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Rain Estimation from Smart City's E-band Links

Roy Janco, Jonatan Ostrometzky, *Senior Member, IEEE*, and Hagit Messer, *Life Fellow, IEEE*

School of Electrical Engineering, Tel Aviv University, ISRAEL

***Abstract*—Smart cities around the world are supported by high-capacity wireless communication networks, which are based on millimeter-waves links. The propagating waves are sensitive to hydrometeors, and their signal level is attenuated by rain. However, most of the links in such networks are shorter than 1 km, imposing large errors on the rain estimation results. In this paper we demonstrate, using actual measurements from the city of Rehovot, Israel, how high-resolution rain maps can be generated from the received signal level measurements collected by these links. We first propose a method for reducing the errors in converting signal attenuation to rainfall estimates in short, in-city links. The proposed method requires calibration of model parameters using side information from either a rain gauge or a long link in the vicinity of the network. We empirically analyze the results of the calibrating method using either auxiliary measurements and show that the performance is satisfactory for both. Then, we apply a spatial interpolation method on the rainfall resulting estimates, and demonstrate the construction of an high-resolution 2-D map of the accumulated rain in a city, a product with great potential for improving well-being of life in urban areas.**

***Index Terms*—Commercial Microwave Links (CMLs), Smart-City, mmWave, Rain Maps, Rain Estimation**

I. Introduction

Monitoring rain in urban areas is important for urban water management, floods risks mitigation, urban planning, transportation management and more. Traditional rainfall measurements have been conducted using rain gauges and weather radars for many years [1], [2].

In recent decades Commercial Microwaves Links (CMLs) have been used to estimate precipitation, based on a physical phenomenon: propagating electromagnetic waves are absorbed and scattered from hydrometeors along the path of propagation and are attenuated as a result.

Attenuation due to rain is usually modeled using the power law [3]:

$$A_r = aR^bL \tag{1}$$

where A_r (in dB) is the rain induced attenuation of the electromagnetic wave modeled by the power-law. a, b are coefficients depending on the link specific frequency, antenna polarization and rain drop size distribution [4], L (in km) is the link path length and R (in mm/hr) is the rain rate (i.e., the rain intensity). It was first suggested in 2006 to use CMLs of cellular networks for rainfall estimation as an opportunistic sensing method [5], and since then extensive research has been done (e.g. [6], [7] among others).

The emergence of Internet of Things (IoT) in recent years and the need to perform city operations more efficiently due to dramatic and fast urbanization have founded the concept

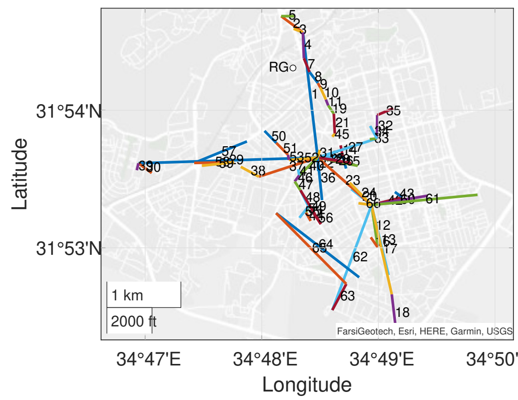


Fig. 1: Rehovot links map. The network contains 66 links, where the longest one is link number 29, with a length of 2.42 km. A rain gauge is placed in the north part of the city and is marked with a circle labeled 'RG'.

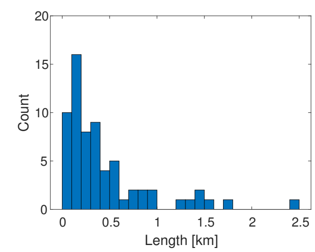


Fig. 2: Links length distribution as a function of their length

of smart cities [8]. Smart cities around the world established in-city communication networks based on millimeter-waves to support high capacity communication for various applications.

In [9], the authors have demonstrated that signal-level measurements collected from E-band CML network in the smart city of Rehovot, Israel, can be used to estimate the movement of an incoming storm-front.

In this paper we show the potential of using smart cities mmWave links as opportunistic sensors for rain estimation in a street-level scale. These links operate at the E-Band range, and most of them are shorter than 1 km. Thus, these links are prone to large errors of rain estimation which is associated with short links when using the power-law of (1), as have been recently reported in [10].

Calibration of the model parameters for short links can be done using a designated rain measuring device such as rain gauge or a weather radar, however such devices are not available everywhere. In this paper, we propose a simple model for rainfall estimation of short links using the longest link in the vicinity as a reference. We compare the results of estimating the model parameters from a rain gauge or from the longest link in the network. Furthermore, we show examples of generated rain maps using the rain-estimates produced using the presented calibration methodology.

The rest of the paper is organized as follows: *Section II* describes the data used from the city of Rehovot, Israel. *Section III* presents the development of the methods used to estimate rain from each link and the generation of rain maps. *Section IV* shows the results and the corresponding generated rain maps. *Section V* concludes this paper.

II. Data

Received Signal Level (RSL) measurements from each link are recorded regularly for network management purposes by the operators. We received the RSL measurements as collected by links from the smart city network of the city of Rehovot, Israel, with the courtesy of the operator company SMBIT Ltd.[1]. Links map of Rehovot and the links length distribution are presented in Fig. 1, and Fig. 2.

The network consists of 66 links, where each link contains two sub-links for the two opposite directions. All links operate at the E-Band frequency range, namely in the range of 70 GHz to 84 GHz, while the majority of the links operate at 74.375 GHz. RSL values are sampled every 30 seconds with quantization of 1 dBm. The Transmitted Signal Level (TSL) is unknown, and can approximated to be constant for each link.

Looking at Fig. 2, it can be seen that most of the links are indeed shorter than 1 km. Rainfall estimation from these short links using the power-law of (1) suffers from large errors compared to the longer ones. In addition, the large quantization of the RSL worsens the errors. A rain gauge[2] located in the northern part of the city is used to calibrate the RSLs of each link. The rain gauge measures the accumulated rainfall for 10-minute intervals, with a resolution of 0.1 mm. For the "long-link calibration approach", we rely on the longest link in the network instead of the rain gauge. In this case link number 29 is used as a reference, with a length of 2.42 km.

III. Methodology

Generating rain maps from CMLs can be separated into the following three stages: (i) Filtering out noisy links; (ii) Converting attenuation measurements to rain measurements; and (iii) Interpolating the estimated rain from the CMLs location to a defined grid.

In this paper we assume the noisy links are filtered out and we focus on the available links that are marked as reliable.

The total attenuation along a link path at time index t, $A_T(t)$ in dB, can be described as [11]:

$$A_T(t) = A_p(t) + A_{WA}(t) + A_{BL}(t) = TSL(t) - RSL(t) \quad (2)$$

[1]SMBIT. LTD. https://www.smbit.co.il/smart-city

[2]The measurements are provided by The Robert H Smith Faculty of Agriculture, Food and Environment (Rehovot), The Hebrew University of Jerusalem. http://www.meteo-tech.co.il/faculty/faculty_periodical.asp?client=1

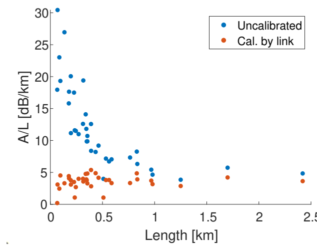


Fig. 3: Normalized attenuation averaged between 01:40 and 03:20, Jan. 24^{th}, 2022, per link, before and after the calibration. Large normalized attenuation can be seen for uncalibrated short links. However, the overestimation is corrected after applying the model which was calibrated by the longest link.

where $A_p(t)$ is the actual rainfall induced attenuation, $A_{WA}(t)$ is the attenuation due to wet antenna, $A_{BL}(t)$ is the attenuation caused by other than rain sources such as free space attenuation and gas attenuation and is referred as the baseline attenuation. Usually $A_{BL}(t)$ slowly changes with time compared to the rain-induced factors.

Extracting $A_p(t)$ from (2) yields:

$$\begin{aligned} A_p(t) &= TSL - A_{BL}(t) - A_{WA}(t) - RSL(t) \\ &= z(t) - A_{WA}(t) - RSL(t) \end{aligned} \quad (3)$$

Where $z(t) = TSL - A_{BL}(t)$ denotes the "resting" level of the RSL. $z(t)$ is calculated by the moving median with a centered window of one week size applied on the RSL averaged over 15-minute intervals [12]. By denoting the observed attenuation at time index t, $A(t) = max(z(t) - RSL(t), 0)$ (in dB), the rainfall induced attenuation can be calculated by:

$$A_p(t) = A(t) - A_{WA}(t) \quad (4)$$

Usually the rainfall induced attenuation, $A_p(t)$ is described using the power-law (1). However, uncertainties in short links, in combination with the wet antenna effect, cause additional attenuation as presented in Fig 3, which shows the observed attenuation measurements, averaged for the entire rainy period and normalized by the specific links length. Large normalized attenuation values are visible for short links.

We relate the actual rainfall-induced attenuation to the one modeled by the power-law of (1) as follows:

$$A_p(t) = \begin{cases} A_r(t) & \text{for long links} \\ A_r(t) + \Delta_s(t) & \text{for short links} \end{cases} \quad (5)$$

where $\Delta_s(t)$ is the difference between the two terms, which is prominent in short links.

For short links, one can substitute (5) into (4), which yields:

$$A_r(t) + \Delta_s(t) = A(t) - A_{WA}(t) \quad (6)$$

Assuming that the additional attenuation in short links is proportional to the rain induced attenuation modelled by the power-law (1), i.e. $\Delta_s(t) = \alpha A_r(t)$, equation (6) becomes:

$$A_r(t) + \alpha A_r(t) = A(t) - A_{WA}(t) \quad (7)$$

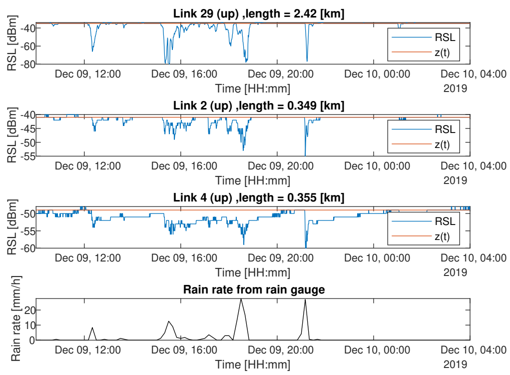


Fig. 4: RSL measurements from different links, corresponding to the rain gauge measurements.

which can be rearranged to:

$$A_r(t) = \frac{A(t) - A_{WA}(t)}{1+\alpha} \tag{8}$$

We propose a model for correcting the rain attenuation of short links. The idea is that each link responds differently to rain, even for links with the same hardware, frequency and length. This can be seen in Fig. 4, where links 2 and 4 are of approximately the same length, but the RSL of link 4 recovers from a rainy period slower, compared to the RSL of link 2.

The model has two parameters (unique per link), which are used to correct the wet antenna and the short links related inaccuracies together. The proposed model is defined as follows:

$$A_r^i(t) = \frac{max(A^i(t) - b^i, 0)}{W^i} \tag{9}$$

where $A^i(t)$ is the observed attenuation (in dB, at time index t) averaged over the two sub-links of link i, b^i is a parameter to compensate for a constant wet antenna attenuation, W^i is a correction factor for short links. From now on, we refer to $A_r^i(t)$ as the rain induced attenuation of link i.

The model parameters for each link are estimated using side information. Side information can be measurements taken from a nearby rain gauge or a weather radar. In cases in which neither are available, attenuation measurements from a long link can be used, assuming wet antenna attenuation and other unknown short links related uncertainties are having smaller impact for long links, and that both links operate at a similar frequency.

Estimating the model parameters is done by minimizing the loss function which depends on the side information type.

Estimation process from the reference source is presented in Fig. 5. Attenuation measurements are aligned with the reference source (rain gauge or long link) signal by shifting the attenuation-measurements time-series in order to maximize the cross correlation between the two signals. This time alignment is done since there is a natural time shift between measurements at different locations. The model is applied to

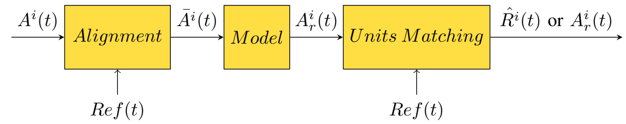


Fig. 5: Model parameters are estimated by aligning the attenuation measurements to the reference signal and applying the model. Rain attenuation is converted to rain by applying the power-law if the reference source is rain measurements. If the reference source is attenuation from a long link this stage is skipped. The output has the same units and sampling rate as the reference source.

extract rain induced attenuation from the observed attenuation. Rain induced attenuation is converted to the same units of the reference signal, e.g. when the reference source is the rain gauge, the power-law of (1) is applied and then a moving average and down-sampling are being done to match the same sampling rate. In our case, a window size of 20 samples is used to match the sampling rate of the RSL with the rain gauge measurements. If a long link is used as a reference, the units matching stage is skipped.

Denoting $\boldsymbol{\theta}^i = [W^i, b^i]$ the model parameters of link i, the optimization function when the reference source is the rain gauge is:

$$\hat{\boldsymbol{\theta}}^i = \underset{\boldsymbol{\theta}^i}{\operatorname{argmin}} ||\hat{\boldsymbol{R}}^i(\boldsymbol{\theta}^i) - \boldsymbol{R}^{rg}||_2^2 \tag{10}$$

where $\hat{\boldsymbol{R}}^i$ is a vector of rain estimates from link i, and $\boldsymbol{R}^{rg}$ is a vector of the rain gauge measurements.

When the reference source is a long link, the optimization function is:

$$\hat{\boldsymbol{\theta}}^i = \underset{\boldsymbol{\theta}^i}{\operatorname{argmin}} ||\frac{\boldsymbol{A}_r^i(\boldsymbol{\theta}^i)}{L^i} - \frac{\boldsymbol{A}_{long}}{L_{long}}||_2^2 \tag{11}$$

where $\boldsymbol{A}_r^i$ is a vector of rain attenuation measurements from link i, $\boldsymbol{A}_{long}$ is a vector of the observed attenuation measurements of the long link, and L^i and L_{long} are the lengths of link i and the long link respectively.

Rain map generation is done using Inverse Distance Weighting (IDW) as described in [13].

$$R(\boldsymbol{x}) = \frac{\sum_{i=1}^{N_L} w_i(\boldsymbol{x})\hat{R}^i}{\sum_{i=1}^{N_L} w_i(\boldsymbol{x})} \tag{12}$$

where:

$$w_i(\boldsymbol{x}) = \begin{cases} \frac{\left(1-\frac{d_i(\boldsymbol{x})}{D}\right)^2}{\left(\frac{d_i(\boldsymbol{x})}{D}\right)^2} & \text{if } \frac{d_i(\boldsymbol{x})}{D} \leq 1 \\ 0 & \text{if } \frac{d_i(\boldsymbol{x})}{D} > 1 \end{cases} \tag{13}$$

$R(\boldsymbol{x})$ (in mm/hr) is the interpolated rain at target grid point $\boldsymbol{x}$, $\hat{R}^i$ (in mm/hr) is the estimated rain at the center of link i, $\boldsymbol{x}_i$, after the calibration process, $d_i(\boldsymbol{x}) = ||\boldsymbol{x} - \boldsymbol{x}_i||_2$ (in km) is the distance between the target grid point $\boldsymbol{x}$ and the center of link i, D (in km) is the radius of influence, i.e., the distance beyond which a link ceases to effect target point $\boldsymbol{x}$ and N_L is the number of links. Here, we set $D = 1$ km and the spacing between grid points to be 300 m.

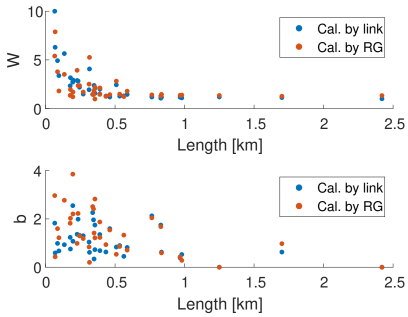
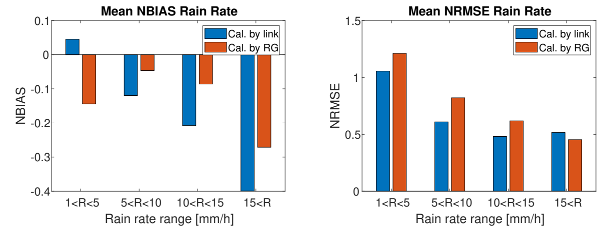
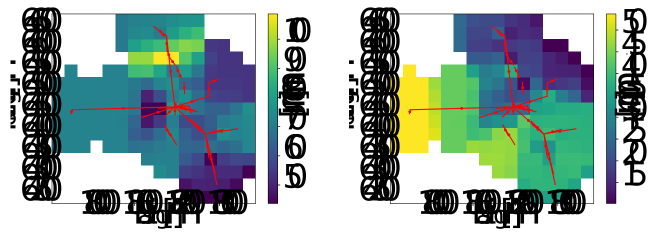


Fig. 6: Model parameters estimated with the longest link or with the rain gauge.



(a) (b)

Fig. 7: a: Mean NBIAS averaged over links 1, 2, 3, 4, 7, 8, 10, divided to different rain intensities b: Mean NRMSE averaged over the same links for different rain intensities.



(a) (b)

Fig. 8: a: Generated rain map of the accumulated rainfall between Jan. $8th$ and Jan 11^{th}, 2020. b: Generated rain map of the accumulated rainfall beteen Jan. 17^{th} and 18^{th}, 2020.

IV. Results

The model parameters described in *Section III* were estimated from 3 major rain events occurred during December of 2019, with a total time of 43 hours. Parameter values estimated from both methods are presented in Fig. 6. The two methods show a similar trend, i.e. W increases as the links length decreases, and it is $W \approx 1$ for links longer than 1 km. In average, b^i values are larger for the models calibrated from the rain gauge, and consequently W^i values are smaller for the models calibrated from the rain gauge. This is not surprising, since in the optimization function of (11), The wet antenna attenuation constitutes a significant part of A_{long} at light rainfall.

The models were validated on 25 periods with different length between Nov. 2019 and Mar. 2020, including approximately 600 hours in total. The red dots in Fig. 3 show that the calibration process based on the longest link corrected the overestimation of rainfall from short links.

The performance of the rain estimation from each link is evaluated using the normalized bias (NBIAS) and the normalized RMSE (NRMSE):

$$\text{NBIAS}(\hat{R}^i, R_{rg}) = \frac{\frac{1}{N}\sum_n(\hat{R}_n^i - R_n^{rg})}{\bar{R}^{rg}} \quad (14)$$

$$\text{NRMSE}(\hat{R}^i, R_{rg}) = \frac{\sqrt{\frac{1}{N}\sum_n(\hat{R}_n^i - R_n^{rg})^2}}{\bar{R}^{rg}} \quad (15)$$

where $\bar{R}^{rg}$ is the average rain rate measured by the rain gauge and N is the number of samples.

Fig. 7a shows the NBIAS, averaged over the 7 closest links to the rain gauge that are longer than 100 m. It shows that both methods are biased with respect to the rain rate, and the bias is smaller (in absolute values) for rain rates greater than 5 mm/h for the model calibrated by the rain gauge. For rain rates larger than 5 mm/h, the two methods underestimate the rain rate. Fig. 7b shows the NRMSE, averaged over the same links. Both methods behave similarly, with a slight advantage for the "long link approach" for rain rates smaller than 15 mm/h. Examples of generated rain maps from January 2020 with model parameters estimated by the "long link approach" are depicted in Figs. 8a and 8b.

V. Conclusions

A simple model for rainfall estimation from short links is presented. The model parameters can be estimated from either a nearby rain gauge or a nearby long link. The results show that it is unclear which calibration method performs better. Nonetheless, as in many cases a rain measuring device is not available, the presented long link based calibration process is beneficial. In addition, this method can be extended by calibrating short links from different long links, taking into consideration the distance between the links, as due to the spatial variability of rain, calibrating using close link is preferred.

In this work we presented rain map generation from a given set of links that are assumed to be reliable. For real applications a dynamic filter can be applied to automatically filter out links that are noisy or too short that can not detect rain.

Acknowledgment

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