Shadowing Correlation Model for Indoor Multi-hop Radio Link in Office Environment

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***Abstract*—Propagation environment greatly affect the performance of wireless network. The existence of obstacles between transmitter and receiver antennas provide shadowing effect to the transmitted signal. In multi-hop radio link, any link pairs experience shadowing effect that can be correlated if the links have a similar propagation environment. Various studies have shown that correlated shadowing has significant impacts on wireless network's performance. This paper discusses shadowing correlation of measured two-hop radio link. We propose models that can be used to predict shadowing correlation coefficient of link pairs using deterministic and stochastic formulas.**

Keywords*— *shadowing, correlation, multi-hop radio link

I. Introduction

Wireless communication system is strongly affected by propagation environment, so as in indoor office environment. Walls, furnitures and equipments made of material consisting metal will give rise to multipath propagation and shadowing to the transmitted signal. So the received signal will be randomly fluctuated. Randomly fluctuate received signal caused by shadowing is due to the existence of obstacles between transmitter and receiver antennas. There are certain conditions where shadowing in a radio-link has correlation with the one in the other radio-link, e.g. shadowing is caused by the same obstacles [1]. Various studies shown that correlated shadowing can affect the performance of a wireless network. Study [2] shown that when correlated shadowing in multi-hop network is ignored, then we will be get an inaccurate result of outage probability analysis. Therefore, we need a mathematical model of correlated shadowing so that we can estimate the correlation coefficient of shadowing effect for wireless networks in order to analyze and design reliable communication system.

Previous studies have proposed the correlation models of shadowing with variety network scenarios. Study [3] have proposed correlated shadowing model in the form of distance as an exponential function at 900 MHz and 1700 MHz. This model verified at outdoor urban environment, so it cannot describe the correlated shadowing in networks with indoor scenario. Correlated shadowing characteristics for indoor scenarios have verified in [2], however the obstacles on these measurements were deliberately set in the environment. Other study about link correlation can be found in [4] where the paper discussed about correlation among converging radio link in terms of the direction of arrival (DOA) and direction of departure (DOD) of multipath signals.

This paper discussed the correlation of shadowing of two radio links which perform multi-hop correlated shadowing models for multi-hop network that consisting of three node at 2.4 GHz band in office environment. These three nodes are node i as transmitter, node j as relay, and node k as receiver. Node k can receive information from node i in two ways. First, node k receive information from node i through relay k. The second way is node k receive information directly from node i. There are three radio link pairs that can be correlated in this situation. It can be seen in Figure 1 that these link pairs are link $\overrightarrow{ij}$ with link $\overrightarrow{jk}$, link $\overrightarrow{ij}$ with link $\overrightarrow{ik}$, and link $\overrightarrow{ik}$ with link $\overrightarrow{jk}$. The modeling based on measurement data of received signal power in office environment. Basic statistical techniques are used to ekstract the shadowing values from the measured received signal as distance function, and correlating this values for all link pairs. All correlation coefficient that has been obtained are modeled as general form of statistical model, so we can estimate correlation coefficient for other office or network mode.

The correlation models that will be proposed are in the form of deterministic and stochastic models. Deterministic models are based on distance, angle, and arrival distance ratio. Shadowing measurements uses the indoor scenario at office environment. The obstacles in this measurements is natural, by allowing the condition of various kinds of the furnitures in the location of measurements as it is. It aims to obtain a valid correlated shadowing characteristics for indoor location in the

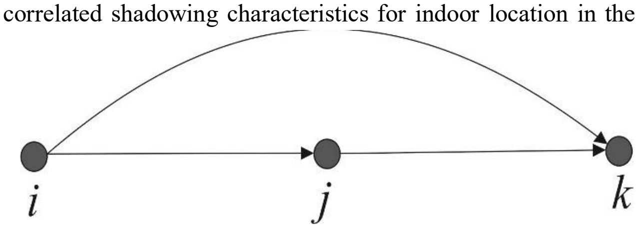

Figure 1. Multi-hop Network [2]

office environment. In order to construct the correlated shadowing models for indoor multi-hop network, this study will first create a model for shadowing and it's average path loss.

A. Average Path Loss

Average path loss which represents averaged signal attenuation as a positive quantity measured in dB, is defined as the averaged difference (in dB) between the effective transmitted power and the received power as distance function, and can be expressed as [5]:

$$\overline{PL_d}(dB) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) \quad (1)$$

In equation (1), $\overline{PL}(d_0)$ is average path loss at reference distance, where reference distance should be at far field region of the transmitting antenna, n represents the path loss exsponent that related to the attenuation's slope of signal power, d and d_0 are the distance of antennas and distance of refference location respectively. Equation (1) is identical to the equations of a straight line where $\overline{PL_d}(dB)$ is the value at y axis, $\overline{PL}(d_0)$ represents y axis intercept, $10n$ and $log(d/d_0)$ represents slope and value at x axis respectively.

B. Shadowing

Average path loss model provide loss prediction based on distance and height of antenna, hence the loss on many channels having the same distance and the same antennas height will be the same too. Actually, although in static condition, the loss variation is occured due to the variation of objects near transmitter and receiver and objects that acts as obstacles. This loss variation is called fading [1]. Fading can be considered as small-scale fading or multipath fading and large scale fading or shadowing. By considering large scale fading caused by any obstacles, the loss at distance d given by [2]:

$$PL_d(dB) = \overline{PL}_d(dB) + Z_d(dB) \quad (2)$$

Where $PL_d(dB)$ denotes path loss at distance d and $Z_d(dB)$ denotes path loss fluctuation caused by large scale fading or shadowing. The variation of shadowing effect $Z_d(dB)$ will be occur after the distance between transmitter and receiver changed equally to the obstacle's dimention [6]. By substituting equation (1) to (2), loss at distance d is given by:

$$PL_d(dB) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + Z_d(dB) \quad (3)$$

Where $PL_d(dB)$ denotes path loss at distance d, $\overline{PL}(d_0)$ is average path loss at reference distance, n represents the path loss exsponent, d and d_0 are the distance of antennas and distance of refference location respectively, and $Z_d(dB)$ denotes the shadowing variations.

C. Correlated Shadowing

Shadowing in any of two links can be correlated if the links have obstacles which are similar [2]. This condition can bee seen in Figure 2. According to Figure 2, link 1 and link 2 may have shadowing with strong correlation, because they have the same obstacle. Whereas link 1 and link 3, and also link 2 and link 3 can have shadowing with low correlation because they have different obstacles.

If there are two radio links $\overrightarrow{X_1Y_1}$ and $\overrightarrow{X_2Y_2}$ with shadowing value S_1 and S_2 respectively, then shadowing correlation coefficient can be calculated by [7]:

$$\rho_{1,2} = \frac{\mathrm{E}\{S_1S_2\}}{\sqrt{\mathrm{VAR}\{S_1\}\mathrm{VAR}\{S_2\}}} \quad (4)$$

where $\rho_{1,2}$ denotes correlation coefficient of shadowing between link $\overrightarrow{X_1Y_1}$ and $\overrightarrow{X_2Y_2}$, $\mathrm{E}\{S_1S_2\}$ is the expectation of shadowing value in both links, $\mathrm{VAR}\{S_1\}$ and $\mathrm{VAR}\{S_2\}$ denotes variance of shadowing in link $\overrightarrow{X_1Y_1}$ and $\overrightarrow{X_2Y_2}$ respectively.

In order to estimate the shadowing correlation coefficient in a multi-hop network, it requires a model that mathematically feasible, so that the model can be used for simulations and analysis [7]. In this study, the correlation of shadowing will be modelled as deterministic and stochastic models. With deterministic model, the correlation coefficient of shadowing can be estimated based on some variables e.g absolute distance or angle. In stochastic models, we can only estimate the probability of correlation coefficient of shadowing. Based on Figure 3, deterministic model for correlated shadowing can be established in three variables: [7]:

1. Absolute distance of Y_1 and Y_2, $d = \left\|\vec{r_1} - \vec{r_2}\right\|$
2. Angle, $\theta = \left|\angle\vec{r_1} - \angle\vec{r_2}\right|$
3. Arrival distance ratio, $R = \left|10\log_{10} r_1 / r_2\right| = (10/\ln 10)\left|\ln r_1 - \ln r_2\right|$

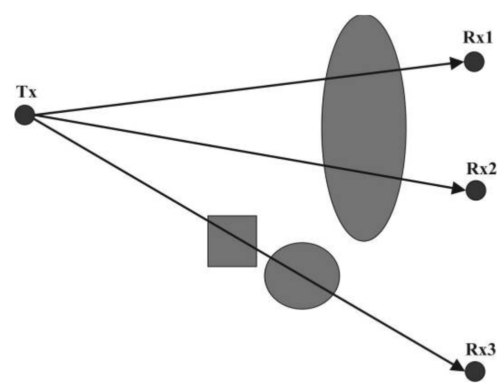

Figure 2. Link Condition With Different Shadowing Correlation [2]

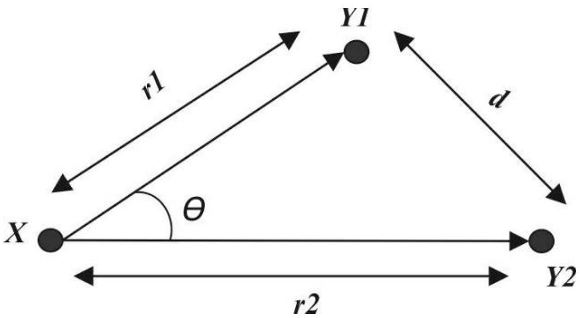

Figure 3. Variables of Determnistic Shadowing Model [7]

II. Measurement System and Set Up

A. Measurement Set Up

Multi-hop network which will be observed have three nodes *i*, *j*, and *k* as shown in Figure 1, where node *i* assumed to be a transmitter, node *j* as relay and node *k* as receiver. So there are three link pairs that can be correlated, they are link $\overrightarrow{ij}$ with link $\overrightarrow{jk}$, link $\overrightarrow{ij}$ with link $\overrightarrow{ik}$, and link $\overrightarrow{ik}$ with link $\overrightarrow{jk}$. In order to modeling shadowing correlation coefficient in angle, distance, and the ratio of arrival distance, then the measurement will be performed on a wide variety of link mode, where link mode is the setup of transmitter, relay and receiver position that we made with variated angle, distance, and the ratio of arrival distance (as shown on Figure 3). Variations of these three variables can be seen in Table 1. Each network scheme will be measured five times at different positions, so that the measurement results can represent the real condition of signal propagation in indoor office environments. One example of measurement scheme can be seen in Figure 4.

Path loss measurements carried out on the 3rd floor of building B in electrical engineering ITS Surabaya. The aim of this location is to get a model that can represent the real correlated shadowing in indoor office environment. Measurements site plan can be seen in Figure 4.

The devices that will used to measure the path loss are: WARP (Wireless Open Access Research Platform) software defined radio, omnidirectional antennas, a computer with MATLAB, Gigabit Ethernet switch, UTP cable, and Wifi amplifier.

The Signal that will used to measure the path loss is a sinusoidal signal at 2.4 GHz band. According to IEEE 802.11 communications standard, the 2.4 GHz band is divided into fourteen channels. Based on the survey of frequency use in measurement location, it can be seen that the channel 1 to channel 13 has been used for university's internet connection. In order to avoid interference, measurements will be performed on channel 14 (2.484 GHz) that is not used around the measurement locations. The used total frequency is sum of carrier frequency (channels 14) and baseband frequency. The used baseband frequency is 8 MHz, so the total signal frequency is 2.492 GHz.

TABLE I. Distance, Angle, and Arrival Distance Ratio Variables on Various Network Schemes

		Scheme					
		1	**2**	**3**	**4**	**5**	**6**
Path Length (Meter)	$\overrightarrow{ij}$	5	8.5	9	7.5	8.5	9
	$\overrightarrow{jk}$	6	7	12	7.5	8.5	9
	$\overrightarrow{ik}$	10	11	14	13	16	18
Arrival Distance Ratio (dB)	$\overrightarrow{ij}$ and $\overrightarrow{jk}$	0.79	0.84	1.25	0	0	0
	$\overrightarrow{ij}$ and $\overrightarrow{ik}$	3.01	1.12	1.92	2.39	2.75	3.01
	$\overrightarrow{jk}$ and $\overrightarrow{ik}$	2.22	1.96	0.67	2.39	2.75	3.01
Angle (Deg)	$\overrightarrow{ij}$ and $\overrightarrow{jk}$	130.5	90	82.3	120	140	180
	$\overrightarrow{ij}$ and $\overrightarrow{ik}$	27.2	39.7	58	30	20	0
	$\overrightarrow{jk}$ and $\overrightarrow{ik}$	22.3	50.3	39.7	30	20	0
Distance (Meter)	$\overrightarrow{ij}$ and $\overrightarrow{jk}$	10	11	14	13	16	18
	$\overrightarrow{ij}$ and $\overrightarrow{ik}$	6	7	12	7.5	8.5	9
	$\overrightarrow{jk}$ and $\overrightarrow{ik}$	5	8.5	9	7.5	8.5	9

Data processing is based on transmitted and received power by WARP. Power output from WARP is 19.29 dBm. In order measurements can be performed in a longer distance, then the signal power will be amplified with a Wifi amplifier that has 15 dB gain, so that the total transmit power is 34.29 dBm.

B. Measurement Campaigns

At each network scheme presented in Table 1, there are three links that should be measured. Due to limitations of the measurement devices, then each link is measured one by one, by terms condition of propagation environment does not change during the measurement process. The measuring process on each link can be illustrated in Figure 5.

The measurement process begins by dividing each link into several measurement points, indicated by point 1, 2, ... *n* in Figure 5. It aims to get the variance of shadowing on each link. The distance of each measurement point at least 4λ. This distance is selected because shadowing expected to occur in the displacement distances equally to the obstacle's dimension that is expected as far as 4λ.

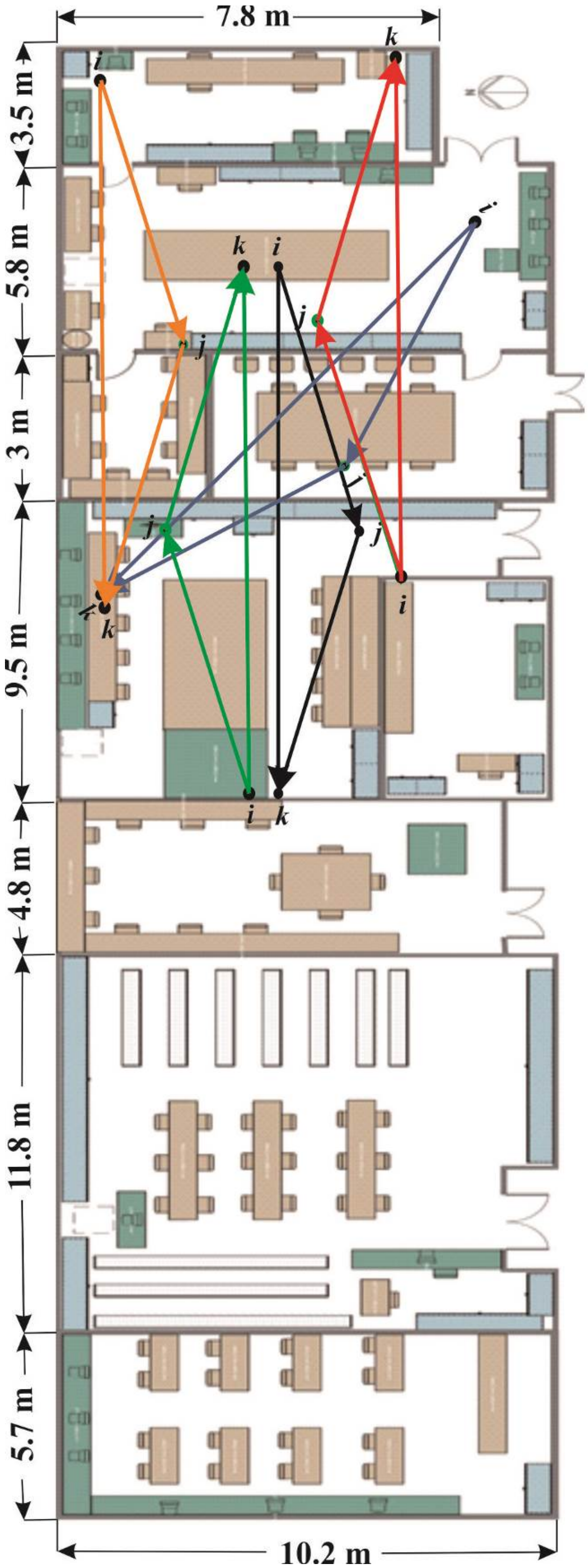

Figure 4. Site Plan of Measurement Location

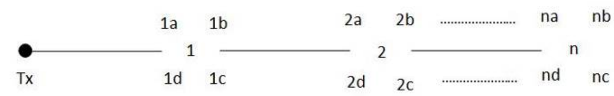

Figure 5. Distribution of Measurement Points

Each measurement point is divided into four subpoints with a distance of 15 cm each, represented by point *na, nb, nc* and *nd* in Figure 5. It aims to get local mean received power and averaging the effect of multipath. Local mean received power obtained by averaging the received power in the four subpoints of measurement.

The process of measurement data collection begins by putting transmitter at point Tx and receiver at point 1. Receiver antenna is placed at subpoint 1a. Then the signal transmitted from the transmitter and the signal power received by receiving antenna is stored into the computer. Once the measurement data is stored followed by moving the position of receiving antenna to subpoint *1b* to *1d*. After the measurement is done at point *1a, 1b, 1c* and *1d*, receiver is moved to point 2, and its antenna is placed at subpoint 2a. The measuring process such as at point 1 is repeated. This process is continued until the receiver is at position *n*. Further measurements with the same process carried out on other links and network schemes.

III. Measurement Results and Data Processing

A. Average Path Loss Model

After all data have been obtained, then this data is analyzed to create it's related shadowing model. The first step is to compute the path loss exponent of average path loss model. Average path loss model is obtained by processing the channel loss data that obtained from measurements using linear regression techniques, so we get a straight line equation that is identical to equation (1). Channel loss obtained by finding the difference of transmit power and received power in logarithmic scale. Result of linear regression of channel loss can be seen in Figure 6.

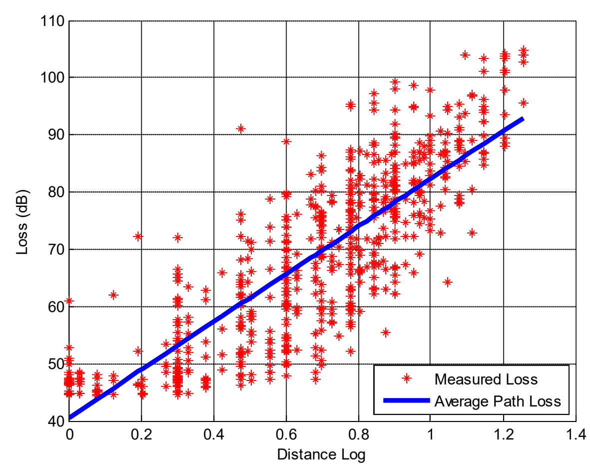

Figure 6. Path Loss as Distance Function

The straight line at Figure 6 has a slope of 41.782 and intercept *y* axis at 40.548. Based on this condition, obtained an equation of average path loss model as follows:

$$\overline{PL}(dB) = 40.548 + 41.782\log\left(\frac{d}{d_0}\right) \tag{5}$$

From equation (1) and (5), the path loss exponent value is 4.178. This value is larger than free space condition, leading to large channel loss with increasing distance between transmitter and receiver antennas. This is caused by measurements conducted in a room with large number of obstacle objects, such as furnishings in the room. Moreover measurements also carried out in two different rooms, so the signal is blocked by a wall that restricts both rooms.

B. Shadowing Model

Shadowing value in this study obtained from the difference between loss that has been obtained from measurements and loss from average path loss model. The obtained shadowing values will be modeled based on average value, standard deviation, and it's related probability function. Shadowing probability function can be determined by plotting it's related PDF (Probability Density Function) graphic. The distribution model obtained from this PDF chart will be verified with Kolmogorov-Smirnov test methods (KS Test).

The shadowing graphic in logarithmic function can be seen in Figure 7. Obtained shadowing model has an average value of 0 dB with a standard deviation of 8.538 dB. PDF chart of this shadowing model can be seen in Figure 8. Based on Figure 8 it can be seen that the PDF of shadowing chart obtained has a normal curve shape, so that it can be said that the shadowing value obtained has a normal distribution in logarithmic scale.

This distribution model is verified by the KS test, which compares the CDF (Cumulative Distribution Function) of shadowing value with CDF of normal distribution theory, and seek the maximum difference. The CDF maximum difference is find using [8]:

$$D_2 = \max\left\{F^0\left[x_{(i)}\right] - F_x\left[x_{(i)}\right]\right\} \tag{6}$$

Where D_2 represent the maximum difference of emprical and theoritical CDF, $F^0[x_{(i)}]$ and $Fx[x_{(i)}]$ represents empirical and theoritical CDF respectively. The maximum difference that allowed by KS test with large data samples is defined with [8]:

$$c_{n,\alpha} = \begin{cases} \dfrac{1.22}{\sqrt{n}}, & \alpha = 0.10 \\ \dfrac{1.36}{\sqrt{n}}, & \alpha = 0.05 \\ \dfrac{1.63}{\sqrt{n}}, & \alpha = 0.01 \end{cases} \tag{7}$$

Where $c_{n,\alpha}$ is the allowed maximum CDF difference, n is the number of samples, and α represents significant degree. When $D_2 < c_{n,\alpha}$ it can be said that the empirical CDF has a normal distribution.

The maximum CDF difference that was obtained (D_2) is 0.021 from totally 648 samples of CDF values. The maximum difference allowed by KS test with 648 samples and significant degree of 0,05 is 0.053. It can be seen that $D_2 < c_{n,\alpha}$. So Thus verified that the obtained shadowing model has a normal distribution in logarithmic scale. This CDF graph can be seen in Figure 9.

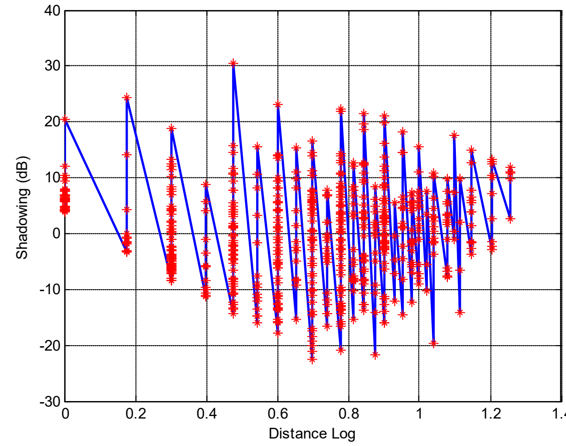

Figure 7. Shadowing Graphic

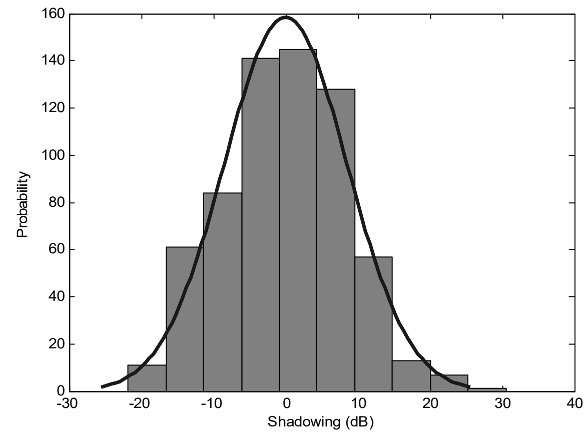

Figure 8. Shadowing PDF Curve

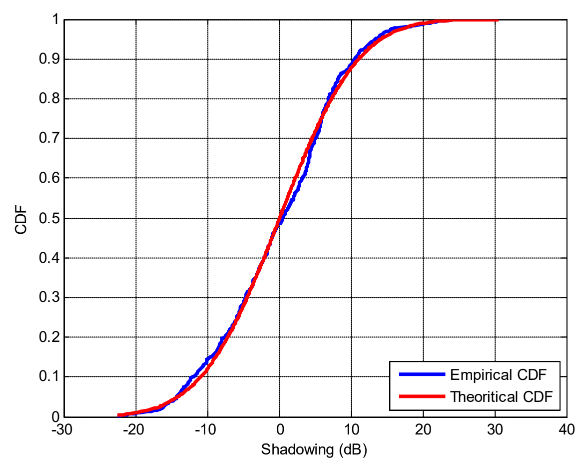

Figure 9. Shadowing CDF Empirical vs. Theoritical

C. Correlated Shadowing

After shadowing values has been obtained, then calculate the correlation coefficient of shadowing on all link pairs using equation (4). Then shadowing correlation coefficient in all link pairs are modelled as deterministic and stochastic models. Deterministic model of correlated shadowing in this paper is based on distance, angle, and arrival distance ratio variables. The distribution of shadowing correlation coefficient to these three variables can be seen in Figure 10, 11, and 12.

Based on Figure 10, 11, and 12 can be seen that shadowing correlation coefficient has a random distribution to the distance, angle, and arrival distance ratio variables. The resulting random distribution cannot be determined in mathematical models, so it can be concluded that distance, angle, and arrival distance ratio does not affect the shadowing correlation coefficient on indoor multi-hop network in an office environment.

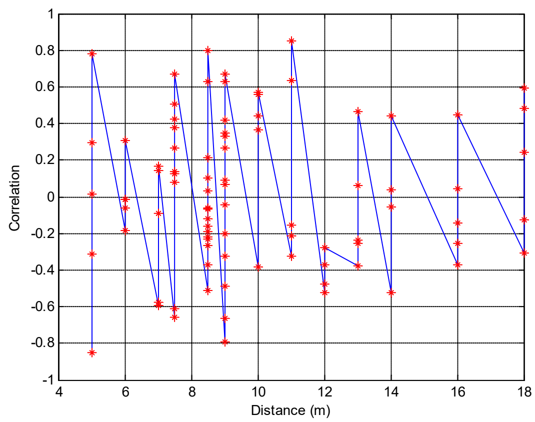

Figure 10. Shadowing Correlation Coefficient as Distance Function

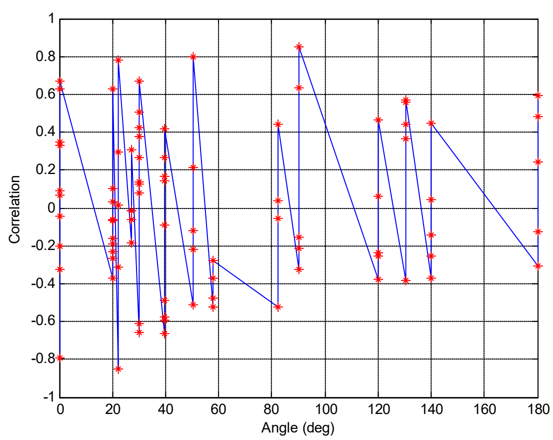

Figure 11. Shadowing Correlation Coefficient as Angle Function

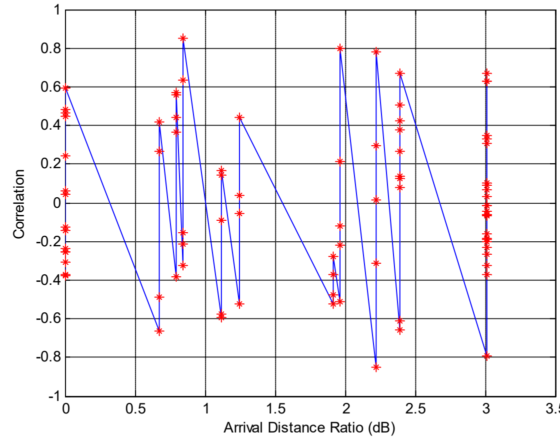

Figure 12. Shadowing Correlation Coefficient as Arrival Distance Ratio Function

Stochastic model of correlated shadowing is expressed by it's related probability distribution. PDF chart of all shadowing correlation coefficients that has been obtained can be seen in Figure 13. Based on Figure 13 it can be seen that the correlation coefficient of shadowing has a shape of PDF curve that similar to a truncated Gaussian distribution with an average of 0.012 and a standard deviation of 0.405.

This distribution was verified using the KS test with CDF graph in Figure 14. The maximum CDF difference that was obtained (D_2) is 0.056 from totally 87 samples of CDF values. The maximum difference allowed by KS test with 87 samples and significant degree of 0,05 is 0.1458. It can be seen that $D_2 < c_{n,\alpha}$. So it can be verified that the correlation coefficient of shadowing on indoor multi hop network in the office environment has a truncated Gaussian distribution, with mathematical expression in (8).

$$\Pr(\rho) = \frac{1}{0.405\sqrt{2\pi}} \exp\left(-(\rho - 0.012)^2 / 0.329\right), -1 \le \rho \le 1 \tag{8}$$

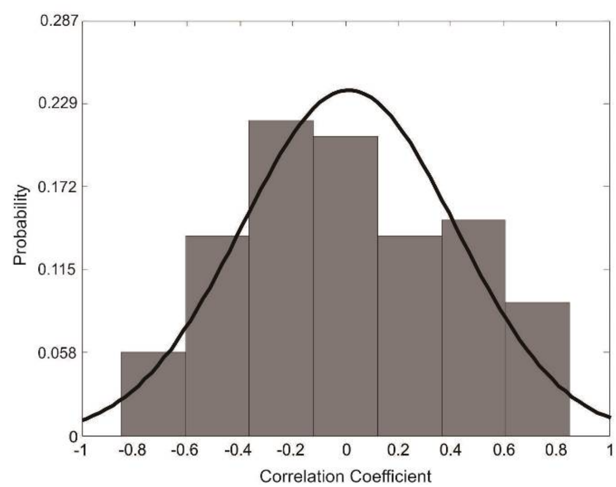

Figure 13. Shadowing Correlation Coefficient PDF Curve

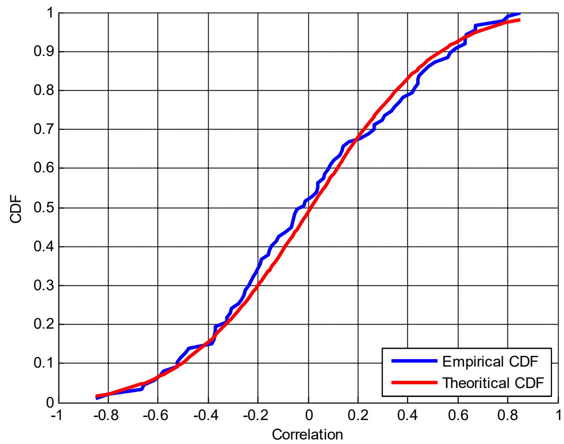

Figure 14. Shadowing Correlation Coefficient CDF Empirical vs. Theoritical

D. Verification of Channel Physical Condition

Based on the correlated shadowing data that has been obtained, the amount of shadowing correlation coefficient in the office environment is very varied. There are link pairs that strongly correlate, either positive or negative correlation, and there are also link pairs are almost uncorrelated. The variation of correlation coefficient is strongly influenced by it's related physical condition of propagation environment.

Based on the measurement results, it is known that a link pair positively correlated due to the similarity of obstacle's condition that passes by this link pair. For example, if a link pair together pass a wall, then shadowing effects that occur in that link pair can has a highly positive correlation.

A highly negative correlation caused by the condition of the obstacles that passed by a link pair are very different. For example when a link does not pass an obstacle, while other link passes too many obstacles. Based on the measurement results can be known that high negative correlation also caused by the differences of link pair length.

Shadowing effect on a link pair is not correlated if the obstacles on that link pair has different characteristics, but the difference is not as much on high negative correlation condition. For example, Shadowing effect on link 1 and link 2 are not correlated if link 1 passes a wall as an obstacle while link 2 pass two walls respectively.

IV. Conclusion

Based on measurement and data processing results, obtained a path loss model with path loss exponent of 4.178. Shadowing model that has been obtained has a log normal distribution with average of 0 dB and standard deviation of 8.538 dB. The distance, angle and arrival distance ratio are not affected the shadowing correlation coefficient of indoor multi-hop network in office environment. The shadowing correlation of indoor multi-hop network in office environment has a stochastic model with truncated Gaussian distribution. This model has an average value of 0.012 and standard deviation of 0.405.

Acknowledgment

The authors wish to thank Ministry of Research, Technology and Higher Education of the Republic of Indonesia that has supported this research.

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