Towards Implantable Body Sensor Networks - Performance of MICS Band Radio Communication in Animal Tissue

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ABSTRACT

Reliable wireless communication inside the human body is crucial for the design of implantable body sensor networks (IBSN). The tissues in human body are heterogeneous and have different conductivity and permittivity, which make the modeling of the wireless channel challenging. The design of upper layers of the network stack requires the physical layer characteristics including the channel model. Currently, there is no unique channel model available for implant communication inside body. Various measurement campaigns of channel characteristics are underway. The channel model characteristics depends on the hardware components used such as antenna and matching circuit as well as the operating frequency, which are not taken into account by the existing channel models for implant communication. Moreover, hardware losses and different tissue characteristics have not been taken into account in the link budget of the existing channel models. The approach used in this paper pays special attention to the losses introduced by hardware components of the implant itself and the physical medium. This paper presents characteristics of radio channel using animal tissue. A comparison is made between these measured characteristics and the existing channel characteristics provided by the IEEE 802.15.6 standard. The empirical measurements are used to validate the simulations of the IEEE 802.15.6 model.

Keywords

Pathloss, Animal tissue, Channel model, MICS band radio

1. INTRODUCTION

Reliability of wireless communication largely depends on the environment and the communication medium. The medium in the case of IBSN is the body itself, which is conductive with varying permittivity and permeability and largely affects the propagation of the electromagnetic waves. The physical layer (PHY) and the medium access control layer (MAC) of implant communication are standardized by the IEEE 802.15 task group 6 [13]. A frequency band called Medical Implant Communication Service (MICS) is introduced, which operates at 402-405 MHz for implant communication [13]. MICS band is used by the U.S. Federal Communications Commission (FCC) and the European Telecommunications Standards Institute (ETSI).

The antenna used for IBSN is limited in size and the RF propagation is not trivial inside the body [18]. The communication channel inside the body is completely different from that in the free space because of the tissue properties. Furthermore, the directivity of the antenna is a challenge because the properties of the body tissues influence the antenna radiation pattern. Channel characteristics provided in the IEEE 802.15.6 standard do not clearly indicate the characteristics of the antenna in the path loss model. Furthermore, it is unclear whether antenna matching has been applied when obtaining the channel model in the IEEE 802.15.6 standard [18].

Although different works in modeling the radio propagation in computer based simulation [1, 10, 21] have been done, the amount of research work estimating the empirical path loss response of the real biological tissue in MICS band communications is not adequate. In order to evaluate these electro-magnetic (EM) parameters in *in-vitro* conditions, an environment that has a close resemblance to tissue is required. For instance, a body phantom can be used to simulate the characteristics of tissues in human body [5, 12]. However, the phantoms cannot simulate the heterogeneous layered structure of human tissue. To understand the layered characteristics of the tissue, an animal tissue, which has

BODYNETS 2015, September 28-30, Sydney, Australia

DOI 10.4108/eai.28-9-2015.2261413

close resemblance to human tissue can be used. It is known that the tissue of the pig has the closest resemblance to human tissue [19]. Hence the performance of radio communication in a layered tissue structure can be obtained from tissue extracted from a pig.

To the best of our knowledge, all existing empirical results addressing human channel modeling are related to, communication between sensors placed on the surface of the body (i.e. communication between on-body sensors) and communication between in-body and on-body sensors [8, 14, 15]. The empirical channel modeling related to the communication between in-body sensors are still in its infancy. To this end, EM properties such as relative permittivity, and conductivity of 57 different human tissues were analyzed for RF and microwave frequencies (10 Hz — 20 GHz) in [9]. A few investigations have been reported to determine the effect of human body as a radio channel in wireless medical communication [20]. There are not any empirical measurements of the channel that are made using the animal tissue in MICS band communication.

1.1 Contributions

This paper focuses on the characterization and evaluation of PHY parameters of IBSN in animal tissue. Performance of radio inside the tissue is evaluated with different PHY configurations including transmission power, transmission distance, antenna orientation, and data rate. The main contributions of this paper are:

- Investigation of relationships between operating frequency, transmission power, packet delivery ratio, and data rate with distance and antenna orientations for implant communication;
- Validation of simulations results provided by the IEEE 802.15.6 standard through experimentation with animal tissue
- Characterize the performance of the radio in terms of packet delivery ratio in animal tissue environment.

The rest of this paper is organized as follows. In Section 2 channel model proposed by the IEEE 802.15.6 standard is summarized and its characteristics are described. Section 3 explains our test environment. PHY configurations and choices of evaluation parameters are presented in Section 4 followed by results and a comparison between the simulations of IEEE 802.15.6 in Section 5. Finally the paper is concluded in Section 6 after presenting the observations made from our experiments.

2. IN-BODY COMMUNICATION CHANNEL OF THE IEEE 802.15.6 STANDARD

The human body model of IEEE 802.15.6 is based on frequency dependent biological material and is claimed to have an accuracy of 2mm in tissue properties [18]. The received signal strength is calculated for a grid of points within a cylinder area around the body. The resulting data is then filtered for 2 scenarios, i.e., (i) in-body propagation (channel model 1 (CM 1)): set of points that completely reside inside the body, (ii) in-body to on-body (body surface) propagation

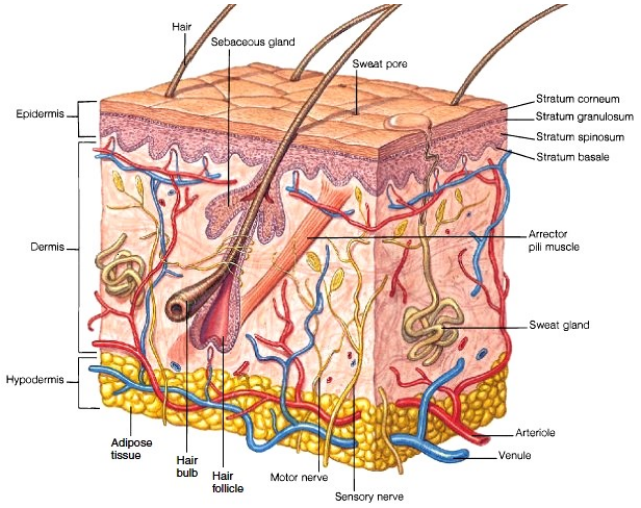

Figure 1: A cross section of animal tissue showing different layers including skin. [6]

(CM 2): set of points that reside within a certain distance (i.e., 2mm, 10mm, 20mm, 50mm) from the body surface. In this paper, we are interested in these two sets of propagation, where the transmitting node is placed inside the body and the receiving node is either placed inside the body or outside the body. The reference path loss $PL(d_0)$ is calculated using the formula shown in Eq. 1, where G_T, P_T, P_R represent the gain of receiving antenna, the transmission power and the receiving power, respectively.

$$PL(d_0) = \frac{G_R.P_T}{P_R(d_0)} \tag{1}$$

$$PL(d) = PL(d_0) + 10n\log_{10}(\frac{d}{d_0}) + S \tag{2}$$

The path loss is expressed in terms of log normal distance as shown in Eq. 2, where d_0, $PL(d_0)$, and n are reference distance, path loss at the reference distance d_0, and the path-loss exponent, respectively. S is a Gaussian random variable with zero mean and standard deviation of σ_s accounting for the losses due to tissue layers. When there is a direct line of sight between the sender and the receiver, a free space path loss can be added to CM 2 to account for the additional loss that the signal sent by the implant will go through once it leaves the body.

2.1 Simulation settings of the IEEE 802.15.6 model

In order to validate the simulation results of the channel model we implement the same settings that are used for the simulations. The settings of simulation are tabulated in Table 1.

Parameter	Value
Antenna position	2 cm beneath tissue surface (in-body)
	0-300 cm away from the tissue (off-body)
Transmission distance	0-16 cm (in-body), 0-300 cm (in air)
Antenna orientation	Parallel to the body surface
Transmit power	25μW EIRP (or) -15dBm
Operating frequency	403.5 MHHz center frequency with 3 MHz bandwidth

Table 1: Simulation parameters from IEEE 802.15.6

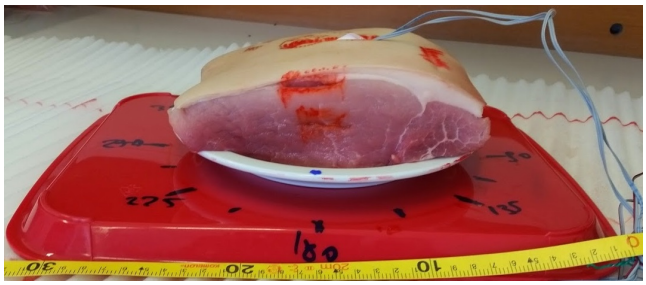

Figure 2: A dissected part of pig tissue used for experimenting with implant communication.

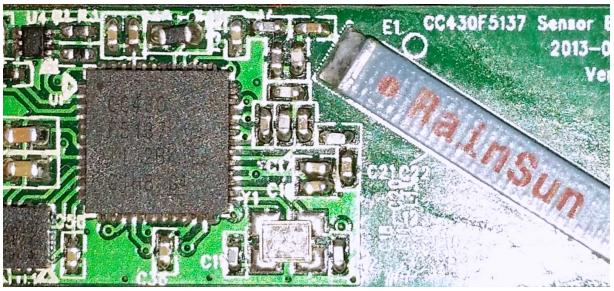

Figure 3: CC430 based implant used in experiments

A complete channel model, which includes shadowing, fading model, delay profile, and spatial properties, is not the aim of this paper. We aim to measure the deviation in path-loss model by measuring the received power at various transmission distances and power. This will ensure the reliability of the computer-simulated model by including the environmental losses which have to be considered in addition to the losses caused by the tissues.

3. EXPERIMENTAL CHARACTERIZATION OF CHANNEL MODEL USING ANIMAL TISSUE

3.1 Log-distance path loss model

In order to obtain a realistic prediction of the received signal strength of in-body communication, we employ the log-distance path loss model [18], in which the received signal strength (in dBm) at a distance d (in meters) from the transmitter ($PL_R(d)$) is expressed as:

$$PL_R(d) = PL_R(d_0) + 10nlog_{10}(d) + S_R, \quad (3)$$

where $PL_R(d_0)$ represents the mean (expected) signal strength at a distance of d_0 = 1cm from the transmitter and is calculated using Eq. 1, n is the path loss exponent. S_R represents a Gaussian random variable with zero mean and standard deviation of σ_s dB [18] contributing to the loss due to the channel characteristics. In the equation above, $PL_R(d)$ denotes a random variable. This model takes into account the different obstacles present in multiple transmitter-receiver paths having the same separation (also known as lognormal shadowing). The parameters (n, σ_s) define the statistical model and are known to be heavily dependent on the environmental characteristics. Measurements in the literature have reported empirical values for n in the range between 4.22 (near tissue implants) and 6.26 (deep-tissue implants), while values for σ_s usually fall into the [6.81,9.05] dB interval [13].

3.2 Animal tissue

Our test environment for the implant communication is a piece of muscle tissue extracted from the thigh of the pig including the (layers of) skin. Anatomically, the near-surface implantable devices are implanted in between the dermis and subcutaneous layer of the skin [2, 3, 17]. The dermis layer, as shown in Fig. 1, is just below the epidermis which forms the outer layer of the skin. From literature the most resemblance to the human tissue is found with the tissue of pigs [19]. The animal tissue is chosen for various reasons such as elimination of difficulties and complexities of test processes using real human tissue, not being dependent on the human phantoms with static EM properties, and identification of practical limitations faced using real tissues. It is important to note that different layers of skin have different conductivity (μ) and permittivity (ϵ). These values change dynamically with body mass, structure, and diet, which cannot thoroughly be validated using simulations.

Therefore, the choice of animal tissue over computer simulations or phantoms is taken to validate the performance of the radio. Fig. 2 illustrates the tissue used for experiments dissected from the thigh of a pig. It was extracted from the animal immediately after euthanization. The experiments were conducted on the tissue within 30 minutes of the euthanasia. We used a biological safety cabinet to prevent any contamination while carrying out the experiments. The ethical codes [7] were carefully followed during the experiments.

3.3 Hardware

While designing an implant two important requirements, namely longer lifetime and compactness, should be taken into account. In terms of ultra low-power radios, there are different radio chips available in the market which can comply with the requirements of the medical implant. The implant we used for experiments is shown in Fig. 3. It comprises of a CC430 chip set from Texas Instruments, a ceramic antenna matched to operate at 400 MHz band, and an accelerometer. The implant has a UART and a SPI connection through which the software is loaded and the output will be debugged. The main features making the CC430 suitable for evaluation are its ultra-low power radio operation - 160μA/MHz, its ability to operate in the MICS band (402-405 MHz), clear channel assessment, configurable access to PHY, configurable MAC layer, 16 bit CPU with 50ns instruction cycle time, memory (32 kB of flash and 4 kB of RAM).

Casing for the hardware: The purpose of casing is two-fold. One is to prevent any contact with the conductive tissue, which would cause a short circuit on the board. The other one is to ensure biocompatibility of the sensor node. The casing is made up of biocompatible ceramic, glass, or polymers [11] depending on the application. These casing provide transparent RF window and do not attenuate the signal [11]. For our experiments, it was sufficient to encapsulate the node in a paraffin cover just to prevent any contact with conductive tissues.

4. EXPERIMENTAL SETUP

The PHY parameters to be examined are transmission power, data rate, and frequency of operation. In addition to these parameters, transmission distance and antenna orientation will also have influences on the performance of in-body communication. To this end, we perform experiments with the following parameters:

1. Transmission (Tx) Power

The power at which the radio signal is delivered from the antenna. If the antenna is matched with the impedance of the channel, the power delivered at the antenna should ideally be equal to the transmission power. The PHY specification of the IEEE 802.15.6 group recommends 25μW effective isotropic radiated power (EIRP), which limits the transmission power to be at -15dBm.

2. Tx Rate

The rate at which data is sent from the transmitter to the receiver. The IEEE 802.15.6 group recommends a minimum data rate of 57.5 Kbps when operating in the MICS band of frequency.

3. Tx frequency

High frequencies have lesser the propagation inside the body. The in-body communication as mentioned earlier is standardized to operate in the MICS band.

4. Distance

The distance between Tx and Rx. This distance will change the radio performance. IEEE 802.15.6 recommended a maximum single-hop coverage distance of 3 meters in the MICS band communication.

5. Antenna orientation

The orientation of the antenna inside the tissue with respect to the receiver. The Tx antenna and Rx antenna can be placed horizontally (0° - posterior plane of the Tx antenna faces the posterior plane of the Rx antenna, 0° - posterior plane of Tx antenna faces the anterior plane of the Rx antenna) or vertically (90°) with reference to the 2D surface of the tissue. For the MICS band, the near-field of the antenna is less than 16 cm. The hardware used in our experiments has an isotropic antenna, which radiates uniformly in all directions and is affected by the near-field reflections for distances less than 16 cm. This effect may induce attenuation and signal loss, which will also be taken into account in our path-loss model. There will be no significant difference in RSSI due to antenna orientations in CM 2, because of the relatively larger distances between the transmitter and the receiver

4.1 Evaluation methodology

The values of the PHY parameters are chosen statistically as shown in Table 2. The parameters are divided into two groups, physical and network parameters. The physical parameters are directly related to the EM propagation such as transmission power, distance and orientation of the transmitting and receiving antennas, whereas the network parameters are related to the performance of the radio in terms of data rate and packet length with respect to the packet delivery ratio (PDR).

Set of parameters	Evaluating parameters
Set of physical parameters	Transmission power (dBm)
	Transmission distance (cm)
	Antenna orientation (degrees)
Set of network parameters	Data rate (Kbps)
	Packet length (bytes)

Table 2: Evaluation of hardware with two different sets of physical and network parameters.

In order to simplify the measurement process, a UART interpreter is developed. The radio has to be reset for every change in the physical parameters. Radio resets will put the radio into sleep mode [22]. Thus for every change, the implant has to be initialized with physical parameters before sending any data. In CM2 scenario, the RSSI at larger distances is limited by the receiver sensitivity of CC430 radio. Optimum values for the physical parameters are found out before experimenting with the network parameters.

Evaluation parameters	Values
Antenna orientation	0°,90°,180°
Transmission power	5, 0, -10, -15, -30 dBm
Transmission distance	CM 1 : 0, 2, 4, 8, 16 cm
	CM 2 : 0, 25, 50, 75, 100, 150, 225, 300 cm

Table 3: Set of physical parameters. Repeated for CM 1 and CM 2

4.2 Setting the physical parameters

Table 3 shows different configurations of set of experiments with CM 1 and CM 2. In case of CM 1, the nodes are placed within the tissue at a distance of at-most 16 cm. The characterization of the channel when devices communicate in such close distance is crucial for the design of the topology of an IBSN [16]. In case of CM 2, larger distances are used, where an implant could communicate to a device placed outside the body. We increase the distance gradually from 25cm to 3m to understand the channel characteristics through RSSI information varying in distance. The values of the physical parameters are shown in Table 3.

4.3 Setting the network parameters

The set of network parameters used for the evaluation are data rate, packet length. We vary the network parameters and measure the packet delivery ratio for each possible combination of parameter values. This will help in finding the optimum settings for network parameters. The values of the network parameters are shown in Table 4.

Evaluation parameter	Values
Packet length	5, 20, 40, 60, 80, 100 bytes
Data rate	5, 20, 40, 60, 80, 100, 150 Kbps

Table 4: Set of network parameters. Repeated for CM 1 and CM 2

The network parameters are set through the UART interpreter of the implant. Received packet information is read back through the UART interpreter and stored in a local PC for further analysis with MATLAB. The results from that data analysis are discussed in Section 5.

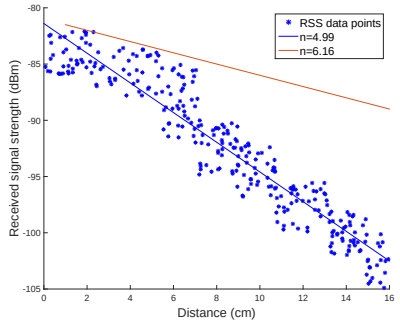

Figure 4: RSSI as a function of distance (Tx=-15dBm) CM 1

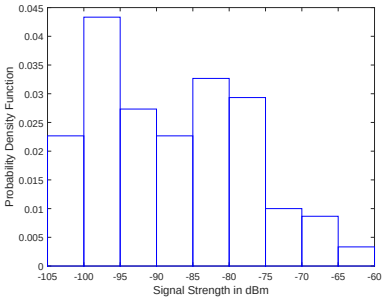

Figure 5: Probability density of RSSI(CM 1 and CM 2 combined) Tx=-15dBm

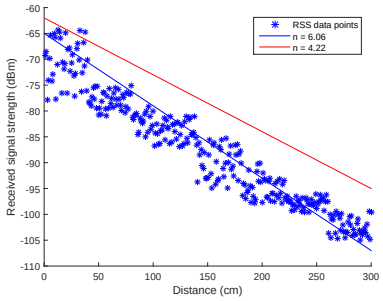

Figure 6: RSSI as a function of distance (Tx=-15dBm) CM 2

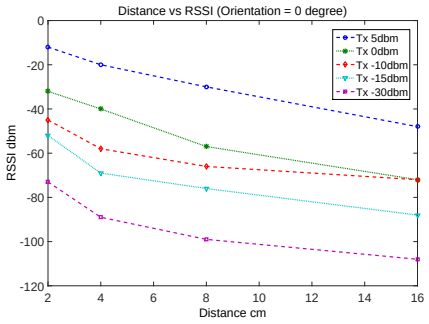

Figure 7: RSSI vs Distance at 0 degree antenna orientation

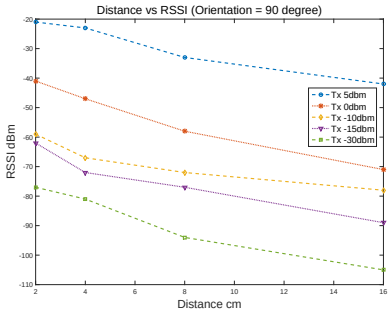

Figure 8: RSSI vs Distance at 90 degree antenna orientation

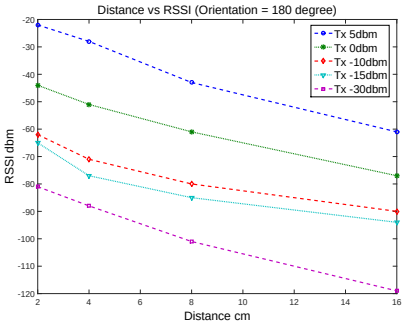

Figure 9: RSSI vs Distance at 180 degree antenna orientation

5. RESULTS AND DISCUSSIONS

In our experiments, we collected 150 data points for each step of the parameters which are shown in Fig. 4 - Fig. 6. The scatter plot of CM 1 shows how RSSI information varies with the transmission distance. The mean value of the received power has an impact over the path loss exponent (n) which is shown in a regression line in the scatter plot. The value of path loss exponent (n) from the IEEE 802.15.6 simulation model is expressed in a regression line, which has n=4.22 [13]. Whereas the empirical estimation of the path-loss exponent (n)is 6.16 which is much higher than the estimated value from path loss model of IEEE 802.15.6. The CM 2 scenario also has variation as shown in the Fig. 6. The deviation in CM 2 is not as much as when the communication takes place completely inside the meat.

Fig. 5 shows the probability density of RSSI of CM 1 and CM 2 combined, which indicates that the received signal strength will be close to -105 dbm at most of the times. In such situations, the receiver has to operate at high sensitivity by consuming more power. When operating at high sensitivity the radio receiver provides reduced data rate [22].

5.1 Evaluation of the physical parameters

Validation results of the set of physical parameters are shown in Fig. 7 - 9. Generally speaking, RSSI is linearly decreasing with distance. This can be formulated as:

$$RSSI \propto \log\left(\left(\frac{k}{Distance}\right)\cdot(\mu\cdot Tx\ power)\right), \qquad (4)$$

where k and μ are statistical constants. In order to match the standards of the MICS band, the transmission power should not be higher than 25μW. By referring to the datasheets of antenna and CC430 radio chip [22], we found out that at a transmitting power of -15dBm, the EIRP of the node will not exceed $25\mu W$. However, no hardware measurement is made in order to verify the EIRP. Additionally, by lowering down the power further below -15dBm, we were not able to communicate at distances larger than 5cm with a packet delivery ratio higher than 95%. Experimenting with larger distances resulted in very low signal strengths as shown in Fig. 6. Having lower RSSI values may result in higher error rates in data transmission, which is not desirable for in-body communication.

As far as CM 1 model is concerned, the attenuation of signal is very high even for short distances. The plot shown in Fig. 7 illustrates that with 0 degree antenna orientation (which implies that the antennas are placed facing each other in line of sight), even at 2cm separation, a transmission sent by 5 dBm is received as -20 dBm. This attenuation is persistent in all the set of repeated experiments, which indicates the presence of large reflection of signals in the near field of the antenna.

A linear decrease in RSSI is expected as the distance increases. However, experimental results show that the decrease in RSSI is not linear at larger distances. An additional path-loss due to NLOS communication is also accounted together with the statistical path-loss model in our

experiments. Based on our experiments, the optimum physical and network parameters are presented in Table 5.

5.2 Evaluation of the network parameters

Both CM 1 and CM 2 models were used to evaluate the set of network parameters. The data rate is varied from the minimum of 2 Kbps to 150 Kbps and the corresponding PDR is measured. The PDR indicates how many packets are successfully received. For most of the application in CM 1 and CM 2 scenarios, the tolerable packet error rate has been set to atmost 10% for a 256-byte payload with a packet delivery ratio of 95% [4, 23]. Different packet sizes will help to identify the number of re-transmissions required in case of larger packet lengths. Upon exceeding the maximum number of re-transmissions, the receiver will ignore the packet. However, in our experiments, we do not use any re-transmission and as soon as a packet fails, it is considered as a dropped packet.

Parameter	Value
Tx power	-15 dBm
Tx distance	CM 1 :16 cm
	CM 2 :100 cm
Packet length	20 bytes
Data rate	40 kbps
Modulation	BPSK

Table 5: Optimum values of physical and network parameters obtained from experiments

Using the CM 1 model, as the packet length increases, the packet delivery ratio decreases even for higher data rates as shown in Fig. 11. This indicates that large packet length allows the implant to communicate for a longer time. The failure of a packet can also occur if a frame is corrupted due to very low RSSI. It is also conversely found that higher data rates will not increase the packet delivery ratio, in case of large packet length. For a fixed packet length, the PDR increases as the data rate increases. An important observation is that the PDR is almost constant at higher data rates for a fixed packet length.

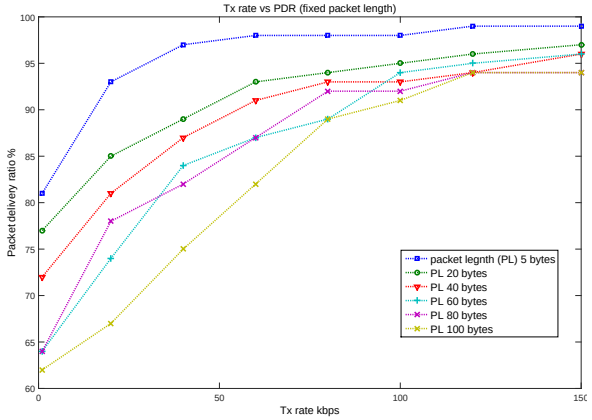

Figure 10: Tx Rate vs Packet delivery ratio evaluated with fixed packet length. Measured in CM2

Using the CM 2 model, as the packet length increases, the packet delivery ratio is decreased even for higher data rates as shown in Fig. 10. This behavior is similar to that of the CM 1. The data rate is directly proportional to the packet delivery ratio; however it changes with that of the packet length. As the packet length increases, PDR is decreased. PDR increases, as the data rate is increases. This indicates that small packet length and higher data rates are required to maintain the reliability of the network.

Small packet length with twice the data rate will have better performance while using both CMs. Sending packets at a faster rate will reduce the congestion in the network.

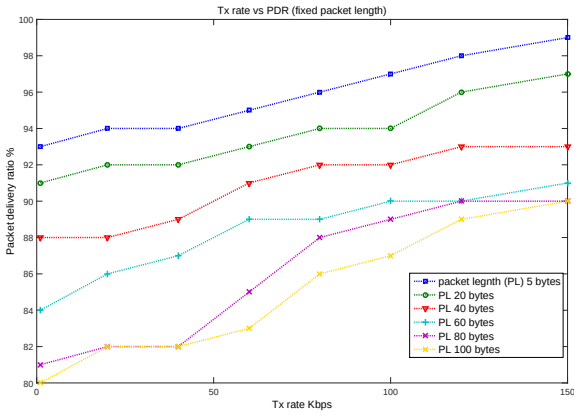

Figure 11: Tx Rate vs Packet delivery ratio evaluated with fixed packet length. Measured in CM1

5.3 Comparison of empirical results and simulation models for IEEE 802.15.6

The deviations in the simulated model and the empirical results are shown in Table 6. The differences in the statistical constants are large and is not in line with the values from the computer simulated models of IEEE 802.15.6. Even though simulations may exhibit a good network performance, this does not guarantee good performance of the radio in a network setup under practical scenarios.

PL parameters	CM 1		CM 2	
	simulation	empirical	simulation	empirical
$PL(d_0)$dB	40.94	56.65	49.81	61.32
n	4.99	6.18	4.22	6.06
σ_s	9.05	10.65	6.81	9.56

Table 6: Comparision of our empirical results and simulation results from [18]

It can be seen that the path loss from our measurements includes the additional losses, which can be due to the indoor propagation losses and multipath effects. In addition to the free space path loss, indoor path loss has to be accounted for. From the results, it can be assumed that the radio waves are partially scattered to the air medium when a transmitting from inside the body. The scattered signal is picked up by the receiver has multipath characteristics such as fading and a delay profile which are not explicitly shown in the results. More experiments are needed to create an appropriate model of the in-body channel with additional losses. This study shows that the existing channel model

from computer simulations is not accurate and cannot be applied for the development of network protocols for IBSN.

6. CONCLUSION

Two different CMs were chosen for evaluation of PHY parameters and characterization of the performance of radio in animal tissue. From the results, it is shown that the attenuation of radio communication is very high inside the tissue. The path loss exponent inside the animal tissue deviates from that of the IEEE 802.15.6 results. Moreover, additional path loss has to be accounted for the in-body to off-body communication, which includes the indoor propagation losses. To compensate for the losses induced by the animal tissue, the settings of PHY parameters can be adjusted such as transmission power, antenna orientation and transmission distance. In order to characterize the channel, it is necessary that rigorous experiments are carried out with different parameters as explained in this paper. These channel model parameters will be used also in our future experiments and simulations when validating the network performance of IBSN.

7. ACKNOWLEDGMENTS

This research is funded by the STW project Cyber Physical Systems (CPS).

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