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A Data-Driven Approach for Studying the Washout Effects of Rain on Air Pollution

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***Abstract*—**Air pollution is a serious environmental threat on a global scale and can cause harm to human health, morbidity and premature mortality. Reliable monitoring and control systems are therefore necessary to develop coping skills against the hazards associated with this phenomenon. However, existing environmental monitoring means often do not provide a sufficient response due to practical and technical limitations. Commercial microwave links that form the infrastructure for transmitting data between cell phone towers can be harnessed to map rain at high tempo-spatial resolution. Rainfall causes a decrease in the signal strength received by these wireless communication links allowing it to be used as a built-in sensor network to map the phenomenon. In this study, we point to the potential that lies in this system to indirectly monitor areas where air pollution is reduced. The relationship between pollutant wash-off and rainfall provides an opportunity to acquire important spatial information about air quality using existing cell-phone tower signals. Since the density of microwave communication networks is high relative to any dedicated sensor arrays, it could be possible to rely on this available observation tool for studying precipitation scavenging on air pollutants, for model needs and more.

***Keywords*—**Air pollution, commercial microwave links, rainfall.

I. Introduction

AIR pollution, as compared to other environmental hazards, requires special focus. This phenomenon may lead to respiratory and cardiovascular diseases including lung cancer, asthma and heart stroke. According to the World Health Organization, for example, in 2012, approximately 3 million premature deaths were attributable to ambient air pollution globally [1]. Therefore, effective use of air pollution monitoring and mitigation resources is crucial to developing the capabilities required to cope with the dangers associated with this phenomenon. However, existing tools for air quality monitoring are often plagued by technical and practical constraints resulting in a lack of sufficient reporting. The observations collected by the conventional monitoring means that including remote sensing systems and ground level measuring instruments may not be representative for the entire space (e.g. in situ sensors) or may suffer from lack of precision when measuring adjacent to the Earth's surface (satellites). Furthermore, the costs entailed in the deployment and maintenance of the specialized means in the field are high, an obstacle that is of specific significance in developing regions, such as Africa, where conventional monitoring instruments are scarce, if they exist at all. Over the past two decades, multi-system informatics has become increasingly spread as it is embedded into our surrounding infrastructure systems. These technologies create remarkable data streams which often contain invaluable environmental information with exceptional levels of coverage and immediacy [2], thus providing a growing opportunity to complement traditional observation techniques [3]. A key example is the use of measurements from commercial Microwave Links (MWLs) that form the data transmission infrastructure in cellular communication networks. These newly available 'virtual sensors' have become an essential monitoring tool over the past decade [4].

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II. Harnessing Microwave Communication Data for Monitoring Environmental Phenomena

Commercial MWLs operate at frequencies of tens of GHz and close to ground level, typically at elevations of tens of meters above the surface. These systems provide measurements of the Received Signal Level (RSL) at typically high temporal resolution (for example, every 15 minutes). The cellular providers typically store this standard data for quality of assurance needs. Weather conditions affect the signal strength of the wireless network and it can therefore be used as an environmental monitoring facility.

Fig. 1 A communication mast in Hyderabad, India; the microwave drum-like antennas, denoted by the arrows, were originally designed for communication needs and can constitute a built-in sensor network for environmental monitoring

Commercial MWLs are deployed all across the world, including in developing regions such as India, or countries across Africa [5]-[7]. Furthermore, the data necessary for carrying out the required observations is the RSL between base stations of the wireless communication network itself. Thus, it does not involve end user privacy issues of any kind.

Given the comprehensive coverage of cellular communication networks and measurement availability from all land locations globally, the proposed low-cost solution introduces a wide range of possibilities which previously existing technologies could not offer. For example, commercial MWLs have been found to be effective in monitoring rainfall [8]-[10]. Rain causes a significant reduction in the signal strength that is received by the MWLs and most of the research conducted to date in this emerging field has demonstrated the ability to monitor this phenomenon. Additional studies indicate the potential of these networks to monitor other hydrometeors including fog [11]-[13], water vapor [14]-[16] and dew [17].

Notably, some air pollutants have absorption lines in the microwave region. However, they induce negligible attenuation on the channel [18] with respect to precipitation in the frequency bands currently prevalent (tens of GHz). Hence, direct detection of atmospheric pollutants through the proposed approach still remains a challenge. However, a recent study has demonstrated the potential to detect air pollution indirectly using commercial microwave measurements [1].

Under standard atmospheric conditions, the temperature in the low atmospheric layer decreases with increasing height. Temperature inversion is a condition in which in a certain atmospheric layer the temperature rises with increasing height. This condition suppresses vertical atmospheric movements and therefore produces optimal conditions for creating increased ground level air pollution [19]. On the other hand, significant temperature inversions are associated with a stable state characterized by atmospheric layering. Under these conditions, the refractive index gradient with height is different from the standard state and causes perturbations (amplification/attenuation) to the microwave RSL. As a result, detection of these conditions using commercial MWLs can directly indicate an increase in air pollution [1]. Here we point to the *potential* to indirectly map air quality using commercial MWLs.

Since commercial microwave networks are widely deployed, especially in urban areas, it is possible to generate 2D rainfall maps on a multiple link basis. In addition, the wash out effect of rain leads to reduced air pollution [20]-[23]. Thus, commercial MWLs can potentially be used to indirectly map areas of improved air quality.

III. Two-Dimensional Rainfall Monitoring as a Basis for Mapping Areas of Reduced Air Pollution

The rainfall intensity, *R*, along the link propagation path can be estimated using the following formula [24]:

$$A = aR^b \text{ (dB/km)} \quad (1)$$

The precipitation induced attenuation, *A*, can be estimated from the RSL measurements taken by the commercial MWL while the parameters a and b are known and depend on the rainfall drop size distribution, on the frequency and polarization of the microwave signals.

During rainfall the microwave antennas become wet and therefore an additional attenuation may be created relative to that caused directly by the rain drops along the propagation path. In order to obtain more accurate assessments this effect should be taken into account (e.g. [25]).

Previous studies have shown the ability to map the intensity of the rain across space using commercial MWLs based on the abundance of available measurements, both spatially and temporally (e.g. [26], [27]). Fig. 2 demonstrates such a capability.

IV. Demonstrating the Potential to Monitor Washing of Particulate Air Pollution Using Microwave Towers

Throughout Israel, on March 8-9, 2006, a severe haze episode caused high quantities of particulate air pollution to be reported. A following rain event that developed across the region, on March 9, led to the washing of pollutants. Fig. 2 presents a 2D rainfall intensity map from the same day at 15:19 produced using commercial MWLs that were deployed across the experiment test site in central Israel.

The image (Fig. 2) is taken from Goldshtein et al. [28] where the ability to map rain based on commercial microwave measurements was first demonstrated using the Shepard's interpolation method [29]. The red asterisks mark the locations of two air pollution measurement stations whose records are shown in Fig. 3. The estimated rain intensities appear on the scale to the right of the figure. The straight lines represent the microwave propagation paths.

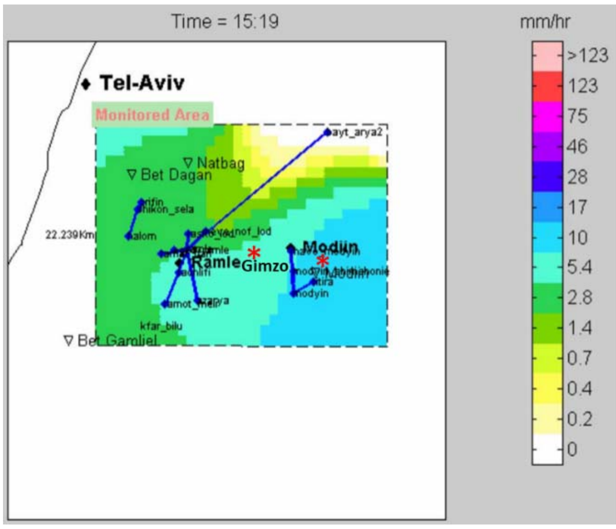

Fig 2 Rain mapping across the experimental site in central Israel using commercial MWLs [28]

Fig. 3 (A) presents the measurements of particle air pollution (PM-10) observed in the area by two different monitoring stations. A significant drop in the pollutant concentration can be observed after approximately 15:00, that is, close to the time when the 2D snapshot of rainfall intensity was produced using microwave measurements (Fig. 2). Fig. 3 (B) shows the amount of precipitation (mm) as measured by a designated rain gauge that was situated in the city of Modi'in in the vicinity of the Modi'in air pollution station (Fig. 2).

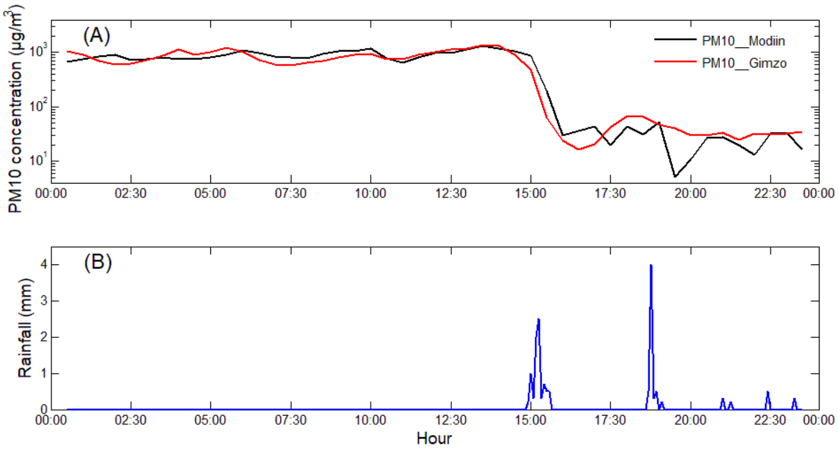

Fig. 3 Environmental measurements: (A) Measurements of PM10 pollution as taken by Modiin (black curve) and Gimzo (red curve) stations on the 9th of March 2009 between the hours of 00:30 and 23:30 of that day. The curves presented are based on half-hour averages. A sharp decline in the concentration of particulate matter as a result of rain washing is observed around 15:15-15:30. (B) The amount of precipitation (mm) as measured by the rain gauge that was situated in the city of Modi'in (in the vicinity of the local air pollution station)

Notably, due to the wash out effect of the rain, the values of the PM concentration fell by two orders of magnitude from severe air pollution conditions, in which the PM values were found to be around 1000 $\mu g/m^3$ to a state where they were measured to be of the order of 10's of $\mu g/m^3$.

Previous studies indicate threshold values of rainfall above which the particulate pollutants are washed off (e.g. [23]) where, on the other hand, recent research indicates the ability to estimate the amount of accumulated rainfall using commercial MWL measurements (e.g. [30]). D'Amico et al. [31] used a tomographic technique for the reconstruction of 2-D fields of rainfall accumulation. Therefore, in future research, it will be possible to examine the ability to map areas in which air pollution is significantly reduced where the cumulative rainfall, as measured using commercial MWLs, exceeded the threshold values for washing off the pollutants.

V. Conclusion

Accurate rainfall monitoring is of significant importance for various applications such as warning against flash floods, pluvial agricultural, or for the planning of urban infrastructures (e.g. [7], [32], [33]). The ability to monitor this phenomenon using commercial MWLs has been proven during the past decade (e.g. [9], [10], [26], [34]), at times, in ways that overcome the abilities of radar systems, due to the proximity of the network links to the ground, and its extensive geographic coverage (e.g. [30]). Alternately, other research has shown that the very fact that the microwave network is deployed in remote areas where the density of conventional rain gauges is particularly low, such as deserts, can provide an alternative solution [35].

As we have pointed out in this paper, the potential to map areas where air pollution is significantly reduced as a result of the rain washing off effect is an added value inherent in the proposed technology. In particular, since the density of these radio links is enormous relative to any dedicated sensor network, especially in urban areas where population density is high, it will be possible to rely on this technology for model needs.

As reviewed by [22], relatively simple variables such as precipitation rate and solubility are factors most washout effect parameterizations are modeled on. Henry's law coefficient or solubility [36] expresses a simple rate illustrated in well-controlled laboratory conditions demonstrating that the washout effect of air pollutants simply involves physical and chemical interactions between air pollutants and water. However, increased accuracy air pollution prediction is possible based on atmospheric chemistry models given the complex chemical processes associated with heterogeneous chemistry, chemical compounds, and atmosphere. The washout effect does not always depend linearly on the solubility, as these air pollutants interact with various meteorological and chemical conditions in the real world. Thus, extensive and reliable measurements as acquired by the proposed technology are essential for model validation.

Note that the combination of air pollution with low rainfall amounts may lead to decreased air quality conditions [23]. Therefore, rain mapping using this method can also assist in mapping areas where air quality is often even lower.

The fact that weather conditions and air pollution are closely interrelated, combined with the widely available microwave data, affords a new window to be opened to a variety of opportunities concerning the monitoring of air quality using this approach. For example, it will be possible to examine the ability to reconstruct two-dimensional maps of areas in which temperature inversions (which form the preconditions for the creation of extreme air pollution) exist. Recent studies indicate the potential to map fog using commercial MWLs [11], while fog was also found to be an effective means of scavenging pollutants (e.g. [37]). Therefore, it will potentially be possible to study the relationship between fog and its effects on air pollution using the proposed technique. Furthermore, in the future, a shift to higher frequencies of operation, such as between 130 GHz and 175 GHz, is expected [38]. In these high operating frequencies, dust and haze particles induced attenuation may reach 0.5-1 dB/km [39]. On the other hand, some MWLs have a magnitude resolution of only 0.1 dB, meaning that they may become potentially sensitive to observe the phenomenon. Further investigation is required regarding this issue, a challenge left for future work.

Due to the relatively simple installation and mobility of MWLs in an area, while allowing for simple information transmission even over complex terrain (valleys, urban areas, etc.), this technology will continue to be a key tool for data transmission in the future [40]. This being the case, the opportunity arises for achieving environmental measurements, instantly, at minimal cost and with the assurance that the technology will be available and sustainable in the years to come.

References

[1] David, N., & Gao, H. O. (2016). Using Cellular Communication Networks To Detect Air Pollution. Environmental science & technology, 50(17), 9442-9451. DOI: 10.1021/acs.est.6b00681

[2] Koonin, S.E. and Holland, M., 2014. The value of big data for urban science. *Privacy, Big Data and the Public Good*.

[3] David, N. (2019). Harnessing Crowdsourced Data and Prevalent Technologies for Atmospheric Research. Advances in Atmospheric Sciences, 36(7), 766-769.

[4] Alpert, P., Messer, H., & David, N. (2016). Mobile networks aid weather monitoring. *Nature*, *537*(7622), 617-617.

[5] Doumounia, A., Gosset, M., Cazenave, F., Kacou, M., & Zougmore, F. (2014). Rainfall monitoring based on microwave links from cellular telecommunication networks: First results from a West African test bed. Geophysical Research Letters, 41(16), 6016-6022. DOI: 10.1002/2014GL060724

[6] Gosset, M., et al. (2016). Improving rainfall measurement in gauge poor regions thanks to mobile telecommunication networks. Bulletin of the American Meteorological Society, 97(3), ES49-ES51. DOI:10.1175/BAMS-D-15-00164.1

[7] David, N., Gao, H. O., Kumah, K. K., Hoedjes, J. C. B., Su, Z., & Liu, Y. Microwave communication networks as a sustainable tool of rainfall monitoring for agriculture needs in Africa. 16th International Conference on Environmental Science And Technology (CEST). Rhodes, Greece, 4-7 September, 2019.

[8] Upton, G. J. G., Holt, A. R., Cummings, R. J., Rahimi, A. R., & Goddard, J. W. F. (2005). Microwave links: The future for urban rainfall measurement?. Atmospheric research, 77(1-4), 300-312.

[9] Messer, H., Zinevich, A., & Alpert, P. (2006). Environmental monitoring by wireless communication networks. Science, 312(5774), 713-713. DOI: 10.1126/science.1120034.

[10] Leijnse, H., Uijlenhoet, R., & Stricker, J. N. M. (2007). Rainfall measurement using radio links from cellular communication networks. Water Resources Research, 43(3). DOI: 10.1029/2006WR005631

[11] David, N., Sendik, O., Messer, H., & Alpert, P. (2015). Cellular network infrastructure: The future of fog monitoring?. Bulletin of the American Meteorological Society, 96(10), 1687-1698. DOI: https://doi.org/10.1175/BAMS-D-13-00292.1

[12] David, N., & Gao, H. O. (2018). Using Cell-Phone Tower Signals for Detecting the Precursors of Fog. Journal of Geophysical Research: Atmospheres, 123(2), 1325-1338.

[13] David, N. (2018). Utilizing microwave communication data for detecting fog where satellite retrievals are challenged. Natural Hazards, 94(2), 867-882.

[14] David, N., Alpert, P., & Messer, H. (2009). Novel method for water vapour monitoring using wireless communication networks measurements. Atmospheric chemistry and physics, 9(7), 2413-2418. DOI: https://doi.org/10.5194/acp-9-2413-2009.

[15] Chwala, C., Kunstmann, H., Hipp, S., & Siart, U. (2014). A monostatic microwave transmission experiment for line integrated precipitation and humidity remote sensing. Atmospheric research, 144, 57-72.

[16] David, N., Sendik, O., Rubin, Y., Messer, H., Gao, H. O., Rostkier-Edelstein, D., & Alpert, P. (2019). Analyzing the ability to reconstruct the moisture field using commercial microwave network data. Atmospheric research, 219, 213-222.

[17] Harel, O., David, N., Alpert, P., & Messer, H. (2015). The Potential of Microwave Communication Networks to Detect Dew—Experimental Study. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 8(9), 4396-4404. DOI: 10.1109/JSTARS.2015.2465909

[18] Frey, T. L.: The effects of the atmosphere and weather on the performance of a mm- wave communication link, Appl. Microw. Wirel. Mag., 76-80, 1999.

[19] Shmool, J. L., Michanowicz, D. R., Cambal, L., Tunno, B., Howell, J., Gillooly, S., ... & Gorczynski, J. E. (2014). Saturation sampling for spatial variation in multiple air pollutants across an inversion-prone metropolitan area of complex terrain. Environmental Health, 13(1), 28.

[20] Croft, B., et al. (2009). Aerosol size-dependent below-cloud scavenging by rain and snow in the ECHAM5-HAM. Atmospheric Chemistry and Physics, 9(14), 4653-4675.

[21] Duhanyan, N., & Roustan, Y. (2011). Below-cloud scavenging by rain of atmospheric gases and particulates. Atmospheric Environment, 45(39), 7201-7217.

[22] Yoo, J. M., Lee, Y. R., Kim, D., Jeong, M. J., Stockwell, W. R., Kundu, P. K., ... & Lee, S. J. (2014). New indices for wet scavenging of air pollutants (O3, CO, NO2, SO2, and PM10) by summertime rain. Atmospheric Environment, 82, 226-237.

[23] Guo, L. C., Zhang, Y., Lin, H., Zeng, W., Liu, T., Xiao, J., ... & Ma, W. (2016). The washout effects of rainfall on atmospheric particulate pollution in two Chinese cities. Environmental Pollution, 215, 195-202.

[24] Olsen, R. O. G. E. R. S., Rogers, D. V., & Hodge, D. (1978). The aR b relation in the calculation of rain attenuation. IEEE Transactions on antennas and propagation, 26(2), 318-329.

[25] Zinevich, A., Messer, H., & Alpert, P. (2010). Prediction of rainfall intensity measurement errors using commercial microwave communication links. Atmospheric Measurement Techniques, *3*(5), 1385.

[26] Zinevich, A., Messer, H., & Alpert, P. (2009). Frontal rainfall observation by a commercial microwave communication network. Journal of Applied Meteorology and Climatology, 48(7), 1317-1334. DOI: https://doi.org/10.1175/2008JAMC2014.1

[27] Overeem, A., Leijnse, H., & Uijlenhoet, R. (2013). Country-wide rainfall maps from cellular communication networks. Proceedings of the National Academy of Sciences, 110(8), 2741-2745. DOI: 10.1073/pnas.1217961110

[28] Goldshtein, O., Messer, H., & Zinevich, A. (2009). Rain rate estimation using measurements from commercial telecommunications links. IEEE Transactions on Signal Processing, 57(4), 1616-1625. DOI: 10.1109/TSP.2009.2012554

[29] Shepard, D. (1968, January). A two-dimensional interpolation function for irregularly-spaced data. In Proceedings of the 1968 23rd ACM national conference (pp. 517-524). ACM.

[30] Liberman, Y., Samuels, R., Alpert, P., & Messer, H. (2014). New algorithm for integration between wireless microwave sensor network and radar for improved rainfall measurement and mapping. Atmospheric Measurement Techniques, 7(10), 3549-3563. DOI: https://doi.org/10.5194/amt-7-3549-2014

[31] D'Amico, M., Manzoni, A., & Solazzi, G. L. (2016). Use of operational microwave link measurements for the tomographic reconstruction of 2-D maps of accumulated rainfall. IEEE Geoscience and Remote Sensing Letters, 13(12), 1827-1831.

[32] Fencl, M., Rieckermann, J., Schleiss, M., Stránský, D., & Bareš, V. (2013). Assessing the potential of using telecommunication microwave links in urban drainage modelling. Water Science and Technology, 68(8), 1810-1818. DOI: 10.2166/wst.2013.429
[33] Hoedjes, J. C., et al. (2014). A conceptual flash flood early warning system for Africa, based on terrestrial microwave links and flash flood guidance. ISPRS International Journal of Geo-Information, 3(2), 584-598. DOI: 10.3390/ijgi3020584
[34] Chwala, C., Keis, F., & Kunstmann, H. (2016). Real-time data acquisition of commercial microwave link networks for hydrometeorological applications. Atmospheric Measurement Techniques, 9(3), 991-999.
[35] David, N., Alpert, P., & Messer, H. (2013). The potential of cellular network infrastructures for sudden rainfall monitoring in dry climate regions. Atmospheric research, 131, 13-21. DOI: https://doi.org/10.1016/j.atmosres.2013.01.004
[36] Seinfeld, J. H., & Pandis, S. N. (2016). *Atmospheric chemistry and physics: from air pollution to climate change*. John Wiley & Sons.
[37] Herckes, P., H. Chang, T. Lee, and J. L. Collet (2007), Air pollution processing by radiation fogs, Water Air Soil Pollut., 181,65–75.
[38] Edstam, J., Hansryd, J., Carpenter, S., Emanuelsson, T., Li, Y & Zirath, H. (2017). Microwave backhaul evolution – reaching beyond 100GHz, Ericsson technology review.
[39] Liebe, H. (1983). Atmospheric EHF window transparencies near 35, 90, 140 and 220 GHz. IEEE Transactions on Antennas and Propagation, 31(1), 127-135.
[40] Ericsson (2016), Ericsson microwave outlook, trends and needs in the microwave industry.