solution for WBAN applications. Additionally, a work [R10] proposes the use of a cooperative sensor scheme employing network coding to create a virtual MIMO system for monitoring sleep apnea. This solution allows for energy efficiency and reduces the impact of phase dispersion. A work [R11] proposes an MIMO system operating in the 5.8 GHz ISM frequency band to mitigate fading.

We have added studies on cooperative MIMO for WBANs to line 125 of page 5 in the revised manuscript.

"Moreover, a study [R12] proposes the use of a cooperative MIMO system for the body channel. Research results indicate that the proposed scheme reduces energy consumption and enables long-distance transmission compared to a cooperative SISO system.

[R8] M. A. I. Oni and S. Dey, "On the Performance Analysis of Super Wide Band MIMO Antenna for Wireless Body Area Network (WBAN) Applications," *2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI)*, Denver, CO, USA, 2022, pp. 1896-1897, doi: 10.1109/AP-S/USNC-URSI47032.2022.9887363.

- [R9] Qudisia Rubani, Sindhu Hak Gupta, Asmita Rajawat, A compact MIMO antenna for WBAN operating at Terahertz frequency, *Optik*, Volume 207, 2020, 164447, ISSN 0030-4026.
- [R10] Rahim, A., & Karmakar, N. C. (2022). Virtual MIMO Using Energy Efficient Network Coding in Sleep Apnoea Monitoring Systems. *In 4G Wireless Communication Networks* (pp. 375-399). River Publishers.
- [R11] Yang, Y., Rahim, A., & Karmakar, N.C. (2013). 5.8 GHz portable wireless monitoring system for sleep apnea diagnosis in wireless body sensor network (WBSN) using active RFID and MIMO technology.
- [R12] Xiangyi Li, Guixia Kang, Xidong Zhang and Dongyan Huang, "An energy-efficient cooperative MIMO strategy for Wireless Sensor Networks with intra-body channel," *2012 International Symposium on Communications and Information Technologies (ISCIT)*, Gold Coast, QLD, 2012, pp. 679-684, doi: 10.1109/ISCIT.2012.6380987.

3.2. *While going through the paper, reviewer finds that author has proposed "AE AF/DF MMSE and RTN", however its connection to the real BAN application is still a miss.*

Reply: We would like to thank you for suggestion. We added motivation and detail scenarios for applying the proposed systems. Additionally, we have adjusted the presentation in certain sections and add to the revised manuscript.

We explain the reason behind proposing a cooperative system for WBAN: To meet the high reliability requirements of WBAN applications in healthcare systems and mitigate the effects of fading in the WBAN channel, we propose the use of cooperative MIMO systems employing AF and DF methods using AE techniques.

We have added motivation for the proposed system: In previous studies, communication within WBANs primarily utilizes cooperative single-antenna, MIMO and virtual MIMO systems to reduce fading effects and enhance communication performance. The research on cooperative MIMO with Space Division Multiplexing in WBANs is still limited, and there have been no studies on cooperative MIMO with Space Division Multiplexing using DL techniques for communication between nodes over the on-body channel. Based on the MIMO systems using AE as proposed in [13], we apply this solution to improve the bit error rate of the cooperative MIMO system for WBAN communication.

We added a description in Section 3.1: In many WBAN applications, especially in health monitoring systems, communication reliability is a crucial parameter that affects the system's performance. Hence, in this section, we present two AF-based cooperative MIMO systems utilizing the AE technique for on-body communications, aimed at alleviating fading effects and enhancing BER performance with modest computational complexity.

We added a description in Section 3.2: To further enhance performance for on-body communication, we propose DF-based cooperative MIMO systems using the AE technique with the MMSE combinator and the RTN combinator, abbreviated AE-DF-MMSE and AE-DF-RTN, respectively. The AE-DF systems offer improved BER performance, but it comes at the cost of a significant increase in computational complexity compared to AE-AF systems.

Revision: We added an explanation for the reason behind proposing a cooperative system for WBAN to line 306 of page 11 in the revised manuscript.

"To meet the high reliability requirements of WBAN applications in healthcare systems and mitigate the effects of fading in the WBAN channel, we propose the use of cooperative MIMO systems employing AF and DF methods using AE techniques."

We are accurately rephrasing the title of Section 3 on page 11 of the the revised manuscript.

“The proposed AE-based cooperative MIMO WBAN system”

We are accurately rephrasing the title of figure 3 on page 12 of the the revised manuscript.

“The AE-AF system using MMSE combinator”

We are accurately rephrasing the title of Figure 5 on page 21 of the the revised manuscript.

“The AE-DF system using MMSE combinator”

We are accurately rephrasing the title of Figure 6 on page 23 of the the revised manuscript.

“The AE-DF system using RTN combinator”

We have added motivation for the proposed system in the context of on-body communication to line 206 of page 7 in the revised manuscript.

“In previous studies, communication within WBANs primarily utilizes cooperative single-antenna, MIMO and virtual MIMO systems to reduce fading effects and enhance communication performance. The research on cooperative MIMO with Space Division Multiplexing in WBANs is still limited, and there have been no studies on cooperative MIMO with Space Division Multiplexing using DL techniques for communication between nodes over the on-body channel. Based on the MIMO systems using AE as proposed in [13], we apply this solution to improve the bit error rate of the cooperative MIMO system for WBAN communication”

We added a description for the first contribution on the line 218 of page 8 in the revised manuscript.

“We proposed two AF-based cooperative MIMO systems using the AE technique (AE-AF) for on-body communication to achieve good performance.”

We added a description in Section 3.1, at line 321 on page 12 in the revised manuscript.

“In many WBAN applications, especially in health monitoring systems, communication reliability is a crucial parameter that affects the system’s performane. Hence, in this section, we present two AF-based cooperative MIMO systems utilizing the AE technique for on-body communications, aimed at alleviating fading effects and enhancing BER performance with modest computational complexity.”

We added a description in Section 3.2, at line 458 of page 19 in the revised manuscript.

“To further enhance performance for on-body communicaiton, we propose DF-based cooperative MIMO systems using the AE technique with the MMSE combinator and the RTN combinator, abbreviated AE-DF-MMSE and AE-DF-RTN, respectively. The AE-DF systems offer improved BER performance, but it comes at the cost of a significant increase in computational complexity compared to AE-AF systems.”

We rewrote the sentence on line 567 of page 25 in the revised manuscript.

“This section focuses on simulating and evaluating the Bit Error Rate (BER) performance of the AE-based cooperative MIMO system in WBAN to mitigate the effects of multi-path propagation and enhance link’s reliability. The transmission channel for the WBAN depends on the placement of the sensors on the human body. Many channel models have been proposed for intra-WBAN networks in specific cases, such as the Lognormal, Weibull, Rice, and Rayleigh distributions [14,15,16]. The Rice and Rayleigh distributions are suitable for narrowband MICS and ISM in environments with multiple scattering and reflections.”

- [R13] T. T. T. Bui, X. N. Tran, and A. H. Phan, “Deep learning based MIMO systems using open-loop autoencoder,” *AEU - International Journal of Electronics and Communications*, p. 154712, 2023
- [R14] R. Rosini and R. D’Errico, “Comparing On-Body dynamic channels for two antenna designs,” in *2012 Loughborough Antennas and Propagation Conference (LAPC)*, 2012, pp. 1–4.
- [R15] S. L. Cotton and W. G. Scanlon, “Characterization and Modeling of the Indoor Radio Channel at 868 MHz for a Mobile Bodyworn Wireless Personal Area Network,” *IEEE Antennas and Wireless Propagation Letters*, vol. 6, pp. 51–55, 2007.
- [R16] L. Liu, R. D’Errico, L. Ouvry, P. Doncker, and C. Oestges, “Dynamic Channel Modeling at 2.4 GHz for On-Body Area Networks,” *J. Adv. Electron. Telecommun.*, vol. 2, 01 2011.

3.3. *Author has considered Rayleigh channel and produced simulation results for the same, however for BAN need to consider Rician with varying K factor will give more insight.*

Reply: We would like to thank you for your useful comment. The channels in WBAN depend on the position of the sensors on the body and the environment surrounding the user. Many studies have proposed channel models for WBAN based on statistical distributions, including Rayleigh, Rice, Weibull, Gamma, Lognormal, Nakagami [R17], [R18], [R19], [20]. In this research scope, we employ a Rayleigh channel for simulating and evaluating the performance of cooperative MIMO systems on the body. This channel model represents the most challenging scenario among fading channels [R17], when the proposed system performs effectively on the Rayleigh channel, it is expected to perform well on all other channels. This is also a common approach for evaluating wireless communication systems, especially in the context of calculating the link budget for the system.

We further simulate the AE-AF-MMSE system with $N = 2$ on Rice channels had different K coefficients, as shown in Figure 1. The Rayleigh channel has a non-line-of-sight ray, which results in the worst system’s BER performance. Whereas, with the Rician channel, an increasing K factor means an increase in the intensity of the light-of-sight ray, resulting in an improved BER performance.

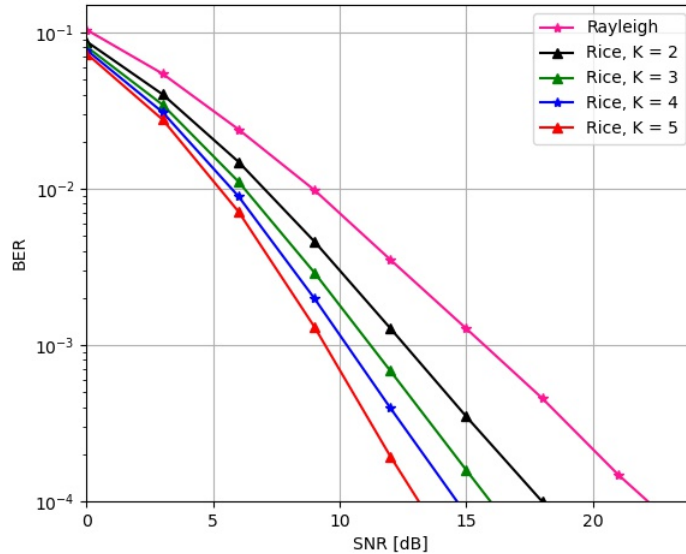


Figure 1: BER of AE-AF-MMSE systems with $N = 2$ over different channels

Revision: We added additional explanation for choosing the Rayleigh fading channel in the simulation to add line 575 of page 25 in the revised manuscript

“In this research scope, we employ a Rayleigh channel for simulating and evaluating the performance of cooperative MIMO systems on the body. This channel model represents the most challenging scenario among fading channels [R17], when the proposed system performs effectively on the Rayleigh channel, it is expected to perform well on all other channels.”

[R17] D. B. Smith, D. Miniutti, T. A. Lamahewa and L. W. Hanlen, "Propagation Models for Body-Area Networks: A Survey and New Outlook," in *IEEE Antennas and Propagation Magazine*, vol. 55, no. 5, pp. 97-117, Oct. 2013, doi: 10.1109/MAP.2013.6735479.

[R18] M. Mohamed, M. Cheffena, F. Perez Fontan and A. Moldsvor, "A Dynamic Channel Model for Indoor Wireless Signals: Working Around Interference Caused by Moving Human Bodies," in *IEEE Antennas and Propagation Magazine*, vol. 60, no. 2, pp. 82-91, April 2018, doi: 10.1109/MAP.2018.2796022.

[R19] A. Nahali, A. Hamdi, M. Gautier, A. Courtay and R. Braham, "Energy Modeling of Wireless Body Area Networks with On-Body Communication Channel Characterization," 2019 *15th International Wireless Communications & Mobile Computing Conference (IWCMC)*, Tangier, Morocco, 2019, pp. 220-225, doi: 10.1109/IWCMC.2019.8766608.

[R20] R. Kadel and N. Islam, "Comparison of Channel Models for Wireless Body Area Networks (WBANs)," 2018 *IEEE Conference on Wireless Sensors (ICWiSe)*, Langkawi, Malaysia, 2018, pp. 77-82, doi: 10.1109/ICWISE.2018.8633288.

- 3.4. *The simulation result seems to conclude "AE- AF/DF cooperative MIMO" system better over "AF/DF cooperative MIMO", so the connection of BAN with the proposed algorithm is quite missing throughout all simulation results. A suggestion is " Simulation results should conclude AE-AF/DF cooperative MIMO - BAN.*

Reply: We sincerely thank you for your suggestion. To enhance the integration of the proposed systems with communication in the WBAN network, we have adjusted the presentation in simulation result section and add to the revised manuscript.

Revision:

We added description of the simulation results to line 604 of page 27 in the revised manuscript.

“First, we simulate the proposed systems in the scenario where the signal is transmitted from the source node to the destination node through a direct and a relay paths. The performance of the AE-AF-MMSE, AE-AF-RTN, AE-DF-MMSE, and AE-DF-RTN systems is depicted in Figures 7, 8, 10, and 11, respectively.”

We added description of the simulation results to line 642 of page 30 in the revised manuscript.

“When the direct transmission is severely affected by extensive propagation loss due to the influence of activities and the position of the WBAN user, the signal from the source to the destination can only rely on the assistance of one or several relay nodes. In this scenario, the BER performance of the proposed systems, AE-AF-RTN and AE-DF-RTN, is illustrated in Figures 9 and 12, respectively.”

- 3.5. *Simulation results quantification is quite unclear as how many layers are required for "BAN having shadowing" or "BAN with LOS path" or "BAN with 3-4 relays" etc is not available throughout the*

paper and thus the contribution of the proposed algorithm is limited to BAN networks. For one ex. On page 29, "Why saturates at 2 or 3 . relate it to BAN."

Reply: We are sorry for the confusion. The signal transmission between two nodes in a WBAN passes through a wireless channel, which includes the influence of multi-path propagation, having Line-Of-Sight (LOS) or Non-Line-Of-Sight (NLOS) components, and is also affected by shadowing. In this work, we utilize cooperative MIMO systems to enhance the communication performance from the source node to the destination node. Cooperative MIMO systems are divided into two cases: one includes a direct path and a relay path, as illustrated in Figures 3, 5, and 6; the other involves one or several relay paths without a direct path. Each relay path is supported by only one relay node, also called as a dual-hop relay path. The structure of a relay node can be an amplifying layer with the AE-AF-MMSE system, as depicted in Figure 3, or a normalization layer with the AE-AF-RTN system, which includes one receiver (RxR) and one transmitter (TxR) with the AE-DF-MMSE and AE-DF-RTN systems shown in Figures 5 and 6, respectively.

In Figure 9, the cooperative MIMO system consists of one direct path and one relay path, denoted as *w/direct*. Additionally, the system has no direct path but includes one, two, or three relay paths, respectively indicated as *1relay*, *2relay*, *3relay*.

cattering and reflectiostems depends not only on their structure but also on parameters such as batch size, learning rate, and the number of training epochs [R21]. The batch size corresponds to the number of CSI samples and transmitted data samples trained in one epoch. When the batch size is sufficiently large, the system is more likely to achieve optimal performance, but it comes at the cost of a higher computational workload.

To match the computational capabilities of the computer, we chose a relatively small training batch size for the proposed systems, $B = 256$. Furthermore, the AE-AF-RTN system with *1relay* transmits signals from the source node (S) to the destination node (D) using a relay path. The received signal is affected by the transmission channel on both the source-to-relay node ($S \rightarrow R$) and relay-to-destination node ($R \rightarrow D$) links, making it challenging to detect and recover the transmitted signals. As a result, the BER of the AE-AF-RTN system with one-relay has not reached its best performance and saturates at a BER of 10^{-3} , as depicted in Figure 9.

To illustrate the influence of batch size on the system's performance during the training phase, we conducted training on the AE-AF-RTN-1relay system using $B = 1024$. Then, we evaluated and compared this system's BER performance with the system using $B = 256$, as presented in Figure 2. The results suggest that the BER performance of the system with $B = 1024$ does not reach saturation, unlike the system with $B = 256$.

[R21] B. Ian Goodfellow and Aaron Courville, *Deep Learning*, online , 2016.

Revision: We have precisely defined the abbreviations on Figure 9 of the of the revised manuscript. "AF-base" is replaced by "AF-MMSE"

We precisely replicate the abbreviations in Figures 9 and 12: "way" is replaced by "relay."

We corrected the error in the sentence at line 656 of page 31 of the revised manuscript.

"With $L = 1, 2, 3$, the BER performance of the proposed system is compared with that of the AF-MMSE system, as shown in Figure 9"

We added additional abbreviation at line 653 of page 31 in the revised manuscript.

"abbreviated as *1relay*"

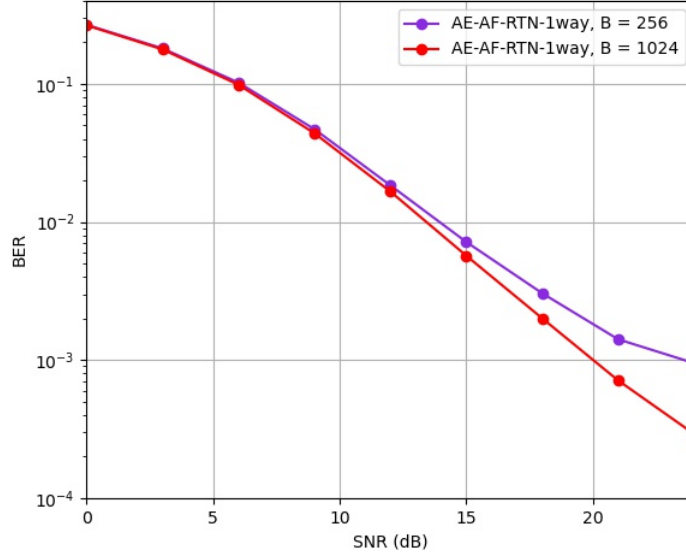


Figure 2: BER comparison between two AE-AF-RTN systems with $B = 256$ and $B = 1024$

We added additional abbreviation in line 662 of page 31 in the revised manuscript.

“abbreviated as *2relay* and *3relay*, respectively”

We added further explanation about the saturated BER curve in Figure 9 at the line 658 of page 31 in the revised manuscript.

“However, the performance of this system saturates at $\text{BER} = 10^{-3}$ because we chose a relatively small training batch size, $B = 256$, while the proposed system requires training with a larger batch size to achieve optimal performance.”

- 3.6.** *Authors are encouraged to compare proposed algorithms results with algorithms from literature with some quantifying number in terms of diversity order/BER gain.*

Reply: We would like to thank you for suggestion. We additionally compare the performance of the proposed system with baseline systems in terms of diversity gain. In Figure 8, the BER curves of the AE-AF-RTN system exhibit steeper slopes compared to the AF-MMSE, AE-AF-MMSE, and AE-MIMO systems, indicating that AE-AF-RTN achieves higher diversity gain than the other systems. In Figure 9, the BER curves of the AE-AF-RTN systems exhibit steeper slopes compared to the BER curves of the AF-RTN systems in cases with and without a direct link. This indicates that the proposed systems using AE technique achieve higher diversity gain compared to baseline systems that do not use AE technique. In Figure 12, in the case where the system uses only one relay (*1relay*) and cooperates directly with the relay (*w/direct*), the AE-DF-RTN system achieves higher diversity gain than the DF-MMSE system, as the BER curve of the system using AE is steeper than that of the baseline system. Meanwhile, in the case of using two relays and three relays, the proposed system achieves increased utility without increasing diversity gain because all systems have the same BER curve slopes.

Revision: We added description of the simulation results to line 619 of page 29 in the revised manuscript to explain for Figure 8

“The BER curves of the AE-AF-RTN system exhibit steeper slopes compared to the AF-MMSE,

AE-AF-MMSE, and AE-MIMO systems, indicating that AE-AF-RTN achieves higher diversity gain than the other systems”

We added description of the simulation results to line 651 of page 31 in the revised manuscript to explain for Figure 9

“The BER curves of the AE-AF-RTN systems exhibit steeper slopes compared to the BER curves of the AF-RTN systems in cases with and without a direct link. This indicates that the proposed systems using AE technique achieve higher diversity gain compared to baseline systems that do not use AE technique.”

We added description of the simulation results to line 696 of page 32 in the revised manuscript to explain for Figure 12

“In the case where the system uses only one relay and cooperates directly with the relay (w/direct), the AE-DF-RTN system achieves higher diversity gain than the DF-MMSE system, as the BER curve of the system using AE is steeper than that of the baseline system. Meanwhile, in the case of using two relays and three relays, the proposed system achieves increased utility without increasing diversity gain because all systems have the same BER curve slopes.”

3.7. *The paper has several typos throughout and need thorough rewriting.*

- a) Section 3.1.1, Bracket is required while writing “diagf1,f2,...”.
- c) Section 3.3.3 , it’s “Training not traning”.
- d) Just belwo Eq.21 , its “label instead labell”.
- e) Instead of training processing , it should be “training process”
- f) Add a space before the sentence starting “Algorithm 1 outlines ...”.
- g) Below Eq. 30 , It should be “MMSE not MME”.
- h) On page 24, third last paragraph, It should be different “Same one used twice i.e. “AE-DF-MMSE”.

Reply: Thank you for taking the time to read carefully. The updated manuscript contains all typographical and grammatical corrections.

3.8. *b) The bracketed sentence is quite unclear “assuming the direct transmission path suffers from significant propagation loss, the direct signal is of negligible strength.” As having a direct link will results in selective DF, While not having a direct link results is DF, both systems are different with different diversity order. Also, system with direct link always results in better diversity compared to not having that link.*

Reply: We sincerely thank you for the your recommendation. The cooperative communication system consists of a direct path and a relay path, enabling the achievement of good quality. However, in some cases, due to the influence of activities and the positioning of the WBAN user, the source node on the right wrist cannot transmit directly to the destination node on the left waist. In such scenarios, the system continues communication via a relay path or cooperates with additional relays to transmit data to the destination node.

Revision: we rewrite from line 376 of page 15 in the revised manuscript. “However, in some cases, due to the influence of activities and the positioning of the WBAN user, the source node on the right wrist cannot transmit directly to the destination node on the left waist. In such scenarios, the system maintains communication through a relay path or cooperates with additional relays to

transmit data to the destination node using MMSE weight matrices, similar to equations (14), (15), and (16).”

4 Responses to the comments of Reviewer 3

We would like to thank you for reading our manuscript and providing us with various constructive comments. Following your comments, we have revised our manuscript accordingly and provided our detailed responses to your comments as follows.

General comment: *The paper proposes AE-AF and AE-DF systems with two combinators, MMSE and RTN, over flat Rayleigh fading channel for on-body communication in scenarios with and without direct links. To improve the reliability of transmission, this paper presents a novel approach using deep learning-based cooperative MIMO systems that leverage the AE technique. However, my concerns are given below:*

Reply: We would like to thank you for your appreciation of the contribution of our paper. In the following parts, we will address your concerns.

- 4.1.** *Based on the intra-WBAN system, the authors analyse the BER performance of single or multiple relays. Please provide a specific introduction to the practical application scenarios of multi-hops and multi-relays proposed in this article.*

Reply: We would like to thank you for your comment and suggestion. Transmission reliability is a critical criterion for ensuring the effectiveness of WBAN, particularly in healthcare and health monitoring applications [R22]. However, due to user's activities and positions, some nodes may become obstructed by body parts, and the direct transmission of signals from sensors to PD is sometimes failures [R23, R24, R25]. In that case, the signal from the source node is transmitted to the destination node through relay paths. A relay paths using one relay node is referred to as a 2-hop. As depicted in Figure 1, our two-hop cooperative MIMO system uses relay paths for mitigating the effects of fading channels, increasing capacity and enhancing the system's error rate performance. When the distance between the source and destination nodes is far, a relay path can use 2 relays (3-hop) or more relays (multi-hop) to improve the network lifetime [R26].

[R22] D. M. Barakah and M. Ammad-uddin, "A Survey of Challenges and Applications of Wireless Body Area Network (WBAN) and Role of a Virtual Doctor Server in Existing Architecture," *2012 Third International Conference on Intelligent Systems Modelling and Simulation*, Kota Kinabalu, Malaysia, 2012, pp. 214-219, doi: 10.1109/ISMS.2012.108.

[R23] L. C. Tran, A. Mertins, X. Huang and F. Safaei, "Comprehensive Performance Analysis of Fully Cooperative Communication in WBANs," in *IEEE Access*, vol. 4, pp. 8737-8756, 2016, doi: 10.1109/ACCESS.2016.2637568.

[R24] D. B. Smith and D. Miniutti, "Cooperative body-area-communications: First and second-order statistics with decode-and-forward," *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, Paris, France, 2012, pp. 689-693, doi: 10.1109/WCNC.2012.6214457.

[R25] D. B. Smith, D. Miniutti and L. W. Hanlen, "Characterization of the Body-Area Propagation Channel for Monitoring a Subject Sleeping," in *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 11, pp. 4388-4392, Nov. 2011, doi: 10.1109/TAP.2011.2164209.

[R26] A. Arfaoui, A. Kribeche and S. M. Senouci, "Cooperative MIMO for Adaptive Physical Layer Security in WBAN," *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*, Dublin, Ireland, 2020, pp. 1-7, doi: 10.1109/ICC40277.2020.9148837.

Revision: We added real-world scenarios to build a cooperative communication system to line 256 of page 9 in the revised manuscript.

”Transmission reliability is a critical criterion for ensuring the effectiveness of WBAN, particularly in healthcare applications [R22]. However, due to users’ activities and positions, some nodes may become obstructed by body parts, leading to occasional failures in the direct transmission of signals from sensors to personal devices (single-hop link) [R23, R24, R25]. Therefore, a cooperative MIMO communication system is proposed for intra-WBAN, abbreviated as WBAN, as presented in Figure 1. This scheme, supported by the IEEE 802.15.6 standard, aims to alleviate the impacts of multipath channels, enhance capacity, and improve error rate performance.”

We add a model system description to line 265 of page 9 in the revised manuscript.

”The on-body communication system comprises sensors transmit data, called source nodes (S_1, S_2), sensors perform the signal forwarding function, called relay nodes (R_1, R_2, R_3) and a personal device/destination node (PD/D) receives signals from the sensors within the intra-WBAN. The source nodes can transmit to the destination node through either a single-hop model ($S_1 \rightarrow D, S_2 \rightarrow D$) or a two-hop cooperative model. The sensor S_2 , worn on the right wrist, should be able to transmit cooperatively to the destination node, worn on the left waist, through both a direct and a relay path, represented by blue arrows, or relay paths in case user movements obstruct the direct transmission, represented by red arrows.”

4.2. Please specify the complexity of each algorithm and compare them.

Reply: We sincerely thank you for the your recommendation. In order to compare the computational complexity between baseline and proposed systems, We represent mathematical transformations from the source node to the destination node using the number of floating-point operations (flops) [R27].

In the context of proposed systems using autoencoder (AE) techniques, the computational complexity is calculated as the sum of operations on each fully connected (FC) layer. The activation functions do not increase the complexity of the system [R28]. In the la -th layer, if the numbers of input nodes and output nodes are respectively N_{la-1} and N_{la} , then the complexity is calculated as follows [R29]:

$$C_{la} = 2N_{la-1}N_{la} + N_{la}$$

The computational complexity of a feedforward neural network (FNN) with La hidden layers is calculated using the expression:

$$C_{FNN} = 2N_{in}N_1 + N_1 + \sum_{la=2}^{La-1} (2N_{la-1}N_{la} + N_{la}) + 2N_{La}N_{out}$$

where N_{in} and N_{out} are the number of neurons at the input and the output layers of the FNN network, respectively.

First, we calculate the complexity of the AE-AF-MMSE system. At the source node of AE-AF-MMSE system, The AE system uses bit-labeling method, where $P = Nk$ and the label is encoded into a transmitted signal by an encoder. Total computational complexity is $128Nk + 258N + 16576$.

At the relay node of AE-AF-MMSE system, the relay node amplifies the signal $\mathbf{y}_{sr}^{am}$ by utilizing the amplification matrix $\mathbf{F}$, as follows: $\mathbf{F}\mathbf{y}_{sr}^{am}$, where $\mathbf{F} = \text{diag}\{f_1, f_2, \dots, f_{2N}\}$, and f_i is calculated in (8). Total computational complexity is $4N^2 + 9N$.

At the destination node, the received signals are detected and decoded following equations (11) - (13), and computational complexity is $48N^3 + 26N^2 + 129Nk + 128NR - N + 16576$ with R is the

Table 7: The neural network architecture of the AE-AF-MMSE System

	Layer $\times$ layer No.	Activation function	Output neurons	Computational complexity (flops)
Source node (TxS)				$128Nk + 258N + 16576$
Encoder (Enc)	input	-	P	0
	FC $\times 3$	relu	64	$128Nk + 16576$
	FC	linear	$2N$	$258N$
	Normalization	-	$2N$	0
Channel	Rayleigh	-	$2NN$	0
Relay	Amplify	-	$2N$	$4N^2 + 9N$
Destination node (RxD)				$48N^3 + 26N^2 + 129Nk + 128NR - N + 16576$
Detector	MMSE	-	$2N$	$48N^3 + 26N^2 - N$
Decoder (Dec)	FC $\times 3$	relu	64	$128NR + 16576$
	FC	sigmoid	P	$129Nk$

number of relay nodes. The computational complexity of AE-AF-MMSE is detail listed in Table 14.

Then, the computational complexity of the baseline and the proposed systems in the case of one direct path and one relay path is listed in Table 8.

In the AF-MMSE system, the modulation and DEMUX at the source node have a complexity of Nk flops with $k = \log_2(M)$; at the destination node, the demodulation and MUX have a complexity of Nk flops. The complexity of the transformations at the relay node and signal detector at the destination node is calculated as in the AE-AF-MMSE system.

Table 8: Compare the computational complexity of the base systems and the proposed systems

	Source	Relay	Destination	Sum of complexity
AF-MMSE	Nk	$4N^2 + 9N$	$48N^3 + 26N^2 + Nk - N$	$48N^3 + 30N^2 + 2Nk + 8N$
AE-AF-MMSE	$128Nk + 258N + 16576$	$4N^2 + 9N$	$48N^3 + 26N^2 + 128NR$ $129Nk - N + 16576$	$48N^3 + 30N^2 + 128NR +$ $257Nk + 266N + 33152$
AE-AF-RTN	$128Nk + 258N + 16576$	0	$272N^2 + 128NR + 129Nk +$ $512N + 49728$	$272N^2 + 128NR + 257Nk +$ $770N + 66304$
DF-ZF	Nk	$24N^3 + 6N^2 + 2Nk - 2N$	$24N^3 + 6N^2 + Nk - 2N$	$48N^3 + 12N^2 + 4Nk - 4N$
DF-MMSE	Nk	$24N^3 + 12N^2 + 2Nk - N$	$48N^3 + 26N^2 + Nk - N$	$72N^3 + 38N^2 + 4Nk - 2N$
AE-DF-MMSE	$128Nk + 258N + 16576$	$24N^3 + 12N^2 + 128NR +$ $257Nk + 257N + 33152$	$48N^3 + 26N^2 + 128NR +$ $129Nk - N + 16576$	$72N^3 + 38N^2 + 256NR +$ $514Nk + 514N + 66304$
AE-DF-RTN	$128Nk + 258N + 16576$	$136N^2 + 128NR + 257Nk +$ $514N + 49728$	$272N^2 + 128NR + 129Nk +$ $512N + 49728$	$408N^2 + 256NR + 514Nk +$ $1284N + 116032$

Table 9: Compare the computational complexity of the base systems and the proposed systems with $k = 1$ for Figure 7, Figure 8, Figure 10 and Figure 11

	$N = 2$	$N = 3$	$N = 4$
AF-MMSE	524	1596	3592
AE-AF-MMSE	34958	36671	39308
AE-AF-RTN	69702	72217	75276
DF-ZF	432	1404	3264
DF-MMSE	732	2292	5224
AE-DF-MMSE	69600	72442	76656
AE-DF-RTN	121772	125866	130776

Table 10: Compare the computational complexity of the base systems and the proposed systems for Figure 9

	complexity	number of flops with $N = 2, k = 1$
AF-MMSE-wdirect	$48N^3 + 30N^2 + 2Nk + 8N$	524
AF-MMSE-1relay	$24N^3 + 16N^2 + 2Nk + 8N$	276
AF-MMSE-2relay	$48N^3 + 34N^2 + 2Nk + 17N$	558
AF-MMSE-3relay	$+ 72N^3 + 96N^2 + 2Nk + 24N$	1012
AE-AF-RTN-wdirect	$272N^2 + 128NR + 257Nk + 770N + 66304$	69702
AE-AF-RTN-1relay	$136N^2 + 128NR + 257Nk + 514N + 49728$	52070
AE-AF-RTN-2relay	$272N^2 + 128NR + 257Nk + 770N + 66304$	69702
AE-AF-RTN-3relay	$408N^2 + 128NR + 257Nk + 1026N + 828804$	87334

Table 11: Compare the computational complexity of the base systems and the proposed systems for Figure 12

	complexity	flops with $N = 2, k = 1$
DF-MMSE-wdirect	$72N^3 + 38N^2 + 4Nk - 2N$	732
DF-MMSE-1relay	$48N^3 + 24N^2 + 4Nk - 2N$	484
DF-MMSE-2relay	$96N^3 + 50N^2 + 6Nk - 3N$	974
DF-MMSE-3relay	$144N^3 + 120N^2 + 8Nk - 6N$	1636
AE-DF-RTN-wdirect	$408N^2 + 256NR + 514Nk + 1284N + 116032$	121772
AE-DF-RTN-1relay	$272N^2 + 256NR + 514Nk + 1028N + 99456$	104140
AE-DF-RTN-2relay	$544N^2 + 384NR + 771Nk + 1798N + 165760$	173842
AE-DF-RTN-3relay	$816N^2 + 512NR + 1028Nk + 2568N + 232064$	243544

The last column of Tables 8 indicates that, the number of required flops for the baseline systems, including AF-MMSE and DF-MMSE, are approximately $\mathcal{O}(48N^3)$ and $\mathcal{O}(72N^3)$, respectively. Similarly, The number of required flops for the AE-AF-MMSE and AE-DF-MMSE systems are approximately $\mathcal{O}(48N^3)$ and $\mathcal{O}(72N^3)$, respectively. Meanwhile, the AE-AF-RTN and AE-DF-RTN systems require approximately $\mathcal{O}(272N^2)$ and $\mathcal{O}(408N^2)$ flops, respectively.

Observing the computed complexity, as in Table 14-11, and the simulated BER performance results, it is evident that the proposed systems allow for a significant improvement in BER performance but come at the cost of increased computational complexity. However, as listed in Table 8, the

Table 12: Total power consumption of both baseline and the proposed systems in different cases

	w/direct	1relay	2relay	3relay
Number of Node	1 source, 1 relay	1 source, 1 relay	1 source 2 relay	1 source, 3 relay
Total power	2	2	3	4

computational complexity of the proposed systems is primarily due to computations at the destination node (Personal Device). The sensor nodes acting as source and forwarding nodes require fewer FLOPs, which aligns with the compact design requirements of sensors in a WBAN. The significant computational complexity of the proposed systems is also a major limitation, and reducing the computational complexity of these systems is one of the directions that we will continue to investigate in future research studies.

We constrain the simulation conditions by normalizing the transmission power of the source node and the relay nodes to 1 for both baseline and proposed systems. According to this assumption, the total power consumption of the systems listed in Table 12. The system’s power consumption will increase as the number of relay nodes increases. The best-case scenario is the cooperative system consisting of one direct transmission path and one relay path, which offers the best BER performance and the lowest power consumption.

[R27] G. H. Golub and C. F. Van Loan, *Matrix computations*, Johns Hopkins, Dec. 27, 2012.

[R28] Dubey, Shiv Ram and Singh, Satish Kumar and Chaudhuri, Bidyut. *Activation Functions in Deep Learning: A comprehensive Survey and Benchmark*, Neurocomputing. 503. 10.1016/j.neucom.2022.06.111.

[R29] Bhoomi Shah, Hetal Bhavsar, *Time Complexity in Deep Learning Models*, Procedia Computer Science, Volume 215, 2022, Pages 202-210, ISSN 1877-0509.

Revision: We added further description regarding the signal power normalization on line 342 of page 13 of the revised manuscript.

“The transmit vector $\mathbf{x}^{am}$ is power-normalized through the normalization layer in the encoder.

We added additional evaluation of the advantages and limitations of the systems to line 666 of page 31 in the revised manuscript.

“When the systems have the number of relay nodes $L = 1, 2, 3$, respectively, the BER curve gradually decreases, which means the performance of the systems improves. However, the system will have to pay the cost of computational complexity and energy consumption. Assuming that the transmission power of the source node and relay nodes is normalized to 1, the system’s power consumption will increase as the number of relay nodes increases. Table 12 lists the total transmission power of the system in various simulation scenarios. It is clear that the cooperative system with one direct transmission path and one relay path, which provides the best BER performance and the lowest power consumption, is the best-case situation. In the specific case where there is no direct path, depending on the requirements of each application, we choose the system configuration with the most suitable value of L .”

we added additional evaluation to line 711 of page 34 in the revised manuscript.

“The system’s performance is greatly enhanced when numerous relay paths are used. However, as shown in Table 12, the system must pay a price in the form of higher computing complexity and power consumption.”

We included additional evaluation of the complexity in the conclusion section to line 727 of page 34 in the revised manuscript.

“However, it is evident that the proposed systems allow for a significant improvement in BER performance but come at the cost of increased computational complexity. This is a significant limitation of the proposed systems, and reducing the computational complexity of these systems is one of the directions that we will continue to investigate in future research studies.”

- 4.3. In the Figure 8, the simulation results show that “the BERs of AE-AF-RTN with $N = 3$ are worse than with $N = 2$. Additionally, at a low SNR range ($\text{SNR} < 5 \text{ dB}$), the performance of AE-AF-RTN with $N = 3$ is poorer than the other two Systems.” Please try to analyze the specific reasons.

Reply: We would like to thank you for your appreciation of the contribution of our paper. The autoencoder based MIMO and Cooperative MIMO systems encode M -ary signals into transmitted signals $\mathbf{x}^{am}$. Each element of the vector $\mathbf{x}^{am}$ is a function of the label $\mathbf{b}$, $x_i^{am} = f_{TxS}(\mathbf{b}; \theta_{TxS,i}^{am})$, $i = 1, \dots, 2N$, so the constellation on each transmitting antenna has $2^{k \times N}$ points, $k = \log_2(M)$ [R30, R31]. For example, the transmitted constellations of AE-AF-RTN schemes with $N = 2, 3; k = 1$ are presented in Figure 3. With $N = 2$, Four red square and four blue circle points are depicted as constellations of transmitted signals on the first and second antennas, respectively. The points on the constellation correspond to the labels listed in Table 1 in our paper. Similarly, with $N = 3$, red squares, blue circles, and green stars represent constellations of transmitted signals on three antennas, and each constellation has eight points.

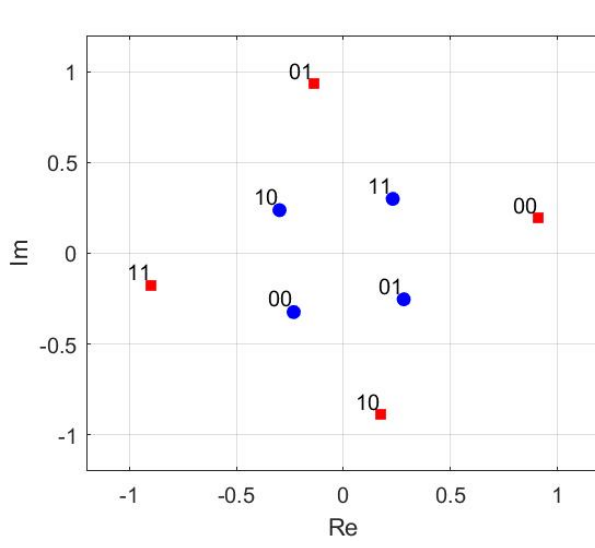
As shown in Figure 3, the different sizes of constellations on the antennas indicate that the transmit power on the antennas is not equal. So, the AE-AF-RTN system encodes transmitted signals using this method, along with the ability for automatic optimization of shape and transmit power levels on each antenna, which significantly enhances the system’s performance compared to the base system.

However, the quantity of points in the constellations increases quickly as AE-AF-RTN increases the number of transmit antennas. As a result, when the system encounters interferences such low SNR and fading channels, there are more mistakes in estimated signals at the receiver, which causes a rapid fall in system performance. This is also reflected in the chart of BCE loss values versus the number of epochs, as shown in Figure 4. After 20,000 training epochs, the system proposed with $N = 2$ achieves a mean loss of approximately 10^{-5} , whereas with $N = 3$, the mean loss only reaches 5×10^{-4} . Due to the reasons mentioned above, the BER performance of the AE-AF-RTN system equipped with three antennas is worse than this system equipped with two antennas, as depicted in Figure 8 in our manuscript.

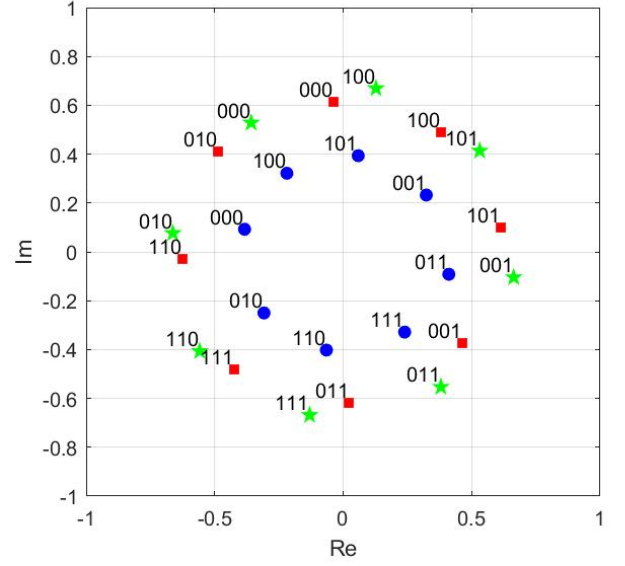
Additionally, we note that whereas the weight matrix of the MMSE combinator in the base system and the proposed AE-AF-MMSE system are computed based on specific SNR values, as in equal (12), the learning parameters of the RTN combinator in the AE-AF-RTN system are automatically learnt through training over a range of SNRs. Specifically, in the simulation evaluating the systems, we train the AE-AF-RTN system within an SNR range from 5 dB to 25 dB with a 5 dB interval. Therefore, the BER of the AE-AF-RTN system with $N = 3$ is worse than the BER of the AE-AF-MMSE and AF-MMSE systems at $\text{SNR} < 5 \text{ dB}$.

[R30] T. Erpek, T. J. O’Shea, Y. E. Sagduyu, Y. Shi, and T. C. Clancy, *Deep Learning for Wireless Communications*. in Development and Analysis of Deep Learning, Springer, 2020, pp. 223–266.

[R31] T. T. T. Bui, X. N. Tran, and A. H. Phan, “Deep learning based MIMO systems using open-loop autoencoder,” *AEU - International Journal of Electronics and Communications*, p. 154712, 2023.

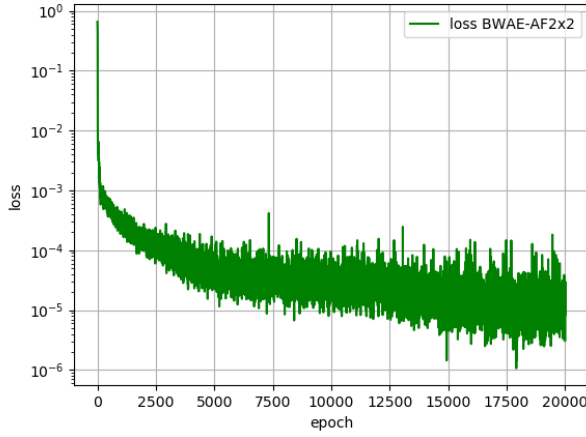


(a) $N = 2, k = 1$

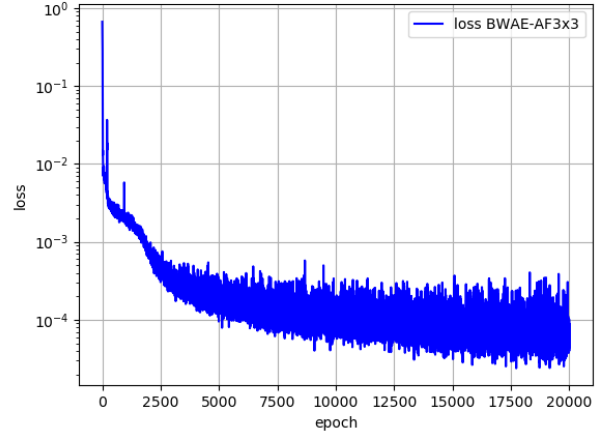


(b) $N = 3, k = 1$

Figure 3: The constellations of AE-AF-RTN systems with $N = 2, 3$



(a) $N = 2$



(b) $N = 3$

Figure 4: The BCE loss of AE-AF-RTN systems with $N = 2, 3$

Revision: We added additional explanation to line 346 of page 13 in the revised manuscript.

“Each element of the vector $\mathbf{x}^{am}$ is a function of the label $\mathbf{b}$, $x_i^{am} = f_{TxS}(\mathbf{b}; \theta_{TxS,i}^{am})$, $i = 1, \dots, 2N$,

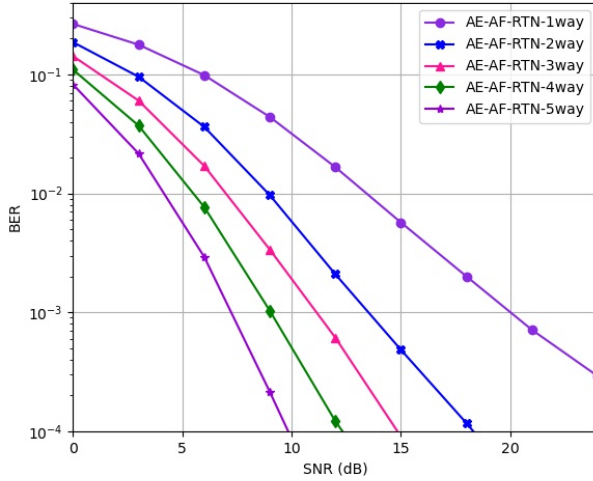
so the constellation on each transmitting antenna has $2^{k \times N}$ points.”

We added additional explanation to the line 628 of page 30 in the revised manuscript.

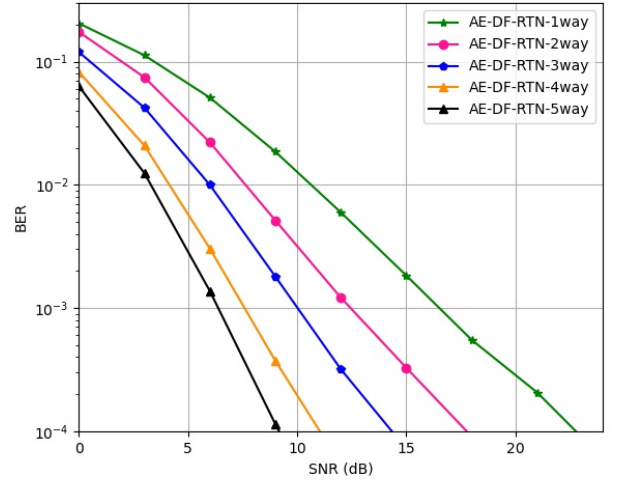
“However, the quantity of points in the constellations increases quickly as AE-AF-RTN increases the number of transmit antennas. As a result, when the system encounters interferences such low SNR and fading channels, there are more mistakes in estimated signals at the receiver, which causes a rapid fall in system performance. Additionally, we note that whereas the weight matrix of the MMSE combinator in the base system and the proposed AE-AF-MMSE system are computed based on specific SNR values, as in equal (12), the learning parameters of the RTN combinator in the AE-AF-RTN system are automatically learnt through training over a range of SNRs.”

4.4. *In the Figure 9 and 12, the authors compare the BER performance between different numbers of relays. As L increases, the BER performance gain gradually decreases. Please explain whether there is an optimal L for this scenario, and if so, what is the optimal number of L .*

Reply: We would like to thank you for your comment and suggestion. As shown in Figures 9 and 12, when the systems have the number of relay nodes $L = 1, 2, 3$, respectively, the BER curve gradually decreases, which means the performance of the systems improves. If the number of relay nodes continues to increase, the system’s performance does not improve significantly, as depicted in Figure 5, while the computational complexity and power consumption continue to rise.



(a) AE-AF-RTN



(b) AE-DF-RTN

Figure 5: BER of AE-AF-RTN and AE-DF-RTN systems with $N = 2, L = 1, 2, 3, 4, 5$

We compare the complexity and power consumption of the systems as shown in Table 14 and Table 8, respectively, corresponding to the AE-AF-RTN and AE-DF-RTN systems.

For the AE-AF-RTN- L relay system, as the relay nodes only perform power normalization without any learning parameters, when increasing L , the computational complexity of the system primarily

Table 13: Total power consumption and complexity of the AE-AF-RTN- L relay systems

	1relay	2relay	3relay	4relay	5relay
L	1	2	3	4	5
No. of RTN network	1	2	3	4	5
Complexity	C_{rtn}	$2 \times C_{rtn}$	$3 \times C_{rtn}$	$4 \times C_{rtn}$	$5 \times C_{rtn}$
Number of transmitted Node	1 source, 1 relay	1 source, 2 relay	1 source, 3 relay	1 source, 4 relay	1 source, 5 relay
Total power	2	3	4	5	6

Table 14: Total power consumption and complexity of the AE-DF-RTN- L relay systems

	1relay	2relay	3relay	4relay	5relay
L	1	2	3	4	5
No. of relay node and RTN network	1	2	3	4	5
Complexity	C_{DF}	$2 \times C_{DF}$	$3 \times C_{DF}$	$4 \times C_{DF}$	$5 \times C_{DF}$
Number of transmitted Node	1 source, 1 relay	1 source, 2 relay	1 source, 3 relay	1 source, 4 relay	1 source, 5 relay
Total power	2	3	4	5	6

increases due to the growing number of RTN networks at the destination node. The complexity of an RTN, including 4 hidden layers $La = 4$ and a matmul layer, is calculated as follows [R27, R29]:

$$C_{rtn} = \sum_{la=1}^{La-1} (2N_{la-1}N_{la} + N_{la}) + C_{matmul} = 136N^2 + 256N + 16576$$

where N presents the number of antenna.

Table 14 lists the computational complexity based on the number of RTN networks and power consumption of AE-AF-RTN systems.

For the AE-DF-RTN- L relay system, when increasing L , the computational complexity of the system primarily increases due to the growing number of relay nodes and number of RTN networks at the destination node, we denote as C_{DF} .

The C_{DF} includes the computational complexity of a relay node C_{relay} and an RTN network C_{rtn} is calculated as follows:

$$C_{DF} = C_{relay} + C_{rtn}.$$

Similarly, C_{rtn} and C_{relay} in the AE-DF-RTN system are respectively calculated as follows:

$$C_{relay} = 136N^2 + 128NR + 514Nk + 770N + 49725.$$

where $k = \log_2(M)$, R depicts the number of relay node.

$$C_{rtn} = 136N^2 + 256N + 16576$$

So, the optimal number of relay nodes L ensures that the system balances performance with complexity and total power consumption according to the application's requirements.

Revision: First, we corrected the typing error in the caption of Figure 9 of page 29

“BER comparison between AE-AF-RTN and the conventional AF-MMSE with $N = 2$ and $L = 1, 2, 3$ ”

We added further explanation of the advantages and limitations to line 666 of page 31 in the revised manuscript.

“When the systems have the number of relay nodes $L = 1, 2, 3$, respectively, the BER curve gradually decreases, which means the performance of the systems improves. However, the system will have to pay the cost of computational complexity and energy consumption. Assuming that the transmission power of the source node and relay nodes is normalized to 1, the system's power consumption will increase as the number of relay nodes increases. Table 12 lists the total transmission power of the system in various simulation scenarios. It is clear that the cooperative system with one direct transmission path and one relay path, which provides the best BER performance and the lowest power consumption, is the best-case situation. In the specific case where there is no direct path, depending on the requirements of each application, we choose the system configuration with the most suitable value of L ”

we added further explanation to line 711 of page 34 in the revised manuscript.

“The system's performance is greatly enhanced when numerous relay paths are used. However, as shown in Table 12, the system must pay a price in the form of higher computing complexity and power consumption.”

- 4.5. *In the section Conclusion, the authors claim to have addressed the shadowing effect rather than alleviating it. Please specify how it was resolved!*

Reply: We would like to thank you for your appreciation of the contribution of our paper. Fading in the body channel is a combination of shadowing and multipath propagation phenomena [R32]. The shadowing phenomenon occurs when the signal transmission between the transmitting node and the receiving node is obstructed by body parts, and it has a lognormal distribution [R33]. Meanwhile, the WBAN user operates in a richly reflective and scattered environment, leading to multipath propagation with distributions such as Rice, Rayleigh, Weibull, etc., as discussed in [R34].

In this study, we propose and evaluate the quality of systems over the Rayleigh fading channel and investigate scenarios in which the direct transmission path experiences significant attenuation, without a direct path. Therefore, to comprehensively assess the impact and propose solutions to address shadowing in WBANs, we must continue researching in future works.

[R32] Cotton, Simon L et al. “A review of radio channel models for body centric communications.” *Radio science* vol. 49,6 (2014): 371-388. doi:10.1002/2013RS005319

[R33] D'Errico, Raffaele & Ouvry, Laurent. (2010). A Statistical Model for On-Body Dynamic Channels. *International Journal of Wireless Information Networks*. 17. 92-104. 10.1007/s10776-010-0122-0.

[R34] Cotton, S. L., G. A. Conway, and W. G. Scanlon (2009b), A time-domain approach to the analysis and modeling of on-body propagation characteristics using synchronized measurements at 2.45 GHz, *IEEE Trans. Antennas Propag.*, 57(4), 943–955.

Revision: First, we rewrote the sentence on line 717 of page 34 in the revised manuscript for more accuracy.

“The proposed systems using AE techniques enhance system’s reliability compared to conventional schemes.”

We added more directions for future research to line 733 of page 35 in the revised manuscript.

“Moreover, the shadowing phenomenon is a importance factor in shaping the characteristics of the body channel and significantly impacts the reliability of the communication process. In the future, it is critical that we continue our research and develop methods to address shadowing in WBANs.”

We hope that the reviewer satisfies our responses. Again, thank you very much for your helpful comments.