Quantitative Analysis of Rainfall Variability in Tokyo Tech MMW Small-Scale Model Network

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***Abstract*—Millimeter-wave band is largely affected by attenuation due to rain. While calculating link budget for wireless systems using this frequency band, behavior of rain, attenuation due to rain and amount of degradation must be accurately understood. Evaluation of localized behaviors of rain and its effect on wave propagation in Tokyo Tech millimeter-wave model mesh network is presented in this paper. A quantitative analysis of rainfall variability using variogram in Tokyo Tech millimeter-wave (MMW) small-scale model network is reported. The unique effects due to highly localized behaviors of the heavy rain have become clear.**

I. Introduction

To cope with the recent demands of broadband communications, millimeter-wave has been receiving substantial attention because of its high-speed data transmission capability, wide bandwidth and generation of new frequency resource. Recent reports on the global warming effects on weather suggests the guerilla types of rain which is extremely localized on the order of less than 1 km [1]. For such small cell sizes, millimeter-wave wireless communication systems are more advantageous. Though, one of the biggest disadvantage is large attenuation due to rain. To overcome this, we could have power margin so that attenuation due to very strong rain is focused. An important aspect of intensive rain is localized behavior in space and time. Of special note is the correlation coefficient, regarded as an essential parameter for diversity [2]. Detailed statistical analysis and discussions on the effects of localized rain on microwave and millimeter-wave links are found in [3]. Detailed analysis and discussions on the spatial correlation characteristics of rainfall within several kilometers are found in [4]. However, these studies are only focus on the spatial correlation of rainfall and it didn't point out the relation between correlation and rain attenuation. This paper discusses the propagation characteristics measured in Tokyo Tech millimeter-wave model network taking localized rain effects into account and evaluates the localized behaviors of rain, its effects on the link attenuation in the small network. A quantitative analysis of rainfall variability using variogram in Tokyo Tech millimeter-wave small-scale model network is presented. Experimental data of 3 years is used to support this analysis.

II. Experiment Setup

Tokyo Tech millimeter-wave model network consists of 9 fixed wireless access (FWA) links, 6 base stations as shown in Fig. 1. The FWA lines are connected with each other using network switches at 6 FWA base stations on the rooftops of 6 buildings. The shortest link is 77 m and the longest one is 1020 m. Some basic research of millimeter-wave propagation characteristics using this network were reported in [5], [6]. Fig. 2 shows photographs of wireless terminals for 25 GHz and 38 GHz, respectively. High gain antennas are used for the FWA terminals which have specifications listed in Table I.

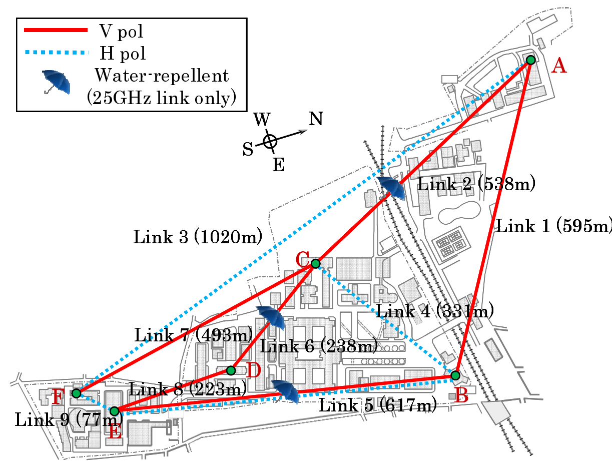
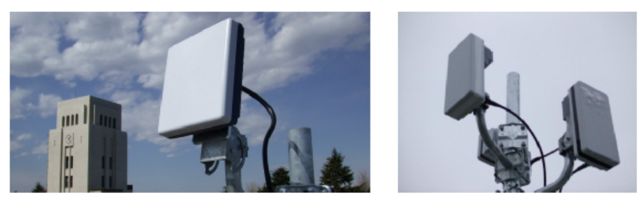


Fig. 1: Tokyo Tech MM-wave model network.



(a) 25GHz Terminal (b) 38GHz Terminal

Fig. 2: Photographs of the wireless terminals.

Rain rate, Rx Level, BER are recorded every 5 seconds. Rainfall intensity is measured by tipping-bucket rain gauges installed at all base stations with 0.2 mm resolution as the average of 1-minute time intervals. In this research, 3 year 3 months' data (4/2009-5/2012) for 25 GHz and 2 year 3 months' data (3/2010-5/2012) for 38 GHz have been used for analysis.

TABLE I: Wireless terminal specification

RF	25GHz	38GHz
Bandwidth	20MHz	200MHz
Duplex Scheme	TDD	TDD
Modulation Scheme	16QAM	QPSK/16QAM/64QAM
Antenna Gain	29dBi	32dBi
Max Transmission Speed	80Mbps	600Mbps/1Gbps

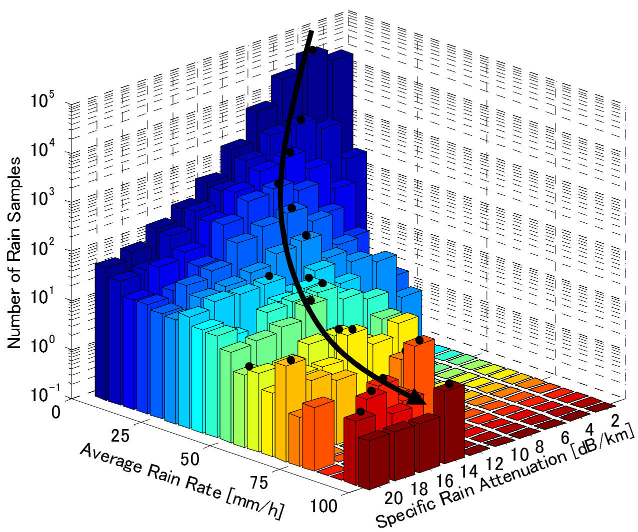
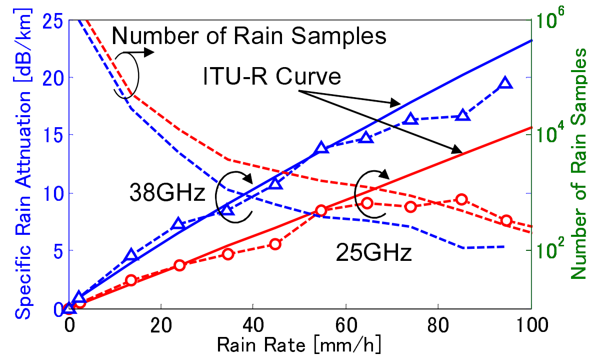
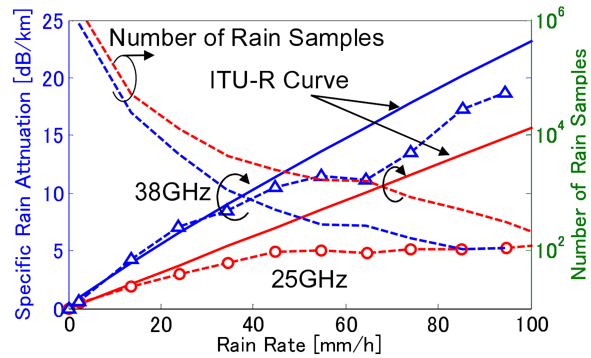


Fig. 3: Number of average rain rate between 2 points of link classified according to rain attenuation of 38 GHz using three years' 1-min rain rate data (Mar. 2010 - May 2012) for links 493, 595 and 1020 m.



(a) The variety of links 77 - 1020 m.



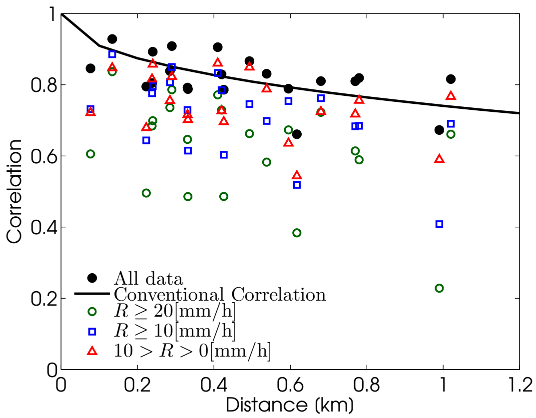
(b) Only longer links 595 and 1020 m.

Fig. 4: Specific rain attenuation of 25 GHz (data of Apr. 2009 - May 2012), 38 GHz (data of Mar. 2010 - May 2012) as a function of 1-min rain rate for the variety of links 77 - 1020 m (a), for only the longer links 595 and 1020 m (b).

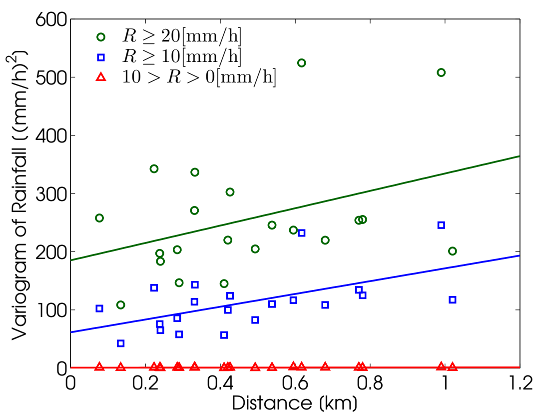
III. Spatial Variability of Rainfall

Fig. 3 shows the distribution of number of samples as function of the rain rate averaged between 2 end points of each link with 493, 595 and 1020 m, and the specific rain attenuation [dB/km] in 38 GHz. Here the specific rain attenuation is grouped with 2 dB/km steps (e.g. 1-3, 3-5, 5-7...) and plotted at (e.g. 2, 4, 6...) on the x-axis while the y-axis shows the rain rate which grouped with 5 mm/h steps (e.g. 0-5, 5-10, 10-15...) and plotted at (e.g. 2.5, 7.5, 12.5...). It can be observed that the number of samples rapidly decreases when the rain rate and rain attenuation increase. The peak for each rain rate is indicated by the black dots and a likelihood relation between rain rate and the specific rain attenuation is indicated by the solid line; the rain attenuation has strong correlation with the rain rate. It is noted however that for the strong specific rain attenuation, the rain rate averaged over the 2 end points, is not always large but is spread widely from 0 mm/h. This result suggests that in the strong rain and large rain attenuation, rainfall may be localized and spatially non-uniform, which may not be identified by the conventional statistical analysis and will be focused in the later section of this paper.

In the millimeter-wave band, the attenuation due to rain increases as the frequency goes up. This is also verified as shown in Fig. 4. The experimental specific rain attenuation is calculated from Rx level (data of Apr. 2009 - May 2012 for 25 GHz and data of Mar. 2010 - May 2012 for 38 GHz) for three links in two groups. Fig. 4 (a) is for the variety of links 77 - 2020 m while Fig. 4 (b) is for only the longer links 595 and 1020 m. For each rain rate, the rain attenuation is plotted as function of the link distance and then the specific rain attenuation [dB/km] is calculated as the slope of linear approximation in the sense of least mean squares, where the shortest link 77 m is used in both for calibrating out the attenuation by radome. The specific rain attenuation thus obtained at the particular rain rate is compared in Fig. 4 with the ITU-R curve [7]. From the figure, it is observed that the attenuation for 38 GHz link is larger than that of 25 GHz link. Moreover, the experimental data in Fig. 4 (a) follows the ITU-R curve in case of rain rate below 60 mm/h, while in Fig. 4 (b) it departs from ITU-R curve in case of rain rate above 30 mm/h and is smaller than ITU-R curve, though in higher rain rate, the accuracy of statistics may be degraded due to smaller number of sample data. This suggests the possibility that the rainfall is not uniformly distributed along the whole path in the strong rain, or put differently, the longer the path is the more variability the rainfall is. This localized feature is the unique



(a) Spatial correlation of rainfall.



(b) Variogram of rainfall.

Fig. 5: Spatial correlation and variogram of rainfall classified according to rainfall intensity (1-min rain rate data of Apr. 2009 - May 2012).

aspect of strong rainfall and large rain attenuation, which should be focused for the millimeter-wave network consisting of the links shorter than 1 km. Most of the propagation studies in the past have focused on the weak rainfall which is critical for the long distance radio links utilizing lower frequencies [2]

In order to quantify the spatial variability of rainfall, a classical tool, namely variogram, is considered in this paper. The detailed analysis will be explained. Variogram is a key tool used in geostatistics to investigate and quantify the spatial of a random function and it is also a plot of average variance between points vs. distance between those points [9]. It is expressed as

$$\gamma(\boldsymbol{d}) = 0.5E\left([z(\boldsymbol{d}+\boldsymbol{x}) - z(\boldsymbol{x})]^2\right), \tag{1}$$

where $\boldsymbol{x}$ is a position vector and $\boldsymbol{d}$ is a distance separation vector. E denotes the expectation and $z(\boldsymbol{x})$ is random function. The classical widely used sample variogram is given as follows [10]

$$\gamma(\boldsymbol{d}) = \frac{1}{2N}\sum_{x_2 - x_1 \approx d}\left([z(x_2) - z(x_1)]^2\right), \tag{2}$$

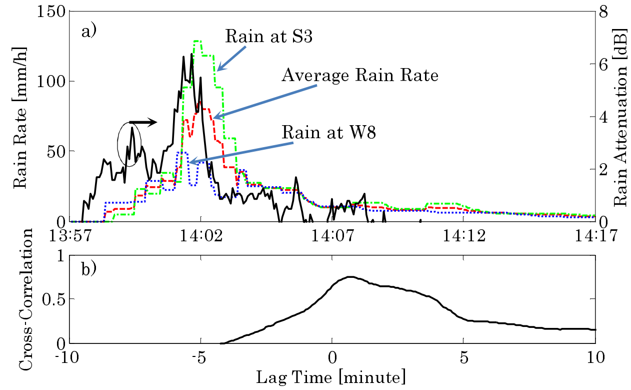


Fig. 6: Rain, rain attenuation (a) and correlation between average rain rate and rain attenuation (b) in heavy rainfall event (peak 1-min average rain rate of 85 mm/h) in 1-min time interval for link 7.

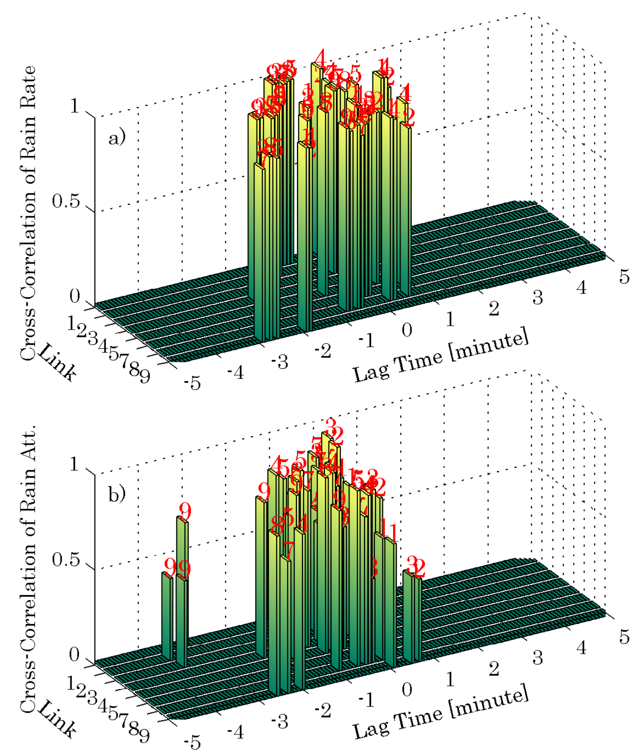


Fig. 7: Peak cross-correlation values between the average rain rate of one link and other links (a), rain attenuation of one link and other links (b) in the heavy rainfall event (peak 1-min average rain rate of 85 mm/h) for whole network.

where N denotes the number of pairs (x_1, x_2) separated by a distance equal to $\boldsymbol{d}$. If data are spatially correlated, variance generally increases with distance and if data are spatially uncorrelated, it will form a straight line.

Fig. 5 shows the spatial correlation (a) [8] and variogram of rainfall (b) classified according to rainfall intensity. For conventional correlation, $\rho = \exp(-0.3\sqrt{d})$ is used. Because the scale of the network is small, a linear variogram model is used [3]. From Fig. 5 (a), correlation of all rainfall data shows reasonable agreement with conventional formula. Also the correlation coefficient decreases with the increase in link distance. It is observed that the heavy rainfall tends to decrease correlation of rainfall. Fig. 5 (b) clearly shows that the variability of rainfall which was analyzed by using variogram correspond to the correlation coefficient. Variogram of rainfall increases with the increase in distance. The variability observed over the network is larger for heavy rainfall than weak rainfall, and this trend becomes much more clearly than that of correlation coefficient. It is noted that the variogram of less than 10 mm/h is very small which is related to large number of sample data.

Fig. 6 shows rain, rain attenuation (a) and correlation between average rain rate and rain attenuation (b) in heavy rainfall event (peak 1-min average rain rate of 85 mm/h) in 1-min time interval for link 7. Fig. 7 shows the peak cross-correlation values between the average rain rate of one link and other links (a), rain attenuation of one link and other links (b) in the heavy rainfall event (peak 1-min average rain rate of 85 mm/h) for whole network. The localized behavior of rainfall and attenuation in space together with their delays in time suggest the effectiveness of diversity even in such a small area, provided the rain is heavy.

IV. Conclution

In this paper, the spatial variability of rainfall and rain attenuation were evaluated by using variogram. The statistical analysis results showed that the rain attenuation at both high rain rates and long distances was affected by the localized behaviors of rain affects. Also it has been suggested that the spatial variability of rainfall and rain attenuation are a good parameter for diversity.

ACKNOWLEDGEMENT

This work was conducted in part as "the Research and Development for Expansion of Radio Wave Resources" under the contract of the Ministry of Internal Affairs and Communications.

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