An Analysis of Noise in Power Line Channels for Narrowband and Broadband Transmission

Rubi Baishya[1], Banty Tiru[2] and Utpal Sarma[3]

[1,2]Department of Physics Gauhati University
[3]Department of Instrumentation & USIC Gauhati University
E-mail: [1]rubibaishya89@gmail.com, [2]banty_tiru@rediffmail.com, [3]utpalsarma@gauhati.ac.in

Abstract—*Communication over the available power line commonly known as Power Line Communication (PLC) can be an alternate or a component of hybrid network. The reason for this is it's readily availability that can solve the last mile and last inch challenges. However, the channel is characterized by non-white noise uncommon to other channels used. In this paper, the noise in indoor power line in several sites is studied. This is modeled using suitable fits for narrowband and broadband application. The channel capacity is estimated both for Additive White Gaussian and Water Filling approach. Results show that a channel capacity of 0.089 Mbps to 1.48 Mbps can be obtain for narrowband channel with a transmit power of few watt. For broadband communication in the frequency range 1-30 MHz a channel capacity of 84 Mbps to 206 Mbps can be obtain for a transmit power as low as 1mW. This result can be used for simulation of power line channels for testing and designing systems and development of suitable transceivers.*

1. INTRODUCTION

In the last few decades, the use of the power line as a channel for communication both independently and as components of hybrid system is attracting interest in various fields [1]. Commonly known as Power Line Communication (PLC), the available infrastructure is exploited for application ranging from control to broadband requirements [2]. The devices available can broadly be divided into two broad groups namely the Narrowband and Broadband devices. Narrowband devices cater to the low bit rate requirements like control applications and broadband devices (commonly known as Broadband Power Line Communication or BPL) to high data rates applications like resource sharing. Though large scale use is expected to decrease the cost of implementation, the problems encountered in the channel are many. To name a few, power line channels suffer from varying channel characteristics and non Additive White Gaussian Noise (AWGN) [3]. The grid structure also differs from place to place and the properties even at times show 'contradictory behavior' [4]. Though much work has been done in many developed countries, such a study is lacking in India where the power line grid reaches to more than 80% of the population [5]. The use of PLC in India has great potential to meets the last mile and last inch requirements of communication [6]. The basic requirement of such an infrastructure would be an extensive study of the channel properties.

In this work, noise in indoor power line in various buildings in the University Campus is studied. The noise is modeled using suitable fits and the same is used to make an estimate of the channel capacity for Narrowband and Broadband applications. The narrowband standards used are the CENELAC (European Committee for Electro technical Standardization) bands. The allowed bands for PLC are known as A, B, C and D bands with frequency ranges 9kHz to 95kHz, 95kHz to 125kHz, 125kHz –140kHz and 140kHz-148.5kHz respectively [7]. The frequency range for BPL is 1-30MHz. Section II of the paper gives the experimental technique and setup used for data acquisition. In Section III, the characteristics of the noise in various sites namely the power spectral density (PSD) is studied and modeled. In Section IV, the noise is used to estimate the Channel Capacity for both Narrowband and Broadband Applications. The paper concludes with some of the key results.

2. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

The experimental setup for acquiring the power line noise consists of a Digital Storage Oscilloscope (DSO SCIENTECH 7060A) connected to a PC as shown in Fig. 1. The DSO is connected to the phase-neutral wire of indoor power line through a coupler Fig. 2a. The coupler is a passive filter constituted of inductances (T) and capacitance (C1) of appropriate values and acts as a High Pass Filter (HPF) filtering off the 230V 50HZ power line signal. The HPF protects the connected instruments from the high voltage. The main features of the coupler are galvanic insulation, differential coupling and are made of coils in bifilar windings over a soft iron core for high frequency applications. The protection circuit consists of a Metal Oxide Varistor (PROTECT) with clipping circuit made of suitable diode connections. The cut off frequency and the roll off rate of the coupler is 17 kHz and 25 dB/decade respectively. The transfer function of the coupler is shown in Fig. 2(b). Data is acquired at 8 sites in different buildings termed as Site 1, Site 2,… Site 8. The sampling rate of the DSO is fixed to be 1MS/s and 100MS/s for observing frequencies up to 500 kHz and 50 MHz respectively. The recorded data is processed offline.

3. AMPLITUDE DISTRIBUTION OF POWER LINE NOISE

An example of the amplitude distribution of the power line noise is shown in Fig. 3. The distribution shows that noise is Non Gaussian and such not naturally occurring but initiated from manmade noise sources that add up to form the net noise. In the Figure, the distribution is also compared against a Gaussian fit of μ= -0.122642 and σ = 0.0150131.

4. POWER SPECTRAL DENSITY OF NOISE (PSD) AND NOISE MODELING

From the plots of the PSD, it is seen that noise is colored and is a maximum at low frequencies and decreases for higher ones. Plots of the PSD at Site 3 are shown in Fig. 4. At frequencies greater than 10 MHz, the noise is nearly white. The one sided noise PSD can be modeled using an exponential fit given by

$$N(f) = ae^{bf} + ce^{df}\, dB/Hz \tag{1}$$

Here, *f* is the frequency in Hertz. The co-efficient *a*, *b*, *c* and *d* are given in Table I. Fig. 5 gives noise fits for different sites in the low and high frequency ranges respectively. It is seen that the noise at Site 3 and Site 6 shows a minimum and maximum respectively.

5. ESTIMATION OF THE CHANNEL CAPACITY

In this section, an estimate of the Channel Capacity is found out using a rough estimate and a more exact one. In the rough estimate, the noise is taken as white and in the exact estimate the variation of the PSD with respect to frequency is taken into consideration.

5.1 Estimation using Rough Bounds with White Noise Approximation

Here, for each bands, the capacity is found out for the 'best' and the 'worst' case models with the noise considered as white. The 'best' case is the noise equal to that at the largest frequency of band taken into consideration while the 'worst' case is the noise at the lowest frequency of the band. Thus for the CENELAC A Band in Site 6, the AWGN noise is given by (2)

$$\begin{aligned} N_{AWGN,best}(f) &= N(f)\big|_{f=95000} = -83.20\, dB/Hz \\ N_{AWGN,worst}(f) &= N(f)\big|_{f=9000} = -69.26\, dB/Hz \end{aligned} \tag{2}$$

The white noise approximation for the CENELAC A band at Site 3 is shown in the Fig. 6.The Channel Capacity is given by the Shannon's Hartley Capacity [8] theorem given by (3)

$$\begin{aligned} C_{best}(T) &= W\log_2\left(1+\frac{S}{N_{AWGN,best}W}\right)\left[\frac{bits}{\sec}\right] \\ C_{worst}(T) &= W\log_2\left(1+\frac{S}{N_{AWGN,worst}W}\right)\left[\frac{bits}{s}\right] \end{aligned} \tag{3}$$

Here, *S* is the received signal power, *W* is the bandwidth and *T* is the transmitted signal power. It is assumed that the channel is ideal and given by $|H(f)| = 1$ and hence *T*=*S*. The Channel Capacity is found out for a maximum power allowable in each band. For this, the following conditions are used [7]

- CENELAC A Band: The maximum allowed peak voltage at 9 kHz is 134dB (μV) and exponentially decays to 120dB (μV) at 95 kHz. As such, the maximum peak voltage is 5V and 1V respectively at the two extremes. However for the calculation, the peak voltage is taken to be 5V throughout the band.
- CENELAC B, C and D bands: The transmitter power must not exceed 116dB(μV)=0.63V
- BPL (1-30MHz): The transmit power must be low to decrease radiation from the power line cables. As such, the Channel Capacity is estimated for a maximum power of 1mW.

Fig. 7 gives the Channel Capacity for the CENELAC A Band throughout the allowed transmit power. Table II gives the estimate of the capacity at the maximum power admissible in each band in different sites. It is seen that from the rough bounds, the bit rates in CENELAC A , B, C and D ranges from 0.854 Mbps to 2.271 Mbps, 0.164 Mbps to 0.657 Mbps, 0.096 Mbps to 0.344 Mbps and 0.058 Mbps to 0.19 Mbps respectively. The capacity of the BPL can be as large as 206 Mbps recorded in Site 2. This is however a rough estimate of the channel capacity, and for a more exact solution, the colored nature of noise is to be considered.

5.2 Estimation using Non White Noise

In this section, the variation of the noise with frequency is taken into consideration and the channel capacity estimated using a Water Filling approach. However like the earlier, the channel is considered to be an ideal filter. The noise in each case is modeled by a linear fit instead of an exponential fit. The Water Filling approach is applicable for any linear filter with noise that is white or non-white [7], [8], [9]. For such a channel, $N(f)/|H(f)|^2$ can be taken as a bottom of a water container to which water of total volume B is poured (Fig. 8). The way the power distributes in the container to achieve equal water level gives the way the power of the transmit signal redistributes itself to give the capacity. The Capacity of such a channel is given by (4)

$$C = \int_{f \in F_B} \frac{1}{2} \log_2 \left[\frac{\left|H(f)\right|^2 B}{N(f)} \right] df \tag{4}$$

Where F_B is the range of frequency for which (5) is satisfied (Fig. 8)

$$\frac{N(f)}{\left|H(f)\right|^2} \le B \tag{5}$$

B being the solution of

$$S = \int_{f \in F_B} \left[B - \frac{\left|H(f)\right|^2}{N(f)} \right] df \tag{6}$$

As the transmit power is increased, the situation falls in either of the two regions: Region I and Region II (Fig. 9). In Region I, the received power is less than the noise level and is applicable for low values of *T* and for Region II, the received power is more than the noise and is applicable for high *T*. As shown in Fig. 9, when in Region I, the condition (5) is not applicable for all frequencies, but only for frequency *x*. The procedure hence reduces two steps: estimating the capacity as well as the transmit power in terms of *x* and estimating the capacity in terms of the transmit power as shown in the following equations

$$T(x) = 2 \times \int_{x}^{f_{\max}} \left[B - N(f) \right] df \tag{7}$$

$$C(x) = \int_{x}^{f_{\max}} \log_2 \left(\frac{N(x)}{N(f)} \right) df \tag{8}$$

Here $N(x)$ is the noise at frequency *x*. *x* is the frequency where the following condition is satisfied.

$$S_x(x) = B - N(x) = 0; \; f_{\min} < x < f_{\max} \tag{9}$$

When the transmit power falls in Region II, the channel capacity is given by (5). The Fig. 7 shows that the channel capacity using this method gives a narrower bound. Table II gives the capacity for the narrower bounds for all the cases studied.

6. CONCLUSION

In this work, the power line noise in eight sites in the university campus is studied. The noise PSD shows that it is colored and decays with frequency and white above 10 MHz The noise is modeled using suitable fits. The capacity estimation shows that the power line is suitable for control and broadband applications. In future, the modeled noise will be used to simulate a PLC channel. The time variation of different types of noise will be studied. A suitable PLC system will be designed in hardware to be used for remote data acquisition.

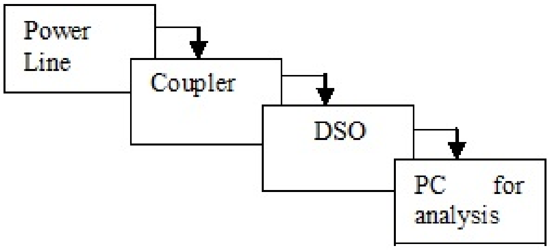


Fig. 1: Block diagram of experimental set-up

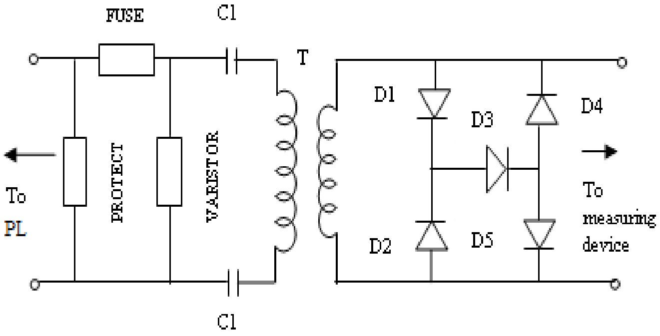


Fig. 2a: Coupler Circuit

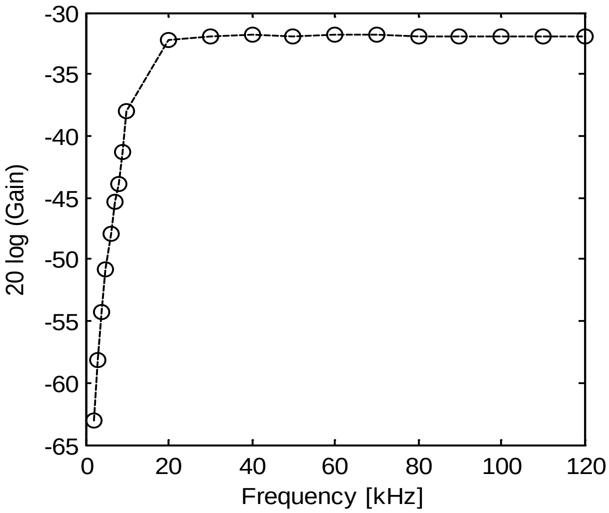


Fig. 2b: Frequency Response of the Coupler

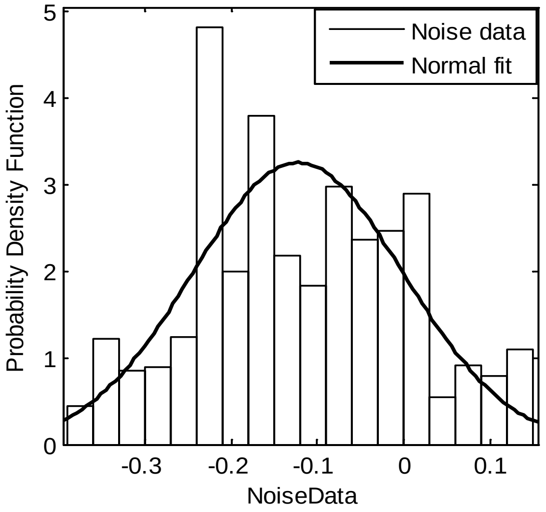


Fig. 3: Probability Density function of the Amplitude of Noise compared with Gaussian distribution of μ= -0.122642 and σ = 0.0150131

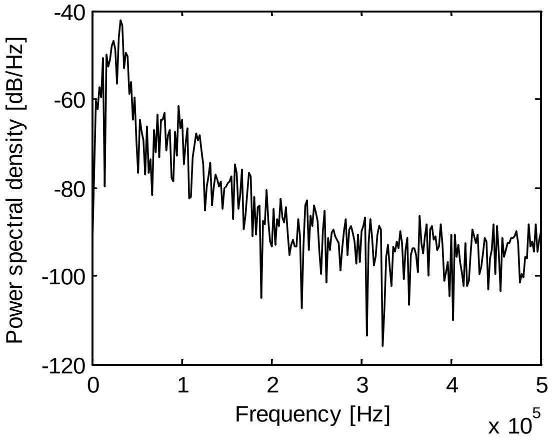


Fig. 4a: Power Spectral density of noise in Site 3 in the Frequency range 0-500 kHz

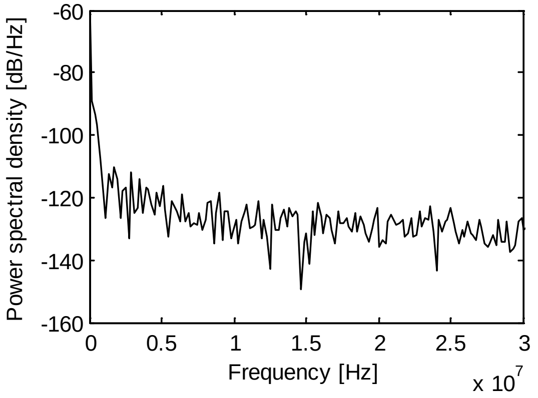


Fig. 4b: Power Spectral density of noise in Site 3 in the Frequency range 0-30 MHz

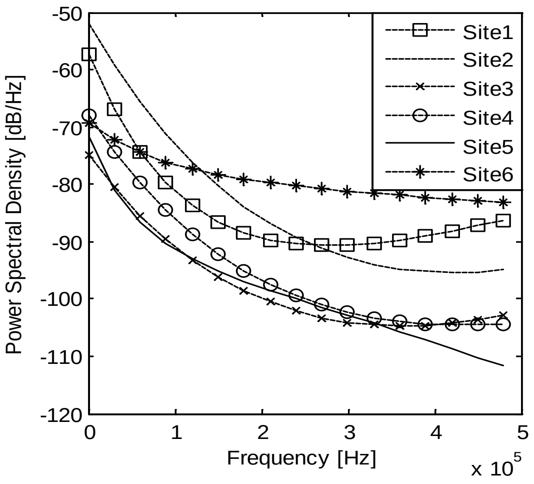


Fig. 5a: Exponential fitting of Power Spectral Density for all sites in the frequency range 0-500 kHz

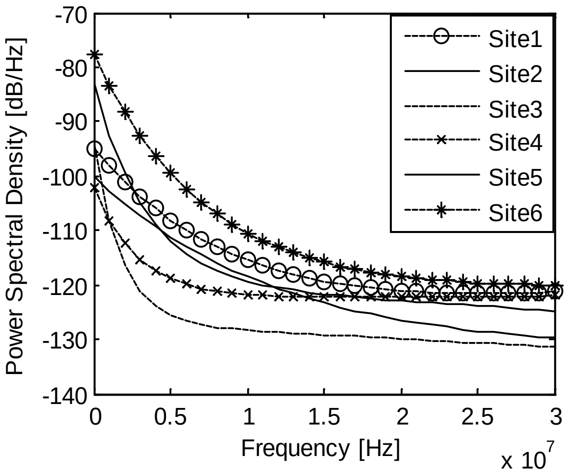


Fig. 5b: Exponential fitting of the Power Spectral Density for all the sites in the Frequency range 0-30 MHz

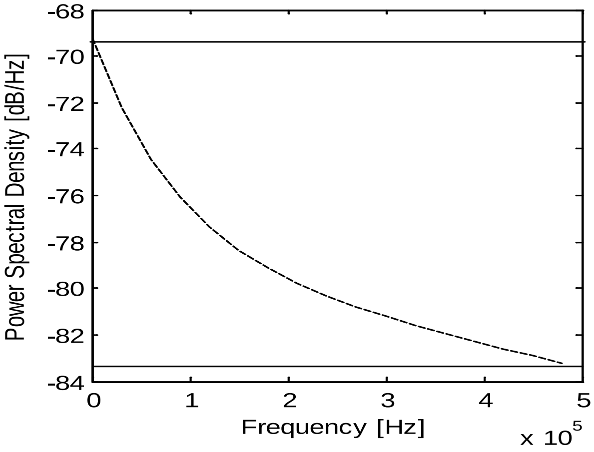


Fig. 6: AWGN approximation in Site 6

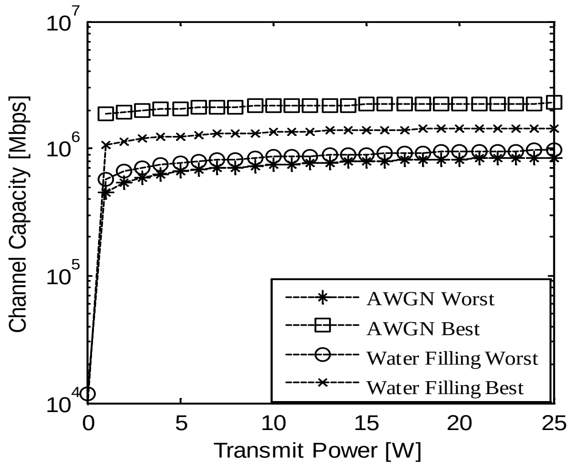


Fig. 7: Channel Capacity vs Transmit Power for CENELAC A Band showing rough and narrow bounds considering all the sites

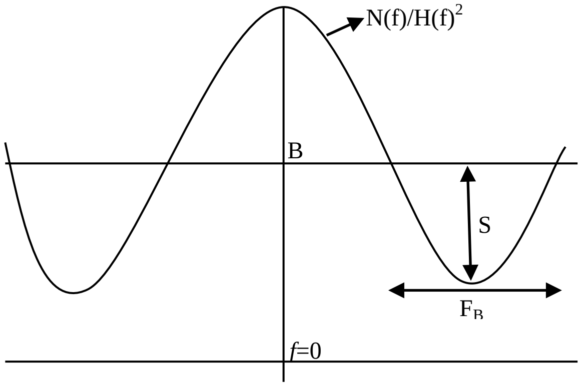
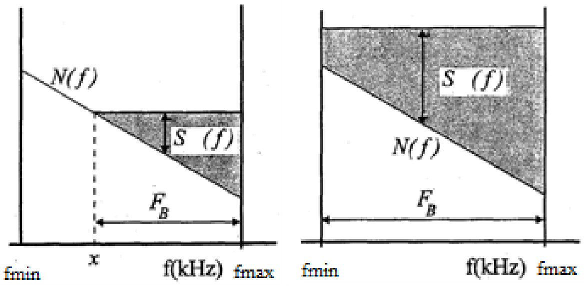


Fig. 8: Interpretation of Water Filling channel capacity



Region I   Region II

Fig. 9: Region I and Region II in the Water Filling Interpretation

Table I: Co-efficient of the Exponential Fitting

Exponential Fitting Co-efficient for 0-500 kHz				
Site	*a*	*b*	*c*	*d*
Site 1	110.9	4.956e^{-7}	53.6	7.915e^{-6}
Site 2	1453	1.866e^{-6}	-1505	-1.63e^{-6}
Site 3	1570	1.579e^{-6}	1495	1.791e^{-6}
Site 4	157.9	5.557e^{-7}	90.06	-3.519e^{-6}
Site 5	89.69	4.579e^{-7}	18.1	1.962e^{-5}
Site 6	78.77	1.152e^{-7}	9.511	1.109e^{-5}
Exponential Fitting Co-efficient for 0-30 MHz				
Site 1	-122.8	-5.39e^{-10}	45.09	-1.351e^{-7}
Site 2	-109.7	1.165e^{-9}	30.42	2.231e^{-7}
Site 3	-127	1.13e^{-9}	32.87	-5.556e^{-7}
Site 4	-119.6	1.402e^{-9}	36.53	-2.903e^{-7}
Site 5	-133.8	2.779e^{-10}	33.77	-8.148e^{-8}
Site 6	-122.8	-5.39e^{-10}	45.09	-1.351e^{-7}

Table II: (a). Maximum Channel Capacity for 1-30 MHz for all sites (Transmit power 1mW)*WF: Water Filling

Site	**AWGN Channel Capacity (Mbps)**		**WF* Channel Capacity (Mbps)**
	Min	**Max**	
Site 1	8.2	160	84
Site 2	112	254	206
Site 3	70	168	139
Site 4	6.6	187	117
Site 5	18	234	141
Site 6	0.286	149	106

Table II: (b). Maximum Channel Capacity using rough and narrow bounds for different bands.

 # Transmit Power that causes transition from Region I to Region II *WF: Water Filling

Site	**CENELAC A**				**CENELAC B**			
	#Power [W] (Transition)	AWGN Channel capacity (Mbps)		WF* Channel Capacity Mbps	#Power [W] (Transition)	AWGN Channel capacity (Mbps)		WF* Channel Capacity Mbps
		Min	Max			Min	Max	
Site 1	0.0036	1.1535	1.6774	1.2071	6.76x10^{-4}	0.26796	0.45065	0.30690
Site 2	0.0063	1.3597	1.9654	1.1280	0.0015	0.33984	0.36042	0.27124
Site 3	4.06 x10^{-4}	1.4168	2.1228	1.4895	6.00 x10^{-5}	0.35977	0.60601	0.41271
Site 4	0.0014	1.2494	2.1826	1.3457	1.59 x10^{-4}	0.30140	0.62689	0.37176
Site 5	5.97 x10^{-4}	1.3597	2.2713	1.4540	6.79 x10^{-5}	0.33984	0.65783	0.40863
Site 6	0.0331	0.85360	1.9654	0.96842	0.0029	0.16422	0.55110	0.24752
CENELAC C					**CENELAC D**			
Site 1	2.70 x10^{-4}	0.14896	0.24032	0.17255	1.28 x10^{-4}	0.086695	0.13543	0.10040
Site 2	6.54x10-4	0.18492	0.19521	0.15313	3.25 x10^{-5}	0.10588	0.11136	0.089613
Site 3	2.21x10^{-5}	0.19488	0.31801	0.22690	2.44 x10^{-4}	0.11119	0.17686	0.087642
Site 4	5.34 x10^{-5}	0.16569	0.32845	0.20820	2.32 x10^{-5}	0.095621	0.18243	0.12029
Site 5	2.29 x10^{-5}	0.18492	0.34391	0.22647	1.00 x10^{-5}	0.10588	0.19068	0.11473
Site 6	8.97x10^{-4}	0.09686	0.29055	0.14742	3.76 x10^{-4}	0.058855	0.16222	0.088251

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