Atmospheric Monitoring Using Commercial Microwave Networks

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Abstract. During the last decade, dozens of papers have indicated the ability of commercial microwave networks to monitor and map rainfall. However, other atmospheric phenomena also affect the radio channel, and cause interference that can be measured by these systems. While fog, water vapor and dew are among the additional hydrometeors that can cause signal loss, anomalies in the atmospheric refractive index identified with temperature inversions also affect these communication links. In this paper we review a variety of different research showing the ability that exists in this technology for environmental monitoring.

Keywords: Microwave links, fog, water vapor, dew, temperature inversions

1. Introduction

Commercial microwave links are the infrastructure that allows for data transmission between cellular network base stations. These links are deployed close to ground level, are installed across vast regions worldwide, and operate in the frequency range of tens of GHz. As such, they are affected by weather conditions adjacent to the ground and can be used as a low cost sensor network for atmospheric monitoring. Figure 1 shows a typical microwave tower. This example demonstrates the relative proximity towers typically have to transportation routes, agricultural areas and to ground level in general, hence the motivation to use this existing infrastructure for environmental monitoring.

The existing environmental monitoring tools have several disadvantages, thus the need for development of additional technologies. In situ sensors, for example, do not represent the measured phenomenon well in space (e.g. humidity gauges that provide a point observation that does not closely represent the humidity in the larger surrounding area). Satellite systems provide good spatial resolution observations, but have difficulties, at times, observing ground level conditions from space (e.g. when high level cloud cover obscures ground level fog from the satellite's point of view). Additionally, the expenses involved in purchasing, installing and maintaining the proprietary equipment is typically high.

Environmental measurements from cellular network infrastructure, then, can provide a complementary tool to existing monitoring instruments, or the principal measurement tool in places where existing instruments fail or do not exist at all.

Of the different atmospheric conditions that affect microwave links, rain has a dominant effect, causing measurable signal loss in the network. Thus, the ability of these systems to monitor rain was first demonstrated over a decade ago, at times even in a way that has advantages over proprietary instruments (Messer *et al*., 2006; Leijnse *et al*., 2007; Schleiss *et al*., 2013; Overeem *et al*., 2013). Monitoring rain is crucial for many reasons, from house chore needs, to support pluvial agriculture, and, for example, to provide early warning of dangers associated with intensive rainfall, such as destructive flash flooding (David *et al*., 2013a).

Other environmental phenomena that are not rain, though, also affect the microwave transmission. Therefore, this already existing “sensor network”, has the potential to monitoring these phenomena, as long as they induce measurable interference in respect to the sensitivity of the microwave system. Recent papers have shown that this technology can monitor a variety of environmental parameters, including fog (David *et al*., 2013b; 2015), water vapor (David *et al*., 2009; 2011; Chwala *et al*., 2014), dew (Harel *et al*., 2015; David *et al*., 2016), and indirectly – air pollution (David and Gao, 2016). In this paper, we review these research works and indicate the future challenges and the potential benefits of using this technology.

2. The potential of commercial microwave networks to monitor environmental phenomena

In this section we briefly discuss the importance of monitoring the different atmospheric parameters and present the connections that describe the physical link between the interference caused to the microwave signal and each of the different phenomena. For complete details, including error calculations, details of uncertainty factors, full description of the monitoring techniques, etc., we point the reader in each section to the papers published on the topic.

2.1. Water vapor

Atmospheric humidity plays a central role in a range of environmental processes, and is one of the most influential greenhouse gases. The water vapor evaporation and recondensation cycle is a key energy redistributing mechanism transferring heat energy from the face of the Earth to the atmosphere. A range of meteorological end products, including weather forecasting, are based on the results of atmospheric models. The accuracy of these results is determined by the quality of the initial condition data that is fed to the model while the humidity field in particular, is a critical variable in model initialization (David *et al.*, 2009). As a result of the limited scope of humidity observations, and particularly the fact that existing point measurements acquired by typical humidity gauges are often not representative, there is uncertainty about water vapor distribution in the atmosphere, and thus partly due to this uncertainty, prediction of convective precipitation, on the storm scale, is limited (e.g. Fabry, 2006).

At microwave frequencies of tens of GHz in the lower troposhpere, the dominant absorbing gases are water vapor and oxygen. While the latter has a resonance band around 60 GHz, atmospheric humidity has an absorption line at 22.235 GHz. Notably, around the water vapor absorption line the dry air induced attenuation is an order of magnitude lower than that of the water vapor. Since commercial microwave links typically operate between 6 to 40 GHz, links that operate around 22- 23 GHz, i.e. around the 22.235 GHz absorption line, can be advantageously chosen for such measurements. Equation 1 describes the attenuation induced by dry air and atmospheric humidity:

$$\gamma = \gamma_o + \gamma_v = 0.1820 f N''(\rho, P, T) \qquad \text{(dB/km)} \qquad (1)$$

Where:

γ_v (dB/km):Water vapor induced attenuation.

γ_o(dB/km): Dry air induced attenuation.

f (GHz): Microwave link's frequency.

N'' (N-units): The imaginary part of the complex refractivity, a function of the water vapor density ρ(g m^{-3}), pressure P(hPa) and the temperature T(°C).

A complete derivation of Eq. (1) can be found in literature (David *et al.*, 2009; 2011; David, 2014).

2.2. Fog

By definition, fog reduces visibility below 1 km (Glickman, 2000), and as such, can cause severe accidents in all transportation modes, extensive property damage and loss of life (e.g. Ashley *et al.*, 2015). The phenomenon, though, also has positive aspects. For example, by harvesting fog, fresh water can be produced and used for gardening, forestation management, and even for use as potable water. In water scarce regions, this contribution can be particularly significant (e.g. Klemm *et al.*, 2012). Fog has also been shown to play an important role in cleaning the atmosphere by particle scavenging, followed by drop deposition (Herckes *et al.*, 2007). However, widespread and reliable mapping of the phenomenon is a challenge. Satellite systems, that are currently used for mapping fog, cannot, at times, reliably detect it. For example, in cases where the satellite detects a low stratus cloud, but cannot reliably determine whether it is fog that exists at ground level, or a higher elevation cloud which does not pose a danger for drivers on the roads, for example.

Herein lies the motivation to develop tools for mapping the phenomenon in high spatial and temporal resolution, and with maximum proximity to ground level. Commercial microwave links have the potential to provide atmospheric information of this type. Notably, recent research has shown the feasibility for monitoring fog using this method (David *et al.*, 2013b). Other research demonstrated the potential for 2D mapping of fog theoretically, as well as potential for improved mapping resolution in the future as commercial microwave networks shift to higher operating frequencies in order to answer the demand for faster data rates (David *et al.*, 2015).

Equation 2 describes the relation between fog induced attenuation, γ_f (dB/km), and the liquid water content – LWC(g/m^3):

$$\gamma_f = 0.273 \cdot Im\left(\frac{\tilde{N}^2-1}{\tilde{N}^2+1}\right) \cdot f \cdot LWC \qquad \text{(dB/km)} \qquad (2)$$

Where $\tilde{N}$ is the complex refractive index and f (GHz) is the link frequency.

A complete derivation of Eq. (2) can be found in literature (David, 2014).

2.3. Dew

Dew takes part in several ecological processes. For example, it provides a source of humidity for animals (e.g. Degen *et al.*, 1992), and in some areas, dew formation serves as a key part of the general vegetation water strategy economy in the arid and semiarid zones (Ben-Asher *et al.*, 2010). On the other hand, the phenomenon has negative effects. Plant pathologists, for example, indicate the negative effect dew has on advancing the spread of plant diseases (Sentelhas *et al.*, 2008). Acquiring high spatio-temporal information about dew may be combined with satellites to derive more precise observations of soil moisture (Du *et al.*, 2012) – an important element of the hydrological cycle, affecting weather and climate.

In cases where relative humidity (RH) is high, a thin layer of water (or water droplets) may condense on the microwave units, attenuating the signal measured across the link (Henning and Stanton, 1996; David, 2014). Recent research (Harel *et al.*, 2015; David *et al.*, 2016) indicates a match between the attenuation caused by this condensation and dew measurements carried out using a leaf wetness sensor. The effect of dew is the result of condensation on the antenna itself and therefore the measured attenuation in the network is not dependent on the length of the propagation path. Thus, it has been demonstrated using the

Generalized Likelihood Ratio Test (GLRT) that dew can be detected using commercial microwave networks based on this principle (Harel *et al.*, 2015).

a. Temperature inversions

Air pollution is associated with a wide range of severe and chronic health impacts. For example, in 2012, the World Health Organization (WHO) claimed that 3 million premature deaths worldwide were attributable to ambient air pollution. Notably, the meteorological conditions existing at a certain location affect the level of air pollution, and particularly –Temperature Inversions (TIs).

In standard conditions, temperature in the troposphere decreases with altitude. A temperature inversion is a case where in a certain layer, temperature increases with altitude. This situation suppresses vertical movement in the atmosphere, and if it takes place close to the ground, creates optimal conditions for air pollution (and when RH is high – for fog) that gets trapped underneath that layer. The atmospheric refractivity index is a function of temperature- T (k), partial water vapor pressure- e (hPa) and the total atmospheric pressure – P (hPa), as shown in Equation 3:

$$\mathrm{N} = 77.6\,\frac{\mathrm{P}}{\mathrm{T}} + 3.732 \times 10^{5}\,\frac{e}{T^{2}} \quad \text{(N-units)} \qquad (3)$$

Thus, strong TIs that capture humidity under them, are identified with gradients of the atmospheric refractivity index with altitude, an effect that leads to abnormal propagation due to bending of the microwaves beyond the standard case. This, according to Snell's Law of propagation between mediums with different refractive indices (here, n_1 and n_2):

$$\mathrm{n}_1 \sin\alpha_1 = \mathrm{n}_2 \sin\alpha_2 \qquad (4)$$

Where:

α_1 – The angle of incidence.

α_2 – The angle of refraction.

The abnormal propagation in these cases can present itself as attenuation or amplification of Received Signal Level (RSL) when compared to standard conditions. The potential for detecting cases of air pollution and fog using commercial microwave networks, based on these principles, was recently demonstrated (David and Gao, 2016).

3. **Summary**

While a large part of the papers in the field of environmental monitoring using commercial microwave links has focused on monitoring rain, the system has the potential to sense other phenomena as well. Future research will need to further examine these new concepts for monitoring other than rain phenomena, including water vapor, dew, fog and temperature inversions using as many events as possible in a wide range of locations across the globe. Deepening the understanding of how meteorological phenomena affect cellular networks essentially means more efficient utilization of existing infrastructure for environmental monitoring on one hand, and the ability to better design these links to operate as a stable communications system, on the other (reducing the interference atmospheric conditions can cause to the links). A major future challenge would be to further examine the potential contribution the proposed technology has for improving environmental monitoring capabilities in developing countries where weather monitoring tools are limited, if they exist at all.

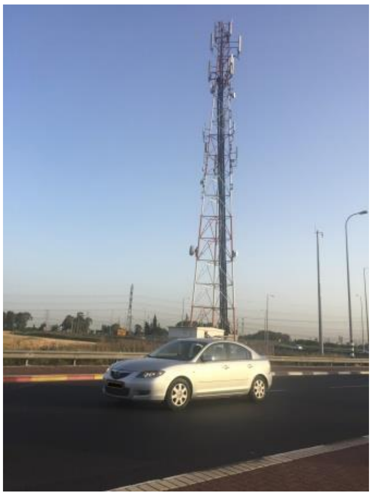

Figure 1. Typical microwave tower (near Hod Hasharon city, Central Israel, 2017). The microwave antennas, the round drum like objects attached to the mast near ground level, are visible.

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