

# Statistical characterization of the dynamic narrowband body area channel

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**Abstract**—A statistical characterization of the narrowband dynamic human on-body area channel, with application to biomedical/health information monitoring, is presented based on measured received signal amplitude. We consider varying amounts of body movement, and a variety of transmit-receive pair (Tx-Rx) locations on the human body. The characterization is presented for two different frequencies, near the 900 MHz and 2400 MHz Industrial, Scientific and Medical (ISM) bands. Common distributions used to describe fading statistics are compared to the received signal component for nine different Tx-Rx pair locations for the subject's body standing, walking and running. The Lognormal distribution provides a good fitting model, particularly when the subject's body is moving. The fit is independent of Tx-Rx pair locations. The Rayleigh distribution is a very poor fit to the received signal amplitude statistics.

## I. INTRODUCTION

Sensing and actuating devices are becoming sufficiently small to allow multiple sensors to be attached to the body. A network of such sensors around the body is referred to as a (wireless) Body Area Network (BAN). It is expected the first applications of BAN's will be in biomedical and sporting domains, as discussed in the IEEE 802.15.6 working documents [2]. The close proximity of transceivers to the human body force a low-power approach to any BAN and demand the wireless channel be well understood: so BAN transceivers take full advantage of their environment [3]. Extensive work exists on the path-loss and power-delay profile of both narrowband and UWB wireless BAN's at ISM frequencies [4, 5]. As a first-order approximation the (static) human body radio channel is reasonably modelled by a uniform cylinder of salty water [6].

Recently work has focussed on the macroscopic statistical properties of the human-radio channel. We have noted [1] that movement is a dominant component of the capacity of a BAN. A Rician distribution [7], and a mixed-parameter distribution [8] have been suggested for mobile BAN channels. In [9] a number of measurements were taken for the ultra-wideband BAN, and Lognormal fading was found between most Tx-Rx pairs for a stationary subject. In contrast to our work [9] suggested a Nakagami-m model was a poor fit for all stationary models, but a good fit for models involving

arm movement; conversely [10] observed strong matching to the Nakagami-m model. In [9] some measurements could not distinguish between Rayleigh and other models, whereas we have found Rayleigh to be consistently poor. The natural outcome for such models are power efficient network protocols such as [11] based on movement characteristics.

In this paper we consider narrowband BAN's which propagate using body-worn antennas. We measured the radio channel characteristics in the 900MHz and 2400MHz ISM bands using wearable antennas: fabric mounted, flexible radio antennas which do not couple directly to the skin. We considered several point-to-point arrangements, with three movement scenarios: standing, slow walking and fast jogging. Our objective is to answer:

- 1) Can the (narrowband) BAN radio channel be characterized using well known statistical fading models?
- 2) What is the dominant statistical model of the BAN channel when the subject is moving?

We find that the channel gain can be reasonably modelled by a log-normal distribution<sup>1</sup>, consistent with the approximation [6] of the human-body acting as a shadow with 40dB/m to 60dB/m path-loss. We have tested the following:

- **Normal (and Rayleigh)** are well known for their maximum entropy characteristics. Channels which have no significant structure are well modelled by these distributions.
- **Lognormal** distribution arises from a law-of-large numbers approach to multiplicative effects, and is commonly used to model shadowing (long-term fading processes) in terms of the average power received.
- **Nakagami-m** is a common model used in mobile fading. It includes Rayleigh as a special case, and may be used to approximate Rician distributions. The **Gamma** distribution [12] is a more efficient model over Nakagami-m in mobile fading channels. When Nakagami-m is a poor fit for channel statistics, Rician will also be a poor fit.
- **Weibull** has been used for multipath modelling and is generally found to model small-scale fading and multipath inter-arrival [13] processes well.

A more detailed description of the experimental method follows in the next section. Section III gives a detailed description of the modeling of the received signal amplitude

<sup>1</sup>Even in the (few) cases where lognormal was not the best fit, it remains close according to the Akaike information criterion.

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A part of this work appeared in [1]

in dynamic narrowband body area channel, with comprehensive characterization and some generic observations. Finally Section IV provides some concluding remarks.

## II. EXPERIMENTAL SETUP

Wireless on-body channel measurements were made using two commercial wearable antennas strapped with VELCRO® tape to the body of a 181.5 cm / 78 kg male test subject in an office environment.

Channel measurements were performed by transmitting test signals emanating from a vector signal analyzer centered in regions around the 900 and 2400 MHz ISM bands. The test signals were separately transmitted from one antenna while the subject performed three different actions: 1) standing still; 2) walking on the spot; and 3) running on the spot. The signal received at the other antenna was down-converted, sampled for approximately 10 seconds, and saved to disk. Analysis of the measurements was later done offline.

For each set of the three movement scenarios, the transmitting and receiving antennas were strapped to different locations on the test subject's body. Figure 1 illustrates the locations of the antennas on the test subject. Table I lists the combinations of transmit and receive antenna locations used, with separate channel measurements made for each combination. For reasons of symmetry, the left wrist and left ankle to chest measurements were not recorded.

Appropriate choices were made when choosing the bit rate (12.5 Mbps), modulation scheme (BPSK) and pulse shaping filters (root raised-cosine). The combination used provided a relatively flat (1 dB attenuation in the sidelobes) signal spectrum over a 10 MHz bandwidth. A wireless system with 1 bit/s/Hz modulation efficiency could provide the 10 Mbps required by the 802.15.6 technical requirements document [2] within this bandwidth.

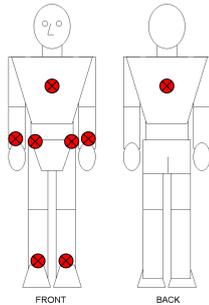


Fig. 1. Antenna locations on test subject.

## III. STATISTICAL MODELING OF RECEIVED SIGNAL AMPLITUDE DISTRIBUTION

### A. Characterization

As mentioned in the previous section the normalized received power was measured over a period of 10s for nine different Tx-Rx measurement positions for three situations of subject movement, standing still, walking and running at the two measurement center frequencies of 820 MHz and

TABLE I

MATRIX OF TRANSMIT AND RECEIVE ANTENNA LOCATIONS. THE SYMBOL  $\times$  IN THE MATRIX DENOTES THAT THE CORRESPONDING CHANNEL MEASUREMENT WAS CONDUCTED, C-CHEST, RW-RIGHT WRIST, LW-LEFT WRIST, RA-RIGHT ANKLE, LA-LEFT ANKLE, B-BACK, RH-RIGHT HIP.

Receiver location	Transmitter location					
	C	Rw	Lw	Ra	La	B
Rh	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$
C		$\times$		$\times$		$\times$

2360 MHz – giving 54 scenarios in total). In this section we attempt to define some reliable statistical models for the signal amplitude distribution over the different scenarios with and without movement of the subject.

The measured received power across one set of measurements for a given scenario was normalized according to the maximum received power for that set of measures. The square root of this normalized receive power was taken to find a normalized received signal amplitude.

We obtained maximum likelihood estimates of received signal amplitude data for these six common distributions often used in channel characterization and modelling:-

- Normal with probability density function

$$f(x|\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\} \quad (1)$$

- Lognormal

$$f(x|\mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left\{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right\} \quad (2)$$

where  $\ln(\cdot)$  is the natural logarithm.

- Gamma

$$f(x|a, b) = \frac{1}{b^a\Gamma(a)} x^{a-1} \exp\left\{-\frac{x}{b}\right\} \quad (3)$$

where  $\Gamma(\cdot)$  is the Gamma function

- Nakagami-m

$$f(x|m, \omega) = \frac{2m^m}{\Gamma(m)} \frac{x^{2m-1}}{\omega^m} \exp\left\{-\frac{m}{\omega}x^2\right\} \quad (4)$$

- Weibull

$$f(x|a, b) = \begin{cases} ba^{-b}x^{b-1} \exp\left\{-x/a^b\right\} & x \geq 0 \\ 0 & \text{else} \end{cases} \quad (5)$$

- Rayleigh

$$f(x|b) = \frac{x}{b^2} \exp\left\{-\frac{x}{2b^2}\right\} \quad (6)$$

Due to normalization, distributions are fitted to data that can only take values between 0 and 1, and we effectively ignore those parts of fitted distribution that takes on values outside this range.

In order to compare between the six distributions we choose the Akaike information criterion (AIC) [14], as used in [9] for

wideband characterization, to choose the best fitting distributions for our dynamic narrowband characterization. The second order AIC ( $AIC_c$ ) is given by

$$AIC_c = -2 \ln(l(\hat{\theta}|\text{data})) + 2K + \frac{2K(K+1)}{(n-K-1)} \quad (7)$$

where  $\ln(l(\hat{\theta}|\text{data}))$  is the value of the maximized log-likelihood over the unknown parameters ( $\theta$ ), given the data and the model,  $K$  is the number of parameters estimated in the model and  $n$  is the sample size. We find the maximized log likelihood from the ML estimates. The Akaike information criterion can be used as a relative measure, such that the model with the lowest  $AIC_c$  approximates the “true” distribution with the minimum loss of information.

We note that from our measurements the sample size  $n$  is constant ( $n = 4000$ ), and  $K = 2$  for all distributions apart from the Rayleigh distribution for which  $K = 1$ . Thus in effect we can use the  $AIC_c$  to distinguish between a Rayleigh model and the five other models. To compare between the five other models we consider the maximized log-likelihood score.

We stress that *in no case does the Rayleigh model provide the best fit* for the measured normalized received signal amplitude data across all scenarios at 820 MHz and 2360 MHz in terms of the  $AIC_c$ . The distributions, or models, that are the best fitting distributions, according to ML estimates and the subsequent  $AIC_c$  are given in the following Table, Table II.

Table II shows the best fitting model to the received signal amplitude data, at the lower frequency of 820 MHz and the higher frequency of 2360 MHz, is the Lognormal distribution. Across all 54 scenarios the ranking of the other models is:- the Weibull distribution (best fit in 10 scenarios); the Gamma distribution (best fit in 5 scenarios); Nakagami-m distribution (best fit in two cases, both when transmitting from left ankle to right hip); the Normal distribution (best fit in one case, back to hip standing) and then the Rayleigh distribution (best fit in no cases). It also appears that fits are independent of carrier frequency.

We note that for the distribution fits compiled in Table II, the best model fits are least accurate in the cases where the subject is standing still. We conjecture that this is predominantly due to the non-ergodic nature of the stationary scenario: in the stationary case, the shadowing is dominated by a single positioning of the limbs – hence a “strong” signal or a “weak” signal tends to dominate the statistics, while for the moving case, strong and weak connections are smoothed out.

In the following figures we show plots of the empirical PDF for two quite different scenarios of Tx-Rx pair location and measurement frequency. The bin size for the histogram used to describe the PDF from the measured data is chosen according to the “Freedman-Diaconis” rule<sup>2</sup>[15]. In Figs. 2,3,4 empirical PDFs for the case of transmission from from the

<sup>2</sup>Bin size  $B_s$  given by

$$B_s = 2I_r(x)n^{-1/3}$$

where  $I_r$  is the inter-quartile range of the data sample  $x$  (in this case measured normalized received power) and  $n$  is the sample size of  $x$ .

back to chest at 2360 MHz (where we can expect no line of sight component) are shown. Figs. 5,6 show empirical PDFs for transmission from right wrist to right hip at 820 MHz where there is more received power, (less path loss), and at periods during measurement (depending on movement and position of the subject) there is some line of sight component. Overlaid on each figure is the PDF of the best fit for four distributions<sup>3</sup>. It is noteworthy that in all these cases the Lognormal distribution is the best fit to the measured data, which from analysis we suggest is the typical result. We also note, as for the general case by analysis of the Akaike information criterion, that the Rayleigh distribution is a very poor fit in these PDF figures, in particular when the subject is standing (it mostly ranks worst for each scenario by  $AIC_c$ ).

In Fig. 7 a plot of normalized received signal amplitude against time over the 10 seconds measurement period, is shown for the case of transmission from back to chest at 2.36 GHz, for the three cases of subject standing, walking and running. Clearly there is greater variation in received amplitude as the motion of the subject’s body increases<sup>4</sup>.

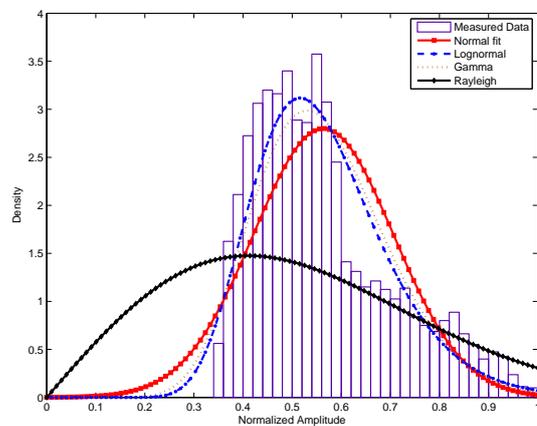


Fig. 2. PDF Back to Chest, Running at 2.36 GHz

## B. Observations

At this stage, we give the physical explanation for why the Lognormal distribution is in general the best model for our narrowband normalized received signal amplitude characterization. This is the same reason as that shared in [9]. There are a large number of effects contributing to the attenuation of the transmitted signal, such as diffraction, reflection, energy absorption, antenna losses etc. In general these effects are multiplicative, or equivalently additive in the log domain. By the central limit theorem a large number of random multiplicative effects will converge to a normal distribution in the log domain. Due to the office environment, and also around the body, there are likely to be additive effects due to

<sup>3</sup>Lognormal, Normal, Rayleigh best-fit PDFs are overlaid, with the best of best-fits between Weibull, Gamma and Nakagami-m PDFs also overlaid

<sup>4</sup>Note also that the rate of variation is greater when the subject is running than walking

TABLE II

SCENARIOS AND THE BEST FITTING MODEL, WITH PARAMETERS (IN BRACKETS), TO THOSE SCENARIOS AT 820 MHz AND 2.36 GHz

Tx location	Rx location	Action	Distribution	
			820 MHz	2.36 GHz
Chest	Right Hip	Standing	Lognormal ( $\mu = -0.086, \sigma = 0.042$ )	Lognormal ( $\mu = -0.2015, \sigma = 0.0921$ )
Chest	Right Hip	Walking	Weibull ( $a = 0.48, b = 2.73$ )	Weibull ( $a = 0.56, b = 2.94$ )
Chest	Right Hip	Running	Lognormal ( $\mu = -2.05, \sigma = 0.71$ )	Lognormal ( $\mu = -1.91, \sigma = 0.56$ )
Right Wrist	Right Hip	Standing	Lognormal ( $\mu = -0.042, \sigma = 0.014$ )	Lognormal ( $\mu = -0.1225, \sigma = 0.0505$ )
Right Wrist	Right Hip	Walking	Lognormal ( $\mu = -1.73, \sigma = 0.79$ )	Weibull ( $a = 0.17, b = 1.11$ )
Right Wrist	Right Hip	Running	Lognormal ( $\mu = -2.20, \sigma = 1.21$ )	Lognormal ( $\mu = -2.29, \sigma = 1.31$ )
Left Wrist	Right Hip	Standing	Lognormal ( $\mu = -0.194, \sigma = 0.049$ )	Weibull ( $a = 0.93, b = 36.1$ )
Left Wrist	Right Hip	Walking	Lognormal ( $\mu = -1.48, \sigma = 0.62$ )	Lognormal ( $\mu = -1.48, \sigma = 0.80$ )
Left Wrist	Right Hip	Running	Gamma ( $a = 3.61, b = 0.073$ )	Weibull ( $a = 0.24, b = 1.11$ )
Right Ankle	Right Hip	Standing	Lognormal ( $\mu = 0.51, \sigma = 0.10$ )	Lognormal ( $\mu = -0.16, \sigma = 0.070$ )
Right Ankle	Right Hip	Walking	Weibull ( $a = 0.52, b = 3.06$ )	Weibull ( $a = 0.57, b = 3.17$ )
Right Ankle	Right Hip	Running	Gamma ( $a = 5.40, b = 0.047$ )	Gamma ( $a = 3.74, b = 0.089$ )
Left Ankle	Right Hip	Standing	Lognormal ( $\mu = -0.47, \sigma = 0.081$ )	Lognormal ( $\mu = -0.51, \sigma = 0.14$ )
Left Ankle	Right Hip	Walking	Weibull ( $a = 0.55, b = 2.87$ )	Nakagami-m ( $m = 1.68, \omega = 0.28$ )
Left Ankle	Right Hip	Running	Nakagami-m ( $m = 1.41, \omega = 0.20$ )	Gamma ( $a = 4.52, b = 0.090$ )
Back	Right Hip	Standing	Weibull ( $a = 0.93, b = 13.5$ )	Normal ( $\mu = 0.92, \sigma = 0.029$ )
Back	Right Hip	Walking	Lognormal ( $\mu = -0.82, \sigma = 0.32$ )	Lognormal ( $\mu = -0.86, \sigma = 0.34$ )
Back	Right Hip	Running	Lognormal ( $\mu = -1.31, \sigma = 0.56$ )	Lognormal ( $\mu = -1.11, \sigma = 0.39$ )
Back	Chest	Standing	Weibull ( $a = 0.92, b = 16.6$ )	Lognormal ( $\mu = -0.25, \sigma = 0.10$ )
Back	Chest	Walking	Lognormal ( $\mu = -1.50, \sigma = 0.59$ )	Lognormal ( $\mu = -0.54, \sigma = 0.21$ )
Back	Chest	Running	Lognormal ( $\mu = -2.55, \sigma = 0.51$ )	Lognormal ( $\mu = -0.60, \sigma = 0.24$ )
Right Wrist	Chest	Standing	Lognormal ( $\mu = -0.14, \sigma = 0.50$ )	Lognormal ( $\mu = -0.071, \sigma = 0.030$ )
Right Wrist	Chest	Walking	Lognormal ( $\mu = -1.71, \sigma = 0.73$ )	Lognormal ( $\mu = -1.46, \sigma = 0.60$ )
Right Wrist	Chest	Running	Lognormal ( $\mu = -1.32, \sigma = 0.44$ )	Lognormal ( $\mu = -1.80, \sigma = 0.86$ )
Right Ankle	Chest	Standing	Lognormal ( $\mu = -0.10, \sigma = 0.019$ )	Lognormal ( $\mu = -0.64, \sigma = 0.25$ )
Right Ankle	Chest	Walking	Lognormal ( $\mu = -0.23, \sigma = 0.019$ )	Gamma ( $a = 4.24, b = 0.094$ )
Right ankle	Chest	Running	Lognormal ( $\mu = -0.13, \sigma = 0.034$ )	Lognormal ( $\mu = -1.10, \sigma = 0.41$ )

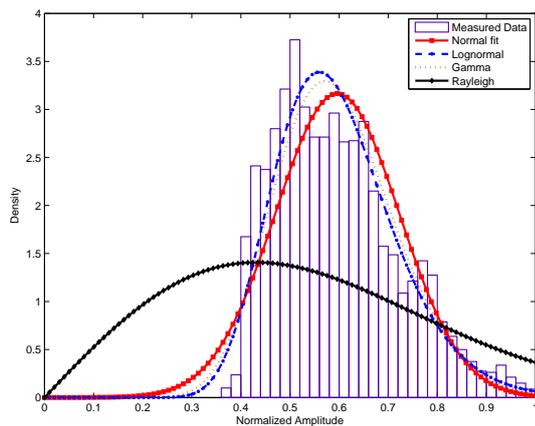


Fig. 3. PDF Back to Chest, Walking at 2.36 GHz

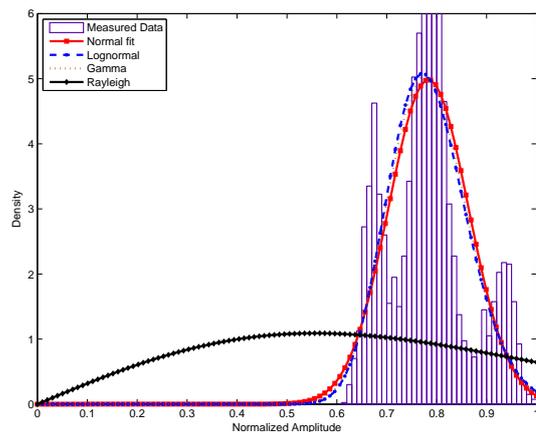


Fig. 4. PDF Back to Chest, Standing at 2.36 GHz

#### IV. CONCLUDING REMARKS

combination of multiple paths. It is shown in [16] that adding together Lognormal variables results in a distribution that can be well approximated by another Lognormal distribution.

Thus is in the same manner since the Normal distribution isn't a very good fit we can assume that there are not alot of random additive effects, particularly when the subject is in motion. When the subject is standing the Normal distribution model is relatively a better fit, graphically and by  $AIC_c$ , but in only one case, when transmitting from back to right hip while the subject is standing, is it the best fit.

A statistical characterization of the dynamic (body movement), human body area propagation channel has been presented, which has application to inform the design of wireless body sensor networks for biomedical information monitoring. This characterization was done in proximity to two candidate ISM frequencies of 900 MHz and 2400 MHz.

It is clear that the signal amplitude distribution for various receive positions is typically poorly described by the Rayleigh distribution, and not well described by the Normal distribution. This can be seen graphically from probability density functions

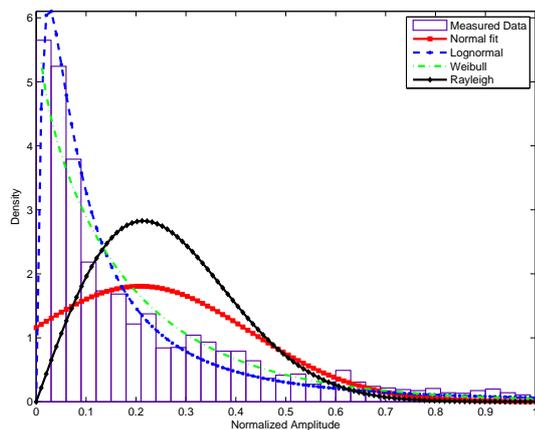


Fig. 5. PDF Right wrist to right hip, running at 820 MHz

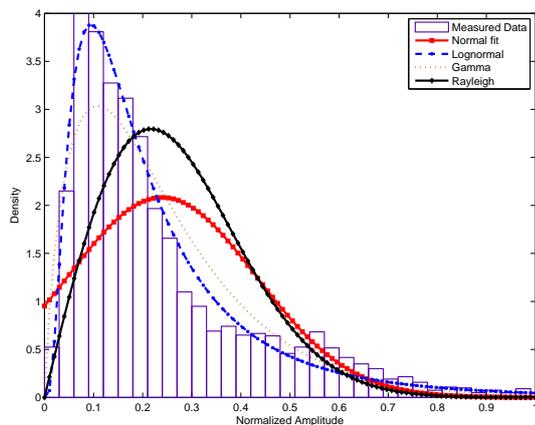


Fig. 6. PDF Right wrist to right hip, walking at 820 MHz

(PDFs) compared to empirical PDFs, and is demonstrated by derivation of the Akaike information criterion. In some cases the Weibull, Nakagami-m and Gamma distributions provide good fits to the normalized amplitude distribution according to their maximum-likelihood (ML) estimates. However in general the Lognormal distribution provides best fit to the received signal statistics, particularly with the subject moving while either running or walking, which we attribute to a large number of random multiplicative effects.

The best-fitted distributions are also less reliable measures of received signal statistics while the subject is standing. Furthermore there is no dissimilarity of the trend of best fitting distributions between characterization at the lower frequency of 820 MHz, and the higher frequency of 2.36 GHz, despite the clearly greater path loss at 2.36 GHz, and also despite the greater stability of the channel that we expect at the lower frequency of 820 MHz.

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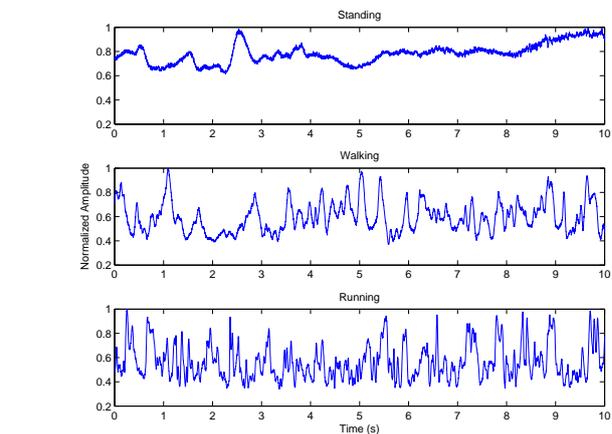


Fig. 7. Received signal amplitude (normalized) for transmission from back to chest at 2.36 GHz; subject standing, walking and running

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