Journal of Engineering Science and Technology
Vol. 13, No. 8 (2018) 2616 - 2631

ENERGY EFFICIENT WIRELESS BODY AREA NETWORK USING RECEIVE DIVERSITY

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Abstract

Energy efficiency is a crucial issue in wireless body area networks where energy-constrained sensor nodes are employed. In this paper, an energy model for multi-level quadrature amplitude modulation based wireless body area network is proposed and its energy efficiency is investigated. To improve the energy efficiency further, Rate Optimized scheme and Optimum Energy Consumption using Receive Diversity scheme are proposed. In Rate Optimized scheme, the data rate is varied according to transmission distance to ensure minimum total energy consumption. The Optimum Energy Consumption using Receive Diversity scheme utilizes receive diversity along with rate optimization. The total energy consumption of the proposed schemes is analysed. An energy saving of 53.16% at a distance of 7 m is achieved by the Optimum Energy Consumption using Receive Diversity scheme over conventional fixed rate scheme. However, the total energy consumption is still higher than multi-level phase shift keying based wireless body area network. The proposed Optimum Energy Consumption using Receive Diversity scheme is extended to multi-level phase shift keying based wireless body area network and achieved an energy saving of 22.44% and 22.31% over conventional fixed rate and Rate Optimized scheme at a transmission distance of 2 m.

Keywords: Diversity, Energy efficiency, Optimal, Sensor, Wireless body area network.

1. Introduction

A Wireless Body Area Network (WBAN) is a special kind of sensor network, which is designed to autonomously connect various medical sensors and devices, located inside and outside of a human body. In recent researches, wireless body area networks have witnessed a great boom due to their tremendous potential for improving quality of life and medical health [1-4].

The sensors deployed in WBAN sense important biological signals like body temperature, heart rate and oxygen level in blood, etc., and transmit the data to Body Control Unit (BCU) or remote medical server for analysis and diagnosis.

However, these nodes are energy constrained and hence, energy efficiency becomes a crucial issue [5]. In a sensor node, the total energy consumption comprises of two components-transmission energy and circuit energy [6, 7]. Though the advent of low power Very Large Scale Integration (VLSI) technology made circuit power consumption increasingly smaller, it is comparable with the transmission energy due to smaller transmission distance in WBAN [8]. Therefore, in the recent past, a significant amount of research has been carried out in the improvement of energy efficiency in WBAN. Uysal-Bikikoglu et al. [9] presented an energy efficient algorithm for the minimization of transmission energy by increasing transmission duration. Dou et al. [10] proposed a hybrid transmission mechanism for optimizing the energy consumption in wireless sensor networks. Zhu and Papavassiliou presented a method for the organization of energy efficient wireless sensor network to improve the network lifetime. Yi et al. [12] proposed an energy efficient scheme for Multi-Level Phase Shift Keying (M-PSK) based WBAN. The authors achieved energy efficiency by optimizing the data rate according to the transmission distance.

Diversity is a technique used to combat the detrimental effect of multipath fading [13]. Bravos and Kanatas [14] and Nguyen et al. [15] proposed a transmission strategy to minimize the total energy consumption by utilizing diversity. The authors have taken the effect of circuit energy consumption into account for minimizing the total energy consumption. Senthil Kumar and Amutha [16] achieved energy efficiency by employing channel codes in wireless sensor networks. Senthil Kumar and Amutha [17] and Kanthimathi et al. [18] proposed an algorithm for improving the energy efficiency of wireless sensor network. The authors achieved energy efficiency by utilizing spatial diversity and optimizing the transmission distance. Therefore, there is a scope for improvement in energy efficiency of a WBAN by utilizing diversity and proper selection of transmission distance and data rate.

The main contributions of the paper are

- The energy model for Multi-Level Quadrature Amplitude Modulation (M-QAM) based WBAN is derived. Two schemes-Rate optimized and Optimum Energy Consumption using Receive Diversity (OECRD) schemes are proposed for improving the energy efficiency of M-QAM based WBAN.
- The proposed Optimum Energy Consumption using Receive Diversity scheme is extended to M-PSK based WBAN to achieve significant energy efficiency over conventional baseline and rate optimization schemes.

The rest of the paper is organized as follows. The energy model for M-QAM based WBAN is presented in Section 2. Section 3 describes the energy model for

M-PSK based WBAN. Simulation results are given in Section 4. Finally, Section 5 concludes the paper.

2. M-QAM Based Energy Model

The total energy consumed per bit by a sensor node [19] is defined as follows:

$$E_{bit\_total} = \frac{P_{act}T_{act} + P_{slp}T_{slp}}{L} \tag{1}$$

where P_{act} is the power consumed when the node is in the active state for a duration of T_{act}, P_{slp} is the power consumed when the node is in the sleep state for a duration of T_{slp} and L is the number of bits to be transmitted by the sensor node.

Let T be the allowable time limit within which, the L bits are to be transmitted and is defined as follows:

$$T = T_{act} + T_{slp} \tag{2}$$

The power consumed by the node in the active state comprises of two components [6] - power consumed by the Power Amplifier (PA) P_{ampr} and power consumed by all other circuit blocks along the signal path P_{ckt} and is defined as follows:

$$P_{act} = P_{ampr} + P_{ckt} \tag{3}$$

The power consumed by the power amplifier [6] is defined as follows

$$P_{ampr} = \left(\frac{\xi}{\eta}\right)P_t \tag{4}$$

where ζ is the peak-to-average ratio, η is the drain efficiency of the power amplifier and P_t is the transmission power.

Using the path loss model specified for WBAN by Kohnoet al. [8], and link power budget relationship, the transmission power is defined as follows:

$$P_t = \bar{E}_{br} R \frac{(4\pi)^2 10^{\left((b\_loss + N\_loss + M_l + N_f)/10\right)} d^{\left(a\_loss/10\right)}}{10^{\left(G_t G_r/10\right)} \lambda^{\left(a\_loss/10\right)}} \tag{5}$$

where $\bar{E}_{br}$ is the required energy per bit at the receiver for a given Bit Error Rate (BER), R is the data rate, *a_loss* and *b_loss* are coefficients of linear filtering, *N_loss* is a normally distributed variable with standard deviation δ_N, M_l is the link margin, Nf is the receiver noise figure, d is the transmission distance, G_t is the transmitter antenna gain, G_r is the receiver antenna gain and λ is the carrier wavelength.

Assume M-QAM is employed by WBAN. Then, the bit error rate p_b at the receiver for M-QAM ($M > 4$) [18] can be expressed as follows:

$$p_b = \frac{4}{b}\left(1 - \frac{1}{2^{b/2}}\right) Q\left(\sqrt{\frac{3b\gamma_{br}}{M-1}}\right) \tag{6}$$

where b is the number of bits used to represent a symbol, $Q(.)$ is the Q-function, M is the modulation order and γ_{br} is the Signal to Noise Ratio (SNR) at the receiver.

The signal to noise ratio of a system with receive diversity [13] is defined as follows:

$$\gamma_{br} = \frac{\left\| H_{1\times M_r} \right\|^2 \bar{E}_{br}}{N_0} \tag{7}$$

where H is a row vector of size $1\times M_r$, $\left\| H_{1\times M_r} \right\|^2$ is the channel gain, M_r is the number of antennas at the receiver and N_0 is the single-sided thermal noise power spectral density. The receive diversity is chosen because a number of transmitting nodes may cause inconvenience to the patient and there may not be a size or energy constraint at the receiver.

By substituting Eq. (7) in Eq. (6), Eq. (6) can be written as follows

$$p_b = \frac{4}{b}\left(1 - \frac{1}{2^{b/2}}\right) Q\left(\sqrt{\frac{3b\left\| H_{1\times M_r} \right\|^2 \bar{E}_{br}}{(M-1)N_0}}\right) \tag{8}$$

By applying Chernoff bound, Eq. (8) can be modified as follows:

$$p_b \le \frac{2}{b}\left(1 - \frac{1}{2^{b/2}}\right) \exp\left(\frac{1.5b\left\| H_{1\times M_r} \right\|^2 \bar{E}_{br}}{(M-1)N_0}\right) \tag{9}$$

From Eq. (9) and by assuming equality, the $\bar{E}_{br}$ can be expressed as follows:

$$\bar{E}_{br} = \frac{(M-1)N_0}{1.5b\left\| H_{1\times M_r} \right\|^2} s(b) \tag{10}$$

where $s(b) = \ln \dfrac{b_{P_b}}{2\left(1 - \dfrac{1}{2^{b/2}}\right)}$ is a function of b.

By substituting Eq. (10) in Eq. (5), the transmission power can be expressed as follows:

$$P_t = \frac{C\xi(M-1)d^{\left(a\_loss/10\right)} s(b) R}{\eta b} \tag{11}$$

where $C = \dfrac{(4\pi)^2 10^{\left(\left(b\_loss + N\_loss + M_l + N_f\right)/10\right)}}{1.5\ \lambda^{\left(a\_loss/10\right)} 10^{\left(G_t G_r/10\right)}}$ is a constant.

The power consumption of all circuit blocks along the signal path except power amplifier [20] of Eq. (3) is defined as follows:

$$P_{ckt} = P_{DAC} + P_{mix} + P_{filt} + P_{syn} \tag{12}$$

where P_{DAC}, P_{mix}, P_{filt}, and P_{syn} are the power consumption values for the Digital-to-Analog Converter (DAC), mixer, active filter at the transmitter and frequency synthesizer respectively.

The data rate can be expressed as follows [12]:

$$R = \frac{L}{T} \tag{13}$$

By substituting Eqs. (3), (4), (11) to (13) in Eq. (1), the total energy consumed per bit can be expressed as follows:

$$E_{bit\_total} = \frac{C\xi\left(M-1\right)d^{\left(a\_loss/10\right)}s(t)}{\eta b} + \frac{P_{ckt} - P_{slp}}{R} + \frac{P_{slp}}{L} \tag{14}$$

The bandwidth for M-QAM is given by [12]:

$$B = \frac{1+\alpha}{b}R \tag{15}$$

where α denotes the roll-off factor of the pulse shaping filter.

By substituting Eq. (15) in Eq. (14), Eq. (14) can be written as follows:

$$E_{bit\_total} = \frac{C\xi\left(2^{(1+\alpha)R/B} - 1\right)Bd^{\left(a\_loss/10\right)}u(R)}{\eta\left(1+\alpha\right)R} + \frac{P_{ckt} - P_{slp}}{R} + \frac{P_{slp}}{L} \tag{16}$$

where $u(R) = \ln\left((1+\alpha)R_{P_b} / 2B\left\{1 - \frac{1}{2^{\frac{(1+\alpha)R}{2B}}}\right\}\right)$ is a function of R.

In Eq. (16), the first term corresponds to transmission energy and the rest corresponds to circuit energy consumption. From the equations, it is clear that transmission energy is a function of transmission distance and data rate. It is also clear that the circuit energy consumption is a function of data rate and independent of distance. Therefore, both the transmission distance and data rate are to be optimized for minimum energy consumption while the others are constants.

Maximum transmission distance

It is clear from Eq. (16) that the total energy per bit comprises of transmission energy and circuit energy. In traditional wireless systems, the transmission distance usually will be higher and hence the transmission energy will be very higher than the circuit energy consumption. Therefore, circuit energy consumption is ignored in the analysis of energy consumption of traditional wireless communication systems. However, since the transmission distance is short in WBAN, the circuit energy consumption becomes comparable to transmission energy and even dominates [21]. Therefore, it is clear that there exist a limit on maximum transmission distance d_{max} up to which, the circuit energy consumption dominates the transmission energy. Therefore, the total energy consumption can be minimized by optimizing the data rate as long as the transmission distance d is lesser than maximum transmission distance (i.e., $d \leq d_{max}$). From Eq. (16), it is clear that for a given transmission distance, the total energy consumption is a function of the data rate and is strictly convex with the data rate as long as $d \leq d_{max}$.

The problem to optimize the total energy consumption can be summarized as follows:

Minimize E_{bit_total}

Subject to $R_{\min} \leq R \leq R_{\max}$

$d \leq d_{\max}$

where R_{min} *and* R_{max} are the minimum and maximum data rate respectively. This is an optimization problem of variable R and the following proposition can be obtained.

Proposition:

The total energy consumption E_{bit_total} is dependent on the data rate R and the whole function is convex and has a minimum value.

Proof: The value of the second derivative of Eq. (16) with respect to R results in a positive value.

i.e., $\frac{\partial^2 E_{bit\_total}}{\partial R^2} > 0$

Hence, E_{bit_total} is convex and has a minimum value.

From Eq. (16), it can be understood that the transmission energy increases with increase in data rate and the circuit energy consumption decreases increase in data rate and hence strictly convex with R. Therefore, the maximum transmission distance d_{max} can be found from the derivative of E_{bit_total} with respect to R at the minimum data rate R_{min}. Using Eqs. (13) and (15) and with $b > 2$ for M-QAM, the minimum data rate [12] can be expressed as follows:

$$R_{\min} = \max\left\{\frac{L}{T}, \frac{2B}{1+\alpha}\right\} \tag{17}$$

By combining Eq. (16) with Eq. (17), the maximum transmission distance is obtained as follows:

$$d_{\max} = \left\{d : \frac{\partial E_{bit\_total}}{\partial R}\Big|_{R=R_{\min}} = 0\right\} \tag{18}$$

In order to minimize the total energy, the range of data rate to make $R \in [R_{min}, R_{max}]$ with a maximum data rate R_{max} is to be determined. In general, the WBAN devices are required to transmit low power to protect the safety of the human body and to reduce interference with other devices. The transmit power P_t must satisfy $P_t \leq P_{max}$ where P_{max} is the maximum transmit power set by the local regulatory bodies [22]. By using Eqs. (5) and (10), the maximum data rate is defined as follows:

$$R_{\max}=\left\{R:\frac{C\left(2^{(1+\alpha)R/B}-1\right)Bd^{\left(a\_loss/10\right)}u(R)}{(1+\alpha)R}=P_{\max}\right\} \tag{19}$$

By assuming the maximum transmit power as 1.5 W as specified by the Federal Communication Commission (FCC) [8] together with the parameters listed in Table 1 [6, 8, 21, 22], the maximum transmission distance is computed as follows:

$$d_{\max}=\left[\frac{\left(P_{ckt}-P_{slp}\right)\eta}{R^2\xi C}\frac{\frac{(1+\alpha)^2R^2}{B^2}}{\left[\frac{(1+\alpha)R}{B}\left(e(R)+f(R)\right)-g(R)\right]}\right]^{\frac{10}{a\_loss}} \tag{20}$$

where

$$e(R)=\left(2^{\frac{(1+\alpha)R}{B}}-1\right)\left(\frac{1}{R}-\frac{1}{1-2^{\frac{-(1+\alpha)R}{2B}}}\frac{(1+\alpha)}{2B}2^{\frac{-(1+\alpha)R}{2B}}\log 2\right)$$

$$f(R)=\frac{(1+\alpha)Ru(R)2^{\frac{(1+\alpha)R}{B}}\log 2}{B}$$

and $g(R)=-\left(2^{\frac{(1+\alpha)R}{B}}-1\right)u(R)$ are functions of R. The values of the simulation parameters listed in Table 1 are reasonable to assume as they have been considered in the references cited.

Table 1. Simulation parameters.

Parameter	Value	Parameter	Value	Parameter	Value
ξ	1	α	0.25	P_b	10^{-5}
G_tG_r	5 dBi	$N_0/2$	-171 dBm/Hz	η	0.5
B	400 kHz	L	2 Kbits	M_l	40 dB
f_c	951.1 MHz	λ	0.3154 m	N_f	10 dB
a_loss	15.5	*b_loss*	5.38	*N_loss*	5.35
P_{ckt}	12.5 mW	P_{slp}	0.5 mW	δ_n	5.35

3. M-PSK Based Energy Model

The total energy consumed per bit by an M-PSK based WBAN is derived Yi et al. [12] as follows:

$$E_{bit\_total}=\frac{Vd^{\frac{a\_loss}{10}}z(R)}{R}+\frac{P_{ckt}-P_{slp}}{R}+\frac{P_{slp}T}{L} \tag{21}$$

where $V = \frac{\xi 10^{\left(\frac{b\_loss + N\_loss}{10}\right)}}{\eta}$ is a constant and

where $z(R) = \frac{-BN_0 N_f}{2} \frac{\ln\left(\frac{(1+\alpha)\, p_b R}{B}\right)}{\sin^2\left(\frac{\pi}{2^{\frac{(1+\alpha)R}{B}}}\right)}$ is a function of R.

From Eq. (21), the total energy consumed per bit by an M-PSK based WBAN with receive diversity can be derived as follows:

$$E_{bit\_total} = \frac{Vd^{\frac{a\_loss}{10}} z(R)}{\left\|H_{1\times M_r}\right\|^2 R} + \frac{P_{ckt} - P_{slp}}{R} + \frac{P_{slp} T}{L} \tag{22}$$

In Eq. (22), the first term corresponds to transmission energy consumption, which is a function of transmission distance and data rate. The rest of the terms correspond to circuit energy consumption, which is independent of transmission distance and a function of data rate. From Eq. (22), it can be understood that the total energy consumption of the M-PSK based WBAN can be minimized using rate optimization according to the transmission distance and by utilising receive diversity.

4. Results and Discussion

In this work, it is assumed that the sensors are placed on the surface of the human body. Therefore, body surface to body surface (Channel Model CM3) model, which covers frequency band 950-956 MHz is appropriate to be considered. The WBAN is simulated using MATLAB version 8 according to the specifications of IEEE 802.15.6 standard. For $d \le d_{max}$, the total energy per bit can be saved by optimizing R through an appropriate convex optimization algorithm, which is termed as Rate Optimized scheme. The total energy per bit can be saved further by the Rate Optimized scheme utilizing receive diversity and is termed as Optimum Energy Consumption with Receive Diversity (OECRD) scheme. A scheme, which uses fixed data rate R_{min} is termed as Baseline scheme. The proposed schemes are compared with the Baseline scheme.

The energy consumed per bit over data rate for a transmission distance d=1 mm is shown in Fig. 1. From the figure, it is clear that the transmission energy increases with increase in data rate. The circuit energy consumption decreases with increase in data rate. The total energy consumption is the sum of transmission energy and circuit energy consumption. Initially, the total energy consumption decreases with an increase in data rate, reaches a minimum value and then starts increasing. The optimum data rate R_{opt} is the data rate at which, total energy consumption is lesser.

The optimum data rate for a minimum distance is the maximum data rate R_{max}. The distance d=1 mm is chosen as it is the minimum possible distance since it cannot be zero. From the figure, it is clear that the minimum energy consumption occurs at 4.2 MHz. Therefore, the maximum data rate R_{max} is set as 4.2 MHz. Also, 4.2 MHz is set as the R_{opt} for the transmission distance d=1 mm.

The total energy consumption per bit of M-QAM based baseline, proposed Rate Optimized, proposed OECRD schemes with M_r=2 to 4 over transmission distance is shown in Fig. 2. In order to have the clear visualization of the influence of rate optimization and receive diversity on the total energy consumption, the transmission distance is limited to d=1 m. From the figure, it can be observed that the total energy consumption of all the schemes increases with an increase in transmission distance. The data rate R for the Baseline scheme is set equal to $R_{min,}$ which is 480 kHz and fixed irrespective of transmission distance. The total energy, consumption of the Baseline scheme is higher at all the transmission distance values considered when compared to other schemes. The proposed Rate Optimized scheme uses R_{opt} for every distance value and hence its total energy consumption is lesser than the total energy consumption of the Baseline scheme up to d=0.54 m.

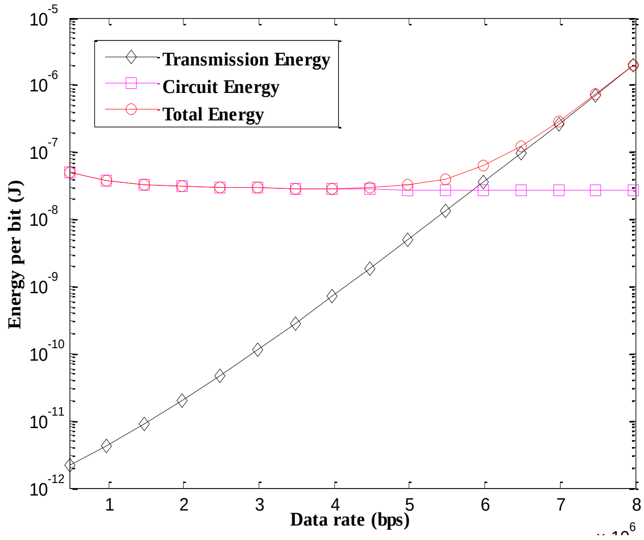

Fig. 1. Energy consumption per bit over data rate.

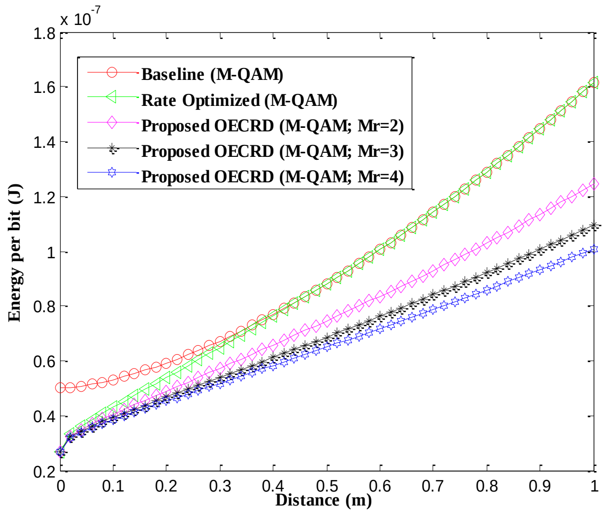

Fig. 2. Energy consumption per bit over distance.

For d > 0.54 m, the R_{opt} becomes equal to R_{min} and hence total energy consumption of Rate Optimized scheme becomes equal to the total energy consumption of the Baseline scheme. The proposed OECRD schemes utilize receive diversity in addition to rate optimization and hence their total energy consumption is lesser than baseline, proposed Rate Optimized schemes. The rate optimization is beneficial for the proposed OECRD schemes with M_r=2, 3 and 4 up to d=0.7 m, d=0.84 m and d=0.9 m respectively. Above these distances, as the R_{opt} becomes equal to R_{min}, the energy saving is only because of the receive diversity. From the figure, it is clear that for a given transmission distance, the total energy consumption decreases with an increase in the order of the receive diversity. The total energy consumption per bit of M-QAM based Baseline, proposed Rate Optimized, proposed OECRD schemes with M_r=2, 3 and 4 over transmission distance is shown in Fig. 3. Since the maximum transmit power is 1.5 W, the minimum data rate is 480 Kbps, the corresponding maximum transmits energy and maximum transmission distance is computed as 3.1×10^{-6} J and 8.55 m respectively using Eqs. (11) and (20). Therefore, in the figure, the transmission distance is limited to 8.55 m. The total energy consumption of the Baseline scheme is higher at all the transmission distance values considered when compared to other schemes.

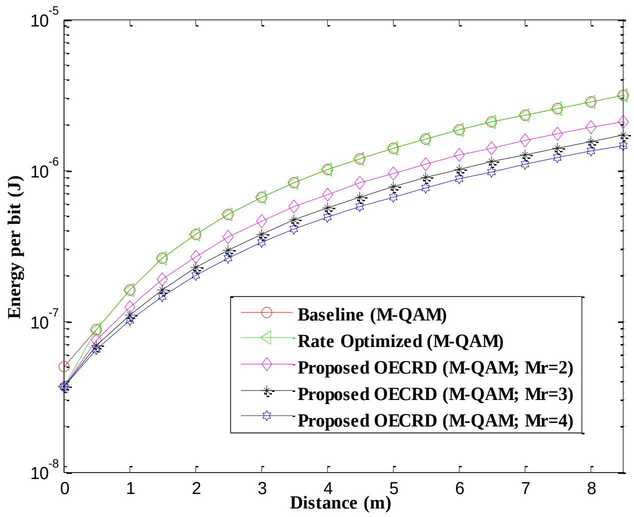

Fig. 3. Energy consumption per bit over distance.

From the figure, it is clear that for a given transmission distance, the total energy consumption decreases with an increase in the order of the receive diversity.

Table 2 shows optimum data rate for M-QAM based schemes at various distances. From the table, it is clear that rate optimization is possible only for smaller distances and also the optimum data rate is higher for higher receive diversity.

Table 3 presents the total energy consumed per bit corresponding to the optimum data rate for M-QAM based schemes at various distances. From the table, it is clear that the total energy consumption of the proposed OECRD with M_r=4 is lesser when compared to other schemes at any given distance. Table 4 shows the percentage of energy saving obtained by the Rate Optimized and the proposed OECRD schemes.

Table 2. Optimum data rate in Kbps for M-QAM based schemes at various distances.

d	Baseline	Rate optimized	OECRD (M_r=2)	OECRD (M_r=3)	OECRD (M_r=4)
0.5 m	480.0	500.1	576.3	622.1	655.8
3.5 m	480.0	480.0	480.0	480.0	480.0
7.0 m	480.0	480.0	480.0	480.0	480.0

Table 3. Energy per bit (10^{-5} J) corresponding to optimum data rate for M-QAM based schemes at various distances.

d	Baseline	Rate optimized	OECRD (M_r=2)	OECRD (M_r=3)	OECRD (M_r=4)
0.5 m	0.0088	0.0080	0.0075	0.0065	0.0065
3.5 m	0.0662	0.0662	0.0460	0.0377	0.0329
7.0 m	0.2325	0.2325	0.1574	0.1139	0.1089

Table 4. Percentage of energy saving over baseline scheme by the M-QAM based proposed schemes at various distances.

d	Rate optimized	OECRD (M_r=2)	OECRD (M_r=3)	OECRD (M_r=4)
0.5 m	9.09%	14.77%	21.59%	26.13%
3.5 m	0.00%	30.51%	43.05%	50.30%
7.0 m	0.00%	32.30%	51.18%	53.16%

From the Table 4, it is clear that the increase in diversity results in diminishing returns and hence the receive diversity is limited to 4.

From the Figs. 1 to 3, it is clear that rate optimization is beneficial for M-QAM based WBAN only for shorter distances. Though the energy consumption is reduced further by using receive diversity the energy consumption is still higher than the M-PSK based WBAN [12] for a given transmission distance. Therefore, it can be understood that M-PSK based WBAN is more energy efficient than M-QAM based WBAN. In order to reduce the total energy consumed by the M-PSK based WBAN, the proposed OECRD scheme is extended to M-PSK based WBAN. The total energy consumed by the proposed OECRD scheme for M-PSK based WBAN is compared with Baseline and Rate Optimized scheme of [12] and is shown in Fig. 4.

The maximum distance is d=2500 mm and the optimum data rate at d= 2500 mm is R_{opt}=480 kHz, which is equal to the minimum data rate. The Baseline scheme fixes the data rate as 480 kHz at all the distance values considered and hence its total energy consumption is higher when compared to other schemes. The Rate Optimized scheme of [12] uses an optimal data rate at each distance and hence its total energy consumption is lesser when compared to the Baseline scheme. The total energy consumption of Rate Optimized scheme becomes equal to the Baseline scheme at d=2500 mm, because at d=2500 mm the optimum data rate is equal to the minimum data rate. From the figure, it can be understood that the proposed OECRD schemes consume lesser energy than Rate Optimized scheme of [12], as the proposed OECRD scheme utilizes receive diversity in addition to rate optimization. It can also be understood that the total energy consumption of the proposed OECRD can be reduced further by increasing the order of receive diversity for a given distance.

Table 5 shows optimum data rate for M-PSK based schemes at various distances. From the table, it is clear that the optimum data rate increases with increase in receive diversity for a given transmission distance. It is also clear that the optimum data rate of Rate Optimized and proposed OECRD schemes decreases with increase in transmission distance.

Table 6 shows the total energy consumed per bit corresponding to the optimum data rate for M-PSK based schemes at various distances. From the table, it is clear that the total energy consumption of the proposed OECRD with M_r=4 is lesser when compared to other schemes at any given distance. Table 7 shows the percentage of energy saving obtained by the Rate Optimized and the proposed OECRD schemes.

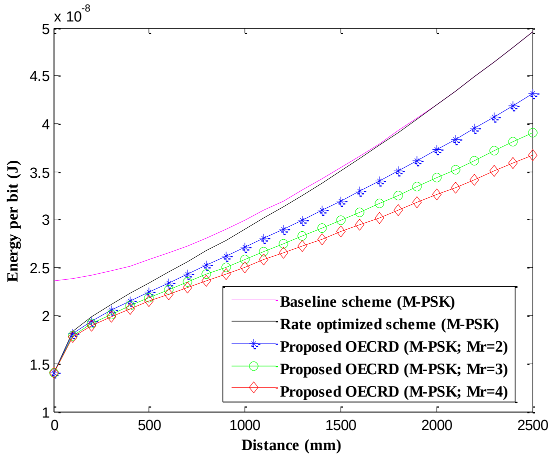

Fig. 4. Energy consumption per bit over distance.

Table 5. Optimum data rate in Kbps for M-PSK based schemes at various distances.

d	Baseline	Rate optimized	OECRD (M_r=2)	OECRD (M_r=3)	OECRD (M_r=4)
100 mm	480.00	1326.60	1380.07	1423.80	1454.50
500 mm	480.00	886.90	932.20	969.20	995.80
1000 mm	480.00	736.30	772.30	802.80	825.40
2000 mm	480.00	632.60	654.70	674.90	690.60

Table 6. Energy per bit (10^{-5} J) corresponding to optimum data rate for M-PSK based schemes at various distances.

d	Baseline	Rate optimized	OECRD (M_r=2)	OECRD (M_r=3)	OECRD (M_r=4)
100 mm	2.386	1.842	1.811	1.789	1.775
500 mm	2.582	2.343	2.343	2.187	2.146
1000 mm	2.994	2.899	2.710	2.585	2.508
2000 mm	4.201	4.194	3.727	3.433	3.258

Table 7. Percentage of energy saving over baseline scheme by the M-PSK based proposed schemes at various distances.

d	Rate optimized	OECRD (M_r=2)	OECRD (M_r=3)	OECRD (M_r=4)
100 mm	22.79%	24.09%	25.02%	25.60%
500 mm	9.25%	13.12%	15.29%	16.88%
1000 mm	3.17%	9.48%	13.66%	16.23%
2000 mm	0.16%	11.28%	18.28%	22.44%

From the Table 7, it is clear that the percentage of energy saving of the Rate Optimized scheme over the Baseline scheme is decreasing with an increase in transmission distance. At any given distance, the percentage of energy saving of Rate Optimized scheme is lesser than proposed OECRD. At any given distance, the percentage of energy saving of the proposed OECRD with higher receive diversity is higher than that of proposed OECRD with lower receive diversity. It is also clear that increase in diversity results in diminishing returns and hence the receive diversity is limited to 4.

5. Conclusion

In this paper, an energy model for M-QAM based WBAN is proposed and its energy efficiency is investigated. Two schemes, Rate Optimized scheme and optimum energy consumption using receive diversity scheme are proposed. In Rate Optimized scheme, data rate is varied according to transmission distance to ensure minimum total energy consumption. In Optimum Energy Consumption using Receive Diversity scheme, receive diversity is utilized along with rate optimization to minimize the total energy consumption further. An energy saving of 53.16% at a distance of 7 m is achieved by the proposed OECRD over conventional fixed rate scheme. The proposed OECRD is extended to M-PSK based WBAN and achieved an energy saving of 22.44% and 22.31% over conventional fixed rate and Rate Optimized scheme at a transmission distance of 2 m. Therefore, it can be concluded that the proposed schemes achieve significant energy saving over conventional schemes and hence proves to be energy efficient than conventional schemes.

Nomenclatures

a_loss	Coefficient of linear filtering
b	Number of bits used to represent a symbol
b_loss	Normally distributed variable
d	Transmission distance, m
d_{max}	Maximum transmission distance, m
E_{bit_total}	Total energy consumed per bit by a sensor node, mJ
$\bar{E}_{br}$	Required energy per bit at the receiver for a given bit Error Rate, mJ
G_1	Transmitter antenna gain
G_r	Receiver antenna gain
$\left\Vert H_{1\times M_r}\right\Vert^2$	Channel gain
L	Number of bits to be transmitted by the sensor node
M	Modulation order

M_l	Link margin, dB
M_r	Number of antennas at the receiver
N_0	Single sided thermal noise power spectral density, dBm/Hz
N_f	Receiver noise figure, dB
P_{act}	Power consumed when the node is in the active state, mW
P_{ampr}	Power consumed by the power amplifier, mW
p_b	Bit error rate
P_{ckt}	Power consumed by all other circuit blocks, mW
P_{DAC}	Power consumption value for the digital-to-analog converter, mW
P_{filt}	Power consumption value for the active filter at the transmitter, mW
P_{max}	Maximum power, W
P_{mix}	Power consumption value for the mixer, mW
P_{slp}	Power consumed when the node is in the sleep state, mW
P_{slp}	Power consumed when the node is in the sleep state, mW
P_{syn}	Power consumption value for the frequency synthesizer, mW
P_t	Transmission power, mW
$Q(.)$	Q-function
R	Data rate, Kbps
R_{max}	Maximum data rate, Kbps
R_{min}	Minimum data rate, Kbps
T	Allowable time limit, s
T_{act}	Active state duration, s
T_{act}	Active state duration, s
T_{slp}	Power consumed when the node is in the sleep state, mW
T_{slp}	Sleep state duration, s

Greek Symbols

α	Signal to noise ratio at the receiver, dB
γ_{br}	Standard deviation
δ_N	Roll-off factor of the pulse shaping filter
η	Drain efficiency
λ	carrier wavelength, m
ζ	Peak-to-average ratio

Abbreviations

BCU	Body Control Unit
BER	Bit Error Rate
DAC	Digital-to-Analog Converter
FCC	Federal Communication Commission
M-PSK	Multi-level Phase Shift Keying
M-QAM	Multi-Level Quadrature Amplitude Modulation
OECRD	Optimum Energy Consumption using Receive Diversity
PA	Power Amplifier
SNR	Signal to Noise Ratio
VLSI	Very Large Scale Integration
WBAN	Wireless Body Area Network

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