Journal of Engineering Science and Technology Review 17 (6) (2024) 173-179

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

ABEP Performance Analysis of Wireless Body Area Network with Efficient Energy Harvesting Technique

Shaik Mohammed Ali[1], Sudhansu Sekhar Singh[1], Hemanta Kumar Sahu[2] and Bhargav Appasani[1,*]

[1]*School of Electronics, Kalinga Institute of Industrial Technology, Bhubaneswar-751024*
[2]*School of Electronics Engineering, Vellore Institute of Technology, Vellore - 632014*

Received 18 January 2024; Accepted 13 September 2024

Abstract

This paper analyzed the average bit error probability (ABEP) in Radio Frequency Energy harvesting in Wireless Body Area Networks (WBAN). Our WBAN model consists of two modules: Sensor Control Unit (SCU) and Medical Control Unit (MCU). SCU sends the physiological signals to the MCU wirelessly. Multiple sensors are connected to acquire various physiological signals from the body. Among all the sensors, only a few sensors' data that are important at that particular moment will be transmitted. The activated sensors are modeled using the Markov Chain to send data to the MCU. Here, binary phase-shift keying (BPSK) modulation was considered under the Rayleigh fading channel for communication. We used Meijer's G-Function to perform ABEP analysis and modified Bessel's function for Asymptotic ABEP analysis. We have found that derived expressions are numerically evaluated and verified by using Monte Carlo simulation.

Keywords: WBAN, Average bit error probability, Sensor Control Unit, Medical Control Unit, RF Energy Harvesting.

1. Introduction

With a fast-expanding worldwide population, the scale of the healthcare industry also expands. Millions of individuals develop deadly diseases, chronic conditions, and pandemics, which makes patient monitoring difficult [1-2]. Electronic Health (eHealth) monitoring systems with wireless body area networks (WBANs) facilitate the integration of the patient's data processing and communications technology into traditional medical facilities and represent a promising method for enhancing the efficiency of health treatment. The fundamental idea behind WBANs is to consistently observe an individual's diverse biological signals, including Electroencephalography (EEG), Electrocardiography (ECG), blood pressure, glucose levels, heart rate, and body temperature. This monitoring is achieved by deploying sensor nodes strategically positioned across various human body organs. The goal is establishing effective communication channels between these nodes and external medical centers. WBANs, which have grown from IEEE 802.15.6 and IEEE 802.15.4j, are the most promising technology for providing a variety of medical and healthcare applications [3].

WBANs consist of a network of sensors that monitor the physiological characteristics of the body in real-time and offer a solution for smart health monitoring [4]. The widespread deployment of WBANs will lower healthcare costs by eliminating the need for expensive hospitalization and physical surveillance [3]. WBAN is a subset of WSNs, with the former being more reliable, swift, and energy-efficient for remote medical care applications. It employs implantable and wearable sensors classified as implant-to-implant, implant-to-on-body, implant-to-external, on-body-to-on-body, and on-body-toexternal channels [4]. Several sensors, embedded controllers, wireless devices, power supply, and energy storage are used to construct WBAN monitoring systems [5]. In WBANs, several external or internal characteristics are measured via sensors. The sensor nodes collect and analyze data for embedded controllers, which wirelessly transfer data [6-7]. In [8], continuous monitoring of various parameters that require continuous usage of stored electrical energy was investigated. The energy has been stored in non-rechargeable or rechargeable batteries. The batteries may be damaged after prolonged usage, so rechargeable batteries are the desirable choice. The batteries can be charged by multiple energy harvesting (EH) techniques such as solar, thermal, wind, and Radio Frequency (RF). Apart from RF-EH, all are time-dependent; therefore, RFEH is one of the promising solutions for recharging the battery. Energy harvesting is a practical approach for developing green communications. Energy harvesting communication systems offer self-sustaining power sources [9]. Wireless RF signals are transformed into the necessary DC voltage for charging batteries in the RF-EH system [10]. This system requires a change in system architecture, status of power information, and power resource allocation.

In the RF-EH system, three transmit schemes needed to be considered. 1) Wireless power transfer (WPT), EH receives only receiver power from the power transmitter without any information exchange [11]. 2) The EH receiver uses harvested power in the downlink in the first time slot of the wireless-powered communication network (WPCN), and it transmits information in the second time slot [12-13]. 3) Simultaneous Wireless Information and Power Transfer (SWIPT) involves the transmission of wireless signals containing both energy and information to multiple entities capable of Energy Harvesting (EH) and decoding the transmitted information [14]. The research group [15] proposed efficient wireless sensor networks (WSNs) capable of self-sustenance through the use of RF energy that has been harvested. The essential difficulty in developing RF energy harvesting devices is to

E-mail address: bhargav.appasanifet@kiit.ac.in

doi:10.25103/jestr.176.19

maximize power conversion efficiency (PCE) at low input power levels by adopting different rectifier circuits and antenna topologies or specific frequency bands. In [16], effective RF energy harvesting is essential for sustainable IoT systems. However, when frequencies are unavailable, the multiband strategy outperforms the single-band front-end strategy in RF energy usage. This can be accomplished by utilizing appropriate impedance-matching networks, RFDC rectifiers, and sophisticated antennas. Significant study has also been done on RF-EH in smart city applications. A dual-hop home area network (HAN) with energy harvesting was suggested by the authors in [17] for smart grid (SG) communication. They examined two scenarios involving two distinct communication channels: Terahertz (THz) and radio-frequency (RF) channels. Both amplify-and-forward (AF) and decode-and-forward (DF) relays are used by the network. Massive multimedia services have been one of the most well-known applications of smart cities, as noted in [18]. Tremendous demand for device-to-access point (D2A) communication has led to a notable increase in energy consumption and greenhouse gas emissions. Therefore, the error performance of smart users in the smart city is analyzed using space shift keying (SSK) modulation and energy-harvesting-based two-way access points (AP). In [19], the proposed system model with the SSK modulation scheme presents a thorough analysis of the performance of a smart grid network with RF energy harvesting over a mixed RF/PLC channel. By capturing RF energy for the networks, they significantly aid in designing and optimizing smart grids. Network protocols are created under the fact that energy-harvesting WBANs differ significantly from battery-powered ones in terms of network performance. A viable strategy for managing media access across different layers in WBANs powered by radio frequency energy harvesting is recommended. In the scenario where sensors harness energy from radio frequency signals emitted by the coordinator, a time switching (TS) method is employed. Additionally, a proposal is made for a technique that adjusts transmission power for sensors based on the prevailing network conditions and the effectiveness of energy harvesting [20].

This paper's structure is set up as follows: The relevant work in RF-EH for WBAN is reviewed in Section 2. Section 3 provides a comprehensive explanation of the system model for WBAN with energy harvesting. It includes mathematical expressions that are used for performance analysis and asymptotic analysis. We present numerical results and Monte Carlo simulations in Section 4. Finally, Section 5 concludes the paper.

As distinguished physicist Nicolas Tesla demonstrated, RF energy is not a new concept. A noisy coupled-inductor circuit was used for a wireless information and power transmission demonstration. A trade-off is made between the feasible rate and the power communicated from the total quantity of power available [11]. Four harvesters operating in various frequency bands were used to examine ambient RF energy harvesting in urban and semi-urban contexts (DTV, GSM900, GSM1800 and 3G). Using their created prototype with GSM900 yields a 40% efficiency. Comparing the output dc power densities of ambient RF energy harvesters and other energy harvesters, it was discovered that RF-EH can be a promising method for energy scavenging [8]. Multiple energy harvesting nodes were used under power splitting protocol with joint best relay and power selection scheme [21]. Reference [22] studied how information is sent by considering the amount of RF energy taken from the battery in three stages as follows. 1) Capacity with an unlimited battery, $\mathrm{E_{max}} = \infty$. 2) Capacity with no battery, $\mathrm{E_{max}} = 0$. and 3) Capacity with unit size battery, $E_{max} = 1$. The linked devices function in an online mode, and they make an intelligent judgement on whether or not they can send the information by evaluating the amount of energy that is currently stored in their batteries. Markov decision theory will be helpful in the process of decision making. As a result, there is a requirement for the accurate distribution of energy. In the work by [23][24] considered a one-bit feedback from receiver antenna used for RF-EH using multiuser selection combining. The average bit error probability (ABEP) performance of smart cities and dynamic HAN, for which RF-EH is derived in closed form over Saleh-Valenzuela (SV) channel. However the concept of WBAN in the context of RF-EH is a open challenge and to the best of authors knowledge has been explored as shown in Table I. In this paper we investigate the ABEP performance of WBAN with linear EH model over Rayleigh fading channel. Since the sensors can adapt to active state or doze state in the network, therefore Markov chain is used to model the system, the main contribution of the paper are as follows.

1. A closed from expression for ABEP is derived for WBANs with Energy Harvesting.
2. Asymptotic analysis is analysed for High SNR over ABEP.
3. The Derived Mathematical expressions are verified with Monte-Carlo simulation.

This is the first work that is focused on WBAN-ABEP performance with linear EH employing Binary Phase Shift Keying (BPSK) modulation scheme over Rayleigh fading channel.

2. Related Work in WBANs with RF-EH

Table 1. State-of-the-art survey comparison summary for RF-EH in WBANs.

Ref.	SWIFT	RF-EH	BER	PDF based method	Markov Channel model	Traffic Intensity comparision	BER depends on number of sensors
[25]	✓	✓	✓	x	x	x	x
[26-29]	✓	✓	✓	✓	x	x	x
[30-34]	✓	✓	✓	x	x	✓	✓
[15, 35]	✓	✓	x	x	x	x	x
This Paper	✓	✓	✓	✓	✓	✓	✓

3. WSystem Model with RF-EH

In WBAN, various physiological signals were acquired from multiple sensors connected to the body. The sensor signals are given to a data acquisition system where analog to digital conversion and processing of signals is done in the Sensor Control Unit (SCU). The processed sensor data were sent wirelessly to a nearby sensor node, which is termed a Medical Control Unit (MCU). The system model is depicted in below Figure (1)

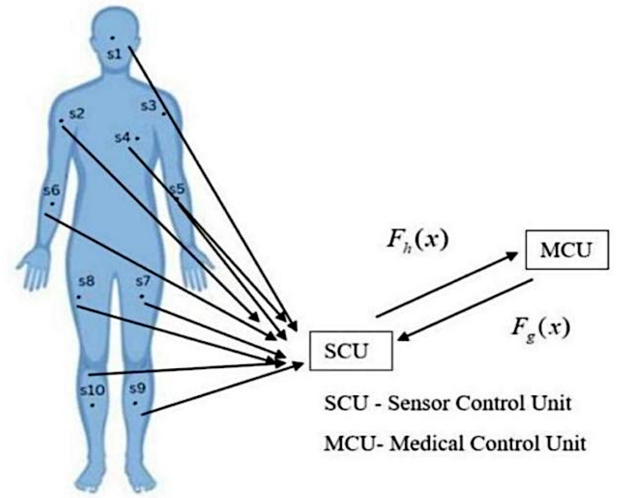

Fig. 1. System Model WBAN with EH

Let Ns be number of sensors connected to body. Among Ns sensors only k sensors will be active because it is not essential to transmit all the sensors data in order to minimize the battery consumption, as transmitting all the sensors data continuously it requires more battery usage. We have only used sensors whose readings are important at that particular period and that are deviated for the normal values, so that the physician will get alert. The sensors are connected to embedded controller interfaced with wireless device. The microcontroller remains in idle state when MCU do not require transmitting data with the help of watchdog timer in the work done by [36]. Let $F_h(x)$ be fading channel from SCU to MCU. The CDF of the received SNR at MCU is given by

$$F_{|h|}(x) = \left[1 - e^{-\frac{x}{\Omega_1}}\right]^k \tag{1}$$

where $\Omega_1 = d_1{}^{-\alpha}$, average power gain with d_1 , distance between SCU and MCU and α, path loss component (2.7) in the work done by [24]. Now the pdf can be derived by differentiating (1) and is given by:

$$f_{|h|}(x) = \frac{k}{\Omega_1}\left[1 - e^{-\frac{x}{\Omega_1}}\right]^{k-1}\left[e^{-\frac{x}{\Omega_1}}\right] \tag{2}$$

When no data is needed to transmit the controller in SCU will remain in idle stage (doze stage) and switches to active state when it requires to transmit data. We have used Markov chain model for finding number of active sensors that are required to send data to MCU. By using Markov channel model, the steady state probability can be defined as P_k:

$$P_k = \frac{\rho^k/k!}{\sum_{m=0}^{N_s}\frac{\rho^m}{m!}}, k = 0,1,2\ldots\ldots N_s. \tag{3}$$

N_s represents total number of sensors and ρ denotes traffic intensity of Markov chain.

Now the PDF from (3) using Markov chain can be written as

$$f_{|h|}(x) = \sum_{k=0}^{N_s}\frac{kP_k}{\Omega_1}\left[1 - e^{-\frac{x}{\Omega_1}}\right]^{k-1} e^{-\frac{x}{\Omega_1}} \tag{4}$$

Now by using binomial expansion, (4) can be rewritten as

$$f_{|h|}(x) = \sum_{k=0}^{N_s}\frac{kP_k}{\Omega_1}\sum_{n=0}^{k-1}(-1)^n\binom{k-1}{n}e^{-(n+1)\frac{x}{\Omega_1}} \tag{5}$$

A. Performance Analysis

The BPSK modulation strategy was used in our implementation, which was successful. One of the advantages of BPSK modulation is that it is more resistant to noise and can be used for long-distance communication. The binary data values 1 and 0 are separated by 180 degrees in the constellation diagram, which is another one of the advantages. Due to the fact that there is multipath fading in WBANs and no Line of Sight (LOS), we decided to conduct our research using the Rayleigh Fading Channel model. The formula for calculating the Average Bit Error Probability (ABEP) for BPSK is as follows:

$$\text{ABEP} = E\left[Q\sqrt{SNR}\right] = E\left[Q\sqrt{\frac{E_s}{N_0}|g|^2}\right] \tag{6}$$

where $E(.)$ represents expectation operator. From the energy received, E_s is the quantity of RF Energy that the MCU harvests, as indicated in (7) and N_0 is the noise power at the MCU.

$$E_s = \eta\tau P_t|h|^2 \tag{7}$$

where η is energy conversion efficiency, τ is power splitting ratio and P_t is transmitted power. Now substituting (7) in (6) we get

$$\text{ABEP} = E\left[Q\sqrt{\frac{\eta\tau P_t|h|^2|g|^2}{N_0}}\right] \tag{8}$$

Let $\Delta = \beta|g|^2|h|^2$ and $\beta = \frac{\eta\tau P_t}{N_0}$

Now we must get PDF of Δ for the ABEP analysis. As $|g|$ are Rayleigh distributed, the PDF can be written as

$$f_{|g|^2}(x) = \frac{1}{\Omega_2}e^{-\frac{x}{\Omega_2}} \tag{9}$$

where $\Omega_2 = d_2^{-\alpha}$, average power gain with d_2 , distance between MCU and SCU

Now we assume that $\Theta = |g|^2|h|^2$. So, we can express the PDF of Θ as:

$$f_\Theta(\lambda) = \int_0^\infty \frac{1}{x}f_{|h|^2}(x)f_{|g|^2}(\lambda/x)dx \tag{10}$$

So, by using (5) and (9) then (10) becomes

$$f_\Theta(\lambda) = \int_0^\infty \frac{1}{x} \sum_{k=0}^{N_s} \frac{kP_k}{\Omega_1} \sum_{n=0}^{k-1} (-1)^n \binom{k-1}{n} e^{-(n+1)\frac{x}{\Omega_1}} \frac{1}{\Omega_2} e^{-\frac{\lambda}{x\Omega_2}} dx \tag{11}$$

$$f_\Theta(\lambda) = \sum_{k=0}^{N_s} \frac{kP_k}{\Omega_1\Omega_2} \sum_{n=0}^{k-1} (-1)^n \binom{k-1}{n} \int_0^\infty x^{-1} e^{-(n+1)\frac{x}{\Omega_1}-\frac{\lambda}{x\Omega_2}} dx \tag{12}$$

The above integral can be solved by using the identity from $[37, (3.471-9)]$ as

$$f_\Theta(\lambda) = \sum_{k=0}^{N_s} \frac{2kP_k}{\Omega_1\Omega_2} \sum_{n=0}^{k-1} (-1)^n \binom{k-1}{n} K_0\left(2\sqrt{\frac{\lambda(n+1)}{\Omega_1\Omega_2}}\right) \tag{13}$$

Where K_0 is the v^{th} order Bessel function of second kind. Now using the principal of transformation of RV's the PDF of Δ can be expressed as:

$$f_\Delta(\lambda) = \sum_{k=0}^{N_s} \sum_{n=0}^{k-1} \frac{2kP_k}{\beta\Omega_1\Omega_2} (-1)^n \binom{k-1}{n} K_0\left(2\sqrt{\frac{\lambda(n+1)}{\beta\Omega_1\Omega_2}}\right) \tag{14}$$

Now from (9) the ABEP can be expressed as

$$\text{ABEP} = \int_0^\infty Q(\sqrt{\lambda}) f_\Delta(\lambda) d\lambda = \int_0^\infty erfc(\sqrt{\lambda/2}) f_\Delta(\lambda) d\lambda \tag{15}$$

Where $\operatorname{erfc}(x) = \frac{2}{\sqrt{\Pi}} \int_x^\infty e^{-t^2} dt$

Now substituting the value of $f_\Delta(\lambda)$.from (14) into (15) the expression for ABEP can be written as

$$\text{ABEP} = \sum_{K=0}^{N_s} \sum_{n=0}^{k=1} \frac{2kP_k}{\beta\Omega_1\Omega_2} (-1)^n \binom{k-1}{n} \int_0^\infty erfc(\sqrt{\lambda/2}) K_0\left(2\sqrt{\frac{\lambda(n+1)}{\beta\Omega_1\Omega_2}}\right) d\lambda \tag{16}$$

The integral mentioned above cannot be solved directly using a closed form expression due to the presence of both the complementary error function and Bessel function. Therefore, we convert it into Meijer's G-Function using [38] in order to obtain a closed form expression without any complication. Thus Eq. (16) can be rewritten as

$$\text{ABEP} = \sum_{K=0}^{N_s} \sum_{n=0}^{k-1} \frac{2kP_k}{\beta\Omega_1\Omega_2} (-1)^n \binom{k-1}{n} \int_0^\infty G_{1\ 2}^{2\ 0}\left(\frac{\lambda}{2}\middle|\begin{matrix} 1 \\ 0,\ 1/2 \end{matrix}\right) K_0\left(2\sqrt{\frac{\lambda(n+1)}{\beta\Omega_1\Omega_2}}\right) d\lambda \tag{17}$$

Now, using the identity $[37, (7.821-3)]$, the integral in (17) can be solved in closed form. Now changing the variable in Eq. (17)

$$\text{ABEP} = \sum_{k=0}^{N_s} \sum_{n=0}^{k-1} \frac{2kP_k}{\beta\Omega_1\Omega_2} (-1)^n \binom{k-1}{n} \frac{n+1}{\beta\Omega_1\Omega_2} \int_0^\infty K_0(2\sqrt{x}) G_{1\ 2}^{2\ 0}\left(\frac{x(\beta\Omega_1\Omega_2)}{2(n+1)}\middle|\begin{matrix} 1 \\ 0,\ 1/2 \end{matrix}\right) dx \tag{18}$$

Now applying the identity, the above integral can be solved as

$$\text{ABEP} = \sum_{k=0}^{N_s} \sum_{n=0}^{k-1} \frac{2kP_k}{\beta\Omega_1\Omega_2} (-1)^n \binom{k-1}{n} G_{3\ 2}^{2\ 2}\left(\frac{\beta\Omega_1\Omega_2}{2(n+1)}\middle|\begin{matrix} 0,\ 0,\ 1 \\ 0,\ 1/2 \end{matrix}\right) \tag{19}$$

The above equation in (19) is the final closed-form expression for ABEP with RF-EH in WBAN

3.2 Asymptotic Analysis

To find the Asymptotic ABEP, the modified Bessel Function $k_0(z)$ of small values of z can be approximated by [39], where $k_0(z) \approx -\ln z$. Therefore, by using (22) and (14) can be rewritten as

$$f_\Delta(\lambda) = \sum_{k=0}^{N_s} \sum_{n=0}^{k-1} \frac{2kP_k}{\beta\Omega_1\Omega_2} (-1)^n \binom{k-1}{n} - \ln\left(2\sqrt{\frac{\lambda(n+1)}{\beta\Omega_1\Omega_2}}\right) \tag{20}$$

$$f_\Delta(\lambda) = \sum_{k=0}^{N_s} \sum_{n=0}^{k-1} \frac{2kP_k}{\beta\Omega_1\Omega_2} (-1)^n \binom{k-1}{n} \left[-\ln 2 + \frac{1}{2}\ln\frac{\lambda(n+1)}{\beta\Omega_1\Omega_2}\right] \tag{21}$$

For the asymptotic ABEP, (17) can be rewritten as

$$\text{ABEP}^\infty = \int_{\lambda=0}^\infty \sum_{k=0}^{N_s} \sum_{n=0}^{k-1} \frac{2kP_k}{\beta\Omega_1\Omega_2} (-1)^n \binom{k-1}{n} \int_{t=0}^\infty \left[-\ln 2 + \frac{1}{2}\ln\frac{\lambda(n+1)}{\beta\Omega_1\Omega_2}\right] e^{-t^2\lambda} d\lambda dt \tag{22}$$

$$\sum_{k=0}^{N_s} \sum_{n=0}^{k-1} \frac{2kP_k}{\beta\Omega_1\Omega_2} (-1)^n \binom{k-1}{n} \ln 2 + \text{higher order terms} \tag{23}$$

As the power of $1/\beta\Omega_1\Omega_2$ is unity, so the diversity is one.

4. Numerical and Simulation Results

Analytical outcomes are assessed through numerical evaluation and validated using Monte Carlo simulation for each SNR in dB. At least 10^4 bits are transmitted in the simulation and averaging over at least 10 iterations is taken for each SNR. The system simulations are executed systematically, commencing with the uniform distribution of randomly positioned constellation points. Subsequently, fading distributions are employed to generate fading channel coefficients using the acceptance-rejection technique. The receiver utilizes a decision-making procedure based on Maximum Likelihood (ML), assuming that CSI is known. The simulation incorporates the subsequent parameters, with a focus on energy conversion efficiency $0 < \eta \leq 1$, and path loss exponent $\alpha = 2.7$ (urban areas [40]). The performance of ABEP is contingent upon the overall quantity of sensors (N_s) connected to the body in WBAN, the traffic intensity (ρ), saturation threshold, and sensitivity of EH circuit.

In Fig. 2 ABEP vs P_T (SNR) is plotted for BPSK modulation in Rayleigh fading channel assuming $\tau = 0.5, \eta = 1, N_s = 10$. These curves demonstrate that the ABEP performance improves as ρ increases. For example, increasing the traffic intensity from 2 to 6, an improvement of $P_T = 6$ dB is achieved at an ABEP of 10^{-3}. Thus, the error performance is better for the higher values of ρ.

Fig. 3 is plotted for fixed ρ and varying number of sensors (N_s). The curves demonstrate that ABEP performance improves as N_s increases.

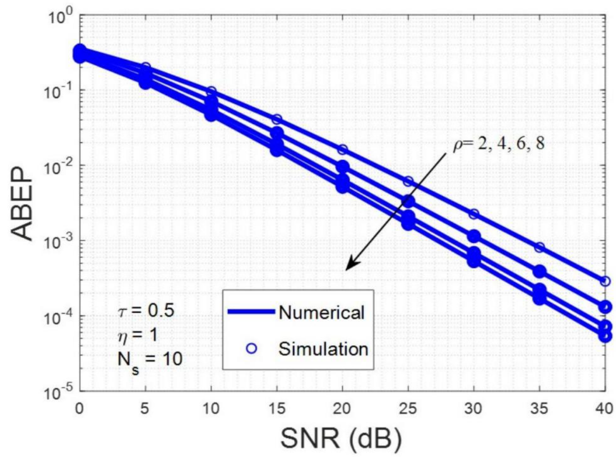

Fig. 2. ABEP versus PT (SNR) for various Traffic intensities.

We found that saturation occurs, and there is no improvement in ABEP even after increasing N_s. For example, in this case, when we are increasing the values of N_s from 12 to $N_s = 14$, the ABEP saturates with no further improvement. For example, $N_s = 12$ and $N_s = 14$, the ABEP performance is the same. If we increase beyond $N_s = 12$, there will be no change in ABEP.

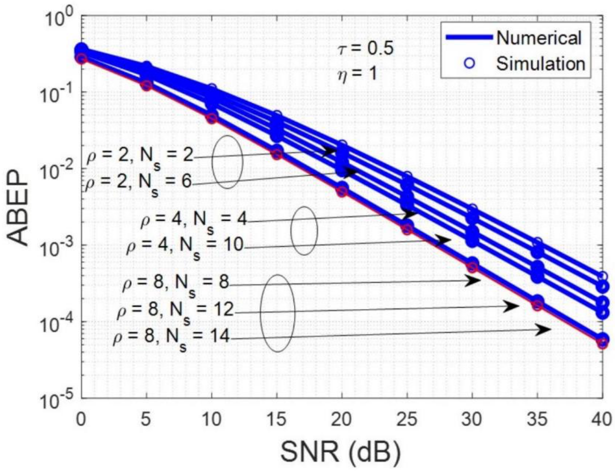

Fig. 3. ABEP versus PT (SNR) for various number of sensors (N_s)

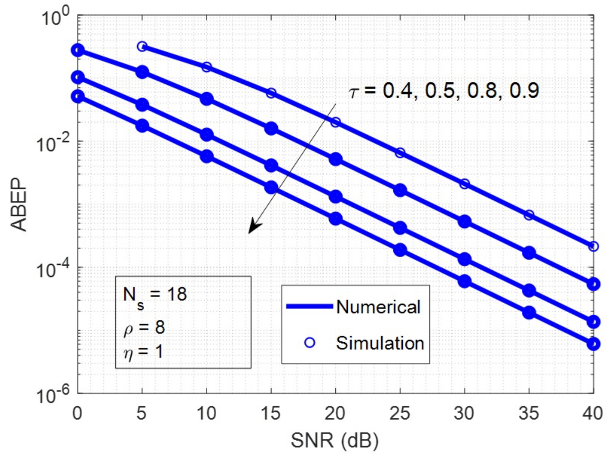

Fig. 4. ABEP versus PT (SNR) for various Power splitting ratio's.

Fig. 4 is plotted by varying power splitting ratio assuming $N_s = 18, \rho = 8, \eta = 1$. The curve demonstrates that ABEP performance improves by increasing τ. For example, increasing the value of τ from 0.5 to 0.8 an SNR improvement of 7 dB occurs at ABEP of 10^{-3}. Thus, splitting the received power at the MCU is beneficial as we can harvest the energy without losing the information.

Fig. 5 is plotted for ABEP vs τ by varying P_T (SNR) assuming $N_s = 10, \rho = 8, \eta = 1$. The curves demonstrate that ABEP performance improves by increasing τ and SNR.

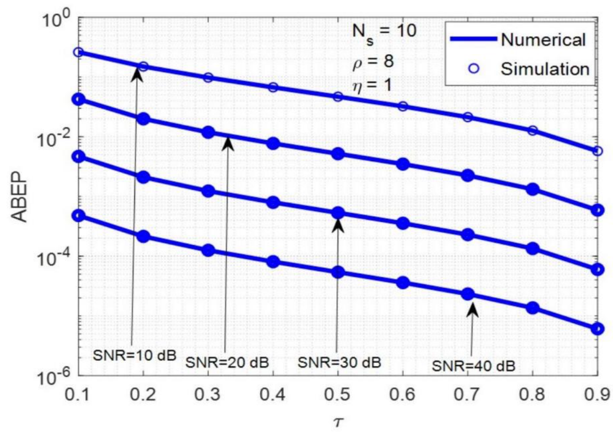

Fig. 5. ABEP versus τ

Fig. 6 is plotted for ABEP vs P_T (SNR) by varying energy conversion efficiency. The curves demonstrate that ABEP performance improves by increasing η. Note that setting η

less than one degrades the system performance since the harvested energy will be decreased as in (8).

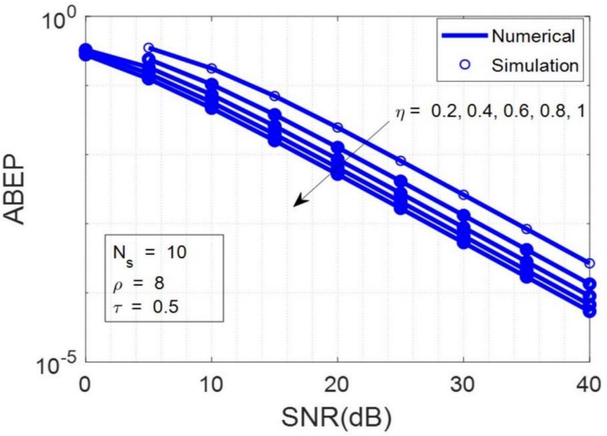

Fig. 6. ABEP versus PT (SNR) for various Energy conversion efficiencies.

5. Conclusion

The ABEP performance of WBAN is investigated in this work using energy harvesting and BPSK modulation. A closed-form equation for ABEP over a Rayleigh fading channel has been developed by the present work. In the case of the active sensors, we have developed the Markov channel model, ensuring that not all sensors will provide the information simultaneously. An analytical equation of ABEP is given after an asymptotic analysis has been presented. Studies are being conducted on performance to investigate the effects of power splitting ratio, traffic intensity, total number of sensors, and energy efficiency. In addition, the asymptotic analysis is analyzed for high SNR, and the diversity is computed. The obtained expressions have undergone numerical analysis and have been validated by comparing them to the outcomes of a computer simulation.

References

[1] N. Arora, S. H. Gupta, and B. Kumar, "Analyzing and Optimizing Cooperative Communication for in Vivo WBAN," *Wireless Pers Commun*, vol. 122, no. 1, pp. 429–450, Jan. 2022, doi: 10.1007/s11277-021-08906-1.

[2] A. F. Jaimes and F. R. De Sousa, "A taxonomy for learning, teaching, and assessing wireless body area networks," in *2016 IEEE 7th Latin American Symp. Circuits Sys. (LASCAS)*, Florianopolis, Brazil: IEEE, Feb. 2016, pp. 179–182. doi: 10.1109/LASCAS.2016.7451039.

[3] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, and A. Jamalipour, "Wireless Body Area Networks: A Survey," *IEEE Commun. Surv. Tutorials*, vol. 16, no. 3, pp. 1658–1686, 2014, doi: 10.1109/SURV.2013.121313.00064.

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

[5] R. Negra, I. Jemili, and A. Belghith, "Wireless Body Area Networks: Applications and Technologies," *Procedia Comp. Sci.*, vol. 83, pp. 1274–1281, May 2016, doi: 10.1016/j.procs.2016.04.266.

[6] B. Latré, B. Braem, I. Moerman, C. Blondia, and P. Demeester, "A survey on wireless body area networks," *Wireless Netw*, vol. 17, no. 1, pp. 1–18, Jan. 2011, doi: 10.1007/s11276-010-0252-4.

[7] M. A. Hanson *et al.*, "Body Area Sensor Networks: Challenges and Opportunities," *Computer*, vol. 42, no. 1, pp. 58–65, Jan. 2009, doi: 10.1109/MC.2009.5.

[8] M. Pinuela, P. D. Mitcheson, and S. Lucyszyn, "Ambient RF Energy Harvesting in Urban and Semi-Urban Environments," *IEEE Trans. Microwave Theory Techn.*, vol. 61, no. 7, pp. 2715–2726, Jul. 2013, doi: 10.1109/TMTT.2013.2262687.

[9] S. Sudevalayam and P. Kulkarni, "Energy Harvesting Sensor Nodes: Survey and Implications," *IEEE Commun. Surv. Tutorials*, vol. 13, no. 3, pp. 443–461, Jul. 2011, doi: 10.1109/SURV.2011.060710.00094.

[10] K. Huang and V. K. N. Lau, "Enabling Wireless Power Transfer in Cellular Networks: Architecture, Modeling and Deployment," *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, pp. 902–912, Feb. 2014, doi: 10.1109/TWC.2013.122313.130727.

[11] P. Grover and A. Sahai, "Shannon meets Tesla: Wireless information and power transfer," in *2010 IEEE Int. Symp. Inform. Theory*, Austin, TX, USA: IEEE, Jun. 2010, pp. 2363–2367. doi: 10.1109/ISIT.2010.5513714.

[12] S. Bi, C. K. Ho, and R. Zhang, "Wireless powered communication: opportunities and challenges," *IEEE Commun. Mag.*, vol. 53, no. 4, pp. 117–125, Apr. 2015, doi: 10.1109/MCOM.2015.7081084.

[13] H. Ju and R. Zhang, "Throughput Maximization in Wireless Powered Communication Networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 1, pp. 418–428, Jan. 2014, doi: 10.1109/TWC.2013.112513.130760.

[14] L. R. Varshney, "Transporting information and energy simultaneously," in *2008 IEEE Int. Symp. Inform. Theory*, Toronto, ON, Canada: IEEE, Jul. 2008, pp. 1612–1616. doi: 10.1109/ISIT.2008.4595260.

[15] P. Sharma and A. K. Singh, "A survey on RF energy harvesting techniques for lifetime enhancement of wireless sensor networks," *Sustain. Comp.: Inform. Sys.*, vol. 37, Art. no. 100836, Jan. 2023, doi: 10.1016/j.suscom.2022.100836.

[16] Y. C. Lee *et al.*, "High-Performance Multiband Ambient RF Energy Harvesting Front-End System for Sustainable IoT Applications—A Review," *IEEE Access*, vol. 11, pp. 11143–11164, 2023, doi: 10.1109/ACCESS.2023.3241458.

[17] H. K. Sahu, A. K. Padhan, B. Das, and D. Dixit, "BER performance of smart grid HAN with RF energy harvesting over RF-THz channel," *AEU – Int. J. Electr. Commun.*, vol. 178, May 2024, Art. no. 155247, doi: 10.1016/j.aeue.2024.155247.

[18] H. K. Sahu and P. K. Panda, "D2A Performance with SSK Modulation and SWIPT in Green Smart Cities," *Wireless Pers Commun*, vol. 135, no. 4, pp. 2319–2330, Apr. 2024, doi: 10.1007/s11277-024-11158-4.

[19] H. K. Sahu, A. K. Padhan, S. G. Dontamsetti, and P. R. Sahu, "Performance Analysis of Smart Grid Network with Energy Harvesting over Mixed RF/PLC Channel," in *2023 Nat. Conf. Commun. (NCC)*, Guwahati, India: IEEE, Feb. 2023, pp. 1–6. doi: 10.1109/NCC56989.2023.10067970.

[20] J. Hu, G. Xu, L. Hu, S. Li, and Y. Xing, "An Adaptive Energy Efficient MAC Protocol for RF Energy Harvesting WBANs," *IEEE Trans. Commun.*, vol. 71, no. 1, pp. 473–484, Jan. 2023, doi: 10.1109/TCOMM.2022.3222872.

[21] H. Guo, Z. Yang, Y. Zou, M. Qian, J. Zhu, and L. Hanzo, "Joint Optimization of Power Splitting and Beamforming in Energy Harvesting Cooperative Networks," *IEEE Trans. Commun.*, vol. 67, no. 12, pp. 8247–8257, Dec. 2019, doi: 10.1109/TCOMM.2019.2945324.

[22] S. Ulukus *et al.*, "Energy Harvesting Wireless Communications: A Review of Recent Advances," *IEEE J. Select. Areas Commun.*, vol. 33, no. 3, pp. 360–381, Mar. 2015, doi: 10.1109/JSAC.2015.2391531.

[23] H. K. Sahu, "Performance Analysis of Energy Harvesting-Based Smart Grid Dynamic HAN With SSK Modulation," *IEEE Commun. Lett.*, vol. 25, no. 8, pp. 2527–2530, Aug. 2021, doi: 10.1109/LCOMM.2021.3083966.

[24] H. K. Sahu, A. K. Padhan, and P. R. Sahu, "Smart Devices Performance With SSK-BPSK Modulation and Energy Harvesting

in Smart Cities," *IEEE Commun. Lett.*, vol. 25, no. 2, pp. 637–640, Feb. 2021, doi: 10.1109/LCOMM.2020.3026737.

[25] S. M. Demir, F. Al-Turjman, and A. Muhtaroglu, "Energy Scavenging Methods for WBAN Applications: A Review," *IEEE Sensors J.*, vol. 18, no. 16, pp. 6477–6488, Aug. 2018, doi: 10.1109/JSEN.2018.2851187.

[26] J. Li, Q. Zhang, and C. Zhai, "Coverage performance of nonlinear energy harvesting based wireless sensor networks for the healthcare in hospitals," *Inter. Techn. Letters*, vol. 6, no. 4, p. e424, Jul. 2023, doi: 10.1002/itl2.424.

[27] F. Liu *et al.*, "Self-powered wireless body area network for multi-joint movements monitoring based on contact-separation direct current triboelectric nanogenerators," *InfoMat*, vol. 5, no. 8, Art. no. e12428, Aug. 2023, doi: 10.1002/inf2.12428.

[28] K. Niotaki *et al.*, "RF Energy Harvesting and Wireless Power Transfer for Energy Autonomous Wireless Devices and RFIDs," *IEEE J. Microw.*, vol. 3, no. 2, pp. 763–782, Apr. 2023, doi: 10.1109/JMW.2023.3255581.

[29] B. Cornet, H. Fang, H. Ngo, E. W. Boyer, and H. Wang, "An Overview of Wireless Body Area Networks for Mobile Health Applications," *IEEE Network*, vol. 36, no. 1, pp. 76–82, Jan. 2022, doi: 10.1109/MNET.103.2000761.

[30] D. Sui, F. Hu, W. Zhou, M. Shao, and M. Chen, "Relay Selection for Radio Frequency Energy-Harvesting Wireless Body Area Network With Buffer," *IEEE Internet Things J.*, vol. 5, no. 2, pp. 1100–1107, Apr. 2018, doi: 10.1109/JIOT.2017.2788207.

[31] M. Boumaiz *et al.*, "Energy harvesting based WBANs: EH optimization methods," *Procedia Comp. Sci.*, vol. 151, pp. 1040–1045, May 2019, doi: 10.1016/j.procs.2019.04.147.

[32] F. Akhtar and M. H. Rehmani, "Energy Harvesting for Self-Sustainable Wireless Body Area Networks," *IT Prof.*, vol. 19, no. 2, pp. 32–40, Mar. 2017, doi: 10.1109/MITP.2017.34.

[33] R. Zhang, A. Nayak, and J. Yu, "Sleep Scheduling in Energy Harvesting Wireless Body Area Networks," *IEEE Commun. Mag.*, vol. 57, no. 2, pp. 95–101, Feb. 2019, doi: 10.1109/MCOM.2018.1800152.

[34] L. Yang, Y. J. Zhou, C. Zhang, X. M. Yang, X.-X. Yang, and C. Tan, "Compact Multiband Wireless Energy Harvesting Based Battery-Free Body Area Networks Sensor for Mobile Healthcare," *IEEE J. Electromagn. RF Microw. Med. Biol.*, vol. 2, no. 2, pp. 109–115, Jun. 2018, doi: 10.1109/JERM.2018.2817364.

[35] A. A. Thabit, M. S. Mahmoud, A. Alkhayyat, and Q. H. Abbasi, "Energy harvesting Internet of Things health-based paradigm: Towards outage probability reduction through inter–wireless body area network cooperation," *Int. J. Distrib. Sensor Netw.*, vol. 15, no. 10, Oct. 2019, Art. no. 155014771987987, doi: 10.1177/1550147719879870.

[36] N. Murphy and M. Barr, "Watchdog timers," *Embedded Sys. Program.*, vol. 14, no. 11, pp. 79-80, Oct. 2014.

[37] I. S. Gradshteĭn and D. Zwillinger, *Table of integrals, series, and products*, 8th edition. Amsterdam Boston: Elsevier, Academic Press is an imprint of Elsevier, 2015.

[38] A. P. Prudnikov, Yu. A. Brychkov, O. I. Marichev, and R. H. Romer, "*Integrals and Series*," *American J. Phys.*, vol. 56, no. 10, pp. 957–958, Oct. 1988, doi: 10.1119/1.15375.

[39] M. Abramowitz and I. A. Stegun, *Handbook of mathematical functions: with formulas, graphs and mathematical tables*, Unabridged, Unaltered and corr. Republ. of the 1964 ed. in Dover books on advanced mathematics. New York: Dover publ, 1972.

[40] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy tradeoff," in *2012 IEEE Global Communic. Conf. (GLOBECOM)*, Anaheim, CA, USA: IEEE, Dec. 2012, pp. 3982–3987. doi: 10.1109/GLOCOM.2012.6503739.