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Research Article

Cellular network measurements can unravel spatiotemporal properties of bird movement to enhance basic and applied knowledge globally

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ABSTRACT

A major problem in studying bird movement in many countries is data scarcity, precluding information about the spatial and temporal properties of avian distribution and dynamics as well as their consequences for human lives. We address this problem by proposing an innovative approach based on the relation between counts of signal attenuation of wireless communication to the presence of birds across or near wireless links of cellular backhaul networks. Wireless point-to-point communication links, on either ground level or earth-satellite links, cover the globe. We statistically relate between signal attenuation in terrestrial Commercial Microwave Links (CMLs) and bird migration. Because modern communication systems measure and often log signal levels routinely, we propose using existing signal level measurements of cellular and other wireless communication systems around the world as sensors for monitoring bird movement. Using actual measurements from operational CMLs, we show that the daily cycle of signal attenuation during bird migration periods matched that of the water-bird migration traffic rate recorded by nearby bird radar. This demonstrates the potential of the proposed method for opportunistic bird movement monitoring by CMLs across the globe, with no additional hardware installation, maintenance, or communication costs.

Keywords: bird movement, cellular networks, commercial microwave links, global bird bioflow, long-term monitoring, radar ornithology, remote sensing, signal attenuation

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LAY SUMMARY

- Data deficiency is substantially hampering our knowledge of bird movement and its implications. By relating counts of signal attenuation of cellular communication networks to counts of migrating birds, we can opportunistically monitor bird movement with no installation, maintenance, or communication costs.
- We propose that existing cellular network infrastructure can be used to characterize bird movement and demonstrate it by comparing attenuation distribution between spring (migration season) and summer (no migration season), and by relating hourly patterns of attenuation to the number of water birds counted by a nearby radar during spring migration in Southern Israel.
- The further development and future application of this method could enhance our understanding of bird movement, including long-term monitoring, detection of phenological patterns and spatial gradients, as well as providing essential information for the mitigation of human-wildlife conflicts—especially bird–aircraft collisions at low altitudes by providing early warning of bird presence where radar coverage is limited.

Las mediciones de las redes de telefonía celular pueden revelar propiedades espaciotemporales del movimiento de las aves para mejorar el conocimiento básico y aplicado a nivel mundial

RESUMEN

Un problema importante en el estudio del movimiento de las aves en muchos países es la escasez de datos, lo que impide obtener información sobre las propiedades espaciales y temporales de la distribución y dinámica de las aves, así como sus consecuencias para la vida humana. Abordamos este problema proponiendo un enfoque innovador basado en la relación entre el conteo de la atenuación de la señal de la comunicación inalámbrica y la presencia de aves a lo largo o cerca de los enlaces inalámbricos de las redes de retorno de telefonía celular. Los enlaces de comunicación inalámbrica punto a punto, ya sea a nivel del suelo o tierra-satélite, cubren el globo. Relacionamos estadísticamente la atenuación de la señal en los Enlaces de Microondas Comerciales (EMC) terrestres y la migración de aves. Dado que los sistemas de

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comunicación modernos miden y registran rutinariamente los niveles de señal, proponemos utilizar las mediciones del nivel de señal existentes de los sistemas de comunicación de telefonía celular y otros sistemas de comunicación inalámbrica en todo el mundo como sensores para el monitoreo del movimiento de las aves. Usando mediciones reales de EMC operacionales, mostramos que el ciclo diario de atenuación de la señal durante los períodos de migración de las aves coincidió con la tasa de tráfico de migración de aves acuáticas registrada por un radar de aves cercano. Esto demuestra el potencial del método propuesto para el monitoreo oportunista del movimiento de las aves mediante EMC en todo el mundo, sin costos adicionales de instalación de hardware, mantenimiento o comunicación.

Palabras clave: atenuación de señal, bioflujo global de aves, enlaces de microondas comerciales, monitoreo a largo plazo, movimiento de aves, ornitología por radar, redes celulares, teledetección

INTRODUCTION

The movement ecology of animals has received increasing attention because of its importance for our understanding of ecological processes at different spatial and temporal scales, and due to its central role in wildlife conservation, the spread of pathogens, threat to aerial transportation, and human activity patterns (Nathan et al. 2008, Bauer et al. 2017, Miller et al. 2019). Yet, we currently lack information to quantify bird movement through the air and specifically near the ground in many areas around the globe, limiting our ability to study aerial animal foraging, commuting, and migration at low altitudes over large spatial scales. Importantly, this lack of information is substantially limiting our ability to mitigate harmful implications of bird movement, including bird aircraft collisions, and precluding better knowledge required for bird conservation. We propose a method to opportunistically monitor aerial movement within several tens of meters above ground level using data from stationary communication networks. This method could fill an important gap in our ability to measure animal movement at these altitudes since many radar systems cannot cover the airspace near the ground due to ground clutter (Liechti et al. 2019). The proposed method requires no capture of individuals nor the attachment of any tracking devices. Unlike community science, the proposed method can be automated and be available in areas where data provided by observers are rare. While other methods such as GPS tags can record low flights close to the ground, they are usually only available for a small set of individuals from the population. To this end, the proposed methodology could fill a critical gap in migration monitoring.

Studying bird migration is important for understanding the causes, patterns, mechanisms, and consequences of a major long-distance biological transport process (Bauer and Hoye 2014, Fritzsche McKay and Hoye 2016, López-Hoffman et al. 2017). Various methods are currently used for studying migrating birds, including weather radars that are unique in allowing the quantification of bird bioflow through the air over long ranges (Dokter et al. 2011), and when operating as a network, facilitating measuring bird migration over entire continents (Van Doren and Horton 2018, Nilsson et al. 2019). Yet, many countries do not have radars for bird monitoring and in particular, many developing countries cannot allocate sufficient budget for purchasing and maintaining weather radars. Other limitations regarding data collection and use (Shamoun-Baranes et al. 2021) substantially limit our understanding of the spatial and temporal properties of bird migration and how it is affected by different factors, as well as its consequences for our lives. Some of these limitations relate to the availability of relevant tools as only recently an automated algorithm using weather radar images was developed to identify flocks of migrating birds (Schekler et al. 2023). Bird–aircraft collisions, some of which take place at low altitudes above ground level where weather radar cover is many times blocked due to ground clutter, may risk human lives in different countries (van Gasteren et al. 2019). Therefore, additional methods for monitoring bird migration over large spatial scales are critically required, particularly where existing methods are not available and specifically for the detection of bird flow near the ground.

We propose using counts of signal attenuation of wireless communication for detecting birds at low altitudes, improving our capacity to detect low-flying birds during migration, as well as during daily commute and foraging movements. Notably, due to ground clutter, weather radars have rather poor coverage near the ground at altitudes of several tens of meters (Liechti et al. 2019) and consequently their ability to provide a warning regarding bird–aircraft collision risk (van Gasteren et al. 2019, Nilsson et al. 2021) is limited when birds move low above the ground. Consequently, the proposed method may fill this gap by providing the means for the development of warning systems for near-ground bird movement in areas of low-altitude aerial transportation, such as airports and military training zones. We anticipate that when further developed into a mature technological solution, the proposed method could substantially enhance our capacity to quantify bird movement and its applied consequences at a global scale given the wide expansion of wireless communication networks around the world.

The use of wireless communication has rapidly spread globally over the last 150 years. Currently, human-made electromagnetic waves carry information almost everywhere in the near-ground earth atmosphere. Propagating through a channel causes the signal's characteristics 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, the fading of wireless signals is caused by additional factors, mainly weather, and therefore each communication link in a network is built with a "link budget" to support the quality of service in changing conditions. To be able to compensate for such changing conditions, modern communication systems track and often log the received signal level (RSL) in each and any link. A network hop may contain one or more links. It was first suggested by Messer et al. (2006), to opportunistically monitor rain from RSL measurements routinely logged by mobile network operators, and additional demonstrations of this approach have followed (Alpert et al. 2016, Uijlenhoet et al. 2018, Chwala et al. 2019, David 2019).

Importantly, the approach does not bear additional hardware installation, maintenance or communication costs, and the required data consists of physical measurements and does not carry any concerns for privacy. Moreover, building on the growing global interest in this approach and on the emerging trend of data sharing, the availability of relevant measurements is expected to grow in the near future. For example, Andersson et al. (2022) presented an open dataset of past

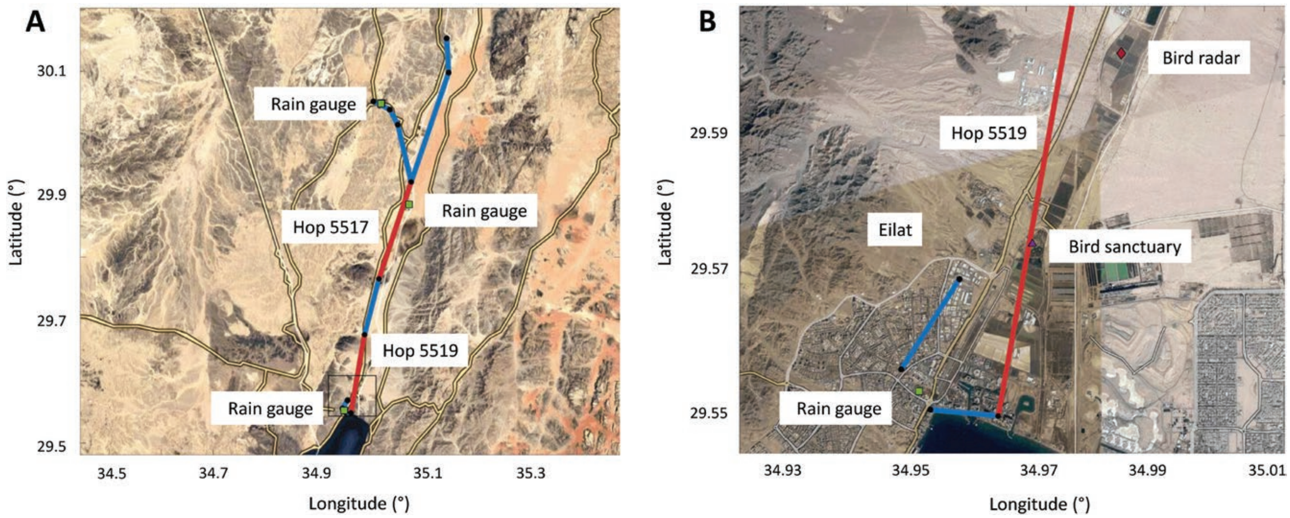

FIGURE 1. (**A**) Map of the Arava region in Southern Israel together with local Commercial Microwave Links (blue, red). Black inset depicts the region of Eilat that is provided in panel (**B**). (**B**) Enlarged map of Eilat region, with the BirdScan MR-1 bird radar marked by a red diamond and the International Birding and Research Center in Eilat (IBRCE) marked by a purple triangle. In both panels, rain gauges are marked by green squares, and hops 5517, 5519 are shown in red.

measurements consisting of 10 s resolution measurements with true coordinates from 364 bi-directional Commercial Microwave Links (CMLs) in Gothenburg, Sweden, together with data from 11 precipitation gauges and the Swedish operational weather radar composite in the area. Also, real-time implementation of opportunistic rain monitoring from CML data has been recently demonstrated by Song et al. (2021).

Ben Moshe et al. (2022) related the presence of individual tagged birds to changes in the signal level in CMLs, which may explain measurable disturbances to the received signal level (RSL). Here we suggest using this feature for opportunistically monitoring of aerial bird movement based on statistical analysis of RSLs collected in wireless communication networks. The feasibility of the proposed approach is demonstrated by actual attenuation measurements from communication links in Southern Israel that cannot be explained by weather, but rather by the movement of migrating birds across or in the vicinity of the links. The links' attenuation patterns were compared to the well-established knowledge regarding the annual phenology of bird migration between the spring (high bird migration intensity) and summer (very low bird migration intensity). In addition, we also explored the within-day attenuation patterns during the spring bird migration, which were compared to the within-day pattern of intensity of water-bird migration recorded by a bird radar positioned near the communication link just north of Eilat, a bird migration hotspot.

METHODS

Commercial Microwave Links Measurement

To demonstrate the proposed approach, we used data collected by operational CMLs in Israel, from a network operated by the Israeli cellular operator Cellcom Ltd. This network consists of thousands of links deployed across the country, connecting base stations as part of the backhaul network of the cellular system. The CMLs are typically a few tens of meters above ground, operating at microwave, and lately at mM-wave frequencies. The provided RSL measurement protocol includes existing signal level measurements routinely collected by the network management system (NMS) that are logged with quantization between 0.3 and 1 dB, and are sampled at various sampling rates and protocols (Ostrometzky et al. 2017, Uijlenhoet et al. 2018, Chwala and Kunstmann 2019). Our study is focused on a CML network located in the Arava Valley in Southeastern Israel (Figure 1), specifically in its southern part near the city of Eilat. This area was chosen because it is a known bird migration flyway where many birds tend to concentrate during migration seasons (Shirihai 1996), including within or near a bird sanctuary, the International Birding and Research Center in Eilat (IBRCE). Notably, the area is extremely arid such that rain events (and consequently affected RSL measurements) are extremely rare. The possible effect of rain events on the RSL measurements was ruled out using data from three nearby rain gauges operated by the Israel Meteoroogical Service (IMS). The specific links vary in their properties including their carrier frequency, length, and polarization (horizontal, vertical) as reported in Supplementary Table S1. Typical time series of the RSL are presented in Supplementary Figure S1.

Radar Measurements of Bird Migration

Bird migration data were collected by the BirdScan MR1, a vertical-looking X-band radar (manufacturer: Swiss Birdradar Solution AG, Winterthur, Switzerland; Liechti et al. 2019, Schmid et al. 2019) that was positioned in 2016 north of Eilat, Israel, near the links, and especially very close to hop 5519 that contains links B479-a469 and a469-B479 (see locations in Figure 1B). The radar operated in alternating, 20 min long modes: static short-pulse (65 ns, range resolution: 7.5 m, PRF: 1,800 Hz), static long-pulse (750 ns, range resolution: 110 m, PRF: 785 Hz), and rotating short-pulse and rotating long-pulse (antenna rotation provided information regarding bird speed and direction which were not examined in the present study). Bird counts were collected from these different modes and we only considered readings from an altitude of 50 m above ground level (AGL) because the radar cannot properly detect targets below this altitude. The

BirdScan radar automatically classifies echoes by the characteristics of the echo signature, including the wing-beat pattern, to bird or non-bird targets, and further classifies birds into several categories, including "Passerine," "Water bird," "Large Single Bird" or "Flock." The radar also classifies targets into "Insect" and "Airplane" target types (Zaugg et al. 2008, 2017). We included data collected during the spring migration season in March–May 2016 and presented the data as hourly means of bird counts collected throughout the entire daily cycle, summed over all the days in which the radar operated during this season (a total of 81 days).

Using Pearson Correlation, we statistically related hourly radar traget counts (relative to sunset hour), to hourly RSL attenuation counts (relative to sunset hour) collected during these months. All measurements within two hours of a rain event were excluded. In this analysis, we included only significantly attenuated samples (stronger than 2 dB, almost 7 times the quantization level) of link B479-a469.

RESULTS

Observations of Unexplained Attenuations

We inspected the CML measurements to detect significant attenuations that cannot be explained by rain, but rather by the presence of birds crossing the CMLs. Supplementary Figure S1 presents examples of measurements taken in the bird migration periods of 2017 and 2018. The measurements protocol provides a Min–Max RSL level calculated every 15 min from 90 instantaneous samples. Many significantly attenuated measurements were found, and the attenuation often correlates well between the 2 down/up links that belong to the same hop, clearly indicating interference that cannot be explained by rain.

Bird-induced Attenuations

In Figure 2A we provide a histogram of all the significantly attenuated samples (stronger than 2 dB, almost 7 times the quantization level) in relation to the hour of the day relative to sunset during March–May 2016, when birds migrate through the area in high numbers. The data is presented for link B479-a469 and in Figure 1 we show the position of hop 5519 of this link, which is located within a distance of a few hundred meters from the IBRCE and the bird radar. The corresponding histogram of attenuated samples from the summer (non-migration season) does not have a similar shape (Figure 2B). We compared the histogram of attenuated samples from the spring migration season (Figure 2A) to that of counts of migrating water birds that were collected by the BirdScan MR1 bird radar (Figure 2C) using the correlation between the hourly values in relation to sunset time throughout the day and found a significantly positive correlation (r = 0.75, P-value = 1.48×10^{-5}, n = 25; Figure 2D). The similarity between the hourly counts obtained by these 2 different measurements suggests that the attenuations are most likely caused by migrating birds. This supports our hypothesis that the passage of birds during migration periods in the area interferes with the electromagnetic waves in CMLs, creating the links' attenuation profile. In Table 1 we provide details of the correlation results of the different radar classes. Waterbirds have the highest correlation with the signal attenuation counts, but other classes of nocturnally migrating birds, such as passerines, also have a positive correlation with these counts. Negative correlations were found between radar attenuation counts and counts of other bird classes that are primarily diurnal, such as large single birds and bird flocks (in this area migrating flocks and large single birds are mainly of soaring birds such as storks and several raptor species that migrate almost exclusively during the day). No correlation was found between attenuation counts and radar-detected counts of insects which move through the area during both day and night.

Further support for the claim that signal attenuation is due to migrating birds is found in Table 2, which compares the amount of the overall available RSL measurements that were not induced by rain, and the percentage of attenuated measurements, between the spring (when bird migration is intense) and the summer (when birds do not migrate through the area). While both seasons include over 11,000 RSL samples, the probability of receiving an attenuated measurement is over 5 times higher in the spring than in the summer.

DISCUSSION

Knowledge of bird movement over large distances is essential for understanding various ecological processes and is required for managing the implications of bird movement for agriculture, disease spread, and human lives. Yet, key properties of this important transport process are only partially known due to highly unequal bird migration monitoring efforts across the globe and the lack of automated methods for monitoring birds at low altitudes of several tens of meters above ground level. Specifically, while knowledge of bird migration through North America and Europe has been studied extensively (Van Doren and Horton 2018, Nilsson et al. 2019), other parts of the world are seldom studied although evidence suggests that many of these understudied regions consist of globally important migration flyways (Shi et al. 2022). The dearth of quantitative bird movement data, largely due to the lack of radar systems for bird monitoring, is especially prevalent in developing countries. Additionally, harmful consequences of bird migration for human lives, in the form of bird–aircraft collisions, are prevalent when aircraft are found close to the ground, during ascent and descent, near and within airports (Nilsson et al. 2021). Many radar systems that monitor aerial biodiversity are limited in their capacity to detect birds near the ground due to ground clutter. We suggest that these technological and knowledge gaps can be addressed by employing existing wireless networks to quantify near-ground bird migration globally. Our work demonstrated a strong positive statistical relationship between counts of communication network signal attenuation and birds counted by a radar. Further development of this method may allow estimating bird numbers passing through and nearby cellular network links from the level of signal attenuation, providing an applicable monitoring methodology. Furthermore, automation of future applications at or near real-time could provide early warning for bird presence in areas of interest (e.g., near airports).

Wireless communication systems have already been shown to serve as exciting opportunistic weather sensors because of the potential to receive measurements from almost everywhere on earth with no added installation, maintenance, or communication costs. We propose using the same setup for monitoring migrating birds. The results of our statistical analysis suggest that attenuation counts that include unexplained

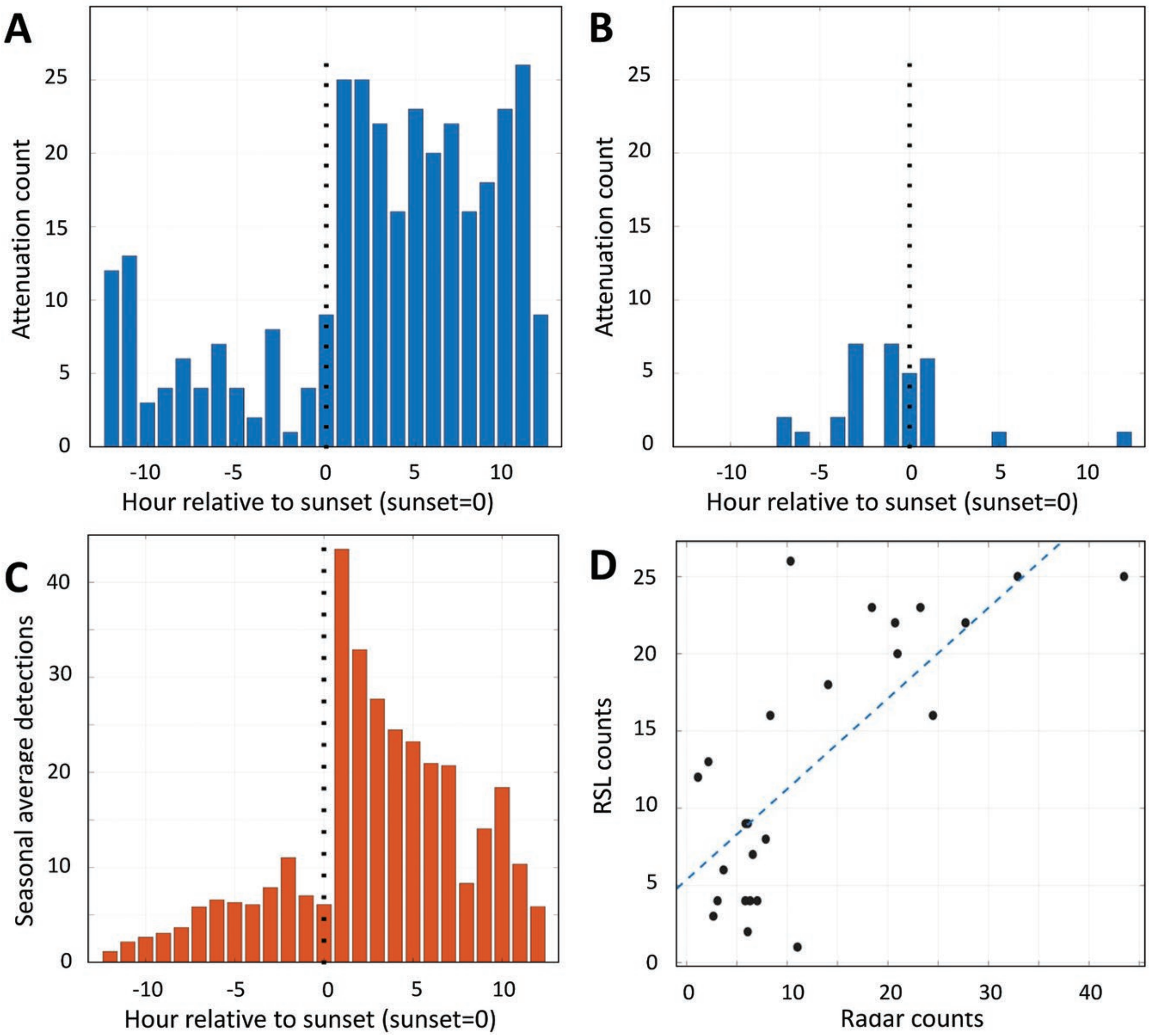

FIGURE 2. (**A**) Number of attenuated measurements in relation to the time of sunset in link B278-a468 of hop 5519 in the years 2014–2018 during spring migration (March 1 to May 31). (**B**) Number of attenuated measurements in relation to the time of sunset in link B278-a468 of hop 5519 in the years 2014–2018 during summer (June 1 to August 15). (**C**) Average number of detections of water birds in relation to the time of sunset as detected by the BirdScan MR-1 radar positioned just north of Eilat in 2016 during spring migration (March 1 to May 31). (**D**) Correlation between the average hourly (relative to sunset) number of waterbird radar detections and the average hourly number of attenuated measurements is positive and significant ($r = 0.75$, $n = 25$, $P < 0.001$).

attenuations highly correlate with the emergence of migratory birds from the ground to their nocturnal migration, immediately after sunset. Thus, our work provides compelling evidence that wireless networks, which have been established in almost all terrestrial, non-polar environments around the globe in recent decades, could serve as a large-scale monitoring sensor of migrating birds. Such capacity is critically needed for better mapping of bird migration in various areas, including where information about this natural phenomenon is limited, as well as for exploring human-wildlife conflicts.

Applying methodology for quantifying near-ground bird migration at a large scale is expected to substantially contribute to our knowledge of bird migration over vast areas around the globe, for example in sub-Saharan Africa, facilitating a much better understanding of entire migration systems, such as the Palearctic-Afrotropical system (Moreau 1972). Specifically, monitoring migration timing will allow quantifying bird movement phenology across this entire flyway over Africa, Asia, and Europe and could be used for studying how climate changes may shape important bird migration properties. Furthermore, data from this method can be used to test spatial distribution patterns and aid the conservation of migrating birds by identifying migration bottle-necks and hotspots, providing stakeholders and policymakers with the necessary information for managing threats to these avian transients. Furthermore, this method could enable a near real-time warning of mass bird migration events in areas where conflicts between migrating birds and humans are intense. For example, many thousands of bird strikes, with a high proportion of en route migrating birds, take place in various parts

TABLE 1. Results of the correlations between signal attenuation counts in different hours of the day during spring migration (March–May 2016) and the counts of different classes of radar targets that were detected by the BirdScan MR1 radar during the same period of the year.

Class type	*R*	*p*	*n*
Insect	0.08	0.703	25
Bird	0.6	0.0014	25
Flocks	–0.37	0.0694	25
Large single bird	–0.69	0.0001	25
Passerines	0.56	0.0033	25
Waders	0.75	1.48E-05	25

of the world every year (van Gasteren et al. 2019, Nilsson et al. 2021). Many of these strikes occur near the ground, especially in and near airports, where such a method could be used for early warning. The knowledge gained through the application of RSL measurements would allow predicting the regions where the risk of aircraft collision with migrating birds is high, as well as the specific times of elevated risk. This knowledge is critically important for mitigating this risk through the separation of aircraft from migrating birds in space and time.

Interestingly, since weather radars routinely face ground clutter issues that limit their capacity to detect low-flying birds, the proposed method could be used to complement information about bird movement near the ground. This could be particularly relevant in rugged terrain and where weather radars are positioned in locations found high above their surroundings (e.g., in Israel: Liechti et al. 2019). Because many birds forage, commute, and migrate at low altitudes above the ground, improved detection of bird movement using cellular networks could be substantial.

This paper highlights the feasibility of a novel approach for large-scale data collection of bird movement using existing cellular networks as opportunistic bird sensors. However, making this approach operational requires access to CML measurements, as well as the development of appropriate algorithms to distinguish between different phenomena affecting the signal level. While the latter is still under study, the former is being promoted, as CML measurements are of great value for meteorology and hydrology (Alpert et al. 2016, Uijlenhoet et al. 2018, Chwala and Kunstmann 2019, David 2019). There are several examples (Andersson et al. 2022), where relevant datasets are already freely available. Importantly, the COST action OPENSENSE (https://opensenseaction.eu/), funded by the European Commission and gathering more than 100 scientists investigating different opportunistic sensors, experts from national weather services, owners of sensor networks, and end-users of rainfall products, has set up to build a worldwide reference opportunistic sensing community. Such initiatives, together with the recent EU legislative initiatives that are aimed at regulating data-sharing and data reuse, suggest that data relevant to opportunistic environmental monitoring is expected to be publicly available in the future. Moreover, many cellular communication operators log signal level measurements in their network management systems (NMS). In some countries, like the Netherlands and Israel, NMS data is made available for research by network operators (Messer et al. 2006, Uijlenhoet et al. 2018). If operators do not store this data, it can be accessed by running a Simple Network Management Protocol (SNMP) given the IP address of each microwave link and the correct OID (Object Identifier) information of TX- and RX-level variables of each microwave link hardware (Chwala and Kunstmann 2019). Querying this information is a typical functionality of the monitoring capabilities supported by all modern network operators. In principle, the data is ready within 1–3 s, enabling real-time processing. The private subnet can then securely transfer the data to a database server, which could further process the measurements.

TABLE 2. Received signal level (RSL) measurements count comparison between spring (migration season) and summer (no migration season). Link B479-a469's dry measurements count, and out of which the percentage of attenuated measurements recorded during 2014–2018.

Period	Duration (days)	Total dry measurements	Total dry-attenuated measurements	Ratio (%)
Spring (1-Mar to 31-May)	92	23,704	322	1.36
Summer (1-Jun to 15-Aug)	76	11,902	32	0.27

While this paper is aimed at demonstrating the ability of opportunistic monitoring of bird migration by establishing a statistical relation between RSL counts in CML and radar-based counts of birds, future research is required to quantitatively relate the measured attenuation level and the number of birds passing through the link and creating the interference. Better information on bird movement could also allow further estimations of bird flock size and individual bird dimensions. A dedicated field campaign that will calibrate between different sensors (Nilsson et al. 2018, Liechti et al. 2019) could be extremely important for the future development of the method. This campaign may include bird radars positioned in the vicinity of communication links, weather radar that covers the area, and optical devices, including LIDAR, for measuring bird movements near the ground. The findings could provide important insights regarding the capacity and limitations in the detection of bird flocks by cellular networks. Yet, even in the absence of these future developments, our work introduces a novel method for bird movement monitoring, showing the utility of zero-cost opportunistic sensing that can be applied in various applications, locations, and circumstances.

Supplementary material

Supplementary material is available at *Ornithological Applications* online.

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Ethics statement

This study did not require any ethical permits.

Conflict of interest statement

The authors declare no competing interest.

Author contributions

HM developed the idea of using attenuation measurements in wireless communication networks for monitoring bird migration. DBM evaluated the predicted attenuation. HM and NS supervised the study and contributed their expertise. DBM performed the analysis of the measured attenuations. YW analyzed the bird radar data. DBM, HM, and NS wrote the first draft and revised the manuscript and all authors made corrections to the draft before submission.

Data availability

Data is available at Ben Moshe (2024a, 2024b, 2024c, 2024d) and Werber (2024).

LITERATURE CITED

Alpert, P., H. Messer, and N. David (2016). Mobile networks aid weather monitoring. *Nature* 537:617.

Andersson, J. C., J. Olsson, R. Van de Beek, and J. Hansryd (2022). OpenMRG: Open data from microwave links, radar, and gauges for rainfall quantification in Gothenburg, Sweden. *Earth System Science Data Discussions* 2022:1–26.

Bauer, S., and B. J. Hoye (2014). Migratory animals couple biodiversity and ecosystem functioning worldwide. *Science* 344:1242552.

Bauer, S., J. W. Chapman, D. R. Reynolds, J. A. Alves, A. M. Dokter, M. M. H. Menz, N. Sapir, M. Ciach, L. B. Pettersson, J. F. Kelly, H. Leijnse, J. Shamoun-Baranes (2017). From agricultural benefits to aviation safety: Realizing the potential of continent-wide radar networks. *BioScience* 67:912–918.

Ben Moshe, D. (2024a). *fig_data_2a.mat. figshare. Dataset*. https://doi.org/10.6084/m9.figshare.26517439.v1

Ben Moshe, D. (2024b). *fig_data_1a.mat. figshare. Dataset*. https://doi.org/10.6084/m9.figshare.26517445.v1

Ben Moshe, D. (2024c). *fig_data_2c.mat. figshare. Dataset*. https://doi.org/10.6084/m9.figshare.26517427.v1

Ben Moshe, D. (2024d). *fig_data_2d.mat. figshare. Dataset*. https://doi.org/10.6084/m9.figshare.26517430.v1

Ben Moshe, D., H. Messer, R. Nathan, and N. Sapir (2022). Empirical study on the effect of birds on commercial microwave links. *IEEE Access* 10:103819–103826.

Chwala, C., and H. Kunstmann (2019). Commercial microwave link networks for rainfall observation: Assessment of the current status and future challenges. *WIREs Water* 6:e1337.

David, N. (2019). Harnessing crowdsourced data and prevalent technologies for atmospheric research. *Advances in Atmospheric Sciences* 36:766–769.

Dokter, A. M., F. Liechti, H. Stark, L. Delobbe, P. Tabary, and I. Holleman (2011). Bird migration flight altitudes studied by a network of operational weather radars. *Journal of the Royal Society Interface* 8:30–43.

Fritzsche McKay, A., and B.J. Hoye (2016). Are migratory animals superspreaders of infection? *Integrative and Comparative Biology* 56:260–267.

Liechti, F., J. Aschwanden, J. Blew, M. Boos, R. Brabant, A. M. Dokter, V. Kosarev, M. Lukach, M. Maruri, M. Reyniers, et al. (2019). Cross-calibration of different radar systems for monitoring nocturnal bird migration across Europe and the Near East. *Ecography* 42:887–898.

López-Hoffman, L., C. C. Chester, D. J. Semmens, W. E. Thogmartin, M. S. Rodríguez-McGoffin, R. Merideth, and J. E. Diffendorfer (2017). Ecosystem services from transborder migratory species: Implications for conservation governance. *Annual Review of Environment and Resources* 42:509–539.

Messer, H., A. Zinevich, and P. Alpert (2006). Environmental monitoring by wireless communication networks. *Science* 312:713.

Miller, H. J., S. Dodge, J. Miller, and G. Bohrer (2019). Towards an integrated science of movement: Converging research on animal movement ecology and human mobility science. *International Journal of Geographical Information Science* 33:855–876.

Moreau, R. E. (1972). *The Palaearctic-African Bird Migration Systems*. Academic Press, London, UK.

Nathan, R., W. M. Getz, E. Revilla, M. Holyoak, R. Kadmon, D. Saltz, and P. E. Smouse (2008). A movement ecology paradigm for unifying organismal movement research. *Proceedings of the National Academy of Sciences USA* 105:19052–19059.

Nilsson, C., F. A. La Sorte, A. Dokter, K. Horton, B. M. Van Doren, J. J. Kolodzinski, J. Shamoun-Baranes, and A. Farnsworth (2021). Bird strikes at commercial airports explained by citizen science and weather radar data. *Journal of Applied Ecology* 58:2029–2039.

Nilsson, C., A. M. Dokter, B. Schmid, M. Scacco, L. Verlinden, J. Bäckman, G. Haase, G. Dell'Omo, J. W. Chapman, H. Leijnse, and F. Liechti (2018). Field validation of radar systems for monitoring bird migration. *Journal of Applied Ecology* 55:2552–2564.

Nilsson, C., A. M. Dokter, L. Verlinden, J. Shamoun-Baranes, B. Schmid, P. Desmet, S. Bauer, J. Chapman, J. A. Alves, P. M. Stepanian, et al. (2019). Revealing patterns of nocturnal migration using the European weather radar network. *Ecography* 42:876–886.

Ostrometzky, J., A. Eshel, P. Alpert and H. Messer (2017). Induced bias in attenuation measurements taken from commercial microwave links. In *2017 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, New Orleans, LA, USA. pp. 3744–3748.

Schekler, I., T. Nave, I. Shimshoni, and N. Sapir (2023). Automatic detection of migrating soaring bird flocks using weather radars by deep learning. *Methods in Ecology and Evolution* 14:2084–2094.

Shamoun-Baranes, J., S. Bauer, J. Chapman, P. Desmet, A. Dokter, A. Farnsworth, B. Haest, J. Koistinen, B. Kranstauber, F. Liechti, et al. (2021). Weather radars' role in biodiversity monitoring. *Science* 372:248.

Schmid, B., S. Zaugg, S. C. Votier, J. W. Chapman, M. Boos, and F. Liechti (2019). Size matters in quantitative radar monitoring of animal migration: Estimating monitored volume from wingbeat frequency. *Ecography* 42:931–941.

Shi, X., C. Hu, J. Soderholm, J. Chapman, H. Mao, K. Cui, Z. Ma, D. Wu, and R. A. Fuller (2023). Prospects for monitoring bird migration along the East Asian-Australasian Flyway using weather radar. *Remote Sensing in Ecology and Conservation* 9:169–181.

Shirihai, H. (1996). *The Birds of Israel*. Academic Press, London, UK.

Song, K., X. Liu, and T. Gao (2021). Real-time rainfall estimation using microwave links: A case study in east China during the plum rain season in 2020. *Sensors* 21:858.

Uijlenhoet, R., A. Overeem, and H. Leijnse (2018). Opportunistic remote sensing of rainfall using microwave links from cellular communication networks. *WIREs Water* 5:e1289.

Van Doren, B. M., and K. G. Horton (2018). A continental system for forecasting bird migration. *Science* 361:1115–1118.

van Gasteren, H., K. L. Krijgsveld, N. Klauke, Y. Leshem, I. C. Metz, M. Skakuj, S. Sorbi, I. Schekler, and J. Shamoun-Baranes (2019). Aeroecology meets aviation safety: Early warning systems in

Europe and the Middle East prevent collisions between birds and aircraft. *Ecography* 42:899–911.

Werber, Y. (2024). *fig_data_1b.mat*. *figshare*. *Dataset*. https://doi.org/10.6084/m9.figshare.26517436.v1

Zaugg, S., G. Saporta, E. Van Loon, H. Schmaljohann, and F. Liechti (2008). Automatic identification of bird targets with radar via patterns produced by wing flapping. *Journal of the Royal Society interface* 5:1041–1053.

Zaugg, S., B. Schmid, and F. Liechti (2017). Ensemble approach for automated classification of radar echoes into functional bird subtypes. In *Radar Aeroecology, Applications and Perspectives*. doi: 10.13140/RG.2.2.23354.80326