STUDY OF ATTENUATION DUE TO WET ANTENNA IN MICROWAVE RADIO COMMUNICATION

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ABSTRACT

Atmospheric conditions are known to affect the Received Signal Level (RSL) in commercial microwave links (MWLs), that operate at frequencies of tens of GHz. Study of these effects is of great importance both for communication engineers and for environmental monitoring. In this paper we study the phenomenon of a wet antenna. During periods of high relative humidity (RH), a thin layer of water may collect on the outside cover of the microwave units, resulting in increased signal attenuation. Here, we focus on the estimation of the signal power loss caused due to this phenomenon. We used a generalized likelihood ratio test (GLRT) to detect transient signal loss of unknown arrival time and duration, based on existing measurements from a network of commercial MWLs, used in for cellular backhauling. The results indicate the ability of the proposed algorithm to detect and estimate the signal loss of antenna moistening. Beyond its value for commercial microwave networks design, this information holds potential for the detection of dew, which is of great environmental importance.

***Index Terms*—** Wet antenna, Environmental sensor networks, GLRT, Microwave links, RSL

1. INTRODUCTION

Precise environmental monitoring is a necessity for many important functions - from early warning against dangers and weather forecasting, through transportation and aviation operations, to day-to-day needs of man and his surroundings. The conventional environmental sensor networks (ESN) common today, though, do not always provide a sufficient response to this need, due to a range of obstacles, including: installation costs, communication and data processing needs, maintenance limitations, and reliability issues. As a result, this field has developed less quickly than many foresaw a decade ago [1].

In 2006, Messer et al. [2], opened the window to the possibility of environmental monitoring using terrestrial line-of-sight MWLs deployed by cellular operators. Atmospheric conditions affect the RSL in these networks, and thus they provide, in effect, an already deployed ESN in the field. This monitoring system, in a sense, does not suffer from disadvantages often ascribed to conventional ESNs, since the operation and maintenance costs are minimal, as the network is being operated for communication needs anyways, and the measurements needed for environmental monitoring are stored, regardless, for quality of service needs. The use of this infrastructure, that is by definition a communication system, as an opportunistic ESN contains challenges [3], and requires the development of smart signal processing techniques. Thus, since 2006, techniques for monitoring rain from the noisy RSL measurements were developed. These were achieved, for example, by extension of the Multifamily Likelihood Ratio Test (MFLRT) which was applied for detection of rain [4], high resolution rain mapping using multiple links in space [5], [6]. Other work presented precipitation classification through Kernel Fisher discriminant analysis followed by a decision making procedure [7]. These works all build on the common underlying approach of using the measured signal loss across the atmospheric medium between the MWLs in order to monitor the selected phenomenon. In periods of high RH, though, a thin layer of moisture may collect directly on the external microwave units, or on the antenna radomes. Information about such condensation can potentially allow for the detection of dew, in itself an important ecological parameter ([8], [9]), and one on which data is needed in order to achieve more precise observations of soil moisture from satellite data ([10], [11]).

The current paper is a natural continuation of [12], in which the potential of commercial MWLs to detect dew was revealed, where here we focus on estimating the signal loss caused by this phenomenon. The GLRT is used to detect a transient signal of unknown arrival time and duration. Detection and attenuation estimation is carried out on real RSL measurements taken from an existing microwave network, during its routine communication operation. For further and more detailed reading regarding the assumptions made in the paper, additional scientific background and suitable mathe-

We are grateful to Pelphone, Cellcom, Orange and the Israeli Meteorological Service for providing the data for our research.

matical developments, the reader is referred to Harel et al [12].

2. MODEL

The principle of moist antenna detection leans on the idea that the measured attenuation is caused as a result of the layer of water directly on the antenna itself. Thus, when the interference is measured simultaneously across a large number of MWLs in the same area, it will be independent of link length. We model the attenuation $\gamma[n,L]$ as follows ([13]):

$$\begin{aligned}\gamma[n,L] = \gamma_p[n,L] + &\gamma_w[n] + \gamma_v[n,L] \\ &+ \gamma_0[L] + r[n] + q[n] \ \text{dB} \\ n = 1,\ldots,N\end{aligned} \tag{1}$$

Let us define a set of $n = 1,\ldots,N$ samples for each MWL, while L is the propagation path length, $\gamma_p[n,L]$ - rainfall attenuation, $\gamma_v[n,L]$ - other-than-rain attenuation (mainly ascribed to atmospheric humidity ([14],[15]), $\gamma_0[L]$ - free space loss, $\gamma_w[n]$ - moist antenna attenuation, $q[n]$ - quantization error, and $r[n]$ - white noise.

We note that unlike $\gamma_w[n]$, $\gamma_p[n,L]$ and $\gamma_v[n,L]$ are dependent on link length, and are considered here as channel interferences. We assume that $\gamma_p[n,L] = 0$, to verify the correctness of this assumption we ruled out precipitation based on rain gauges located in the area. Additionally, we assumed that the dew and the humidity field (the water vapor in the air) were homogeneous in the observed area.

For simplicity, the quantization effect was approximated using additive quantization noise $q[n]$. This is modeled as an additive uniformly distributed random process with variance $\Delta^2/12$, where Δ is the quantization step. As long as the dispersion of $\gamma_p[n,L]$, $\gamma_w[n]$ and $\gamma_v[n,L]$ is higher than the quantization interval, this approximation is valid for them. The measurement noise at the MWL receiver, $r[n]$, is assumed to be an additive Gaussian noise. Since it is added at the receiver of the MWL, it is independent on link length.

Then, under these assumptions, the attenuation model described in (1) can be converted into a binary hypothesis test that seeks to detect moist antenna induced attenuation. Thus, for the ith MWL out of a given set of M links, we get:

$$\begin{aligned}\mathcal{H}_0: \ &\gamma_i[n,L_i] = L_i \cdot \gamma_v[n] + \gamma_{0i}[L_i] + r_i[n] + q_i[n] \\ \mathcal{H}_1: \ &\gamma_i[n,L_i] = \gamma_w[n] + L_i \cdot \gamma_v[n] + \gamma_{0i}[L_i] + r_i[n] + q_i[n] \\ &n = 1,\ldots,N \ , \ i = 1,\ldots,M\end{aligned} \tag{2}$$

Water vapor concentration typically varies over space and time. Here, these spatial variations were neglected for the observed test area. The justification for this is stemming from the fact that the test area is in a flat region with approximately homogeneous geo-meteorological conditions [16]. Thus, $\mathcal{H}_0$ is defined as the null hypothesis and ascribed to attenuation changes induced by fluctuations in atmospheric humidity, and $\mathcal{H}_1$ is defined as the moist antenna attenuation hypothesis.

Dew is a phenomenon that typically extends for several hours from its initial occurrence, and it is assumed that the absolute humidity (i.e. the amount of atmospheric water vapor) changes more slowly over time [16]. Under these assumptions their attenuations $\gamma_w[n]$ and $\gamma_v[n]$ are considered constant transient signals of unknown arrival time n_w and n_v and of unknown durations τ_w and τ_v, respectively. We assume that free-space loss and atmospheric water vapor attenuation, cause the base-line attenuation of each link i. Excess water vapor induced attenuation is expected since, humidity on dewy nights is typically high (where RH characteristically exceeds the threshold of 85%). We denote the increase in attenuation caused by the difference in water vapor quantity between the early morning hours (dew period) and the late afternoon hours, typical to conditions in Israel, as $\Delta\gamma_v[n]$ (for additional detail please see [12], [16]). The typical late afternoon attenuation induced by atmospheric humidity and the unknown zero level attenuation $\gamma_{0i}[L]$ together are defined as an unknown mean, and represent the baseline attenuation for each link μ_i. The noise measurement $r_i[n]$ and quantization noise $q_i[n]$ for each link i, is modeled by an additive white Gaussian noise (AWGN) $w_i[n]$ of unknown variance σ^2, so that only the second order statistics of the real noise are used. This substitution leads to suboptimal parameter estimation, in the estimation step of the GLRT solution as discussed in the conclusions section. Further, we also assume that the noise processes at the different sensors are independent and identically distributed (IID). Based on the above, the binary hypothesis problem (2) is reduced to:

$$\begin{aligned}\mathcal{H}_0: \ &\gamma_i[n,L_i] = L_i \cdot \Delta\gamma_v[n\,;\tau_v\,,n_v] + \mu_i + w_i[n] \\ \mathcal{H}_1: \ &\gamma_i[n,L_i] = \gamma_w[n\,;\tau_w\,,n_w] \\ &\qquad + L_i \cdot \Delta\gamma_v[n\,;\tau_v\,,n_v] + \mu_i + w_i[n] \\ &n = 1,\ldots,N \ , \ i = 1,\ldots,M\end{aligned} \tag{3}$$

It is worth noting that under each hypothesis there are unknown parameters. We define the $(M+4)$ dimensional vector of unknown parameters under $\mathcal{H}_0$ as $\underline{\theta}_0 \triangleq [\Delta\gamma_v, n_v, \tau_v, \underline{\mu}^T, \sigma^2]^T$ and the $(M+7)$ dimensional vector of unknown parameters under $\mathcal{H}_1$ as $\underline{\theta}_1 \triangleq [\gamma_w, n_w, \tau_w, \Delta\gamma_v, n_v, \tau_v, \underline{\mu}^T, \sigma^2]^T$. In (3), γ_w is the unknown constant moist antenna attenuation and $\Delta\gamma_v$ is the unknown constant additional water vapor attenuation per unit of link length. It is also worth noting that γ_w, n_w, and τ_w are the unknown parameters of the desired signal, while $\Delta\gamma_v[n]$, n_v and τ_v are the unknown parameters of the interference signal. $\underline{\mu} \triangleq [\mu_1,\ldots,\mu_M]^T$ is $(M \times 1)$ vector consisting of the M unknown measurement means (baseline attenuation).

3. DETECTION AND ESTIMATION USING GLRT

No prior information regarding the probabilities of the various hypotheses exists in this detection problem, and one can see that the probability density function (PDF) for each assumed hypothesis is not completely known. The uncertainty is expressed by including unknown non random parameters in the PDF. In cases such as this, where no uniformly most powerful (UMP) test [17] exists, the GLRT is commonly used to provide a solution [18]. The ln version of the GLRT for the binary hypothesis testing model (3) is thus:

$$L_G(\underline{X}) = \ln\left(\frac{P(\underline{X}\,;\,\hat{\underline{\theta}}_1\,,\,\mathcal{H}_1)}{P(\underline{X}\,;\,\hat{\underline{\theta}}_0\,,\,\mathcal{H}_0)}\right)\underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}}\eta \qquad (4)$$

where $P(\underline{X}\,;\,\underline{\theta}_1\,,\,\mathcal{H}_1)$ is the PDF of the received signal $\underline{X} \triangleq [\gamma_1[1,L_1],\ldots,\gamma_1[N,L_1],\ldots,\gamma_M[1,L_M],\ldots,\gamma_M[N,L_M]]^T$ under $\mathcal{H}_1$ with the unknown parameters vector $\underline{\theta}_1$, while $P(\underline{X}\,;\,\underline{\theta}_0\,,\,\mathcal{H}_0)$ is the above signal's PDF under $\mathcal{H}_0$ with the unknown parameters vector $\underline{\theta}_0$. $\hat{\underline{\theta}}_1$ is the Maximum Likelihood Estimates (MLE) [19] of $\underline{\theta}$ assuming $\mathcal{H}_1$ is true (maximizes $P(\underline{X}\,;\,\underline{\theta}_1\,,\,\mathcal{H}_1)$), and $\hat{\underline{\theta}}_0$ is the the MLE of $\underline{\theta}$ assuming $\mathcal{H}_0$ is true (maximizes $P(\underline{X}\,;\,\underline{\theta}_0\,,\,\mathcal{H}_0)$).

The procedure for estimating MLE under each hypothesis is described in detail in Harel et al [12] and when substituting the estimates into (4) we get:

$$L_G(\underline{X}) = -\frac{MN}{2}\ln\left(2\pi\hat{\sigma}_1^2\right) - \frac{MN}{2} + \frac{MN}{2}\ln\left(2\pi\hat{\sigma}_0^2\right) + \frac{MN}{2}$$

$$= \frac{MN}{2}\ln\left(\frac{\hat{\sigma}_0^2}{\hat{\sigma}_1^2}\right)\underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}}\eta$$

where $\hat{\sigma}_1^2$ is the estimation of σ^2 under $\mathcal{H}_1$ and $\hat{\sigma}_0^2$ is under $\mathcal{H}_0$. The threshold η is set to determine the desired false alarm rate using standard techniques [20]. We included the added assumption (prior information) that moist antenna attenuation would only appear during periods of high RH, that is, during periods where additional attenuation resulting from water vapor is expected to occur. This is a reasonable assumption since the appearance of dew is highly dependent on atmospheric RH, and typically, dew occurs during periods of RH above 85% [16].

4. TEST REGION AND WORKING ASSUMPTIONS

Figure 1 presents the region where the test took place, in the southern coastal plain of Israel. An 18 commercial MWL system was deployed in the area operating in the frequency range between 18 and 24 GHz, and providing RSL measurements for each link at one minute intervals. Five RH gauges are also located in the area as well as a Leaf Wetness Sensor (LWS) that detects accumulation of liquid water, i.e. dew

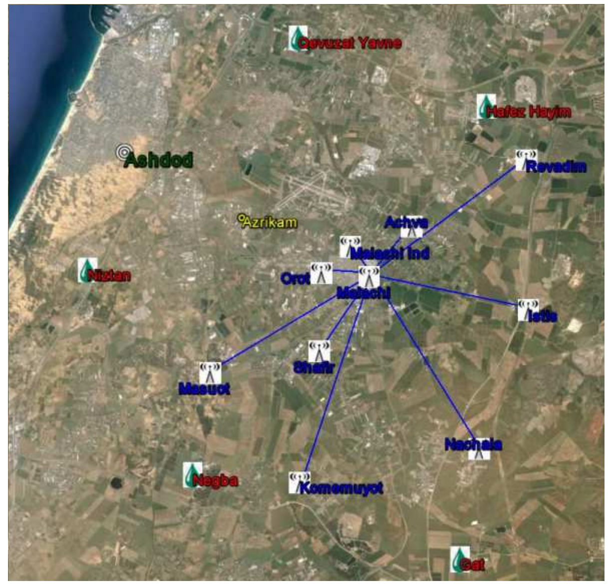

Fig. 1. The test area. The MWL system (blue lines) is shown beside the RH gauges (green drops) and the LWS (at Azrikam).

[12], and indicated whether or not the phenomenon occurred on each night of the test. The LWS and the humidity gauges were used as our ground truth against which the performance of the proposed method for detecting cases of antenna moistening was compared. A night was considered dewy when all of the humidity gauges measured RH greater than 90%, and the LWS simultaneously detected the phenomenon. We note that dew is defined as water condensed onto objects at ground level, whose temperature has fallen below the dew-point of the surface air as a result of radiational cooling during night time [21]. The justification, then, for comparing the measurements of the LWS that detects dew (combined with the humidity gauges) and the link measurements for detection of cases of antenna wetness is due to the fact that dew, as well as condensation on the antennas are phenomena that occur, by definition, when the condensation rate is greater than the evaporation rate, i.e. during periods of high RH. As a result, detection of cases of antenna wetness may indicate the occurrence of dew as will be demonstrated in the results section. Additionally, we calculated the induced attenuation from the accumulation of liquid water on the antennas for each event. We note that for this calculation we neglected the differences in frequencies between the MWLs. The justification for this is the relatively low dependence of wet antenna induced attenuation on frequency in the narrow frequency range in this case [22]. Obviously, use of as narrow a frequency range as possible will lead to a more precise estimation of the attenuation, and this is left to future research. The goal of this part is, therefore, to derive an order of magnitude of this quantity.

Further, the algorithm calculates the excess water vapor attenuation $\Delta\gamma_v$, that was shown in prior research [12] to have low dependence on the operating frequency used here.

5. RESULTS

We selected 40 nights between the months of February and July 2010. Of them, the proprietary sensors (humidity gauges and LWS) identified 20 as dewy, and 20 as not. We then applied the algorithm on those same 40 nights. The observation interval N (i.e. the duration of the event) was chosen to be 14 hours ($N = 840$ samples) a sufficient period to accommodate the variations in the atmospheric phenomena observed (dew, water vapor). Under hypothesis $\mathcal{H}_0$, we assumed that the duration of additional water vapor attenuation can receive any value between 2 and 10 hours for τ_v . Under $\mathcal{H}_1$, we assumed that $n_w \geq n_v$ and $n_w + \tau_w < n_v + \tau_v$ as explained in the section describing the model.

Figure 2 presents the Receiver Operating Characteristic (ROC) curve describing the probability of detection - P_D against the probability of false alarm - P_F using the GLRT.

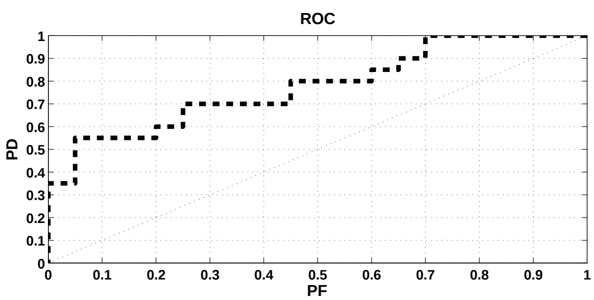

Fig. 2. ROC curve. Probability of detection of moist antenna episodes (P_D) vs probability of false alarm (P_F) using the GLRT based on the measurements from 18 MWLs.

Table 1 shows the results of the moist antenna induced attenuation estimations during the 20 events where dew was detected to have occurred.

Table 1. Estimation Results

Date	$\hat{\gamma}_w$ dB	Date	$\hat{\gamma}_w$ dB
17.7.10 - 18.7.10	0	9.3.10 - 10.3.10	-0.06
31.5.10 - 1.6.10	-0.74	12.3.10 - 13.3.10	-0.26
28.5.10 - 29.5.10	-0.15	18.3.10 - 19.3.10	0
3.6.10 - 4.6.10	-0.34	23.3.10 - 24.3.10	-0.28
6.4.10 - 7.4.10	-0.52	26.3.10 - 27.3.10	-0.67
5.3.10 - 6.3.10	-0.32	27.3.10 - 28.3.10	-0.07
10.5.10 - 11.5.10	0	4.7.10 - 5.7.10	-0.05
11.5.10 - 12.5.10	-0.05	12.7.10 - 13.7.10	-0.06
13.5.10 - 14.5.10	-0.1	13.7.10 - 14.7.10	0
4.4.10 - 5.4.10	-0.26	19.2.10 - 20.2.10	-0.37

6. SUMMARY AND CONCLUSIONS

The results indicate the potential of existing commercial MWLs for detecting dew, and estimating the attenuation induced by moistening of the antennas. Figure 2 shows a moderate ability to detect between the two hypotheses $\mathcal{H}_0$ and $\mathcal{H}_1$. The reason is stemming from both environmental and technical factors affecting the system's capabilities [12].

For example, the quantization error built into the system detracts from its performance in detecting the phenomenon and estimating its attenuation. Notably, the atmospheric humidity and moist antenna excess attenuation are of the same order of magnitude as that of the quantization step, which leads to suboptimal performances. Thus, the goal was to derive an order of magnitude of the attenuation induced by the liquid water film. Prior work [12] showed that in identical conditions, decreasing or eliminating the quantization error will improve performance. Further investigation is required in future possible work in order to asses the possibility of improving performance.

In conclusion, the ability to detect cases of antenna wetness and estimate the induced attenuation that results is interesting for several different reasons. First, applying the method in order to estimate the induced attenuation caused by the phenomenon may aid in better planning and designing of communication networks. Hening and Stanton [23] found that dew induced attenuation, at the operating frequency of 20 GHz, to be 0.5 dB, a similar result, in order of magnitude, to the results reached here (Table 1). However, there are only few works, at this point, dealing with this phenomenon. Most of the International Telecommunication Union (ITU) recommendations regarding hydrometeors, deal with the effects of rain [24], fog [25] and humidity [15]. Based on the results reached here, moist antenna induced attenuation is on a similar order of magnitude as the interference caused by fog and humidity. The proposed method, then, can shed light on this topic. Secondly, regarding the use of commercial microwave systems as ESNs, direct detection of dew is an interesting parameter from an environmental perspective ([8], [9], [10] and [11]). Estimating the induced attenuation caused by the phenomenon may, then, provide a basis for estimating the amount of dew collecting on the antennas, and further research in this direction is needed. Furthermore, estimating the amount of wet antenna induced attenuation is interesting in order to allow adjusting for its effect when using commercial microwave systems as ESNs for measurement of other atmospheric parameters, such as fog ([13], [26]) that occurs, like dew does, during periods of high RH.

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