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A New Radio Propagation Model at 2.4 GHz for Wireless Medical Body Sensors in Outdoor Environment

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Abstract—**This study investigates the effect of antenna height, receive antenna placement on human body, and distance between transmitter and receiver on the loss of wireless signal power in order to develop a wireless propagation model for wireless body sensors. Although many studies looked at the effect of distance, few studies were found that investigated methodically the effect of antenna height and antenna placement on the human body. Transmit antenna heights of 1, 2, and 3 meters, receive antenna heights of 1 and 1.65 meters, "on-body" and "off-body" placements of receive antenna, and a total of 11 distances ranging from 1 to 45 meters are tested in relation to received power in dBm. Multiple regression is used to analyze the data. Significance of a variable is tested by comparing its p-value with alpha, and model fit is assessed using adjusted R^2 and σ of residuals. It is found that an increase in antenna height would increase power—but only for transmit antenna. The receive antenna height has a surprising, opposite effect in the on-body case and an insignificant effect in the off-body case. To formalize the propagation model, coefficient values from multiple regression are incorporated in an extension of the log-distance model to produce a new empirical model for on-body and off-body cases, and the new empirical model could conceivably be utilized to design more reliable wireless links for medical body sensors.**

I. INTRODUCTION

There has been an increased interest in wireless on-body sensors which can measure and transmit real-time physiological data wirelessly for monitoring and archiving. Several advantages exist in using wireless medical sensors. They allow long-term monitoring of patients' health without physically constraining them. With body sensors, patients can be rehabilitated while also being easily supervised [10] via wireless communications. However, wireless on-body sensors operate over a radio link, which is inherently less reliable than a wired link. Such unreliability presents a challenge to telemedicine applications which require dependable receipt of physiological data transmitted by the on-body sensor. So an assessment of propagation behavior for medical sensor nodes is important to understanding the radio link encountered by these sensor applications.

The propagation environment is largely characterized by radio propagation loss models, which are mathematical constructions that describe the amount of signal power loss as a function of some variable (e.g., distance between transmitter and receiver). Propagation loss models are important as they are used to predict, for a given transmit power, whether received power is strong enough to allow data to be reliably received.

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Although there have been studies on wireless sensor propagation models in indoor environments (e.g., hospitals), there have been little study on short-range radio propagation of on-body sensors in outdoor environments. In terms of actual field measurement, two studies related to telemedicine at 2.4 GHz were found; both investigated the propagation environment inside hospitals and performed actual measurements [1,9]. But the two studies concerned themselves with indoor measurements at close range, not outdoors. In addition, while there have been studies investigating wireless signal power as a function of *distance*, fewer have looked at wireless signal power as a function of another variable dimension—*height*, especially in an environment that might be found in a healthcare facility's outdoor open-area walking space, for example. Also, the effect of antenna height may be more challenging to study for body sensors in indoor environments.

Therefore, this study addresses those areas that have not been investigated much by past studies—first, by actually measuring and analyzing the propagation effect outdoors, at close range and at 2.4 GHz in the context of telemedicine sensors, and second, by investigating the effect of the following multiple independent variables: antenna height, antenna placement on-body (as in wireless on-body sensors) and off-body, and distance between transmitter and receiver on the loss of signal power in order to develop a wireless propagation model. It is expected that this field study, done outdoors in an open, flat environment for both on-body (telemedicine) antenna and off-body (freestanding) antenna, can provide a "baseline" on sensor outdoor propagation behavior upon which future studies may be based.

II. PROPAGATION MODELS

A wireless propagation loss model is a way to predict the loss of signal power over some distance between the transmitter and the receiver [2]. Propagation models are often derived for specific scenarios. They can be classified as either analytical or empirical, though some may be a hybrid of the two [6]. *Analytical* models are based on some physical and mathematical representation and explain what theoretically "should" happen. The free-space model is an example of an analytical model. The model originated as the Friis Transmission Formula and was credited to H. T. Friis at Bell Labs in 1946 [5]; the model itself is as follows [14]:

$$P_R(d) = P_T G_T G_R \left[\frac{\lambda^2}{(4\pi)^2 d^2} \right] \quad (1)$$

P_R is the power detected by the receiver, P_T is the transmitted power, G_T is the gain of the transmit antenna, G_R

is the gain of the receive antenna, and d is distance between the receiver and the transmitter.

However, propagation is a complex phenomenon; it is difficult to characterize radio propagation loss across environments with a single model [6]. Hence *empirical* models, which are based on actual experimentation and field measurement, are often used. Usually, analysis of actual data points is used to define certain parameters (i.e., intercept and coefficients) which form the model. The advantage of such models is their "implicitly taking into account all propagation factors, both known and unknown, through actual field measurement" [12, p. 138].

The log-distance model is an example of an empirical model while also being theoretically sound. Unlike the free-space model, the log-distance model applies to general environments. It is generic, explaining the loss of signal power as an exponential relationship to distance [2]. The model is represented by the following:

$$P_R(d) = P_R(d_0)G_T G_R \left(\frac{d_0}{d}\right)^n \qquad (2)$$

$P_R(d_0)$ is the power at reference distance d_0 (usually 1 m), and n is the propagation loss index. Unlike the free-space model which specifies $n = 2$, the general log-distance model's n varies depending on the environment. The above equation can be written in the dB form. For reference distance $d_0 = 1$ meter and reference direction $\theta = 0°$, defining $P_0 = P_R(d_0 = 1)$ [11] at $\theta = 0°$ gives:

$$P_R[\text{dB}] = P_0[\text{dB}] + G_T[dB] + G_R[dB] - 10\,n\log(d) \qquad (3)$$

In addition to modeling by using distance d, past studies have also incorporated antenna height gain into their models. Conceptually, height gain, as used in [15] refers to how much the receive power increases when the antenna height increases [15]. John J. Egli in 1957 was one of the first to reference such behavior [3]. His study stated height gain for both transmit antenna and receive antenna to be proportional to the second power of antenna height [3]. In this study, attempts will be made to model in terms of both *loss* due to distance and *gain* due to antenna height.

III. Methods

Four independent variables are involved in the study: the transmit antenna height, the receive antenna height, the placement of the receive antenna by the body (or off the body), and the distance from the base of transmitter to the base of the receiver. For the transmit antenna, three heights are used (1 meter, 2 meters, and 3 meters). For the receive antenna, two heights are used (1 meter for "waist" height and 1.65 meters for "head" height). The dependent variable for the experiment is received power in decibel-milliwatts (dBm). To measure received power, a Wi-Spy DBx wireless USB device and the Chanalyzer Lab spectrum analyzer software running on a laptop computer were employed. The TP-Link 150 Mbps Wireless N Router (Model: TL-WR741ND) was used as the transmitter. The router's browser interface was used to set the channel to channel 6, and all measurements were made at the frequency of 2438 MHz. The polarizations of the antennas were vertical.

A generally flat, open location was chosen for experimentation to minimize reflections and scattering of the transmitted radio waves. This was a large, empty parking lot. The transmitter and receiver units were arranged as described by Fig. 1. Transmission took place in a line-of-sight propagation from the wireless router (transmitter) to the USB Wi-Fi device (receiver). Note the actual photo of the experimental setup as provided in Fig. 2.

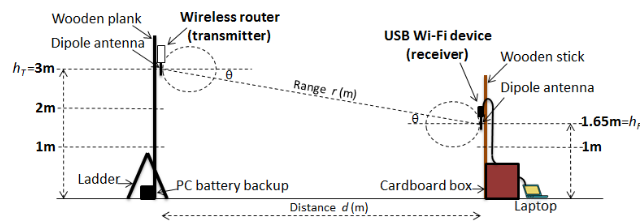

Figure 1. Experimental setup.

Figure 2. Actual photo of experimental setup.

Data were collected at a total of 11 distance locations. For each distance location, received power measurements were taken for 12 different combinations of transmit antenna height, receive antenna height, and antenna placement. These combinations arose from three possible transmit antenna heights at 1 m, 2 m and 3 m, two possible receive antenna heights at 1 m and 1.65 m, and the receive antenna placement on or off the human body. Note that the receive antenna height of 1.65 m is the "head" placement, and the receive antenna height of 1 m is the "waist" placement. So there are a total of 132 experimental data values.

For the "off-body", freestanding receive antenna scenarios, no person stood next to the USB device/receiver antenna (fastened on the wooden stick). To simulate the receive antenna placement on the human body ("on-body" or telemedicine scenarios), a person stepped beside the wooden stick and stood right next to the USB device/receiver antenna. Sixty seconds were allowed to elapse before recording the power value displayed by the software. Such process was repeated for all distances of 1, 2.5, 5, 10, 15, 20, 25, 30, 35, 40, and 45 meters.

IV. Results and Discussion

A. Regression Analysis: Off-Body and On-Body

To characterize the general behavior of received power values as a function of log-distance and antenna placement (off-body and on-body), Fig. 3 and Fig. 4 show the scatter plots, lines of best fit and single-variable regression equations for off-body and on-body cases.

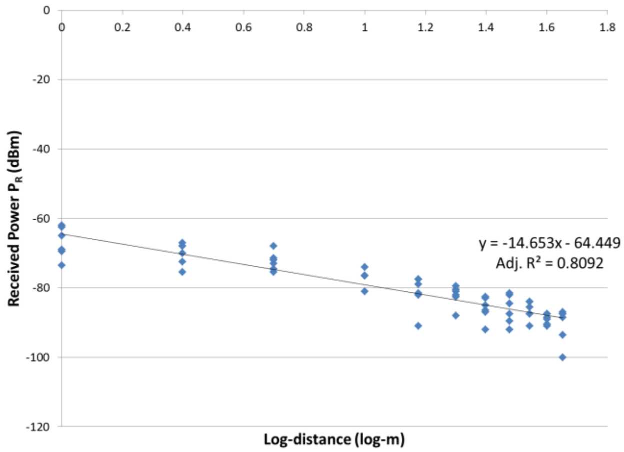

Figure 3. Received power as a function of log-distance for off-body receive antenna placement.

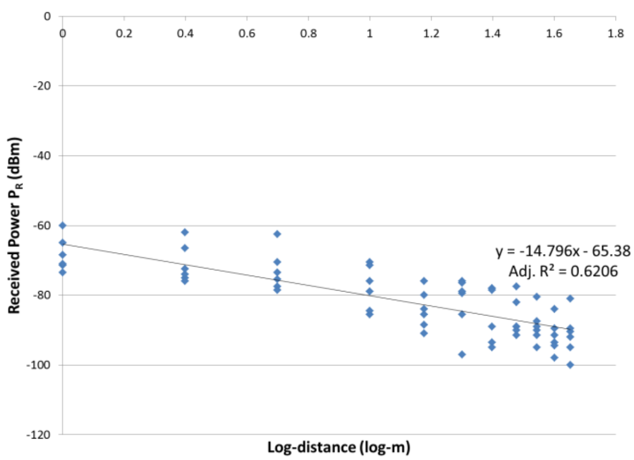

Figure 4. Received power as a function of log-distance for on-body receive antenna placement.

B. Multiple Regression Analysis: Off-Body

Since there are more than one independent variable (distance d, transmit antenna height h_T and receive antenna height h_R), multiple regression analysis is used to generate the model. Raw received power values were first normalized in observance of the antenna gain pattern. This transformation of data was also performed by another study [7] to compensate for the antenna gain, which depends on the relative positions of transmit and receive antennas (and hence the angle θ—see Fig. 1). Then Excel was used to perform multiple regression of normalized received power with independent variables log-d, log-h_T and log-h_R. Because graphs in four dimensions are not possible, tables of multiple regression results are provided. Table I summarizes the results of the multiple regression for off-body antenna placement, including adjusted R^2, coefficient, and intercept values for the multiple regression model. Adjusted R^2 is a more stringent measure because it makes allowance for how many independent variables there are in the model [8].

TABLE I. Results of Multiple Regression of Normalized Received Power for Off-Body Antenna Placement

Regression Statistics	
Multiple R	0.945496
R Square	0.893962
Adj R Sqr	0.888831
Std Error	3.115074
Observati	66

	Coeff	*Std Error*	*t Stat*	*P-value*
Intercept	-62.8755	1.113282	-56.4776	4.97E-55
log-h_R	-0.25876	3.526137	-0.07338	0.941736
log-h_T	6.557729	1.946417	3.369129	0.001301
log-d	-16.8746	0.746241	-22.6128	1.21E-31

In addition to adjusted R^2, the statistical significance of a coefficient/slope of an independent variable in a regression model is assessed using the "alpha" measure. Alpha is the chance of showing a significant relationship when there actually is not [8]. Alpha is set to 0.05 or 5%, which is the traditional threshold. If a coefficient is "statistically significant," then the relationship is significant. As seen in Table I, multiple regression produces a p-value for the coefficient of each independent variable involved. If that p-value is less than 5%, then that independent variable is deemed a significant term in the regression.

Table I shows that all independent variables are significant determinants of the regression except log-h_R. For off-body antenna placement, the coefficient value for log-d is -17 (i.e., propagation loss index n is 1.7). The adjusted R^2 value for the model is high at 0.89. The fact that the coefficient of the independent variable log-h_T is positive suggests there is a height gain for transmit antenna. As shown by the regression, as height of the transmit antenna increases so does power. Statistically because the p-value for the coefficient of log-h_T is 0.0013, which is less than 0.05, log-h_T (and h_T) is a significant independent variable.

However, the p-value for the coefficient of log-h_R is 0.94, which is greater than 0.05. The receive antenna height is not a significant independent variable. This insignificant result is probably due to the fact that the two receive antenna heights tested (1 meter and 1.65 meters) are very close to each other. In retrospect, 65 centimeters between the two sole receive antenna heights was probably not enough to produce a significant difference in received power.

C. Multiple Regression Analysis: On-Body

A multiple regression is also performed for the on-body antenna placement. The results are summarized in Table II.

TABLE II. Results of Multiple Regression of Normalized Received Power for On-Body Antenna Placement

Regression Statistics	
Multiple R	0.917631
R Square	0.842046
Adj R Sqr	0.834403
Std Error	4.310227
Observati	66

	Coeff	*Std Error*	*t Stat*	*P-value*
Intercept	-60.1159	1.540412	-39.0259	2.37E-45
log-h_R	-35.2317	4.879001	-7.2211	8.9E-10
log-h_T	6.9902	2.693194	2.595506	0.011776
log-d	-17.0179	1.032549	-16.4815	2.45E-24

The coefficient for log-d and therefore propagation loss index remain approximately the same as at -17 and 1.7. The coefficient of transmit antenna height also remains positive with higher transmit antenna height being more conducive to propagation. The adjusted R^2 value is 0.83. For the transmit antenna height, the coefficient of log-h_T is 7.0 with a p-value of 0.012 which is less than 0.05. Thus, log-h_T and ultimately h_T remains a significant independent variable.

For the receive antenna height, a major distinction emerges between the regressions for off-body and on-body scenarios. This time, log-h_R is highly significant statistically. Its p-value of 8.9 x 10^{-10} is much less than the threshold alpha value of 0.05. In addition, the coefficient of log-h_R is very negative at -35. This meant that *as receive antenna height increases, received power decreases*. This is a surprising result for on-body antenna placement. It is known that placing a conductor in the near field of an antenna could alter the antenna pattern [13]. Since the waist/abdomen has more conductive (water) volume than the head, a "focusing" effect may have occurred, resulting in a higher antenna gain in the direction of the transmitter/receiver. The alteration of the receive antenna pattern as a result of placing a conductor in the near field of the antenna could explain the higher received power at h_R = 1 meter.

D. Formulating the Models

Finally, in reference to the multiple regression of normalized P_R with log-d, log-h_T, and log-h_R for off-body and on-body antenna placements, the final propagation model for off-body and on-body cases are developed. For off-body, freestanding antenna placement, the multiple regression coefficients are written formally in the following propagation model (in dB form):

$$P_R = P_0 + G_T + G_R - 10n\log(d) + 10u\log(h_T) \quad (4)$$

$$n = 1.7, u = 0.66$$

n is the propagation loss index, and u is the transmit antenna height gain index. As previously defined, P_R is the received power in dBm, P_0 is the reference received power at reference distance d_0 = 1 meter and reference angle θ = 0° in dBm, G_T is the transmit antenna gain in dB, G_R is the receive antenna gain in dB, d is the distance in meter, and h_T is the transmit antenna height in meter. Note that the term for h_R is excluded. This is because this independent variable is construed as insignificant by the p-value of the multiple regression for the model. n and u (and v later) are experimentally-determined index exponents; Table I shows that the coefficient of the log-d term is -17 and the coefficient of the log-h_T term is 6.6, so n = 1.7 and u = 0.66 for the propagation model with off-body, freestanding receive antenna.

For on-body, telemedicine antenna placement, the multiple regression coefficients are written formally in the following propagation model (in dB form):

$$P_R = P_0 + G_T + G_R - 10n\log(d) + 10u\log(h_T) + 10v\log(h_R) \quad (5)$$

$$n = 1.7, u = 0.70, v = -3.5, h_R \in \{1, 1.65\}$$

u is the transmit antenna height gain index, v is the receive antenna height gain index, and h_R is receive antenna height in meter. Because the model is developed using data collected at h_R = 1 meter and h_R = 1.65 meters, the model is valid for those two h_R values. Table II shows that the coefficient of the log-d term is -17, the coefficient of the log-h_T term is 7.0, and the coefficient of the log-h_R term is -35, so n = 1.7, u = 0.70, and v = -3.5 for the propagation model with on-body, telemedicine antenna.

The corresponding model in linear form is:

$$P_R = P_0 G_T G_R \frac{h_T^{\,u} h_R^{\,v}}{d^n}, h_R \in \{1, 1.65\} \quad (6)$$

P_R is the received power now in milli-watt, P_0 is the reference received power also in milli-watt, and both G_T and G_R are now unitless antenna gain factors.

These propagation models' validities are also supported by the standard deviation of residuals. The standard deviation σ of residuals or errors (not standard deviation of measurements themselves) is a measure of model accuracy [4]. For the model with off-body, freestanding antenna placement, σ is calculated to be 3.0 dB. For the model with on-body antenna placement, σ is calculated to be 4.2 dB; these standard deviation values compare favorably with those shown by past studies (e.g., σ = 6 dB to 10 dB reported for optimized regression models by [4]).

V. Conclusion

This study investigates the effect of transmit antenna height, receive antenna height, receive antenna placement on/off the body, and distance on the loss of signal power, as well as to build more accurate propagation models based on field measurements. Although measurements were made in base station-to-sensor direction, by antenna reciprocity [13] the results could be applied to sensor-to-base station direction—enabling the model to describe transmissions by on-body medical sensors.

From regression analysis, d and h_T are significant independent variables in determining normalized P_R in the off-body case, while d, h_R, and h_T are all significant in the on-body case. Significance of the results is established by p-values less than 5%, and good model fit is shown by high adjusted R^2. In the on-body case, a surprising result is that waist-height receive antenna had statistically significantly higher received power than head-height antenna. An application of this finding is that it may make sense for a system to first aggregate data from body sensors back to a smartphone clipped to the *waist* side before transmission instead of transmitting sensor data directly from a *head*-height transmitter. Based on multiple regression results, comprehensive off-body and on-body propagation models are developed. It is expected that the results of this study can provide a baseline on sensor outdoor propagation behavior upon which future studies may be based.

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