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RESEARCH ARTICLE

Empirical Study on the Effect of Birds on Commercial Microwave Links

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ABSTRACT With emerging technologies, such as the $5G$ and IoT, wireless communication has become increasingly dominant in human life. Many applications require high quality of service (QoS), in which even momentarily interruptions may cause irreversible damage. The signal level in wireless point-to-point communication links is affected by environmental phenomena, including objects that blocking the propagating electromagnetic waves. While the relationship between signal attenuation and weather phenomena such as rain have been well studied, in this paper we empirically show, for the first time, the relationship between the presence of birds and attenuation in Commercial Microwave Links (CMLs). Using real CMLs' data collected in Israel that were intersected with GPS data from tagged birds, we empirically associated measured attenuation in the signal in a given link with the presence of birds in its vicinity. We quantified this relationship by evaluating the Receiver Characteristics Operating (ROC) curve describing the false positive vs. false negative decision on the presence of birds by setting a threshold on the measured attenuation in CMLs. The results demonstrate encouraging performance and empirically establish the potential of a novel approach for opportunistic monitoring of migrating birds, as well as for the understanding the hazards to QoS in sensitive applications.

INDEX TERMS Commercial microwave links, bird movement data, received signal level, remote sensing, signal processing.

I. INTRODUCTION

The use of wireless communication has spread rapidly on a global scale over the last 150 years, and currently human-made electromagnetic waves carry information almost everywhere in the near-ground earth atmosphere. Propagating through a channel causes the characteristics of the signal to change according to the properties of the channel. In particular, in a static free space Line-of-Sight (LoS) propagation, the signal is attenuated proportionally to the length of the link connecting the transmitter and the receiver. However, fading of wireless signals is caused by additional factors, mainly weather, and therefore each communication link is built with a "link budget" to support quality of service in changing conditions. To be able to design robust wireless networks, the effects of changing weather conditions on the signal attenuation have been widely studied (e.g., [1], [12], [14], [21]). However, very little attention has given to the effects of other phenomena that may cause changes in the received signal level (RSL). In particular, due

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to their water content, animals may cause variation in *RSL* and thus disrupt communication, but empirical information regarding such effects have not yet been described. Specifically, birds that pass through communication links have been considered as a momentarily, unavoidable disruption. An exception is the study in [9], where experimental local setup was built to study the path loss of a wireless signal in a specific application of concentrated animal feeding operation. In modern applications, however, e.g., autonomous cars, even a momentarily fading of the communication signal may have dramatic consequences for the operation and function of the system and thus such effects should be thoroughly explored. Therefore, a systematic study of the effects of birds on the *RSL* of signals in wireless networks is much needed.

Modern communication systems log and track the *RSL* in each and any link. In 2006 it was first suggested [17] to capitalize on it to opportunistically monitor rain from *RSL* measurements routinely logged by mobile network operators and followed by various demonstrations of this approach, e.g., [3], [8], [10], [16], and [26]. Importantly, the approach does not bear additional installation, maintenance or communication costs. Exploring the effects of birds on the *RSL* may allow characterising the phenomenon and its implications for communication systems, as well as its potential of using signal attenuation measurements in commercial microwave links (*CMLs*) for opportunistic monitoring of bird migration [7].

In this paper we empirically relate variations in the attenuation in a *CML*, extracted from standard signal level measurements, and the presence of birds in its vicinity. By capturing intersections between *GPS*-tagged birds and *CML*s across Israel, we demonstrate a direct relation between the presence of birds and the measured attenuation in the link. Then, attenuated *RSL* measurements from the links are analyzed and compared against counterpart samples from a times that are bird-free in the south of the country. The comparison is done using Receiver Operating Characteristic (*ROC*) curve, that quantifies false positive vs. false negative decisions on the presence of birds. The results demonstrate how birds influence the *RSL* in operational *CMLs* and thus provide first empirical information about potential bird-related disruptions to communication systems, and support the potential of the proposed approach to opportunistically detect birds at the vicinity of communication links.

The paper is organized as follows: section II presents our available measurements; section III presents the methodology we used, and section IV presents the results. The paper is closed by a discussion, conclusions, and proposals for future directions.

II. SETUP AND DATA

The available data consists of two data-sets:

The bird data includes *GPS* locations acquired by a designated tracking device (see [11], [20], and [22]). It includes tracking of 81 individual birds of 3 species: White Stork (*Ciconia ciconia*, 3-4 *kg*, hereafter "Stork"), Great White Pelican (*Pelecanus onocrotalus*, 5-9 *kg*, "Pelican"), and Common Crane (*Grus grus*, 3-6 *kg*. "Crane"). These species nearly always move in flocks, hence a single tracked individual likely represents movement of an entire flock of dozen to thousands individuals. The database includes over 1.2 million *GPS* samples, most of them in Israel. Each sample (a localization) is coupled with a timestamp, in time intervals of ≥ 5 minutes. Birds were tracked mostly between 2014 and 2016, and some additional tracks were recorded until 2019. We searched this database for events in which a tracked bird intersected a *CML* link, as described below.

The available *CML*s' data-set include signal level measurements from thousands of links, operated by the Israeli cellular operator Cellcom$^{\text{TM}}$, together with the corresponding metadata, including the exact locations of the transmitter and the receiver of each link. The Network Management System (*NMS*) produces measurements in various protocols. However, for the relevant period and links, the useful protocol is the one in which min and max values, out of signal level measurements taken every 10 seconds over an entire week, are available. These low temporal resolution signals seem restrictive in terms of relating them to instantaneous events such as bird intersection. Nevertheless, under terms discussed in section III, such relation can be made up to certain level of certainty.

III. METHODOLOGY

We propose to decide on the presence of birds at the vicinity of a *CML* based on comparison of the attenuation of the signal (excluding other, known causes to such attenuation - and in particular, rain) to a threshold.

A. IDENTIFYING RELEVANT EVENTS

The birds' locations in the available database were compared against the metadata of all links in order to detect closeness or intersection. *CML*s with insignificant amount of *RSL* measurements around the *GPS*'s timestamp were filtered out. The distance of the bird from the link, d, and the maximal angular proximity to either transmitter (α) or receiver (β) antennas, $\theta = \max\{\alpha, \beta\}$, were calculated, as illustrated in Fig. 1. Only cases of distance shorter than 200 meters were saved and further analyzed.

Figure 2 (left) displays examples of time series of relevant, collected $GPS - CML$ intersection snapshots. The continuous lines display the min-max signal levels (red and black, respectively) while the blue dots display the distance of the bird from the link. Figure 2 (right) displays the corresponding 2-D location of the link and the tagged birds during the recorded event. Different colors represent different altitudes of the bird.

As can be seen, the presence of an individual bird is followed by varying level of attenuation, either in its max or min levels. However, as the *GPS* database does not provide with knowledge of the entire flock, we can only infer from the presence of a tagged bird on the presence of others. In Fig. 2a we observe significant max attenuation with almost constant min level, whereas in Fig. 2c, no change in the max

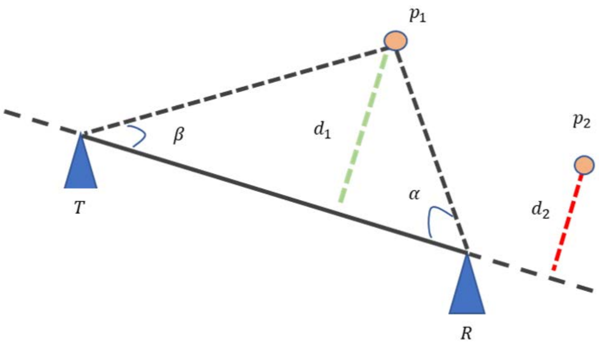

FIGURE 1. Bird-*CML* intersection snapshot description. The link is defined by antennas *R* and *T*, and two possible *GPS* bird's location are denoted by p_1, p_2. The 3-dimensional distance of p_1 to the link is d_1 with corresponding angular proximate to the antennas, α, β. A snapshot is relevant for intersection only if the distance is small enough and both angles are acute, unlike in the case of p_2, which is not considered as relevant.

RSL appears while the min level increases. In Fig. 2e, 2f we observe varying attenuation given a flock member that reaches extremely close to the link (25 meters) multiple times in multiple days. The considerable attenuation recorded by $RSL_{\max}$ measurements can indicate on a flock crossing the beam, as the theoretical analysis in [7] predicts, as well as on its order of magnitude. Moreover, on most examples on Fig. 2, the $RSL_{\min}$ variations are much smaller with a slight tendency for decreased attenuation when birds are around the link. This is also predicted by the theoretical model in [7], where we suggest that in-phase reflections of the flock members dominate the measured signal, causing constructive interference.

B. BIRD-INDUCED ATTENUATION

Next we aim at quantifying the birds (intersection) induced attenuation level in the measurements. Recalling that in this study most of the available measurements are given in a daily update of the last 7-day min-max form, therefore not every single measurement can be related directly to a specific *GPS* sample. Moreover, *GPS* samples from the same bird need to be divided into sequential day periods with minimal distance-to-link and minimal angular proximity for being considered as presenters. Denote by $r_{min}[n]$ the $RSL_{\min}$ measurement of day n, starting at the *GPS* timestamps day. The following rule is suggested for representing the *GPS*-related *RSL*:

$$RSL_{rep}[n] = \begin{cases} \max\left\{r_{min}[n], \ldots, r_{min}[n+7]\right\} & \text{c.p.} \\ N.A & \text{else,} \end{cases} \tag{1}$$

where c.p. (climbing pattern) refers to a monotonic non-decreasing series of samples. This kind of pattern ensures that lower *RSL* levels prior to the *GPS* time step will not screen over an intersection day, and provides a descent approximated lower bound on the *RSL* that can possibly be related to the presence of the tagged bird. This conservative approach has been taken for isolating birds-related attenuation from attenuation caused by more common weather related phenomena, specifically rain [17]. Figure 3 shows an example of an intersection occurring two days after a rain event. The *RSL* sequence does not enable us to distinguish between the maximal $r_{min}[-2] = -85dBm$ rain-induced attenuation and any bird-induced effect. Therefore the *RSL* is estimated by applying (1) on $r_{min}[5]$, $r_{min}[6]$ only. The fact that even after the rain event, significantly attenuated signal is measured until May 17th - completing exactly 7 days from the day of intersection - increases the likelihood that the *RSL* sample are induced by birds.

To set up the incremental attenuation level, evaluation of the baseline level *BL* (which can vary due to changing natural conditions, as humidity) is required. A common approach is to consider the median value of $RSL_{\min}$ over long, dry periods as the baseline level [23]. However, here even during dry periods links are likely to be affected by other, non-tagged, flocks, potentially biasing the baseline estimation. In order to compensate for that, we apply an adjustment, as follows:

$$BL[n] = P_c\left\{\max_{-45\leq n\leq 45}{}^{k}\left\{r_{min}[n]\right\}\right\}, \tag{2}$$

for k-maximum pooling and c-percentile operators, $\underset{n}{\max}{}^{k}\{\cdot\}$ and $P_c\{\cdot\}$, respectively. We used $k = 5$ and $c = 90$. We then evaluated the resulting attenuation for the cases where $RSL_{rep}[n]$ is available by:

$$A[n] = BL[n] - RSL_{rep}[n]. \tag{3}$$

Lastly, we address the case where measurements are available from both up-link and down-link of the same hop. In general, due to the different locations of the *CML*'s endpoints and to the asymmetry of the birds with respect to the up-link/down-link obstruction points, we should not expect the same attenuation for both directions. Taking a conservative approach, we represent each such pair of attenuations via their maximal value. We also select the maximal angular proximity in order to possibly relate non-attenuated samples to extreme proximity of the flock to the antenna (denoted as θ).

Although many temporal-spatial intersections are acquired via the method specified in this section, relevant *RSL* measurements were not available for most of the links. Moreover, after filtering out intersections occurring on rainy days and retrieving only ''valid'' measurements (which follow all specified restrictions above), we are left with 11 unique hops with valid intersections in the north of Israel, most of which are presented on Fig. 4. These links were transected by tracked birds 16 times: 10 times by 2 Pelicans and 6 times by 2 Storks. All links are located very close to fishponds and other water bodies in which these species tend to roost overnight, and some are also used for foraging during the day. Given the relatively low height of the *CML* links (typically about 20m above ground), they are most effective in detecting birds that land in (or take-off from) these roosting hotspots.

C. CONTROL DATA WITH NO PRESENCE OF BIRDS

Our ''bird detector'' is based on comparing the assumed birds induced attenuation to a threshold. Its positive operation is proved when such attenuation coincides with tagged bird's

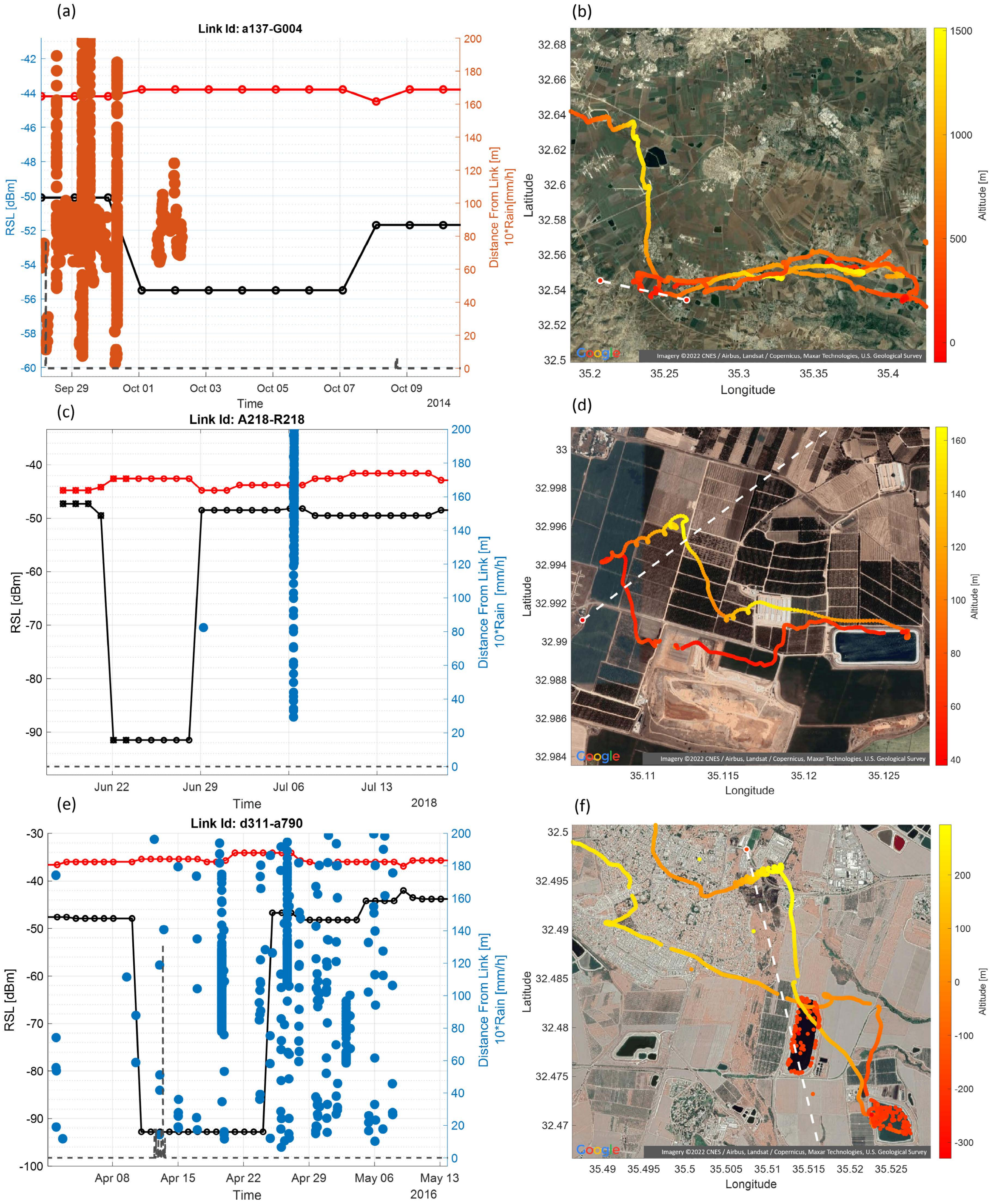

FIGURE 2. Three examples of intersections between birds and a link. Each row is associated with a different event. The right figures show a bird's eye view of the bird's trajectory created by the corresponding GPS locations, with the link shown in white dash. The colors indicate the altitude (including the links' masts). The left figures display the available RSL measurements vs. time. The min, max RSL values over successive 7 days are presented by the black and red lines, respectively. The blue points represent tagging samples of an individual bird. The right y-axis shares the distance of the bird from the link (scatter dots) in [m], and the rain rate (gray dash line) in [mm/10h]. (a) Multiple intersections occurring on September and October, 2014, including Pelican number 3710. (b) The corresponding visualization of the intersection from September 30th. (c) Two intersections from June and July, 2018, including Stork number 3730. (d) The corresponding visualization of the intersection from July 6th. (e) Multiple intersections on April 2016, including Pelican number 3674. Note the rain on April 12th, indicated by the vertical line that may affect the measured RSL. (f) The corresponding visualization of the intersection from April 29th, 2016.

intersection, as demonstrated in Fig. 2. However, in order to fully characterize our proposed "bird detector" statistically, it is essential to study its operation in birds-free environment from which data of a control group can be collected. Ideally,

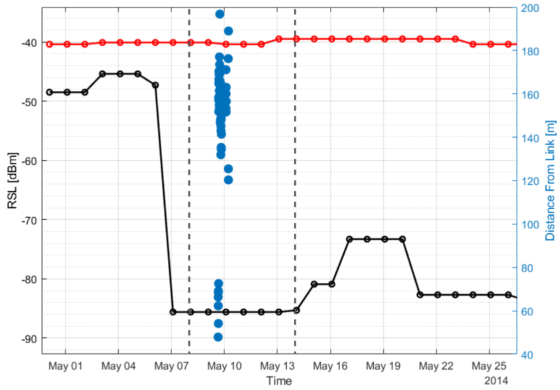

FIGURE 3. Intersection visualization between Stork number 2950 and link B320-a158 during May 2014. The min, max *RSL* sequence of the last 7 days is given by the black and red lines, respectively. Each scatter point represents a *GPS* sample of an individual bird. The distance of the bird from the link is given by the right y-axis. The gray vertical lines indicate a 7-day period starting at May 8^{th} which included a rain event.

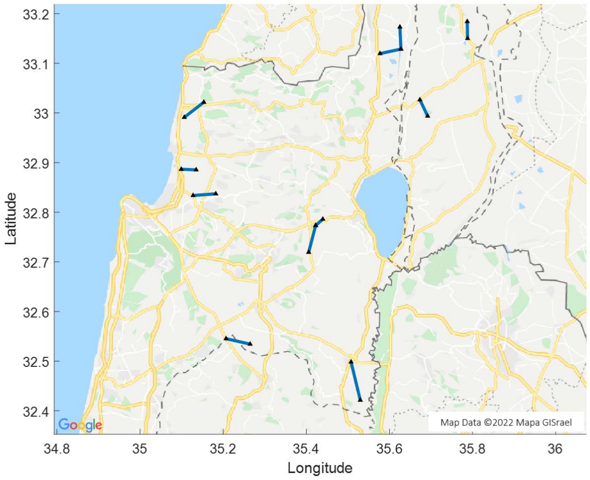

FIGURE 4. Locations of the *CML*s in the north of Israel with acquired intersection.

it would have been best practice to compare the very same intersected links while no flocks are located nearby. However, the proximity of those links to areas that are hotspots for birds makes such experiment unrealistic. We are also aware that collecting a true control group representing the "False" hypothesis is impractical due to lack of complete information regarding birds whereabouts. Therefore, with the purpose of creating a Receiver Operating Characteristic (*ROC*) curve, we utilized a third *CML* data-set of links located in the Israeli Negev and Arava, with measurements collected on July 2020. Bird migration is extremely rare in these regions during this period. The *CML* network is presented on Fig. 5. This arid desert does not populate plenty of flying animals, especially in July, and thus can be used to obtain an appropriate control group. Generally, we prefer to sever with our measurements in return with getting more certainty in our conclusions. As a consequence, we apply the following measures: First, in order to ensure sensitivity to weather-related phenomena, only links with lengths of 3-12 kilometers are considered (same as the intersected links). Second, for each hop, the attenuation was estimated similarly as in section III-B. We also assume that the links are not subject to any extreme meteorological phenomena that might compromise the *RSL*, as these areas are extremely arid during this time of the year.

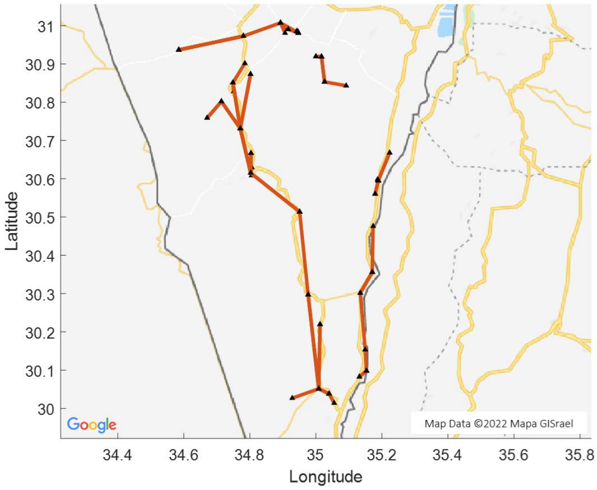

FIGURE 5. Locations of the reference *CML*s in the south of Israel (the Negev and the Arava).

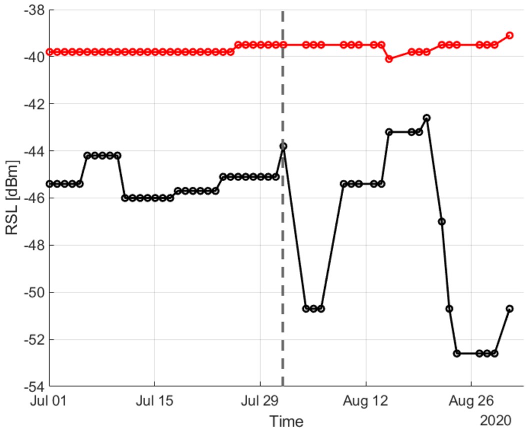

FIGURE 6. Example of *RSL* measurements from link 356b-A902 from the control group. The red and black lines indicates 7 day max and min *RSL*, respectively. The vertical dashed line indicates August 1^{st}, 2020.

An example of an *RSL* sequence recorded by one of the control links is shown in Fig. 6. It demonstrates how steady and uncompromising is the signal during July, unlike August, in which the fall migration season commences.

IV. RESULTS

The suggested *CML*-based bird detector includes the following:

1) Given received and transmitted signal level measurements in a *CML* and side information about (the absence of) rain, extract the potential bird-induced attenuation as detailed in subsection III-B.

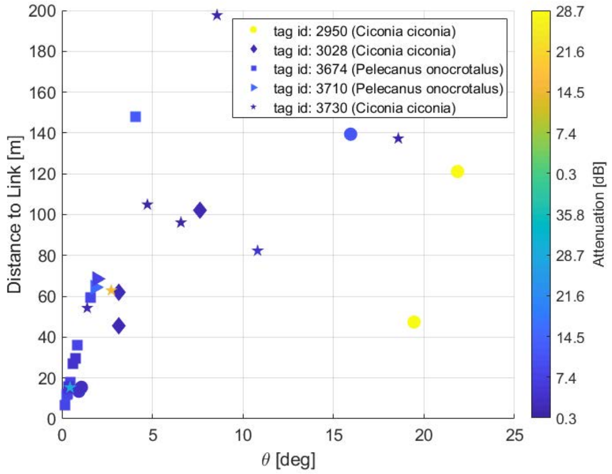

FIGURE 7. All intersections' features, colored by measured attenuation. Each shape corresponds to a different individual bird.

2) Compare it to a pre-set threshold to decide on detection of birds.

This procedure has been applied to the measurements of both *GPS*-supported and unsupported snapshots, yielding a labeled data-set of describing intersection features (d, θ, A) and binary labels (positive, negative) indicating an intersection. In purpose of explaining the positive-labeled (bird-induced) decisions, Fig. 7 scatters all positive decisions (validated by *GPS* intersections) against the snapshot parameters. One might expect that the closer each point is to the origin, the higher its attenuation is, and vice versa. However, since attenuation may be caused by other, non-tagged, members of the flock (that might be closer to the link), and since given a single validating bird does not guarantee an attenuation due to beam blocking, this conjecture cannot be supported. Moreover, it can be seen that the attenuation level tends to be higher for Storks over Pelicans, despite the latter is usually heavier. This could be explained by the size of the flock.

The proposed threshold-based detector is applied on both intersection data-set (described in III-A) and on the control data-set (III-C) to study the performance of bird detection from *CML*s measurements. It has been done by applying a certain threshold on each record, and then evaluating the percentage of overall detected records for each label, yielding the true-positive and false-positive rates of the detector for this threshold. Repeating it for many thresholds in the dynamic range of the attenuation, creates the detector's *ROC* curve. In Fig. 8 we depict the empirical *ROC* curve of this detector with the real data described in II. The curve is highly concave, therefore indicating a good performance - substantially better than a random coin-flipping decision. The overall performance of a detector is often measured using the area-under-curve (*AUC*) which here equals to 0.75. We also note the low false-alarm working point of 48.3% true positive rate over 14.3% false positive rate, which is very reasonable operation point for actual detectors. Generally, by noticing that the areas with high slope in the curve occurs at low-to-medium false alarm rates, we conclude that most of the correct decisions are made on high-to-medium attenuation levels, whereas both groups share low attenuation levels which can hardly be separated. By this curve we empirically prove that there is a clear positive relation between presence of birds and the measured attenuation in the *CML*s.

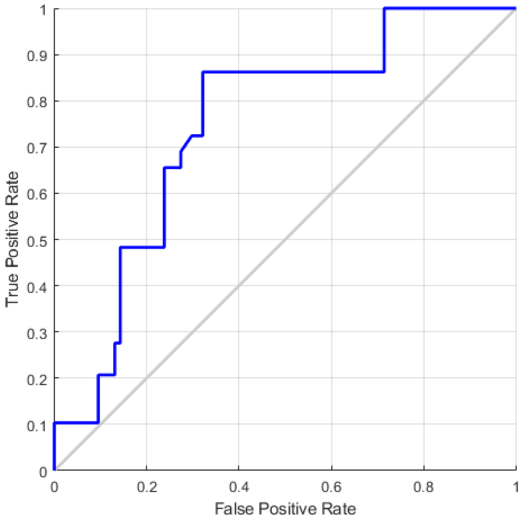

FIGURE 8. Empirical ROC curve of an attenuation-based birds detector.

Note that we do not discuss the overall detection error, as the prior probability of each label cannot be evaluated. It is reasonable to assume that the presence of birds near links is much scarce, therefore it is recommended to further analyze the low false-alarm range of the *ROC*, given appropriate, controlled data.

V. DISCUSSION AND CONCLUSION

In this paper we have empirically and systematically proven the significant effect of birds on the attenuation of wireless signals in commercial microwave links by showing, for the first time, that the presence of individual birds that are part of a flock near the links affect the *RSL*. Creating data-sets from existing measurements, we show the desired direct connection between signal attenuation and presence of birds in the link's vicinity, and suggest an algorithm for detecting intersecting birds. The proposed detector shows reasonable performance, featuring a good recall to low false-alarm operating point. This study is different than in [7], in which the relation between the presence of birds and attenuation in *CMLs* is studied via indirect, statistically evidences.

Bird migration has been studied for centuries using low-resolution methods such as ringing [2], [5], but various high-resolution tracking technologies are currently in use, including small tracking devices such as *GPS* tags that are attached to the birds [18]. Yet, these tracking devices could affect the behavior of the tagged animals, and are also expensive and require special efforts for animal trapping, hence are limited to a small number of individuals (up to about one hundred, at most [13], [22], [24]) in specific populations, comprising a tiny fraction of the individuals that migrate through any area in the world. While radar is considered the most effective technology to quantify passage of migrating birds [25], as shown e.g. in [15], it has its own limitations. In particular, such advanced technological systems are expensive and require high level of engineering for their construction, as well as non-negligible maintenance resources in terms of manpower and financial support. Therefore, the use of radars to monitor bird migration is mostly restricted to Western and Northern Europe [19] and North America [27], while very little is known about the intensity of bird migration elsewhere. Consequently, our understanding of bird migration ecology [6] and its implications for human lives [4] is not well understood on a global scale.

The idea of using *CMLs* for opportunistic monitoring of birds, first suggested in [7], is therefore very interesting, especially since the ability to monitor bird migration in many areas around the world, including many developing countries that cannot allocate sufficient budget for purchasing and maintaining radars or *GPS* tags, is severely impeded. Additional methods for monitoring bird migration which could be used nearly anywhere, and specifically where existing methods are not available, are critically needed to substantially advance our capacity to monitor the movement of birds and its implications for our lives. However, more research and development is required to make this idea operational. In [7] we presented theoretical model and analysis based on times of bird migration hours as detected by a bird radar pointing on the potential of using wireless communication measurements for detecting birds at low altitudes, allowing unprecedented detection of bird movement during migration, as well as during daily commute and foraging movements. In the current work, we introduce empirical results regarding detection of large birds that are equipped with *GPS* trackers, allowing to explore potential intersections of *CML*s data and bird movement at the individual bird level. The results further support our suggestion that this methodology could significantly advance our capacity to monitor bird movement at a global scale given the wide expansion of wireless communication networks around the world. Therefore, the utility of this methodology that uses *CML*s data for monitoring bird movement can contribute to studying important ecological interactions as well as potential harmful consequences of migrating birds on human lives (e.g., bird-aircraft collisions; [28]).

It is important to note that the attenuation estimation process we used is rather conservative, as we disqualified many observed attenuation measurements due to lack of certainty of their cause. The desire to maintain pure, low false-alarm conclusions regarding the target relation led to underestimation of the connection between our variables and consequently under-determination of the related events. Also, using the available low temporal resolution measurements provided by the *NMS* is a limiting factor. We believe that more frequent measurements may enable us to provide with larger number of high-resolution examples and better detection performance. In addition, the available tagging method does not provide us with full, continues information on the location of neither the tagged bird nor the entire flock. The next step would naturally be to deal with these limitations. In order to reliably quantify the effect of birds on *CML*s, a controlled experiment may be conducted. Putting together such experiment is far from being simple, If done, it should include, inter ilia: each individual bird position at high-frequency rate, physical properties (surface area, weight etc.), and high resolution signal level measurements. Alternatively, existing *CML*s can be monitored to indicate on the existence of near-bye birds by placing designated monitoring equipment next to them (e.g., cameras).

The lack of species recognition ability, the sensitivity to rain and the relative low altitude of the *CML*s impose limitations for scaling up *CMLs*-based methods for studying and monitoring bird movements. Nevertheless, the finding that *all* observed bird-*CML* intersections occurred near major roosting sites of the study species implies that the method is most effective in detecting active hotspots at which many large waterbirds land and take off. This has important practical implications for the management of fishponds and water reservoirs, and for protection of migrating birds. Thus, despite all the limitations above, the results are encouraging, representing the first empirical evidence for opportunistic monitoring of individual birds by analysing received signal levels in *CML*s.

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