Energy and path loss analysis of wireless sensor networks on a robotic body ($WS_{Robotic}$)

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ABSTRACT

The objective of this work is to simulate and mathematically model both path loss and transmitted energy in a robotic wireless sensor network (WSN). The simulation and analysis showed an increase in both path loss and transmitted energy as a function of distance. The correlation between transmitted energy and path loss proved to be exponential relationship with both logarithmic and power relationships between path loss and distance. Both expressions describing path loss, using close-in (CI) dual model and transmitted energy, using wireless body area network (WBAN) model, are modified and combined in one single expression to enable optimization of energy management. The newly developed expression is simulated and produced reliable results, relating effect of frequency and message size on transmitted energy as a function of distance. Combining these results with the results showing effect on path loss on transmitted energy, enables a better optimization of energy management of nodes on robotic body. The main objective of this work, which is the development of a single expression relating transmitted energy to critical parameters (frequency, path loss exponent, message size, distance) is achieved and is logically derived and based on analysis using two separate models for path loss and transmitted energy.

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1. INTRODUCTION

In the near future, wireless sensor networks (WSNs) will play a crucial role in human existence and are already a significant area of research. A WSN is an interconnected system of sensor nodes that are spatially dispersed throughout the environment and each of which serves a specific function both on its own and in conjunction with other nodes. The basic purpose of these networks is to gather data on the environment and communicate it to the base station (BS) or distant server. The data is then carefully examined. The smallest component of a network, a wireless sensor has special properties including wide dispersion support, mobility, and dependability. WSNs can be used for a variety of purposes, including monitoring and managing industrial processes, environmental monitoring, device monitoring, traffic management, intelligent homes, military and security applications, agricultural applications, health monitoring applications, robotics among others [1]-[4].

The world is experiencing a surge in research on WSNs, which requires knowledge that is both highly interdisciplinary and highly integrated. It incorporates distributed information processing, embedded processing technology, and wireless communication. Through a variety of integrated sensing devices, WSN can monitor, perceive, and gather data through monitoring objects in real time. WSN has garnered considerable interest from academic and industrial circles, as it consist of randomly distributed nodes that are integrated with sensors, data processing units, and communication modules [5]-[8]. WSNs can perform many tasks, such as detection of temperature changes, humidity levels, noise, and light intensity, using built-in sensors. WSN Nodes are more vulnerable to failure mainly due to energy shortages. The alteration of a network's topology can be easily caused by node failure. Sensor nodes are mainly fixed. The processing, storage, and communication capabilities of sensor nodes are extremely constrained. Sensor nodes are also compact in size and typically contain batteries [9].

The environment monitoring, target tracking, and positioning tasks are completed by deploying a WSN in a particular positions. In these applications, the processes of gathering data from the sensor nodes is of prime importance in terms of energy consumption, data size, and accuracy. Energy cost, sensible area, and network reliability are adopted for effective node placement in WSN. This can be achieved by separating any covered region into separate sub-regions and imposing active and passive modes of operation in each area [10]-[15]. The majority of WSN applications require to know where the sensor nodes are, in order to monitor the location with events, and to respond to them. The information gathered is only usable in any of the applications when the location of the events' occurrence is known. A number of localization techniques are developed to ascertain the location of sensor nodes in a WSN. The nodes' deployment in the area of interest is not always specified. They may therefore be deployed randomly or deterministically within a selected area. Deterministic deployment is preferred in circumstances where there is prior knowledge in area of interest [16]-[20].

By utilizing cutting-edge technology to improve communication and safety systems, WSNs have established a highly concrete benchmark for the internet of things (IoT). WSNs are becoming more and more popular in a variety of application areas, smart homes, industrial control, wearable applications, and robotics. This is due to the benefits offered by these technologies, particularly the ability to collect data in real time at a low cost. WSNs must be incredibly adaptable, scalable, interoperable, and dependable in addition to energy efficiency. Low power consumption is a key factor for the long stream of autonomous battery-powered devices [21]-[23]. To achieve optimum energy efficiency in wireless sensor technology, different algorithms, clusters, and protocols are used. Multiple nodes make up a WSN, which is utilized for multi-hopping communication. WSNs are self-configuring wireless networks free of any infrastructure. WSNs track or send data through the network. Any node in the WSN has a speed, storage, and bandwidth constraint [24], [25].

A sensor is a device that monitors its surroundings and communicates information about events or changes to another electrical system. Memory size, computational power, and energy consumption are some of the major restrictions on sensor networks. Various WSN applications need for the fulfilment of various quality criteria (such as latency, reliability, bandwidth, and security). It's important to guarantee the quality of service (QoS) in each field of application. QoS requirements are necessary because WSNs struggle with issues including limited bandwidth, power, erratic communications, and node vulnerabilities [26]-[30]. Robotics and WSNs have each received much research over the past few years. However, these research areas intersection offers a wealth of novel prospects and research directions that are still mostly untapped. Robots and wireless sensors were formerly thought of as different network nodes, but wireless sensors and robots complement one other in numerous ways. The result of their integration, would have a variety of applications in many areas such as military, transportation monitoring, healthcare, autonomous driving, and search and rescue [31].

Robot-assisted and robot-dependent WSNs are two categories for mobile robots. Robots are an essential component of robot-dependent WSNs and are necessary to maintain the system's functionality. In contrast, although they are not a fundamental component of robot-assisted WSNs, robots aid in raising the system's overall performance. Robots can also assist in finding a proactive or reactive solution to the sensor replacement issue. Robots in a reactive strategy are on standby and only depart the BS in the event that there is a material modification in area pf interest coverage. On the other side, under the proactive technique, robots continuously check WSNs [32], [33]. If localization is used in a new way with a mobile robot, the consumed energy can be reduced, using certain robot movement and positions [34]-[36]. The nodes in robots have significant requirements for routing protocol efficacy due to their relatively great movement and limited energy [37].

The issue of finite energy supply is an important issue. Each sensor node used in a mobile robot needs to have energy, which makes nodes vulnerable to failure if the supply is low. Additionally, it's critical to confirm that the network lifespan is sufficient for the tasks required by the mobile robot to fulfil. Thus, it is necessary to conserve energy [38]. It is expected that mobile robots as carriers will have sensors. To enable a linked WSN with the appropriate coverage, mobile robots move around the area of interest in accordance with predetermined strategies. One solution is to have spare sensors, which are fully charged [39], [40].

This work aims to simulate and predict route loss and transmitted energy in a robotic WSN quantitatively. Both route loss and transmitted energy increased with distance, according to the simulation and study. To enable optimization of energy management, both the route loss expression using the close-in (CI) dual model and the transmitted energy expression using the wireless body area network (WBAN) model are to be updated and integrated into a single mathematical model.

2. RELATED WORKS

Fernández *et al.* [41] investigated interaction between mobile robots and sensor nodes. The work looked at communication effectiveness, throughput and efficiency. However, no mathematical modeling is presented regarding pathloss or energy consumption in terms of relating communication effectiveness to energy consumption and channel fading. This work, looks at all the critical parameters covering WSNs and robots in terms of pathloss, pathloss coefficient, and energy. The work in this research support the proposed idea with mathematical models and simulation results.

Rady *et al.* [42] investigated efficient routing algorithms in WSNs to enable energy conservation. The work covers different techniques, but no mathematical model is presented regarding communication channel and associated pathloss and energy consumption. This work covers these parameters comprehensively with modeling and simulation. Using wireless sensor nodes and transmitting at 2.4 GHz, researchers examined WBAN design and application for robots, focusing on energy saving and very low power radio features [43]. Several scholars [44] examined comparable energy-efficiency techniques utilized in robotics structures. However, these works in [43], [44], did not consider signal propagation in terms of separating interface and threshold distance (ds), and did not did not consider as this work considered, the existence of two pathloss exponents corresponding to the different robotic areas with corresponding interfaces. In addition, no mathematical model describing different robotic areas with different pathloss expressions is presented in [43], [44]. In addition, this work considers different transmitting frequencies and various free space distances to enable proper design and placement of nodes on robotic structures. It is known, that at different frequencies, signal properties change in accordance with the transmitting frequency, and wavelength also affected by such frequency variation. This also, affects signal gain and signal to noise ratio, and other signals interference from nearby sources. Channel communication will markedly be affected by both frequency and path loss coefficient corresponding to the transmitting medium. Also, energy consideration in relation to the interface between two different areas on the robotic structure surface with different propagation properties is important, but not discussed in [43], [44].

Researchers also took into consideration robots, which use sensors to interact with people or their environment [45]. The work proposes a cloud based software architecture for humanoid robots along with a wearable sensor setup. The setup consists of perception sensors communicating using wireless connectivity modules. Similar research with antenna placement consideration and soft robotic structures [46] supports the approach in [45], but none of the works discusses the interface between the different parts of the robotic body structure (covered parts and uncovered parts). Also, none of the works examined effect of frequency and free space distance on pathloss. In addition, no mathematical model that takes into consideration pathloss coefficient is described and modeled in [45], [46]. The path loss and energy modeling is critical to enable proper design and characterization of surface placed robotic sensor nodes. For robots, communication energy and throughput analysis are crucial for enabling optimal robotic design. The analysis is predicated on simulating the communication between the robot nodes utilizing wireless communication concepts, which are mostly applied to and within robotic bodies and comparable human bodies having WBANs, as documented in [47], where Markov, and Hilbert models are used with entropy considerations. The work in [47] looked at different frequency components, but no direct energy or path loss considerations. Also, no mathematical model covering different interfaces is discussed.

Researchers discussed clustering in connection to energy optimization in [48]. Additionally, clustering is connected to WBAN design and routing. This study does not propose a specific energy model with different frequencies and free space distance. Also, no interface effect on pathloss coefficient is considered in details.

Huang *et al.* [49], examines several methods for mobility robots in WSNs. The work looks at three groups based on the jobs that mobile robots perform. The authors discusses energy issues, but no mathematical modeling or correlation to pathloss is presented.

Phaiboon *et al.* [50], discussed WSN design and optimization, and considered path loss models to be crucial tools for evaluating projected large-scale signal fading in a particular propagation environment. The work looks at fuzzy logic in predicting pathloss. The work uses received signal strength indicator (RSSI) as a model. The work did not consider energy parameters explicitly with different frequencies and free space distance. Also, the work in [50] did not present the types of models and simulation presented in this work. Ramaiah *et al.* [51] used the clustering approach to data transmission and energy efficiency in heterogeneous WSNs. The work looks at different types of nodes with differing characteristics, and attempt to recommend new approach. The presented work in this research operates efficiently regardless of the types of sensor nodes.

There are no previous works that combined and correlated two models into one single model as this work intended. This work presents detailed analysis and mathematical models for robotic WSNs, supported by simulation, which covers the following:

a. Pathloss model over a communication channel.
b. Energy consumption model as a result of data communication.
c. Effect of transmitting frequency on pathloss.
d. Effect of changing free space distance on pathloss.
e. Effect of interface between two different robotic structure regions.

3. METHOD

The simulation is carried out using the following steps:

a. Distributing WSNs over and inside a robotic body can be modelled using WBAN. A WBAN links separate nodes, representing different types of sensors and actuators that are positioned in a covering body or on the body surface. The wireless communication channel links the nodes together. A WBAN's wireless connections between the devices might happen at several frequencies. To design a WBAN, it is crucial to characterize the physical layer of the network, which includes estimating the delay spread and the path loss between two nodes. Because the radios used in WBANs are so tiny, there isn't much room left for a battery. Therefore, in order to increase the network's lifetime and fulfill the criteria, energy efficiency is of the utmost importance.
b. WSRobotic is a wireless network with communication between sensor nodes functioning on the robot's surface or inside the robot body, to gather data on numerous bodily parameters, such as motion, and perception. Nodes communication must consume less power and provide high reliability. The objective of this work is to analyse energy and path loss for a 12 nodes network, covering all robot body. Nodes placement, in the simulation ensured that no interference, as a radius threshold level is used. The default shape of robot is shown in Figure 1.

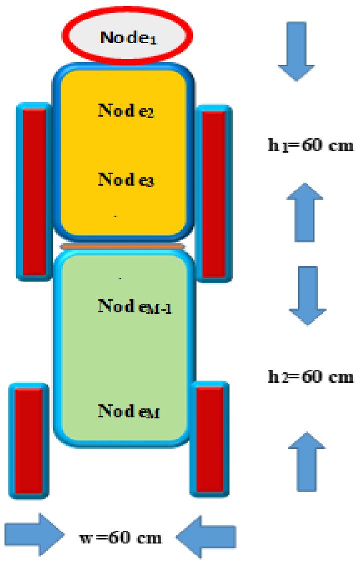

Figure 1. Mobile robot with WSRobotic network nodes

A computational methodology for designing robotic systems is presented in this research. To determine the optimal robot design for a given task, the framework correlates energy with pathloss, in order to optimize energy consumption. The approach in this work address energy efficiency and introduce new models that take into account the losses. Thus, based on this work, mobile robot design should take the following parameters into account; i) minimizing node load, ii) minimizing node energy consumption, iii) sustaining link stability, and iv) performing dynamic maintenance.

To enable effective energy consumption, and to optimize robotic design, both pathloss models and energy models need to be presented and correlated, with Table 1 presents definition for all used variables in the simulation and mathematical modelling.

Table 1. Nomenclature

Symbols/acronyms	Meaning
PL	Path loss, which is a function of transmitter-receiver separation distance (d) over a frequency range in GHz and measured (dB).
f	Carrier frequency (GHz).
d	Antenna separation (cm).
d_o	CI free space reference distance (cm).
PL_o	Path loss at a distance d_o (free space path loss) (dB).
n	Path loss exponent (between 2 and 7).
χ_σ	Shadow fading which is zero-mean Gaussian random variable with a standard deviation σ measured (dB), used to predict signal strength between transmitter and receiver (dB).
c	Speed of light.
P_{Tx}	Transmission power (dB).
P_{Rx}	Received signal power (dB).
E_{Tx}	Transmission energy (J).
E_{Rx}	Receiver energy (J).
E_{Tx} (elec)	Energy dissipated by radio transmission in the transmitter circuit (nJ/bit).
E_{Rx} (elec)	Energy dissipated by radio transmission in the receiver circuit (nJ/bit).
E_{Tx} (amp)	Energy for the transmit amplifier (nJ/bit/mn).
k	Number of transmitted bits.
d_s	Distance separating two areas with different propagation and path loss properties.

3.1. WS$_{Robotic}$ pathloss model

The expression in (1), represents, the CI path loss between the transmitting and receiving antenna as a function of distance. The model, is used in the simulation of WSR$_{obotic}$. It is stated in decibels and originally based on the Friis formula.

$$PL(f,d) = PL_o(f,d_o) + 10nlog_{10}\left(\frac{d}{d_o}\right) + \chi_\sigma \tag{1}$$

PL_o is given by (2):

$$PL_o(f,d_o) = 20log_{10}\left(\frac{4\pi f d_o}{c}\right) \tag{2}$$

Two cases can be derived from general path loss (1) and (2):

a. $d \le d_s$:

$$PL(f,d) = 20log_{10}\left(\frac{4\pi f d_o}{c}\right) + 10nlog_{10}\left(\frac{d}{d_o}\right) \tag{3}$$

b. $d > d_s$:

$$PL(f,d) = 20log_{10}\left(\frac{4\pi f d_o}{c}\right) + 10n_1log_{10}\left(\frac{d_s}{d_o}\right) + 10n_2log_{10}\left(\frac{d}{d_s}\right) \tag{4}$$

Assuming a uniform propagation environment in robots, then $d_s = d_o$, (4) can be approximated as in (5).

$$PL(f,d) = 20log_{10}\left(\frac{4\pi f d_o}{c}\right) + 10n_2log_{10}\left(\frac{d}{d_o}\right) \tag{5}$$

where: $n_2 \ge n$.

This design feature is very beneficial in terms of simplifying calculations and enabling better energy management and control. Transmitter and receiver powers can be related to the path loss expression in (1), as in (6):

$$PL(f,d) = \left(\frac{P_{Tx}}{P_{Rx}}\right) = PL_o(f,do)\left(\frac{d}{d_o}\right)^n \chi_\sigma \tag{6}$$

Path loss would have different values related to configurations for robotic body, the environment, and the positioning of the antennas. In decibels, (7) represent powers relationship for transmitter and receiver.

$$P_{Rx}(dB) = P_{Tx} - PL(f,d) \tag{7}$$

3.2. WS$_{Robotic}$ energy model

Energy model of the WS$_{Robotic}$ can be based on the radio first order model, as shown in Figure 2.

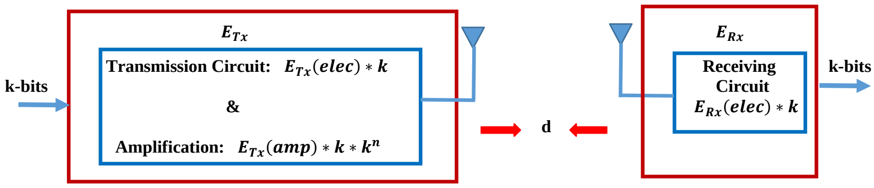

Figure 2. $WS_{Robotic}$ energy model

The general form of the energy model covering WSR_{obotic}, is given by (8) and (9):

$$E_{Tx}(k, d_{i,j}, n) = kE_{Tx}(elec) + kE_{Tx}(amp){d_{i,j}}^n \tag{8}$$

$$E_{Rx}(k) = kE_{Rx}(elec) \tag{9}$$

To account for different robotic materials and their propagation properties. Two proposed models are presented, as in (10) and (11). The expression in (10), uses same path loss exponent twice, while the second model uses higher values of path loss exponent.

$$E_{Tx}(k, d_{i,j}, n) = kE_{Tx}(elec) + knE_{Tx}(amp){d_{i,j}}^n \tag{10}$$

From (10) can be further approximated, considering (5). Thus, resulting in (11).

$$E_{Tx}(k, d_{i,j}, n) = kE_{Tx}(elec) + kE_{Tx}(amp){d_{i,j}}^{n_2} \tag{11}$$

where: $n_2 > n$.
When (11) is used, (5) is used with changing condition to $n_2 > n$.

In considering energy loss due to communication channel transmission, and for simplification, an assumption of bidirectional equal energy loss can be made, particularly in a one hop networks. Some sensor nodes for constant monitoring can be assumed to transmit at a fixed data rate with regular sending intervals. This is true in general robotic sensing, except in cases where a robot is required to detect an abnormal situation, then event driven transmission can be utilized. The simulation parameters are shown in Table 2.

Table 2. Simulation parameters

Parameter	Value
E_{Tx} (elec)	16.7 (nJ/bit)
E_{Rx} (elec)	36.1 (nJ/bit)
E_{Tx} (amp)- on robot body	1.97 (nJ/bit/m^n)
V_{supply}	1.9 Volts
f	2.4 GHz
k	4096 bits

The simulation process followed the following steps:

a. Specify robotic structure dimensions: this enables determination of transmission radius and antenna power, and electronic transmitter energy specification.
b. Allocate initial frequency and frequency range in GHz.
c. Initialize CI free space distance.
d. Determine pathloss coefficients as functions of used robotic material n and n_2.
e. Determine increments in distance for propagating signal within robotic structure dimensions.
f. Distribute WSN nodes on the robotic structure and determine regions of interface for n and n_2: this is related to the distance separating two areas (d_s), which is related to material difference with pathloss properties.
g. Equate n to n_2 when there is a homogenous interface between different materials with small difference. This will approximate well over many cycles of simulation.
h. Compute both pathloss and energy using different frequencies and various Clos-In free space values and plot the results.
i. Apply mathematical curve fitting to obtain simulated response parameters over a range of materials, frequencies and free space distances.

4. RESULTS AND DISCUSSION

Figure 3 shows simulation results for the condition of $d > d_s, n = 3, and\ for\ 12\ nodes$. The plot shows an increase in path loss as a function of increasing distance, with (12) representing a logarithmic law describing the relationship. The coefficients for (12), obtained through curve fitting.

$$PL = \alpha log_e\ (d)\ + \beta \tag{12}$$

where: $\alpha \leq 30$ and $\beta \geq 76$.

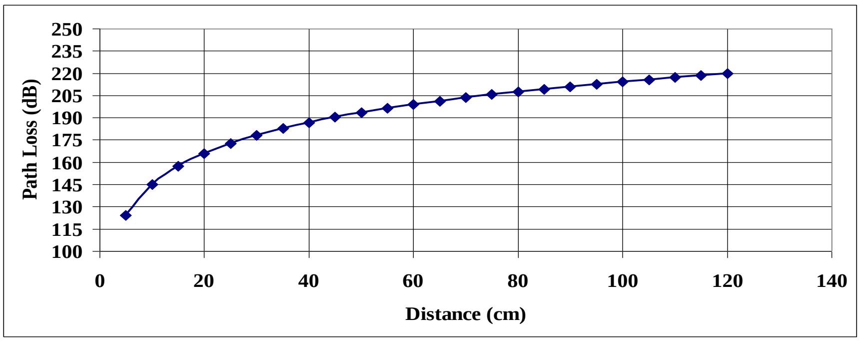

Figure 3. Relationship between path loss and distance

Table 3 shows simulation data relating path loss to free space distance, with Figure 4 illustrating the power law describing average path loss as a function of free space distance. The plot shows a decrease in average path loss as a function of increasing free space distance, which agrees with inclusivity approach of $d \leq d_s$ that expands the area of free space in a robotic environment with $d_s = d_o$. The power law expression is shown in (13), with curve fitting to produce coefficients.

$$PL = \gamma d_o{}^{-\zeta} \tag{13}$$

where: $\gamma \geq 213$ and $\zeta \leq 0.06$.

Table 3. Relationship between path loss (PL) and frequency (F)

d (cm)	Free space distance d_o (cm) 20	35	50	65	80
	PL (dB)				
5	110.52	104.93	101.36	98.74	96.66
10	131.32	125.72	122.16	119.53	117.46
15	143.48	137.89	134.32	131.70	129.62
20	152.11	146.52	142.95	140.33	138.25
25	158.81	153.21	149.65	147.02	144.95
30	164.28	158.68	155.11	152.49	150.41
35	168.90	163.31	159.74	157.12	155.04
40	172.91	167.31	163.75	161.12	159.05
45	176.44	170.85	167.28	164.66	162.58
50	179.60	174.01	170.44	167.82	165.74
55	182.46	176.87	173.30	170.68	168.60
60	185.07	179.48	175.91	173.29	171.21
65	187.47	181.88	178.31	175.69	173.61
70	189.70	184.10	180.53	177.91	175.83
75	191.77	186.17	182.60	179.98	177.90
80	193.70	188.11	184.54	181.92	179.84
85	195.52	189.93	186.36	183.73	181.66
90	197.24	191.64	188.07	185.45	183.37
95	198.86	193.26	189.70	187.07	185.00
100	200.40	194.80	191.23	188.61	186.53
105	201.86	196.26	192.70	190.07	188.00
110	203.26	197.66	194.09	191.47	189.39
115	204.59	198.99	195.43	192.80	190.73
120	205.87	200.27	196.70	194.08	192.00

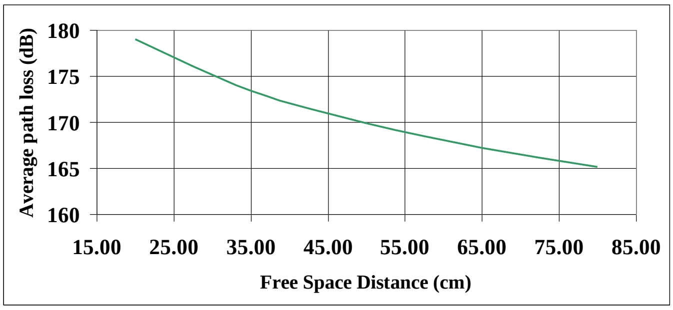

Figure 4. Relationship between average path loss (PL) and free space distance (d_o)

Table 4 shows simulation data relating path loss to transmitting frequency, with Figure 5 showing the relationship between average path loss and frequency. The plot and (14) show a logarithmic relationship between path loss and transmitting frequency, using curve fitting to obtain coefficients.

$$Average\ PL = \rho log_e(f) + \varepsilon \tag{14}$$

where: $\rho \geq 20$ and $\varepsilon \leq 176$.

Table 4. Relationship between path loss (PL) and frequency (F)

d (cm)	1.2	2.4	f (GHz) 3.6 PL (dB)	4.8	6
5	110.52	124.39	132.50	138.25	142.71
10	131.32	145.18	153.29	159.05	163.51
15	143.48	157.35	165.46	171.21	175.67
20	152.11	165.98	174.09	179.84	184.30
25	158.81	172.67	180.78	186.53	191.00
30	164.28	178.14	186.25	192.00	196.47
35	168.90	182.77	190.87	196.63	201.09
40	172.91	186.77	194.88	200.63	205.10
45	176.44	190.30	198.41	204.17	208.63
50	179.60	193.47	201.57	207.33	211.79
55	182.46	196.32	204.43	210.19	214.65
60	185.07	198.94	207.04	212.80	217.26
65	187.47	201.34	209.45	215.20	219.66
70	189.70	203.56	211.67	217.42	221.89
75	191.77	205.63	213.74	219.49	223.96
80	193.70	207.57	215.67	221.43	225.89
85	195.52	209.38	217.49	223.25	227.71
90	197.24	211.10	219.21	224.96	229.42
95	198.86	212.72	220.83	226.58	231.05
100	200.40	214.26	222.37	228.12	232.59
105	201.86	215.72	223.83	229.59	234.05
110	203.26	217.12	225.23	230.98	235.45
115	204.59	218.45	226.56	232.32	236.78
120	205.87	219.73	227.84	233.59	238.06

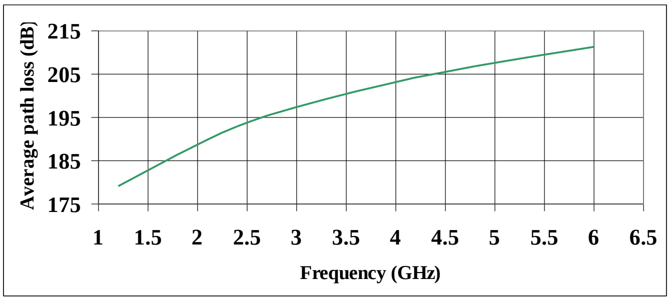

Figure 5. Relationship between average path loss (PL) and frequency

Figure 6 shows relationship between transmitted energy and distance. The plot shows power law relationship illustrated in (15), with coefficients obtianed through curve fitting. As the plot shows, the trasmitted energy increases as distance increases.

$$E_{Tx} = \delta d^{\mu} \quad (15)$$

where: $\delta \geq 8x10^{-6}$ and $\mu \leq 3$.

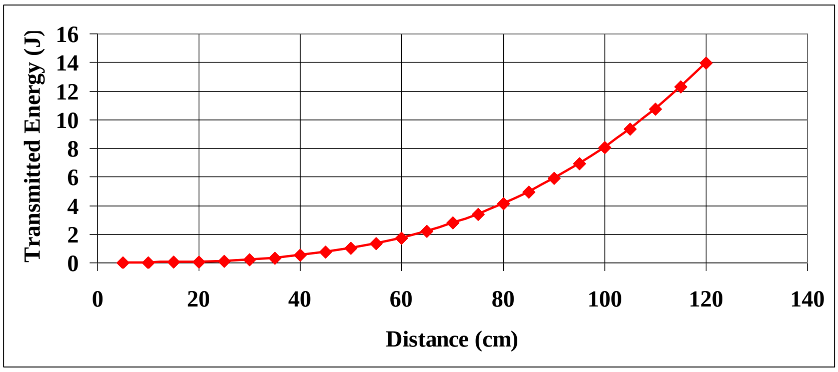

Figure 6. Relationship between transmitted energy and distance

Figure 7 shows the relationship between transmitted energy and path loss. The obtained relationship is exponential and indicative of effect of path loss on energy consumption.

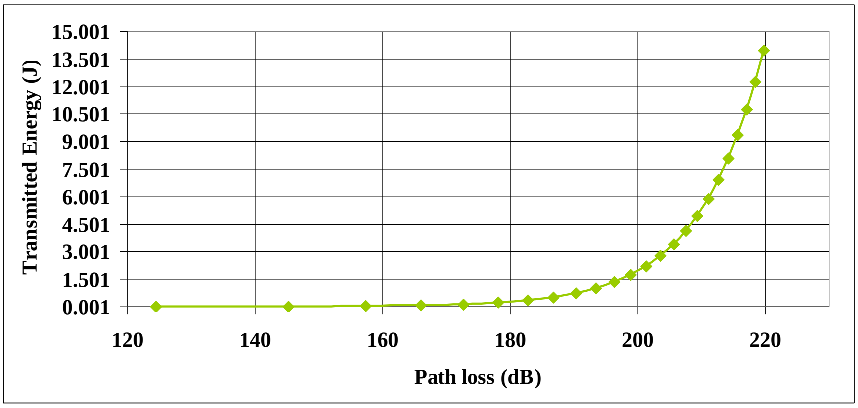

Figure 7. Relationship between transmitted energy and path loss

The relationship in Figure 5 can be represented as in (16), with coefficients obtained using curve fitting.

$$E_{Tx} = \phi exp(\psi PL) \quad (16)$$

where: $\phi \geq 4x10^{-9}$ and $\psi \leq 0.1$.

Using the modelling expression in (16), it is possible to establish an expression relating the transmitted energy to path loss, and including all parameters from both original equations. Substituting (3) and (8) in (16) with the generalization of $d_{ij} \equiv d$, results in (17).

$$kE_{Tx}(elec) + kE_{Tx}(amp)d^{n} = \phi exp\left(\psi\left(20log_{10}\left(\frac{4\pi f d_o}{c}\right) + 10nlog_{10}\left(\frac{d}{d_o}\right)\right)\right) \quad (17)$$

From (17) can be represented as in (18).

$$kE_{Tx}(elec) + kE_{Tx}(amp)d^n = \phi exp\left(\psi\left(10log_{10}\left(\frac{4\pi f d_o}{c}\right)^2 + 10log_{10}\left(\frac{d}{d_o}\right)^n\right)\right) \quad (18)$$

In building a robot, an environment can be designed such that the exponents in (18) are approximately equivalent. Thus, (18) can be represented by (19).

$$kE_{Tx}(elec) + kE_{Tx}(amp)d^n = \phi exp\left(\psi\left(10log_{10}\left(\frac{4\pi f d_o}{c}\right)^n + 10log_{10}\left(\frac{d}{d_o}\right)^n\right)\right) \quad (19)$$

From (19) is represented as in (20).

$$kE_{Tx}(elec) + kE_{Tx}(amp)d^n = \phi exp\left(\psi\left(10nlog_{10}\left(\frac{4\pi f d_o}{c}\right)\left(\frac{d}{d_o}\right)\right)\right) \quad (20)$$

From (20) is reduced to (21).

$$kE_{Tx}(elec) + kE_{Tx}(amp)d^n = \phi exp\left(\psi\left(10nlog_{10}\left(\frac{4\pi f d}{c}\right)\right)\right) \quad (21)$$

Applying the approximation

$$k(E_{Tx}(elec) + E_{Tx}(amp)d^n) = kE_{Tx}$$

From (21) is further reduced to (22).

$$kE_{Tx} = \phi exp\left(\psi\left(10nlog_{10}\left(\frac{4\pi f d}{c}\right)\right)\right) \quad (22)$$

From (22), (23) is obtained.

$$E_{Tx} = k^{-1}\left(\phi exp\left(\psi\left(10nlog_{10}\left(\frac{4\pi f d}{c}\right)\right)\right)\right) \quad (23)$$

From (23) is reduced to (24), which can be can be regarded as a modelling function for robotic design:

$$E_{Tx}(k, n, f, d) = \left(\frac{\phi}{k}\right)\left(exp\left(\psi\left(10nlog_{10}\left(\frac{4\pi f d}{c}\right)\right)\right)\right) \quad (24)$$

The expression in (24) allows to optimize the energy management of a designed robot, and after that select the most appropriate transceivers based on selection of the parameters in (24), which takes into account data rate, frequency, distance, and path loss exponent. Using the developed mathematical model, Table 5 shows the relationship between transmitted energy and used transmission frequency, while Figure 8 shows a power curve representing the relationship between average E_{Tx} and f, which is represented in (25), with coefficients obtained through curve fitting. Table 6 contains simulation data describing the relationship between transmitted energy and number of bits per message, with Figure 9 representing the relationship between average E_{Tx} and k. Such a relationship, which shows to be linear.

$$Average\ E_{Tx} = \vartheta f^{\upsilon} \quad (25)$$

where: $\vartheta \geq 0.336$ and $\upsilon \geq 3$.
The linear plot in Figure 9 is represented by (26), with coefficients obtained through curve fitting.

$$Average\ E_{Tx} = \xi k + \sigma \quad (26)$$

where: $\xi \leq 0.001$ and $\sigma \geq 3x10^{-7}$.

Table 5. Relationship between transmitted energy (Etx) and frequency (F)

d (cm)	f (GHz) 1.2	2.4	3.6	4.8	6
	E_{Tx} (J)				
5	0.0002	0.0012	0.0042	0.0099	0.0193
10	0.0012	0.0099	0.0334	0.0793	0.1548
15	0.0042	0.0334	0.1128	0.2675	0.5224
20	0.0099	0.0793	0.2675	0.6340	1.2384
25	0.0193	0.1548	0.5224	1.2384	2.4187
30	0.0334	0.2675	0.9028	2.1399	4.1795
35	0.0531	0.4248	1.4336	3.3981	6.6369
40	0.0793	0.6340	2.1399	5.0723	9.9069
45	0.1128	0.9028	3.0468	7.2221	14.1058
50	0.1548	1.2384	4.1795	9.9069	19.3495
55	0.2060	1.6483	5.5629	13.1861	25.7541
60	0.2675	2.1399	7.2221	17.1192	33.4359
65	0.3401	2.7207	9.1823	21.7655	42.5108
70	0.4248	3.3981	11.4685	27.1846	53.0949
75	0.5224	4.1795	14.1058	33.4359	65.3044
80	0.6340	5.0723	17.1192	40.5788	79.2554
85	0.7605	6.0841	20.5338	48.6727	95.0639
90	0.9028	7.2221	24.3748	57.7772	112.8461
95	1.0617	8.4940	28.6671	67.9516	132.7180
100	1.2384	9.9069	33.4359	79.2554	154.7957
105	1.4336	11.4685	38.7062	91.7480	179.1954
110	1.6483	13.1861	44.5032	105.4889	206.0331
115	1.8834	15.0672	50.8518	120.5376	235.4249
120	2.1399	17.1192	57.7772	136.9533	267.4870

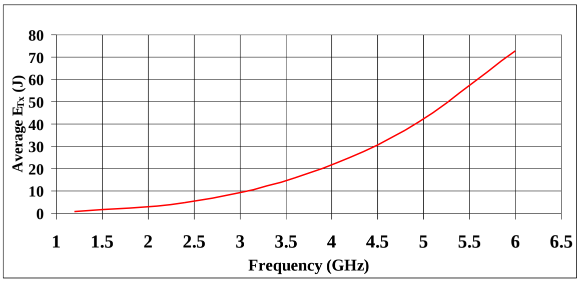

Figure 8. Relationship between transmitted energy and frequency

Table 6. Relationship between transmitted energy (Etx) and transmitted number of bits (k)

d	k (bits) 2^{10}	2^{11}	2^{12}	2^{13}	2^{14}
	E_{Tx} (J)				
5	0.0003	0.0005	0.0011	0.0022	0.0043
10	0.0020	0.0041	0.0081	0.0163	0.0326
15	0.0068	0.0137	0.0273	0.0546	0.1092
20	0.0162	0.0323	0.0646	0.1292	0.2585
25	0.0315	0.0631	0.1261	0.2523	0.5046
30	0.0545	0.1090	0.2179	0.4359	0.8717
35	0.0865	0.1730	0.3460	0.6921	1.3841
40	0.1291	0.2582	0.5165	1.0330	2.0660
45	0.1838	0.3677	0.7354	1.4707	2.9415
50	0.2522	0.5044	1.0087	2.0174	4.0348
55	0.3356	0.6713	1.3426	2.6851	5.3703
60	0.4357	0.8715	1.7430	3.4860	6.9720
65	0.5540	1.1080	2.2161	4.4321	8.8642
70	0.6919	1.3839	2.7678	5.5356	11.0711
75	0.8511	1.7021	3.4042	6.8085	13.6169
80	1.0329	2.0657	4.1315	8.2629	16.5258
85	1.2389	2.4778	4.9555	9.9110	19.8221
90	1.4706	2.9412	5.8825	11.7649	23.5298
95	1.7296	3.4592	6.9183	13.8367	27.6733
100	2.0173	4.0346	8.0692	16.1384	32.2768
105	2.3353	4.6705	9.3411	18.6822	37.3643
110	2.6850	5.3700	10.7401	21.4801	42.9603
115	3.0680	6.1361	12.2722	24.5444	49.0888
120	3.4859	6.9718	13.9435	27.8870	55.7740

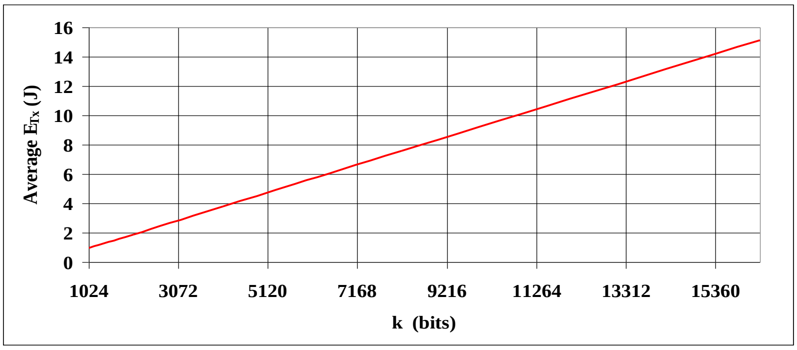

Figure 9. Relationship between transmitted energy and number of bits

5. CONCLUSION

This work investigated through simulation path loss and transmission energy parameters for robotic WSNs. The work related path loss to energy and established mathematical models describing the relationship between path loss and transmitted energy. The work also presented WSRobotic mathematical model to be a special case of the conventional WBAN model used for humans. A simplified, yet accurate approximation relating transmitted energy parameters (k, n) to path loss parameters (f, d, n) is established, which when optimized using two optimizing variables (ϕ, ψ), will result in better design for robotic energy management, which include transceiver design and location of nodes. Taking into account previous analysis, there is a limitation in terms of the possible number of nodes over a robotic body structure, as there is a possibility if large number of nodes used, an interference would occur and influence the communication channel. This might result in a distorted signal and corrupted data. Also, minimizing the transmission power for a larger number of nodes, might in theory save energy, but will also reduce signal-to-noise ratio, and result in an attenuated signal. Thus, a balance of number of nodes that can be regarded as optimum should be investigated. Practically, robots can be used in daily living, and interact with people in many areas, such as, medical, service, defence, and general monitoring in smart homes. However, energy is a main concern in terms of robot communication and nodes energy falling below a threshold. In addition, placing enough nodes on the robots body for monitoring and diagnostic functions, can be challenging in terms of data rate and wireless connection, especially in closed spaces, where receiving data to a central station can suffer due to signal degradation. Also, environmental effects and robotic materials can be challenging in terms of providing minimum pathless and reliable communication channel. Such communication channel performance and security is a main concern, as secure communication is essential to enable reliable and trusted data. Future work should look at robotic materials and pathloss coefficient more closely, with emphasis on nodes placements and correlate all of that to energy, pathloss, and efficient data transfer, specifically using IoT applications.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Author state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article [and/or its supplementary materials].

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