Environmental Sensor Networks Using Existing Wireless Communication Systems for Rainfall and Wind Velocity Measurements

Hagit Messer, Artem Zinevich, and Pinhas Alpert

The microwave links that form a wireless communication network (WCN) for a cellular network infrastructure can be considered for an environmental sensor network (ESN). Every radio link that connects a base station to the core network is a sensor. For such an ESN, the key challenge is to develop algorithms to estimate the intensity of weather effects that impair communication performance – first rainfall and wind, and then, humidity, fog, and snow.

Introduction

Accurate measurements of rainfall are important in meteorology, hydrology (e.g. flood warning), agriculture, environmental policy and weather forecasting. Atmospheric observation systems currently include surface stations (rain gauges), weather radiosondes, radar, and satellite systems. They require costly installation and operation, and the combined measurements are not sufficient in temporal or in spatial resolution, especially close to the ground. The need for better measurements has inspired the use of microwave links, which can provide accurate rainfall estimation at the near-surface level.

The use of existing microwave links in cellular communication networks for an ESN (Fig. 1) offers these unique advantages:

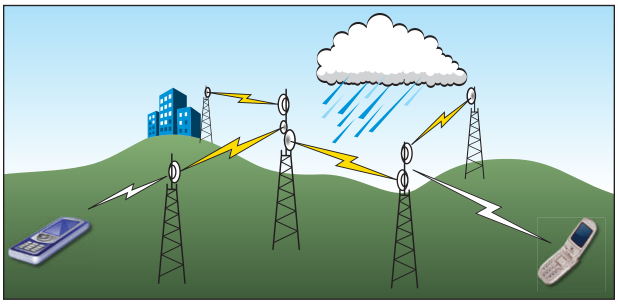

Fig. 1. A microwave network using fixed wireless electromagnetic communication links between the base stations that operate at frequencies of tens of GHz. Rainfall is the major source of communication impairments.

- *Coverage*: Microwave communication networks are widespread; about 75% of European cellular providers employ point-to-point microwave links for backhaul in their cellular infrastructure. They cover wide areas including poorly accessible regions over complex terrain where using other methods of observation of the atmosphere (radiosondes, rain gauges and weather radars) are either impractical or technically impossible. In Israel, for instance, there are several thousand microwave links compared to about 400 rain gauges available to the Israeli Meteorological Service.
- *Diversity*: It is a new source of accurate, near-the-ground atmospheric information.
- *Efficiency*: It uses an existing wireless infrastructure and adds another application to it with no extra cost for equipment and no extra radiation.
- *Accuracy*: Superior accuracy of the method for rainfall measurements has been demonstrated in [1].

In particular, this method enables important meteorological and hydrological benefits: mapping near-the-ground precipitation over wide areas including currently unmapped areas (e.g. regions with complex orography), high-resolution accurate measurement of urban precipitation where the high density of microwave links assures the required redundancy, and mapping of the horizontal wind field at the steering level of a storm (typically around 3 km above sea level), similar to the ones produced by Doppler radars. The resulting information is beneficial for a range of applications:

- In many poor and third-world countries where water management is of tremendous importance due to fresh water shortages, WCN-based ESN may be the only approach for precipitation measurements which will enable better water management.
- Real-time estimation of spatial distribution and dynamics of precipitation and wind allows short-term forecasting ("now-casting") and warning of severe storms. Also, these observations can serve as data for hydrological models and flood warnings.

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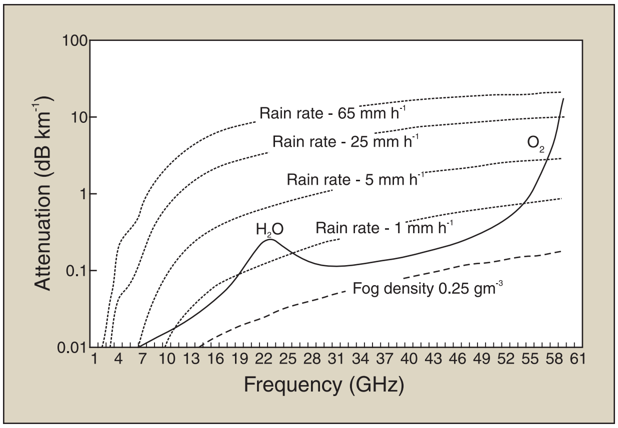

Fig. 2. A graph of transmission losses in the atmosphere.

- Near-the-ground rainfall and wind fields aloft can be used for initialization or be assimilated into numerical weather prediction models, which can improve weather forecasting.

This research may also lead to contributions to other areas, e.g. telecommunications (for predicting rain fades for either terrestrial or space communications) or traffic management (since precipitation is an important factor in the throughput of transport channels).

Background

Years of research have improved modeling, interpretation, and control of atmosphere-induced impairments on the quality of the electromagnetic channel. The presence of line-of-sight, Fresnel zone clearance, and propagation phenomena (diffraction, refraction, absorption and scattering), all cause severe impairments to the received radio frequency signals. At frequencies above 10 GHz, absorption and scattering are directly related to the atmospheric conditions, primarily precipitation, oxygen, water vapor, mist and fog (Fig. 2) [2].

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Rain has long been recognized as one of the major causes of unwanted signal loss on centimeter or millimeter wave propagation paths through the lower atmosphere. A firm theoretical basis validated in numerous propagation tests has been established for calculating the attenuation due to the rainfall intensity along the path [3]:

$$A_r(dB\,km^{-1}) = aR^b \tag{1}$$

where A_r is the rain induced attenuation, R is rain rate in mm/hr and the coefficients a and b are generally functions of frequency, polarization and drop size distribution (DSD).

It has long been known that the relationship in (1) could serve as a basis for measurements of path-integrated and area-integrated rainfall. Tomographic reconstruction of two-dimensional rainfall maps from a specially designed system of microwave links appears in a number of works which rely on dedicated, calibrated equipment. Existing techniques are either theoretical or evaluated on small-scale examples [4]. Only recently have advances in communication technology enabled the use of commercial off-the-shelf microwave equipment enabling automatic on-line measurement of radio signals that are affected by precipitation.

The most challenging research issue is establishing a concept and practical algorithms for converting a given WCN into an ESN and using it for environmental monitoring. In the context of rainfall monitoring, the major sub-problems concern how to:

- Extract and process the atmospheric information – rainfall intensities and dynamics – from heterogeneous cellular networks and combine them with other information sources, and
- Evaluate the confidence intervals of the obtained estimates by making use of available information (such as the link density, frequency band, instrument noise, and environmental uncertainties).

Other Challenges

Since WCN are built for communication purposes, we typically do not have an opportunity to optimize them for environmental monitoring. We consider them as they are and search for statistical signal processing techniques to cope with the limitations imposed by the WCN's design.

While a WCN-based ESN is free of some practical challenges characterizing a conventional ESN (e.g., design and installation of equipment and communications, multipath, energy and bandwidth limitations and survivability issues), there are other challenges. The equipment is irregularly (arbitrarily) distributed in space, the quality of measurements, spatial representativeness and temporal resolution at each microwave link are different, and the environment is dynamic (configuration of a network constantly changes, data are sporadically missed) and harsh (observations are complicated by various noise sources, both environmental and instrumental; some pre-processing of the measurements may be imposed). Finally, the network is inherently heterogeneous, composed of microwave links from different manufacturers, providing observations at various temporal and magnitude resolutions.

Determination of Specific Attenuation Due to Rainfall

To measure rainfall-induced attenuation of a radio signal, the baseline (no-rain) Received Signal Level (RSL) has to be estimated. Then, the baseline estimate should be subtracted from the measured (logarithmic) RSL value to obtain the specific attenuation due to rainfall.

The problem is, however, that the baseline RSL constantly changes due to variations of vapor concentration in the atmosphere (Fig. 2), atmospheric scintillation, and anomalous propagation in the atmosphere (ducting). Besides, variations in temperature affect the analog data processing path, and movement of the cellular towers due to wind may lead to additional signal variations.

In general, a 'rain/no rain' decision can be made based on the statistical properties of measured signals [5], and then during the 'no rain' periods, the baseline signal level can be measured and interpolated over the rainy periods. More advanced techniques will involve joint processing of multiple links installed in parallel or nearby [6].

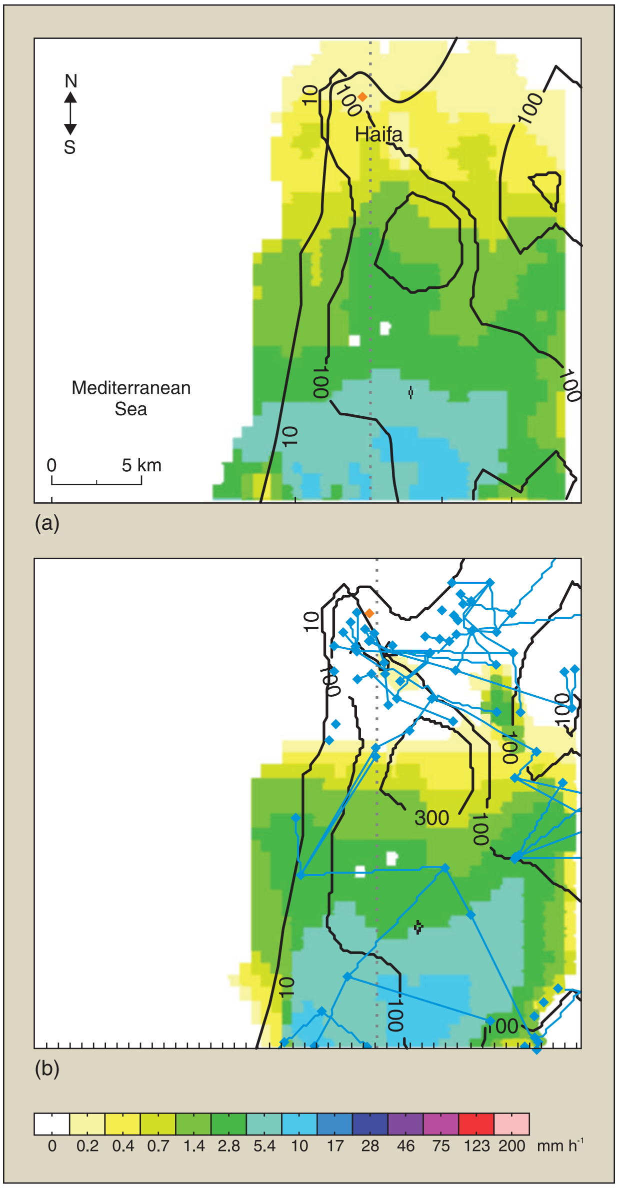

Fig. 3. (a) A rainfall intensity field produced by weather radar. (b) The same rainfall field reconstructed from simulated multiple microwave links data (MATLAB). The black contours are geographic elevations in meters above sea level.

Reconstruction of Rainfall Intensity Fields

When dealing with existing operating networks, we have no control over the system configuration and parameters. The structure of the network, frequency and polarization of electromagnetic waves for a specific link, and temporal and magnitude resolution of the observations are predetermined by the equipment manufacturers and transmission engineers.

On the other hand, the geometry of the system of links is arbitrary, and the spatial resolution of the WCN-based ESN is therefore determined by the given link topology. The link density is highly variable: from 3 links per km^2 in urban areas to 0.3 and lower in rural ones.

To overcome the above issues, various spatial interpolation algorithms can be considered, such as stochastic interpolation, where each link is represented as a set of discrete points from which measurements are then interpolated using linear or non-linear parameter estimation techniques. These techniques may include inverse distance weighting-like algorithms or non-linear tomography over a variable density grid, where the cell sizes on a grid follow the density of the underlying WCN [7]. Fig. 3a shows a rainfall intensity field produced by weather radar. Fig. 3b is the same rainfall field obtained by reconstruction of observations from simulated multiple microwave links showing rainfall measured directly near the ground.

This tomographic approach provides a practical solution to the problem of reconstruction of 2D rain rate maps over an irregular microwave network with non-uniform distribution of frequency and polarization among links. This algorithm can easily be adapted to new networks or changing operational frequencies. Still, the major problem of the technique is its limited accuracy due to low density of microwave links in sparse rural regions, an issue that is addressed in the following sections.

Determination of Wind Dynamics

Sensor networks are frequently used for target tracking, which finds applications in the proposed WCN-based ESN. Utilizing joint processing of data from multiple links, one can track the movement of a convective rain system front from a network of microwave links. The velocity and direction of rain cloud movement at every point over a surface can be estimated by correlating the time series coming from different microwave links to identify peaks of rainfall that correspond to the same rain cell. This can be quite a challenging issue in multiple rain-producing clouds moving over the surface and stratiform rainfalls, uniformly covering a large territory. Another issue, specific to WCN-based ESN, is that a link has finite length and cannot be considered as a point in space. In addition, the orientation of microwave links relative to the rainfall front is generally irregular. The goal here is to adopt the approach of multiple target tracking using a sensor network to estimate the speed and direction of cloud movement, which is essential for both effective model-based joint processing of multiple microwave links and forecasting applications [8].

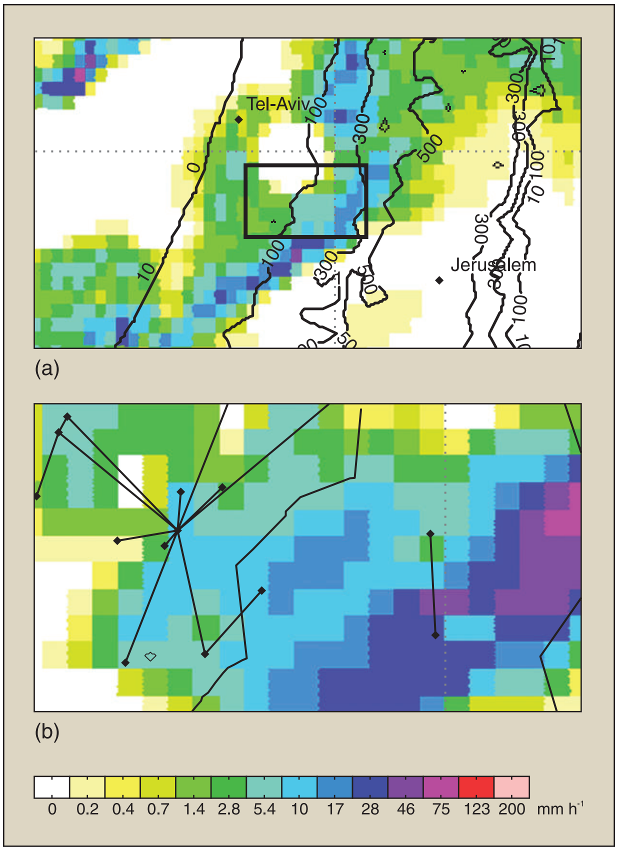

Fig. 4. (a) A rainfall intensity field produced by weather radar. (b) Rainfall measured directly near the ground by constructing data from microwave multiple links over the selected area in (a) (MATLAB).

Data Assimilation

The performance of any 2D reconstruction algorithm over an already existing network is limited by its physical properties. Thus, the accuracy of rainfall estimation decreases with reducing link density. In this case, utilizing the time dimension may help to circumvent the lack of observations in data-void regions. Knowing the velocity and direction of the rainstorm at its steering level, the microwave RSL measurements are assimilated into a stochastic space-time model based on rainstorm advection with an extended Kalman filter [8]. This allows the data to be aggregated in time and space along the direction of motion of the rainstorm. The ability of the model to estimate the rainstorm advection velocity is similar to Doppler weather radars. Fig. 4 shows an example of the spatio-temporal reconstruction. Fig. 4a shows a rainfall intensity field produced by weather radar. Fig. 4b shows rainfall near the ground as determined from multiple microwave links data from the selected area in Fig. 4a. Note that the rainfall in the data-void area is estimated using temporal information predicted from past observations.

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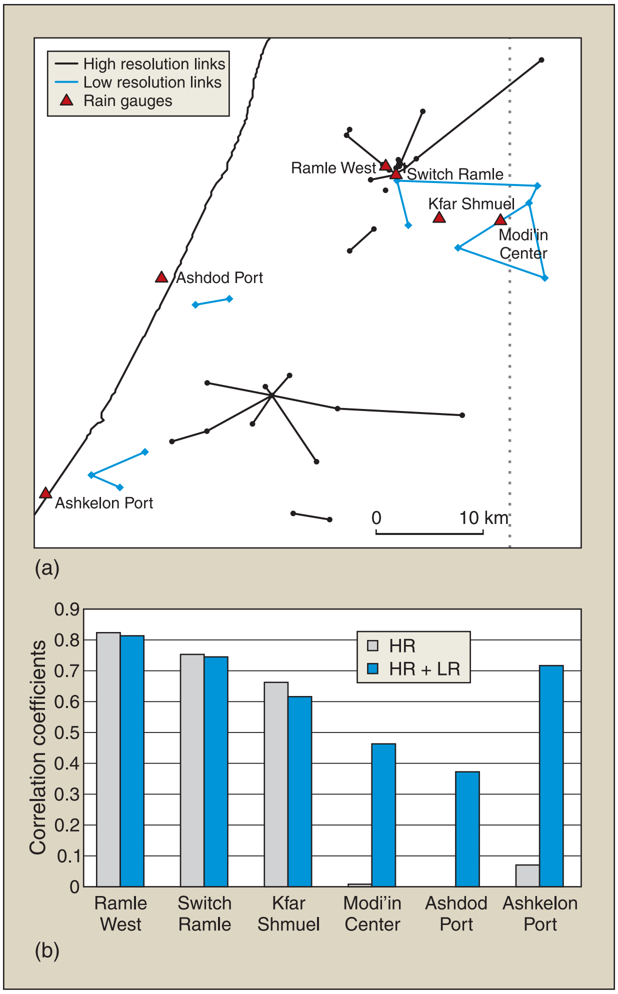

Fig. 5. Integration of data from multiple networks: (a) A map of the area with HR links marked in black, LR links in blue, and rain gauges are noted by red triangles (MATLAB). (b) The correlation coefficients between rain gauge and microwave link measurements.

Integration of Data from Multiple Networks

Each cellular provider uses different microwave networks equipped with heterogeneous hardware that operate over the same area or in adjacent areas. The integration of this heterogeneous data becomes quite challenging.

Let us consider an example of two segments of microwave networks from Israeli cellular providers operating in central Israel at frequencies of 18-23 GHz. One of the networks, abbreviated as 'High Resolution' (HR), provides instantaneous Received Signal Level (RSL) measurements at a temporal resolution of 1 min, while the second one, abbreviated 'Low Resolution' (LR), only allows measurement of maximum and minimum RSL over a 15 min interval. (The data were provided by Israeli cellular providers Cellcom and

Pelephone.) Here, the spatial distribution of rainfall fields, reconstructed from performance measurements of HR alone or from both networks are compared with the time series of point rainfall measurements, recorded by five rain gauges installed in the area.

Clearly, the HR measurements are more accurate (even after resampling to the uniform 15 min resolution), as Fig. 5b illustrates. When only the HR network measurements are used for rainfall reconstruction (Fig. 5), one can see that in the areas where there are no nearby (i.e. around 10 km) HR links (Fig. 5a), the correlation between the measurements made by the reconstruction technique and the rain gauge measurements is low (Fig. 5b). The gauges in Modi'in Center, Ashdod Port and Ashkelon Port demonstrate nearly-zero correlation with microwave rainfall estimates due to the large distance to the nearby links and due to the high spatial variability of the convection rainstorm, typical for Israel. Inclusion of LR microwave data into the reconstruction leads to considerable improvement of the accuracy (correlation of WCN-based ESN measurements with rain gauge samples increases up to 0.35-0.72) at these sites, but it leads to a slight degradation in the performance of the method in the areas where there are HR links: near the Ramle West, Switch Ramle, and Kfar Shmuel rain gauges. In these locations, the integration of more uncertain (LR) rainfall measurements did not bring any additional information, just noise.

The technique can find applications in thunderstorm short-term forecasting (nowcasting), where the accurate measurement of precipitation and rainstorm dynamics with sufficient time and space resolution is essential.

As Fig. 5 illustrates, more sophisticated techniques are needed to optimally utilize the potential of multi-net WCN-based ESN. In general, there are many methods of fusion of different quality data from multiple sensors (here: links and subnetworks). They vary from simple rule-based (e.g. selection of the best available result – robust due to simplicity but suboptimal) to a variety of linear and non-linear parameter estimation techniques. The latter must take into account the measurement uncertainty to properly weight observations. Most advanced model-based techniques employ mechanisms of phenomena generation similar to the rainfall advection models described above. It should be noted, though, that the rainfall advection models are sensitive to the assumptions about the physics of the phenomena and should be carefully verified.

Uncertainty Quantification

The rainfall measurements from commercial microwave communication networks are inherently uncertain, since the frequency bands and network geometry are chosen by telecommunication engineers to maximize the communication performance, rather than optimize measurement (e.g., choose frequency where the relation of (1) is close to linear). In general, the accuracy of microwave rainfall measurements and its theoretical limits has already been studied in the past [9]. However, as Fig. 5 shows, in the case of heterogeneous microwave networks, it is important to have online estimation of measurement uncertainties for reconstruction of rainfall intensity distribution from multiple links and WCN at each time frame and each point in space [10].

Isolating rainfall-induced attenuation is complicated by the fact that the power control measurements from microwave networks are quantized, frequently at the magnitude resolution of 1 dB, causing irrecoverable information loss in the case of weak signals (corresponding to weak rainfall). On the other hand, some microwave communication systems employ automatic power control, adjusting the transmit power according to the RSL drops due to rainfall and other effects. In this case, the records of transmit power (typically also available in a quantized form) should be taken into account to reconstruct the rainfall-induced power loss.

On the other hand, the type of observation may vary. Some stations are able to report the instantaneous RSL measurements every minute, while others supply only limited information about attenuation such as minimum and maximum RSL over 15 min intervals or even once per day, so that the measurements are even more uncertain and unreliable. Considering these error sources as random variables, the accurate estimation of their variances becomes vital for integration of data from multiple heterogeneous observations.

Besides measurement errors due to baseline signal level variations and excess attenuation due to antenna wetting, there are other environmental impairments that should be taken into account. First of all, there are variations in DSDs from large scale (variation for different climates) to small scale (variation of DSD between different events and even within the same event, at different spatial locations or different times). Links, operating at various frequencies and polarizations, are affected differently by DSD variations. At frequencies of around 34 GHz where the power-law relation (1) becomes nearly-linear, the measurements are quite insensitive to DSD, while at lower frequencies (beneath 18 GHz), considerable errors may be encountered.

Finally, reconstruction of rainfall intensity over an area is affected by the spatial variation of rainfall. Microwave links sample the rainfall field in a small number of locations, while the data-void areas between links remain uncovered. Reconstruction of rainfall intensity in these areas requires knowledge of spatial correlation properties of rainfall, for example, in the form of semivariograms.

Emerging Research

While the non-linear 2D tomographic reconstruction technique over a variable density grid can readily be applied for practical applications, further research is needed for improving its performance by avoiding some of its basic assumptions (such as constant rainfall over a grid cell), reformulating the (deterministic) algorithm in a statistical framework, and introducing regularization according to data-driven spatial correlation estimates using non-linear parameter estimation techniques and geostatistics methods. Such accurate modeling of spatial variability is especially important since it is spatial rainfall variability that is the major source of uncertainties, at least for convective rainstorms. Statistical algorithms require knowing variances of path-averaged rainfall estimates, and the mean squared error (MSE) expressions can be applied there. Similar modeling of spatial variability is essential for subsequent interpolation of the data from reconstruction grid into the regular (fine) grid. Application of optimal geostatistical interpolation algorithms may be beneficial. The isotropic spatial variability model allows one to explain most of the errors; however, more accurate anisotropic spatial variability models would fit the convective rainstorms more accurately.

The spatio-temporal reconstruction approach partially resolves the problem of lack of observations and can be adopted to large-scale assimilation systems. The technique can find applications in thunderstorm short-term forecasting (now-casting), where the accurate measurement of precipitation and rainstorm dynamics with sufficient time and space resolution is essential.

However, some research may be needed to enable real-time applications. Thus, knowing rain/no-rain periods for determination of baseline signal level requires a robust algorithm for rain/no-rain period classification. Prediction of a baseline for real-time applications from past no-rain RSL estimates implies additional (forecast accuracy) errors. Another limitation of the spatial-temporal reconstruction is the necessity to have data samples available for determination of the advection direction. For real-time measurement and now-casting applications, prediction of wind direction changes should be applied instead, taking into account the uncertainty increase, again, due to forecast errors. Resolving the abovementioned issues is necessary to enable practical use of the method, and it requires more research and development of appropriate algorithms.

WCN Use in Other Environmental Studies

This paper is devoted to rain rate measurements and wind velocity; however, applications of microwave links for environmental studies are not limited to rainfall [1], [11]. The use of commercial microwave links for measurement of other hydrometeors is a natural extension of the technique. In some cases, the necessary theoretical basis already exists. Thus, hail is typically described as either dry or spongy spheres, distributed either exponentially or uniformly (in case of large monodisperse hail spheres). Mie scattering in two-layer spherical models is appropriate for describing either melting hail (water-coated spheres) or freezing rain (ice-coated spheres). However, the applicability and experimental verification of models for frozen and mixed-phase hydrometeors require further research. Enabling monitoring of hydrometeors other than rain may require research on classification of hydrometeors. Microwave rainfall and water vapor measurements may find applications in numerical weather prediction, facilitating improved initialization of atmospheric models.

It may be beneficial to fuse microwave rainfall data with other sources (gauges, radar or satellite) using data assimilation techniques. Combining radar and microwave links in real time enables taking advantage of the near-surface location of the microwave links and the high spatial resolution of the radar. Simultaneous observations of radar and microwave links may facilitate hydrometeor classification applications.

Conclusion

We demonstrated the feasibility of using microwave communication links from a cellular communication infrastructure as environmental sensor networks for rainfall monitoring. To date, research has been focused mostly on studying the potential of commercial microwave networks for rainfall observation as a standalone tool. There is still much work to be done to fully explore the potential of this tool.

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