Article

Capitalizing on Cellular Technology—Opportunities and Challenges for Near Ground Weather Monitoring †

Hagit Messer

School of Electrical Engineering, Tel Aviv University, Tel Aviv 6997801, Israel; messer@eng.tau.ac.il;
Tel.: +972-3640-8119
† This publication is an extension of Messer H. Capitalizing on Cellular Technology—Opportunities and Challenges for Environmental Monitoring, Proceedings of CEST 2017.

Received: 8 May 2018; Accepted: 19 June 2018; Published: 22 June 2018

Abstract: The use of existing measurements from a commercial wireless communication system as virtual sensors for environmental monitoring has recently gained increasing attention. In particular, measurements of the signal level of commercial microwave links (CMLs) used in the backhaul communication network of cellular systems are considered as opportunistic sensors for precipitation monitoring. Research results have demonstrated the feasibility of the suggested technique for the estimating and mapping of rain, as well as for monitoring other-than-rain phenomena. However, further advancement toward implementation and commercial use are heavily dependent on multidisciplinary collaborations: Communication and network engineers are needed to enable access to the existing measurements; signal processing experts can utilize the different data for improving the accuracy and the tempo-spatial resolution of the estimates; atmospheric scientists are responsible for the physical modeling; hydrologists, meteorologists, and others can contribute to the end uses; economists can indicate the potential benefits; etc. In this paper I will review state-of-the-art results and the open challenges, demonstrating the benefit to the public good from utilizing the opportunistic-sensing approach. I will also analyze the various obstacles on the way there.

Keywords: opportunistic sensing; rain monitoring; commercial microwave links

1. Introduction

The relation between the rain intensity \( R \) (in mm/h) and the attenuation of a microwave wireless signal \( A \) traveling in the atmosphere is relatively simple:

\[
A = aR^b l
\]  

where \( A \) is in dB, \( l \) is the path length (in km) of the link and \( a, b \) are constants, depending on the frequency and the polarization of the signal, as well as on the drop size distribution (DSD) of the rain, which is considered as typical to an area. This relation is a simplified model of complex physical relations [1,2] which has empirically been found to be a good approximation for the rain-induced signal’s attenuation, for microwave frequencies and for links of length of about 0.5–20 km. Equation (1), which become linear \((b = 1)\) for a certain choice of signal parameters, first suggested in Reference [3]. This raised the idea to use microwave links (MLs) for rainfall measurements in the early 90s [4–6], and it was experimentally tested in a multinational European project [7]. However, as the installation of dedicated MLs is costly, in combination with their limited coverage and questionable accuracy, this idea has not spread. In 2006, Messer et al. [8] first demonstrated the idea of taking advantage of the existing, widely spread, cellular communication technology, and used the MLs, which are part of its backhaul network, for environmental monitoring. While the relation (1) still forms the basis of...
this idea, the use of commercial microwave links (CMLs) instead of dedicated MLs as in Reference [9],
brings new opportunities, as well as challenges. The major opportunity is obvious: the availability
of millions of potential virtual meteorological sensors almost everywhere on Earth, with no costs
for installation, maintenance, or communication. Since 2006, interest in this technology has rapidly
increased and many research groups around the world are contributing to it. However, the fact that it
has not yet been commercialized is indicative of the challenges its implementation poses.

In this paper, I will review the most advanced CML technology and its future directions as regards
becoming an operational environmental monitoring system.

2. Materials and Methods

The CML-based weather monitoring technology depends on the availability of materials:
measurements of the received signal level (RSL) and the transmitted signal level (TSL) from the
microwave backhaul network of a cellular communication system. In most countries, a cellular
company owns the infrastructure, so the required measurements are owned by a private company.
While the use of measurements of the transmitted/received signal levels is of no risk to either the
communication services or to the privacy of the users, most cellular providers are reluctant to provide
a third party access to their intra-network. On the other hand, researchers interested in CML technology
have approached cellular companies and succeeded in receiving measurements. The following sections
explore these protocols.

2.1. The Passive Approach

Manufacturers of the backhaul transmission networks have implemented tools in their systems
which monitor and log the signal levels of all links in the network. The tool, known as the network
management system (NMS), produces RSL and TSL indicators which are automatically logged by the
network operators (i.e., the cellular providers). The passive approach relies on the use of the already
existing NMS records as inputs for the CML weather monitoring technology. The major advantage of
the passive approach is that it puts neither burdens nor risks on the cellular providers, so it is relatively
simple to get them to share this data. However, as the NMS data is kept for network monitoring,
and in particular, for monitoring the actual link budget, the RSL (and TSL) signals in the NMS go
through a highly nonlinear process. Typically, only the minimum and the maximum RSL (and TSL)
values, from the measurements taken over a window of 15 min, are stored. Moreover, these values
are quantized at a 0.1–1 dB resolution. Furthermore, as they are mostly used for analysis, the NMS
records are rarely available in real time. An example of a typical RSL time series from an NMS record
is depicted in Figure 1.

![Figure 1](image-url)

**Figure 1.** Typical time series of the minimum/maximum received signal level (RSL), extracted from
network management system (NMS) records. The X-axis represents time at 15-min intervals.
2.2. The Active Approach

Modern microwave communication networks are remotely managed. That is, the network operators can access and inquire the status of the different CMLs remotely. Specifically, most CML hardware is connected to the provider’s intra-net, and uses the simple network management protocol (SNMP) to submit queries to the CMLs, and receive the requested information. The active approach is to use the SNMP to collect RSL measurements dedicated for weather monitoring. A recent publication details this methodology, and establishes a set of open-source tools which can be used to actively access the CMLs of main manufacturers, and receive the instantaneous RSL (and TSL) samples [9]. With this approach, RSLs (and TSLs) are available in real time as instantaneous samples, at sampling intervals that can be as small as 10 s. Note that to avoid unnecessary traffic load for the cellular provider, the active approach also requires adding a designated server for handling the RSL measurements. Also, in most cases, the RSL and the TSL samples collected by this approach still suffer from quantization, as the quantization process is a property (and a limitation) of the sampling hardware itself.

CML measurements collected by the active approach are most suitable for environmental monitoring, both because of the excellent temporal resolution and the lack of the highly nonlinear min/max processing of the NMS. Moreover, the availability of real time measurements is most attractive for applications such as now-casting and flood prediction. However, the active approach requires a high level of involvement from the cellular provider, including permission to a third party to cross its firewall. Most providers are reluctant to allow it, as they see it as a potential risk to their main business, i.e., communication.

Table 1 summarizes the two approaches.

| Characteristics          | Passive                                                                 | Active                                                                 |
|--------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------|
| Source of measurements   | Existing records from network management systems (NMS)                 | Designated data collection system                                      |
| Temporal resolution      | Minutes-days, Typical-15 min                                           | Seconds-minutes, Typical-10 s                                         |
| Non-linear preprocessing | Typically min/max values over a given interval                          | Non                                                                   |
| Quantization             | Yes                                                                    | Yes                                                                   |
| Major advantage          | Simple access, no risk for cellular operators                          | Real time                                                             |
| Major disadvantage       | Not available in real time                                             | Hard to get                                                           |
| Summary                  | Recommended for research purposes and for historic studies             | Essential for real time applications                                  |

2.3. Methods

If instantaneous RSL/TSL measurements are available (as in the Active approach), the total attenuation (in dB) of the CML’s signal can be extracted by subtracting one from the other, and it can be described by [10]:

\[ A_T(t, l) = A_0(l) + A_P(t, l) + A_H(t, l) + A_C(t) + N(t) \]  

(2)

where \( t \) is the time index and, as in Equation (1), \( l \) is the length of the link. \( A_0 \) is the frequency-dependent propagation loss which is constant over time. \( A_P \) is the attenuation caused by precipitation, if existing. For rain, for example, \( A_P = A \) of Equation (1). \( A_H \) is the attenuation due to hydrometeors other than precipitation, e.g., fog or water vapor. This component changes slowly over time, while being small compared with \( A_P \), if existing. \( N(t) \) represents the measurements noise,
and $A_C(t)$ is a component which represents the disruption of the signal by other objects, if existing. Note that Equation (2) is a simplified description of the heavily studied physics of the attenuation of a signal propagating in the atmosphere \[11,12\], which has a great effect on the performance of communication systems \[13\].

Depending on the application, the first stage is to isolate $A_P(t,l)$ (for precipitation monitoring), or $A_H(t,l)$ (for monitoring other-than-rain atmospheric phenomena). This is commonly done by using side information, or by taking advantage of the built-in diversity of CML technology, as there are usually multiple CMLs in a given area of different lengths and frequencies \(\text{(e.g., Reference [14]).}\) The next step is to estimate the parameter of interest \(\text{(e.g., rain-rate)}\) from the corresponding term, using the known relation between the signal attenuation and the phenomenon of interest. A flowchart of this possible process is presented in Figure 2.

![Figure 2. A possible workflow for a commercial microwave link (CML) based environmental monitoring, where the input is the transmitted/received signal level measurements (TSL/RSL) (after O. Harel).](image)

Obviously, measurements collected by the passive approach are far from being \textit{ready to use for this analysis}. The instantaneous total attenuation $A_T(t,l)$ required by Equation (2) cannot be extracted from the min/max indicators of the TSL/RSL. A systematic approach, for example, for extracting rain-rate estimates from extreme measurements provided using the passive approach is described in Reference \[15\] and is depicted in Figure 3.

![Figure 3. A possible workflow for rain estimation from passive measurements, where appropriate power-law (PL) is adjusted to maximum attenuation (after J. Ostrometzky [15]).](image)

3. Results

Since first introduced in 2006, research groups from different disciplines have started to study this technology, and dozens of peer-reviewed papers have been published. The references include many selected publications of studies which are CML measurement-based. In general, these papers can be divided into four groups:

1. Papers in which the capabilities of CML technology for environmental monitoring have been demonstrated (see Table 2). Naturally, foremost potential is attributed to the near-ground rainfall
monitoring capability. Several papers demonstrated the CML as a rainfall sensor, and many CMLs as a sensors network, capable of 2D rainfall mapping. Later, other papers have demonstrated the use of CMLs for monitoring other-than-rain phenomena, including humidity, fog, dew, snow and sleet, and even wind and air pollution (indirectly).

Table 2. Demonstrations of capabilities.

| Atmospheric Phenomenon     | Reference                |
|----------------------------|--------------------------|
| Rainfall sensing           | [8,16–18]                |
| Rainfall mapping           | [8,19]                   |
| Humidity sensing           | [20]                     |
| Fog sensing                | [21–23]                  |
| Precipitation classification| [24]                     |
| Dew detection              | [25]                     |
| Wind estimation            | [26]                     |
| Air pollution detection    | [27]                     |

2. The next step was to study the accuracy of CMLs as virtual rainfall sensors. Since cellular networks have been designed to operate optimally for efficient telecommunication service and not for measuring rain (or other atmospheric variables), its opportunistic use for rain monitoring is challenging, since the network must be taken as is. Table 3 presents a summary of the major contributions to an errors and uncertainties analysis. The analysis aims at quantifying the different sources’ errors and their effect on the resulting rain estimates. Generally speaking, the uncertainties can be put into two groups: one which is related to physical, atmospheric effects, e.g., wet antenna, which cause attenuation that may read as higher rain-intensity value in Equation (1) if not properly handled. The second group consists of errors caused by the opportunistic use of existing technology not aimed at atmospheric monitoring. This may include signal quantization and non-linear pre-processing (applied on the signal for efficient network management), as well as errors resulting from the non-optimal, given spatial spread of links and frequencies in the CML network, when being used for atmospheric monitoring.

Table 3. Errors and uncertainties analysis.

| Sources of Errors        | Reference                     |
|--------------------------|-------------------------------|
| General                  | [10,28–31]                   |
| Dry/Wet                  | [32–35]                      |
| Wet antenna              | [36–38]                      |
| Calibration              | [39]                          |
| Quantization bias        | [40]                          |
| Non-linear preprocessing | [15,41]                      |
| Network topology         | [42]                          |

3. In Table 4, a list of papers suggesting algorithms for rainfall monitoring is presented. As the main opportunity in CML technology is in near ground, bottom-up rain mapping, most algorithms are focused on this. The straightforward approach is to treat each CML as a local point measurement and to interpolate local measurements to a grid, using standard spatial interpolation techniques (e.g., inverse distance weighting IDW, Kriging, etc.). On the basis of this approach, open software tools were developed [43,44]. More advanced algorithms have been developed by signal processing experts, on which the tempo-spatial resolution of the rainfall maps, their accuracy and their coverage have been improved by exploiting the spatial spread of the CML measurements. Different authors used different approaches, such as: an iterative approach in which variability of rain along the links is exploited [19]; a compressed sensing approach [45,46]; a model based, parametric approach; a tomographic approach [47]; and dynamic mapping [48,49].
The main future challenge is to improve CML rainfall maps by merging with other types of measurements (mostly radar), where these exist (see Reference [50] for a review of this issue).

Table 4. Algorithms and tools.

| Focus of the Algorithm                  | Reference                  |
|----------------------------------------|----------------------------|
| Instantaneous rain mapping             | [19,45,46,51–54]           |
| Dynamic rain mapping                   | [48,49,55]                 |
| Heavy rain detection                   | [56]                       |
| Merging with other measurements        | [50,57,58]                 |
| Rainfall tomography                    | [47,59]                    |
| Accumulated precipitation             | [60]                       |
| Open software tools                    | [43,44]                    |

4. Table 5 details a partial list of applications. In all papers in this table, actual CML measurements were employed and empirical results were presented and validated over time, in different climatological areas.

Table 5. Applications and use.

| Application                                      | Reference (Year) | Area/Comments |
|--------------------------------------------------|------------------|---------------|
| Large scale rainfall estimation/mapping          | [61,62]          | Holland       |
| Rainfall measurements                            | [63,64]          | Africa        |
|                                                  | [65]             | Israel        |
| Rainfall measurements                            | [66,67]          | Germany       |
|                                                  | [68]             | Holland       |
|                                                  | [69]             | Ecuador       |
| Flood prediction                                 | [70]             | Israel        |
| Disaster alarm                                   | [71]             |               |
| Calibration of other sensors                     | [72–77]          |               |
| Hydrology                                        | [78–82]          | Urban drainage|

Lately, after more than a decade of expanding research, the proposed approach has finally gained the attention of the private sector. First, Ericsson initiated a pilot project [83], and in 2015 a startup company was established [84].

4. Conclusions

The CML environmental monitoring technology was introduced and has developed into academic research. By negotiating with local cellular providers, multidisciplinary research groups all over the world have received access to CML measurements in their countries, mostly for no cost, and are studying different aspects of this technology. Most of these groups are now collaborating and sharing experience, tools and knowledge in different ways, so a new scientific community has been built. While the achievements of this community are impressive, the road ahead is challenging.

4.1. The Commercialization Challenge

Proving the feasibility of CML technology and having an active scientific community are most important for the sustainability and for the future advancement of this emerging technology. However, the next step in the journey is the technology transfer for the public good. The established research is an important component, but is not sufficient. A necessary condition for CML technology to be used is to ensure access to measurements. Fortunately, the changes in the communication markets push
cellular companies to look for new business, so they are now more open to explore the potential of creating revenues from CML technology. Another part in this equation is the market itself, in which measurements and (big) data of any kind become valuable assets. Multinational companies such as IBM™ and Google™ are now interested in weather, and CML technology is the best source for weather-related (big) data. Note, however, that sustainable access to the measurements is a key issue for the commercial use of CML technology, and a necessary pre-condition for its practical use.

4.2. Potential Use

The vast research reviewed in this paper indicates the great potential of CML technology in future environmental monitoring, once the availability of measurements is granted. Potential use can be divided between three main families:

a. Covering blind spots. There are areas where almost no near-ground measurements are available. One such example includes country-wide areas in developing countries, such as Africa [60,63]. Other examples are local, and include specific challenging landscapes such as slopes and urban areas, where traditional ground weather stations are known to be less reliable. Even with the limited accuracy of CML technology, in cases where there is no alternative, its potential is extremely important.

b. Improving monitoring accuracy. Even in areas where the coverage of conventional weather-monitoring facilities (e.g., gauges and radar) is good, the use of additional ground-level measurements can improve performance. The potential improvement highly depends on the topology of the network (e.g., its density) and on the temporal resolution of the available measurements.

c. Improving models. Complex meteorological and hydrological models, used for forecasting, are continuously improved by comparing their predictions to actual measurements. CML technology offers a new dimension of data to be assimilated in such models.

4.3. Limitations

As discussed in Reference [53], cellular networks have been designed and dimensioned to operate optimally for efficient telecommunication service and not for measuring rain (or other atmospheric variables). The design of microwave links as designated sensors for the observation of the lower atmosphere would be very different. This raises an intriguing scientific challenge for the research community. Signal processing and machine learning algorithms are being developed to overcome limitations in the measurements. Moreover, the question of potential improvements in performance resulting from using CML measurements is an open, and important one. If it can be theoretically proven that the potential performance improvement is significant, then the motivation to use CML technology will be higher. Note, however, that performance can be defined in different ways, depending on the application. It can be the accuracy of measuring total rainfall in a given area and time slot, or accuracy of measuring instantaneous rain rate at a given point, or accuracy of the spatial, 2-D representation of the rain in a given time slot or period, etc. The analysis and the results will depend on the CML network as well as on the characteristics of the atmospheric phenomenon under study (e.g., the spottiness of the rain). In Reference [42], for example, the achievable spatial resolution of rain mapping was studied and has been characterized as a function of the sparsity of the rain, as well as of the statistical features of the CMLs in the area.

4.4. A Test Case for Opportunistic Sensing of the Environment

CML technology has recently been mentioned as one of the first Internet of Things (IoT) applications [85], which is now getting much attention. While the conditions for CML technology becoming useful seems to be right, and we may see it soon in products as well as in public-good services, it also serves as a pioneering example of the new trend of capitalizing on existing technology
by utilizing it for non-intended, opportunistic use [86–88]. Opportunistic sensing is believed to be the future of environmental monitoring, being a sustainable source of (big) environmental data. The analyses provided in this paper for the case of CML technology can serve as a test case for this emerging trend of opportunistic sensing, demonstrating the need for open bi-directional communication channels within the world of academia, where innovative ideas are initiated and studied, and for contemporary industry, which serves as a source of opportunistic measurements as well as a platform for utilization of new ideas.

To conclude: The uniqueness of CML technology stems from its special situation, standing between science and technology, between academia and industry. Future development of this technology and its potential use in practice depend on business challenges as well as on science and technology. The focus of this paper is to review the most advanced developments in CML technology and to anticipate its future development, based on an analysis of the opportunities and challenges faced by researchers in this area over the years. Depending on the future evolution of CML technology, it will be important to provide a deep scientific critical review of this technology, including meticulous scientific background on the different sources to the signal’s attenuation, comparative analysis of the different algorithms, etc.

**Funding:** This research is based on integration of works and has received no specific external funding.

**Acknowledgments:** I would like to thank all my students and my collaborators over the years, and especially my co-PI Pinhas Alpert, for their contributions to advancing the research on this topic. A special acknowledgment is given to the major cellular providers in Israel, Cellcom, Pelephone and Partner, and to Ericsson AB for sharing knowhow, measurements and data with us.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Atlas, D.; Ulbrich, C.W. Path-and area-integrated rainfall measurement by microwave attenuation in the 1–3 cm band. *J. Appl. Meteorol.* 1977, 16, 1322–1331. [CrossRef]
2. Hogg, D.C. Millimeter-Wave Communication through the Atmosphere. *Science* 1968, 159, 39–46. [CrossRef] [PubMed]
3. Olsen, R.O.G.E.R.S.; Rogers, D.V.; Hodge, D. The aRb relation in the calculation of rain attenuation. *IEEE Trans. Antennas Propag.* 1978, 26, 318–329. [CrossRef]
4. Giuli, D.; Toccafondi, A.; Gentili, G.B.; Freni, A. Tomographic reconstruction of rainfall fields through microwave attenuation measurements. *J. Appl. Meteorol.* 1991, 30, 1323–1340. [CrossRef]
5. Giuli, D.; Fachetris, L.; Tanelli, S. Microwave tomographic inversion technique based on stochastic approach for rainfall fields monitoring. *IEEE Trans. Geosci. Remote Sens.* 1999, 37, 2536–2555. [CrossRef]
6. Ruf, C.S.; Aydin, K.; Mathur, S.; Bobak, J.P. 35-GHz dual-polarization propagation link for rain-rate estimation. *J. Atmos. Ocean. Technol.* 1996, 13, 409–425. [CrossRef]
7. D’Amico, M.; Pinotti, M.; Capsoni, C. The MANTISSA project: First results from the Italian field experiments. In Proceedings of the 2003 IEEE International Geoscience and Remote Sensing Symposium (IGARSS’03), Toulouse, France, 21–25 July 2003; Volume 7.
8. Messer, H.; Zinevich, A.; Alpert, P. Environmental monitoring by wireless communication networks. *Science* 2006, 312, 713. [CrossRef] [PubMed]
9. Rahimi, A.R.; Holt, A.R.; Upton, G.J.G.; Cummings, R.J. Use of dual-frequency microwave links for measuring path-averaged rainfall. *J. Geophys. Res. Atmos.* 2003, 108. [CrossRef]
10. Zinevich, A.; Messer, H.; Alpert, P. Prediction of rainfall intensity measurement errors using commercial microwave communication links. *Atmos. Meas. Tech.* 2010, 3, 1385. [CrossRef]
11. Ulaby, F.T.; Moore, R.K.; Fung, A.K. *Microwave Remote Sensing: Active and Passive, Vol 1: Microwave Remote Sensing Fundamentals and Radiometry*; Artech House Inc.: Norwood, MA, USA, 1981.
12. Liebe, H.J.; Hufford, G.A.; Cotton, M.G. Propagation modeling of moist air and suspended water/ice particles below 1000 GHz. In Proceedings of the AGARD 52nd Specialists Meeting of Electromagnetic Wave Propagation Panel, Mallorca, Spain, 17–20 May 1993; pp. 3.1–3.10.
13. International Telecommunication Union Recommendation. ITU-R P.530-17: Propagation Data and Prediction Methods Required for the Design of Terrestrial Line-of-Sight Systems; International Telecommunication Union Recommendation: Geneva, Switzerland, 2017.

14. Messer, H.; Sendik, O. A new approach to precipitation monitoring: A critical survey of existing technologies and challenges. *IEEE Signal Process. Mag.* **2015**, *32*, 110–122. [CrossRef]

15. Ostrometzky, J. Statistical Signal Processing of Extreme Attenuation Measurements Taken by Commercial Microwave Links for Rain Monitoring. Ph.D. Dissertation, Tel Aviv University, Tel Aviv, Israel, 2017.

16. Fencl, M.; Rieckermann, J.; Sýkora, P.; Stránský, D.; Bareš, V. Commercial microwave links instead of rain gauges: Fiction or reality? *Water Sci. Technol.* **2015**, *71*, 31–37. [CrossRef] [PubMed]

17. Matzler, C.; Koffi, E.; Berne, A. Monitoring rain rate with data from networks of microwave transmission links. In Proceedings of the 3rd European Conference on Antennas and Propagation (EuCAP 2009), Berlin, Germany, 23–27 March 2009; pp. 907–910.

18. Leijnse, H.; Uijlenhoet, R.; Stricker, J.N.M. Rainfall measurement using radio links from cellular communication networks. *Water Resour. Res.* **2007**, *43*. [CrossRef]

19. Messer, H.; Goldstein, O.; Rayitsfeld, A.; Alpert, P. Recent results of rainfall mapping from cellular network measurements. In Proceedings of the IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP 2008), Las Vegas, NV, USA, 31 March–4 April 2008; pp. 5157–5160.

20. David, N.; Alpert, P.; Messer, H. Novel method for water vapour monitoring using wireless communication networks measurements. *Atmos. Chem. Phys.* **2009**, *9*, 2413–2418. [CrossRef]

21. David, N.; Sendik, O.; Messer, H.; Alpert, P. Cellular network infrastructure: The future of fog monitoring? *Bull. Am. Meteorol. Soc.* **2015**, *96*, 1687–1698. [CrossRef]

22. David, N.; Alpert, P.; Messer, H. The potential of commercial microwave networks to monitor dense fog-feasibility study. *J. Geophys. Res. Atmos.* **2013**, *118*. [CrossRef]

23. David, N.; Gao, H.O. Using Cell-Phone Tower Signals for Detecting the Precursors of Fog. *J. Geophys. Res. Atmos.* **2018**, *123*, 1325–1338. [CrossRef]

24. Cherkassky, D.; Ostrometzky, J.; Messer, H. Precipitation classification using measurements from commercial microwave links. *IEEE Trans. Geosci. Remote Sens.* **2014**, *52*, 2350–2356. [CrossRef]

25. Harel, O.; David, N.; Alpert, P.; Messer, H. The potential of microwave communication networks to detect dew—Experimental study. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2015**, *8*, 4396–4404. [CrossRef]

26. Messer, H.; Zinevich, A.; Alpert, P. Environmental sensor networks using existing wireless communication systems for rainfall and wind velocity measurements. *IEEE Instrum. Meas. Mag.* **2012**, *15*, 32–38. [CrossRef]

27. David, N.; Gao, H.O. Using cellular communication networks to detect air pollution. *Environ. Sci. Technol.* **2016**, *50*, 9442–9451. [CrossRef] [PubMed]

28. Gaona, R.M.F.; Overeem, A.; Leijnse, H.; Uijlenhoet, R. Measurement and interpolation uncertainties in rainfall maps from cellular communication networks. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 3571–3584. [CrossRef]

29. Leijnse, H.; Uijlenhoet, R.; Berne, A. Errors and uncertainties in microwave link rainfall estimation explored using drop size measurements and high-resolution radar data. *J. Hydrometeorol.* **2010**, *11*, 1330–1344. [CrossRef]

30. Leijnse, H.; Uijlenhoet, R.; Stricker, J.N.M. Microwave link rainfall estimation: Effects of link length and frequency, temporal sampling, power resolution, and wet antenna attenuation. *Adv. Water Resour.* **2008**, *31*, 1481–1493. [CrossRef]

31. Berne, A.; Uijlenhoet, R. Path-averaged rainfall estimation using microwave links: Uncertainty due to spatial rainfall variability. *Geophys. Res. Lett.* **2007**, *34*. [CrossRef]

32. Harel, O.; Messer, H. Extension of the mflrt to detect an unknown deterministic signal using multiple sensors, applied for precipitation detection. *IEEE Signal Process. Lett.* **2013**, *20*, 945–948. [CrossRef]

33. Wang, Z.; Schleiss, M.; Jaffrain, J.; Berne, A.; Rieckermann, J. Using Markov switching models to infer dry and rainy periods from telecommunication microwave link signals. *Atmos. Meas. Tech.* **2012**, *5*, 1847–1859. [CrossRef]

34. Schleiss, M.; Berne, A. Identification of dry and rainy periods using telecommunication microwave links. *IEEE Geosci. Remote Sens. Lett.* **2010**, *7*, 611–615. [CrossRef]

35. Ostrometzky, J.; Messer, H. Dynamic Determination of the Baseline Level in Microwave Links for Rain Monitoring from Minimum Attenuation Values. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2018**, *11*, 24–33. [CrossRef]
36. David, N.; Harel, O.; Alpert, P.; Messer, H. Study of attenuation due to wet antenna in microwave radio communication. In Proceedings of the 2016 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Shanghai, China, 20–25 March 2016; pp. 4418–4422.
37. Schleiss, M.; Rieckermann, J.; Berne, A. Quantification and modeling of wet-antenna attenuation for commercial microwave links. *IEEE Geosci. Remote Sens. Lett.* 2013, 10, 1195–1199. [CrossRef]
38. Ostrometzky, J.; Raich, R.; Bao, L.; Hansryd, J.; Messer, H. The Wet-Antenna Effect—A Factor to be Considered in Future Communication Networks. *IEEE Trans. Antennas Propag.* 2018, 66, 315–322. [CrossRef]
39. Ostrometzky, J.; Raich, R.; Eshel, A.; Messer, H. Calibration of the attenuation-rain rate power-law parameters using measurements from commercial microwave networks. In Proceedings of the 2016 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Shanghai, China, 20–25 March 2016; pp. 3736–3740.
40. Ostrometzky, J.; Eshel, A.; Alpert, P.; Messer, H. Induced bias in attenuation measurements taken from commercial microwave links. In Proceedings of the 2017 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), New Orleans, LA, USA, 5–9 March 2017; pp. 3744–3748.
41. Ostrometzky, J.; Messer, H. Accumulated rainfall estimation using maximum attenuation of microwave radio signal. In Proceedings of the 2014 IEEE 8th Sensor Array and Multichannel Signal Processing Workshop (SAM), A Coruna, Spain, 22–25 June 2014; pp. 193–196.
42. Gazit, L.; Messer, H. Sufficient Conditions for Reconstructing 2-D Rainfall Maps. *IEEE Trans. Geosci. Remote Sens.* 2018. [CrossRef]
43. Overeem, A.; Leijnse, H.; Uijlenhoet, R. Retrieval algorithm for rainfall mapping from microwave links in a cellular communication network. *Atmos. Meas. Tech.* 2016, 9, 2425–2444. [CrossRef]
44. Chwala, C.; Keis, F.; Kunstmann, H. Real-time data acquisition of commercial microwave link networks for hydrometeorological applications. *Atmos. Meas. Tech.* 2016, 9, 991–999. [CrossRef]
45. Liberman, Y.; Messer, H. Accurate reconstruction of rain field maps from Commercial Microwave Networks using sparse field modeling. In Proceedings of the 2014 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Florence, Italy, 4–9 May 2014; pp. 6786–6789.
46. Roy, V.; Gishkori, S.; Leus, G. Spatial rainfall mapping from path-averaged rainfall measurements exploiting sparsity. In Proceedings of the 2014 IEEE Global Conference on Signal and Information Processing (GlobalSIP), Atlanta, GA, USA, 3–5 December 2014; pp. 321–325.
47. D’Amico, M.; Manzoni, A.; Solazzi, G.L. Use of operational microwave link measurements for the tomographic reconstruction of 2-D maps of accumulated rainfall. *IEEE Geosci. Remote Sens. Lett.* 2016, 13, 1827–1831. [CrossRef]
48. Roy, V.; Gishkori, S.; Leus, G. Dynamic rainfall monitoring using microwave links. *EURASIP J. Adv. Signal Process.* 2016, 2016. [CrossRef]
49. Zinevich, A.; Messer, H.; Alpert, P. Frontal rainfall observation by a commercial microwave communication network. *J. Appl. Meteorol. Climatol.* 2009, 48, 1317–1334. [CrossRef]
50. Messer, H. Multimodality for Rainfall Measurement. In Proceedings of the International Conference on Latent Variable Analysis and Signal Separation, Grenoble, France, 21–23 February 2017; Springer: Cham, Switzerland, 2017; pp. 333–343.
51. Goldshtein, O.; Messer, H.; Zinevich, A. Rain rate estimation using measurements from commercial telecommunications links. *IEEE Trans. Signal Process.* 2009, 57, 1616–1625. [CrossRef]
52. Zinevich, A.; Alpert, P.; Messer, H. Estimation of rainfall fields using commercial microwave communication networks of variable density. *Adv. Water Resour.* 2008, 31, 1470–1480. [CrossRef]
53. Messer, H. Rainfall monitoring using cellular networks [in the spotlight]. *IEEE Signal Process. Mag.* 2007, 24, 142–144. [CrossRef]
54. Haese, B.; Hörning, S.; Chwala, C.; Bárdossy, A.; Schalge, B.; Kunstmann, H. Stochastic Reconstruction and Interpolation of Precipitation Fields Using Combined Information of Commercial Microwave Links and Rain Gauges. *Water Resour. Res.* 2017, 53, 10740–10756. [CrossRef]
55. Mercier, F.; Barthès, L.; Mallet, C. Estimation of finescale rainfall fields using broadcast TV satellite links and a 4DVAR assimilation method. *J. Atmos. Ocean. Technol.* 2015, 32, 1709–1728. [CrossRef]
56. Abrajano, D.G.; Okada, M. Compressed sensing based detection of localized heavy rain using microwave network attenuation. In Proceedings of the 2013 7th European Conference on Antennas and Propagation (EuCAP), Gothenburg, Sweden, 8–12 April 2013; pp. 2383–2386.
57. Liberman, Y.; Samuels, R.; Alpert, P.; Messer, H. New algorithm for integration between wireless microwave sensor network and radar for improved rainfall measurement and mapping. *Atmos. Meas. Tech.* 2014, 7, 3549–3563. [CrossRef]

58. Bianchi, B.; Jan van Leeuwen, P.; Hogan, R.J.; Berne, A. A variational approach to retrieve rain rate by combining information from rain gauges, radars, and microwave links. *J. Hydrometeorol.* 2013, 14, 1897–1909. [CrossRef]

59. Cuccoli, F.; Facheris, L.; Gori, S.; Baldini, L. Retrieving rainfall fields through 5 tomographic processing applied to radio base network signals. In Proceedings of the Remote Sensing for Agriculture, Ecosystems, and Hydrology XIII, Prague, Czech Republic, 19–22 September 2011.

60. Ostrometzky, J.; Cherkassky, D.; Messer, H. Accumulated mixed precipitation estimation using measurements from multiple microwave links. *Adv. Meteorol.* 2015, 2015, 707646. [CrossRef]

61. Overeem, A.; Leijnse, H.; Uijlenhoet, R. Two and a half years of country-wide rainfall maps using radio links from commercial cellular telecommunication networks. *Water Resour. Res.* 2016, 52, 8039–8065. [CrossRef]

62. Overeem, A.; Leijnse, H.; Uijlenhoet, R. Country-wide rainfall maps from cellular communication networks. *Proc. Natl. Acad. Sci. USA* 2013, 110, 2741–2745. [CrossRef] [PubMed]

63. Gosset, M.; Kunstmann, H.; Zougmore, F.; Cazenave, F.; Leijnse, H.; Uijlenhoet, R.; Chwala, C.; Keis, F.; Doumounia, A.; Boubacar, B.; et al. Improving rainfall measurement in gauge poor regions thanks to mobile telecommunication networks. *Bull. Am. Meteorol. Soc.* 2016, 97, ES49–ES51. [CrossRef]

64. Doumounia, A.; Gosset, M.; Cazenave, F.; Kacou, M.; Zougmore, F. Rainfall monitoring based on microwave links from cellular telecommunication networks: First results from a West African test bed. *Geophys. Res. Lett.* 2014, 41, 6016–6022. [CrossRef]

65. Rayitsfeld, A.; Samuels, R.; Zinevich, A.; Hadar, U.; Alpert, P. Comparison of two methodologies for long term rainfall monitoring using a commercial microwave communication system. *Atmos. Res.* 2012, 104, 119–127. [CrossRef]

66. Chwala, C.; Kunstmann, H.; Hipp, S.; Siart, U.; Eibert, T. Precipitation observation using commercial microwave communication links. In Proceedings of the 2012 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Munich, Germany, 22–27 July 2012; pp. 2922–2925.

67. Chwala, C.; Gmeiner, A.; Qiu, W.; Hipp, S.; Nienaber, D.; Siart, U.; Eibert, T.; Pohl, M.; Seltmann, J.; Fritz, J.; et al. Precipitation observation using microwave backhaul links in the alpine and pre-alpine region of Southern Germany. *Hydrol. Earth Syst. Sci.* 2012, 16, 2647–2661. [CrossRef]

68. Overeem, A.A.R.T.; Leijnse, H.I.D.D.E.; Uijlenhoet, R.E.M.K.O. Quantitative precipitation estimation using commercial microwave links. In Proceedings of the Weather Radar and Hydrology, Exeter, UK, 18–21 April 2011; pp. 129–134.

69. Ramos, B.; Cordero, M.; Hurtado, K.; Núñez, A.; D’Amico, M. Rain rate estimation using a microwave link in Guayaquil City. In Proceedings of the Ecuador Technical Chapters Meeting (ETCM), Salinas, Ecuador, 16–20 October 2017; pp. 1–6.

70. David, N.; Alpert, P.; Messer, H. The potential of cellular network infrastructures for sudden rainfall monitoring in dry climate regions. *Atmos. Res.* 2013, 131, 13–21. [CrossRef]

71. Gustilo, R.C. Design of Wireless Disaster Alarm System Using Microwave Links. *J. Telecommun. Electron. Comput. Eng. JTEC* 2018, 10, 103–108.

72. Bianchi, B.; Rieckermann, J.; Berne, A. Quality control of rain gauge measurements using telecommunication microwave links. *J. Hydrol.* 2013, 492, 15–23. [CrossRef]

73. Zhang, P.; Liu, X.; Li, Z.; Zhou, Z.; Song, K.; Yang, P. Attenuation Correction of Weather Radar Reflectivity with Arbitrary Oriented Microwave Link. *Adv. Meteorol.* 2017, 2017, 6124149. [CrossRef]

74. Trömel, S.; Ziegert, M.; Ryzhkov, A.V.; Chwala, C.; Simmer, C. Using Microwave Backhaul Links to Optimize the Performance of Algorithms for Rainfall Estimation and Attenuation Correction. *J. Atmos. Ocean. Technol.* 2014, 31, 1748–1760. [CrossRef]

75. Krämer, S.; Verworn, H.-R.; Redder, A. Improvement of X-band radar rainfall estimates using a microwave link. *Atmos. Res.* 2005, 77, 278–299. [CrossRef]

76. Yang, X.; Liu, X.; Gao, T.; Yang, C.; Song, K. Regional Attenuation Correction of Weather Radar Using a Distributed Microwave-Links Network. *Adv. Meteorol.* 2017, 2017, 8621239. [CrossRef]

77. Rahimi, A.R.; Holt, A.R.; Upton, G.J.; Krämer, S.; Redder, A.; Verworn, H. Attenuation Calibration of an X-Band Weather Radar Using a Microwave Link. *J. Atmos. Ocean. Technol.* 2006, 23, 395–405. [CrossRef]
78. Fencl, M.; Rieckermann, J.; Schleiss, M.; Stránský, D.; Bareš, V. Assessing the potential of using telecommunication microwave links in urban drainage modelling. *Water Sci. Technol.* 2013, 68, 1810–1818. [CrossRef] [PubMed]

79. Overeem, A.; Leijnse, H.; Uijlenhoet, R. Measuring urban rainfall using microwave links from commercial cellular communication networks. *Water Resour. Res.* 2011, 47. [CrossRef]

80. Fenicia, F.; Pfister, L.; Kavetski, D.; Matgen, P.; Iffly, J.; Hoffmann, L.; Uijlenhoet, R. Microwave Links for Rainfall Estimation in an Urban Environment: Insights from an Experimental Setup in Luxembourg-City. *J. Hydrol.* 2012, 464, 69–78. [CrossRef]

81. Zohidov, B.; Andrieu, H.; Servières, M.; Normand, N. Retrieval of rainfall fields in urban areas using attenuation measurements from mobile phone networks: A modeling feasibility study. *Hydrol. Earth Syst. Sci. Discuss.* 2016. [CrossRef]

82. Upton, G.; Holt, A.; Cummings, R.; Rahimi, A.; Goddard, J. Microwave Links: The Future for Urban Rainfall Measurement? *Atmos. Res.* 2005, 77, 300–312. [CrossRef]

83. Ericsson™: Microweather: The Surprising Future of Microwave Links in Weather Forecasting. Available online: https://www.ericsson.com/thinkingahead/the-networked-society-blog/2016/06/02/9373/ (accessed on 8 May 2018).

84. Jeff, T. Rain forecasts go mobile. Analysis of wireless communications data could give accurate weather at street level. *Nature* 2017, 544, 146–147.

85. Muller, C.L.; Chapman, L.; Johnston, S.; Kidd, C.; Illingworth, S.; Foody, G.; Overeem, A.; Leigh, R.R. Crowdsourcing for climate and atmospheric sciences: Current status and future potential. *Int. J. Climatol.* 2015, 35, 3185–3203. [CrossRef]

86. McCabe, M.F.; Rodell, M.; Alsorf, D.E.; Miralles, D.G.; Uijlenhoet, R.; Wagner, W.; Lucieer, A.; Houborg, R.; Verhoest, N.E.C.; Franz, T.E.; et al. The future of Earth observation in hydrology. *Hydrol. Earth Syst. Sci.* 2017, 21, 3879. [CrossRef]

87. Uijlenhoet, R.; Overeem, A.; Leijnse, H. Opportunistic remote sensing of rainfall using microwave links from cellular communication networks. *Wiley Interdiscip. Rev. Water* 2018. [CrossRef]

88. Tauro, F.; Selker, J.; van de Giesen, N.; Abrate, T.; Uijlenhoet, R.; Porfiri, M.; Manfreda, S.; Caylor, K.; Moramarco, T.; Benveniste, J.; et al. Measurements and Observations in the XXI century (MOXXI): Innovation and multi-disciplinarity to sense the hydrological cycle. *Hydrol. Sci. J.* 2018, 63, 169–196. [CrossRef]