Advances in Water Resources 31 (2008) 1470–1480

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Estimation of rainfall fields using commercial microwave communication networks of variable density

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ARTICLE INFO

Article history:
Received 5 July 2007
Received in revised form 31 January 2008
Accepted 24 March 2008
Available online 8 April 2008

Keywords:
Microwave
Backhaul
Link
Rainfall
Tomography

ABSTRACT

The use of commercial microwave radio networks which are a part of cellular communication infrastructure for mapping of the near-the-ground rainfall is challenging for many reasons: the network geometry in space is irregular, the distribution of links by frequencies and polarizations is inhomogeneous, and measurements of rain-induced attenuation are distorted by quantization. A non-linear tomographic model over a variable density grid is formulated, and its applicability and performance limits are studied by means of a simulated experiment using a model of a real microwave network. It is shown that the proposed technique is capable to accurately measure integrated near-the-ground rainfall amounts over the area of 3200 km^2 with a bias smaller than 10%. In urban area, where the density of microwave links is high, the average correlation in space between the simulated model and reconstructed rainfall fields reaches 0.89 over the variable density grid with average cell size of 5.7 km^2 and 0.74 when interpolated into the rectangular grid with pixel size 0.775×0.775 km^2, for the quantization interval of 0.1 dB.

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1. Introduction

The use of commercial microwave communication links which are a part of cellular telephony infrastructure for estimation of precipitation [1,2] is advantageous for many reasons: they are widespread over the world, fixed, line-of-sight and operate at frequencies of tens GHz, where precipitation is the major source of interruptions, resulting in attenuation of the received signal. Moreover, terrestrial microwave links (or backhaul links, connecting cellular towers back to a core network) are typically located a few tens of meters above the ground, providing therefore a useful facility for measurements of near-surface precipitation. Such links form dense networks and employ power control facilities for monitoring of network performance and adjusting power to assure undisturbed reception. These automatic power control systems require routine measurements of Received Signal Level (RSL) by receivers. Records of transmitted and received power, reflecting rainfall-induced attenuation A (dB km^{-1}) are collected at a control center and naturally allow estimation of average rain rate R (mm h^{-1}) per link based on the well-known power-law attenuation equation [3]:

$$A = aR^b \quad (1)$$

where the coefficients a and b are, in general, functions of frequency, polarization and drop size distribution (DSD) [4].

It has long been known that nearly linear relation of microwave attenuation A to rainfall R at wavelengths of 1 cm could serve as a basis for measurements of path-integrated and area-integrated rainfall [4–6]. The recent advances in communication technology enabled use of off-the-shelf commercial microwave equipment to measure near-the-ground rainfall. Thus, the advantage of microwave links for high temporal resolution measurements over conventional rain gauges was demonstrated in [7]. The use of dual-frequency links, operating at different, specially selected frequencies, allows estimation of rainfall rate as a linear function of ratio of two attenuations, lowering the effects of unknown DSD and producing reliable estimates of path-integrated rainfall [8,9] and rainfall spatio-temporal distribution, in conjunction with rain gauges and radar [10]. Following these findings, a number of applications of microwave measurements were explored. Thus, the advantages of use of single-frequency links for urban rainfall measurements were shown in [11]; others include calibration of weather radar [12], a two-steps procedure for correction of X-band radar attenuation and resulting rainfall estimates [13], identification of melting snow [14] and even estimation of DSD parameters [15].

The use of microwave attenuation measurements for tomographic reconstruction of rainfall fields was pioneered by Giuli et al. [16,17] who suggested a specially designed hypothesized system of microwave links with a predefined geometry, operating at specially selected frequencies where the A–R relationship is linear,

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doi:10.1016/j.advwatres.2008.03.003

combined with point rain gauges. This system allowed application of linear tomography to reconstruct spatial distribution of rainfall.

The existing approaches, however, heavily rely on dedicated equipment. The use of commercial hardware installations poses new challenges because commercial microwave networks are optimized for high communication performance and are designed in the way that reduces the effect of weather-related impairments on quality of service. Thus, the observation type, time and magnitude resolution, network geometry and frequencies are predefined and, in most cases, cannot be changed.

While some systems allow direct attenuation measurements at the temporal resolution of 1 min, others are designed to only measure minimum and maximum RSL for the 15-min time interval [1], or one instantaneous value each 15 min [2]. Time resolution for old equipment can even be worse, e.g. once per day measurements of minimum RSL. Power resolution (quantization) depends on specific equipment and may vary from 0.1 dB to several dB, which can result in large errors. The attenuation measurement error in estimation of integrated rainfall over a link [18] in presence of Δ dB quantization does not exceed $\Delta/2$. Therefore, the maximum error can be estimated according to (1) as

$$\delta R = \left(R^b + \frac{\Delta}{2aL}\right)^{\frac{1}{b}} - R \quad (2)$$

In Fig. 1, we show simulation of maximum error in estimation of average rainfall due to $\Delta = 1$ dB quantization as a function of link frequency and length, according to [19].

Other difficulties in estimation of average rainfall per link from signal attenuation include uncertainties due to variability of DSD along the link [20], wet antenna attenuation [2] and uncertainty in determination of clear air attenuation due to water vapor-induced attenuation and scintillation effects [8,9].

Next, the geometry of the system of links is arbitrary, and the spatial resolution of the precipitation measurements is therefore determined by a given link topology. The analysis of a real microwave link network from an Israeli cellular provider (249 links, covering Israeli coastal plain which is discussed in the paper) shows that link density is highly variable – from 3 links per km^2 in urban areas up to 0.3 in rural ones.

Finally, the power-law equation (1) is non-linear at the frequency bands of 8, 18, 23 and 38 GHz – typical frequency bands used for communications; it is impossible to use linear tomography, since each link, in general, operates at its own frequency. It was demonstrated [6] that at the frequencies of about 35 GHz, the power-law relationship is approximately linear and is essentially independent on DSD and temperature, showing empirical errors of less than 10%. However, the uncertainties in determination of path-averaged rainfall intensity due to variation in DSD increase with lowering the frequency, reaching more than 20% at the frequencies of about 9 GHz. On the other hand, it was found in [15] that the instantaneous estimates based on the power-law equation (1) tend to overestimate the actual rainfall rate, especially at intense rain rates, where variations in DSD affect the power-law measurements, even though the agreement between power-law and dual-frequency estimates is very good during intervals of stratiform rain.

The aim of this paper is to demonstrate the potential of the commercial microwave communication links in large-scale rainfall measurements using a model of a real microwave system. We propose a non-linear tomographic model over a variable cell size grid and conduct a simulated experiment to obtain quantitative estimates of the major effects which are specific for commercial microwave networks – irregularity of the network topology, observation quantization and non-linearity of the power-law equation for different links, constituting the network.

2. Tomographic model

We formulate a non-linear tomographic model, where each link i is characterized by power-law coefficients a_i, b_i, corresponding to the link's frequency.

Suppose we have a set of observed rainfall-induced RSL attenuations A_i, $i = 1, \ldots, m$ from m wireless links of length L_i each one. Using (1), we obtain m expressions, relating the observed A_i with path-averaged rainfall R_i for the ith link [6]:

$$A_i = a_i R_i^{b_i} L_i = a_i \int_{L_i} r(x)^{b_i} dx, \quad i = 1, \ldots, m \quad (3)$$

where $r(x)$ is the true instantaneous rainfall in the point x.

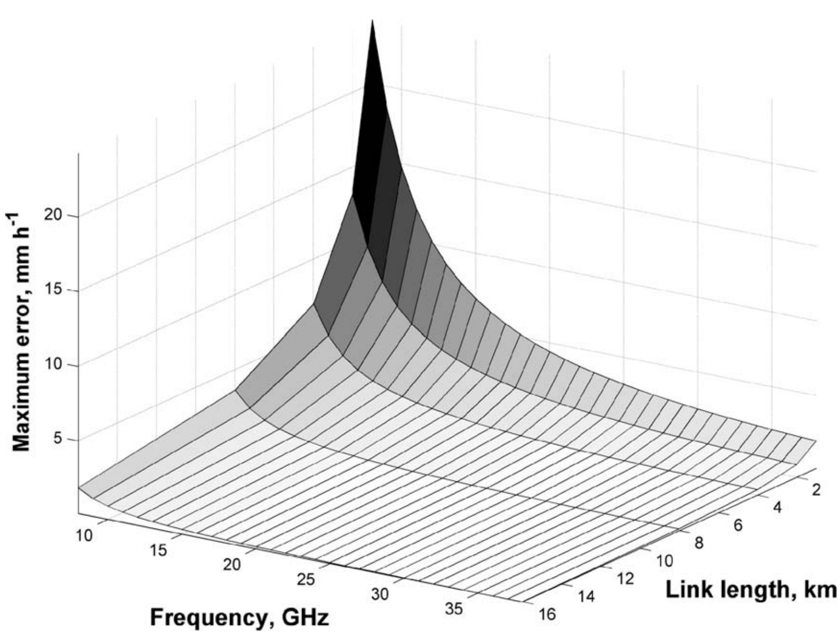

Fig. 1. Maximum rainfall estimation error due to 1 dB quantization as a function of link length and frequency, at the rain rate $R = 15$ mm h^{-1}.

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