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Tracking and Monitoring Horses in the Wild using Wireless Sensor Networks

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***Abstract*—The Retuerta is one of the oldest breed of horses in Europe, which roams wild in the Donana National Park, Andalusia, Spain. Thirty-two of these horses were marked with wireless sensors to gather spatio-temporal data on their behaviour over a period of several months. This paper describes our experiences of tracking and monitoring these wild horses attached with body-worn sensors and operating in a harsh and challenging environment. Analysis of this data for the first two months has revealed rare insights into the horses' social behaviour, such as the group dynamics (group sizes and memberships), dispersal and home ranges which are of interest to both animal ethologists and practitioners managing the ecology of their wild habitats. The paper introduces the Virtual Beacon - Time Division Multiple Access (VB-TDMA) protocol for orchestrating the data collection, and describes the choices that were made for addressing the many technical challenges for an extended deployment, such as in the design of the sensor platform, wireless data collection and battery lifetime issues. Our experiences point to the virtue of simplicity in design of wireless sensor networks to support core functionalities for achieving good average case performances.**

I. INTRODUCTION

Environmental monitoring has made substantial progress in the previous decade thanks to the availability of platforms, which combine sensors, a low-power processor and a radio. These are capable of processing the sensed data and transmitting the derived information using either client-server or mesh protocols to base-stations, which act as bridges to IP networks and the rest of the Internet. Environmental sensor networks can be divided into two kinds: static and dynamic. Stationary sensors have been used to record environmental parameters such as ambient light, temperature, relative humidity, sound, and air quality (levels of carbon monoxide, ozone, nitrous oxides, and particulates). This paper is concerned with the second variety: autonomous dynamic sensor networks to record the activities of animals in their natural habitat, in terms of parameters such as activity levels, feeding patterns, movement dynamics and social behaviour (proximity to other tagged animals), along with temperature and ambient light. Each sensor reading has accompanying metadata – the location and the time when the data was recorded.

This paper relates the design considerations and experiences of deploying sensors on wild horses found in an area covering 550km^2. The sensors were required to be deployed for a period of around 12 months, to account for any seasonal variations, with the collected data being relayed as soon as practically possible to a central server for analysis. During this period the sensor platform will be powered off a primary cell, as there is no option for recharging or changing the battery. The maximum size and weight of the battery (which constitutes the bulk of the sensor node) is relative to the bulk of the animal and was fixed by the welfare consideration of the horses. The frequency of data sensing was a trade-off between the desire of biologists for as high a data resolution as possible and the size of the battery; the bargain struck was to provide GPS and a summary of sensor readings once every 20 minutes during the twelve-month deployment.

Animal tracking and activity monitoring offer biologists high-resolution data on the location and behaviour of animals. The spatial and temporal tagging of activity is useful in acquiring quantitative measures to better understand key parameters of animal ecology such as resource usage, home range, animal dispersal, and population dynamics [8]. However, a number of research challenges exist for the long-term tracking and monitoring of mobile entities using body-worn sensors with limited battery capacity. In addition, these networks have to be reliable with low maintenance costs, making use of robust and durable packaging, as they have to be deployed in a hostile environment. Overcoming these challenges requires both capable hardware and low-power algorithms for wireless communication.

The architecture comprises of a wireless network of mobile on-body nodes – the custom-designed Prospeckz-5 mobile platform – attached to the animals, and stationary nodes acting as base-stations connected to the IP network. The sensors on each platform include a GPS module, an accelerometer for sensing the head orientation and measuring the activity, a magnetometer for measuring the horses' orientation and a photovoltaic cell for light intensity measurements. The device is enclosed in a ruggedized, off-the-shelf enclosure, which is attached to the animal's neck using a custom-designed strap.

The paper considers two protocols for the transfer of data from the mobile platforms to the base-stations. The first protocol is an ad-hoc asynchronous data transfer protocol with acknowledgement and redundancy. This protocol is simple and deemed appropriate in the deployment scenario in which the base-stations are mains-powered and can be switched on all the time. The second one is a synchronous protocol developed specifically for this project involving tracking using GPS called the Virtual-Beacon TDMA (VB-TDMA) protocol.

The VB-TDMA algorithm is potentially more power efficient than existing MAC protocols for applications involving tracking mobile entities using GPS, because it optimises the radio usage to the extent of using it solely for exchanging data packets, without any communication overhead for synchronisation. This is possible by using the GPS time data to generate an internal virtual beacon for precise synchronisation (order of milliseconds). This can be used by all the nodes to synchronise without being in range of any other node, and minimises the time during which the radio is turned on. Also, obtaining the time information from the GPS module does not imply any extra cost in terms of battery consumption, as this information is acquired along with the position coordinates which are essential requirements for the target class of applications.

The main contributions of this paper are the following. Firstly, the deployment of the Prospeckz-5 wireless sensor nodes has been proven in one of the harshest and uncompromising environments. Secondly, a TDMA algorithm has been proposed for an applications class of tracking mobile entities using GPS which does not incur communications overhead for synchronisation. Thirdly, for the first time, results are presented on the behaviour of an endangered species of wild horses which is proving to be invaluable to biologists, ecologists and conservationists.

In the rest of the paper, Section 2 gives the background to animal tracking, Section 3 presents the custom-designed Prospeckz-5 wireless sensor nodes, Section 4 elaborates on the two communication protocols, Section 5 presents the results of deployment in the field for the asynchronous data transfer protocol for mains-powered base-stations, including novel insights into the behaviour of wild horses, Section 6 presents results of experiments in the test deployment of the VB-TDMA protocol using battery-powered base-stations, Section 7 discusses the experiences and lessons learned, and, finally, Section 8 presents the conclusions drawn based on the results, along with ideas for future work.

II. BACKGROUND

Various deployments have taken place for tracking and monitoring different types of animals on the ground [6], [4], [16], [18], [7], [12], [5], [13], in the air [5], underground [10], [15], [17] and underwater [11]. This paper focuses on the solutions for terrestrial deployments for monitoring animals (especially, tracking solutions that use GPS for determining their locations). Research in animal tracking and behaviour monitoring applications falls into two broad categories: non-GPS animal tracking and animal tracking based on GPS.

A. Non-GPS Animal Tracking

Chen Liu et al. [13] present a solution for tracking monkeys in the wildlife reserve of Qiling Mountain, China. Their locations are determined by analysing the sounds that the monkeys make and using video surveillance, and through applying pattern recognition on audio-visual data. Markham et al. [15] suggest using magneto-inductive localisation for underground tracking of burrowing animals (badgers). Collars are attached to the badgers, containing nodes with sensors that measure magnetic field strengths. The recorded data is stored locally until the animal surfaces, at which point it is uploaded using a 2.4GHz radio. Osechas et al. [17] describe a Wireless Sensor Network (WSN) deployment for tracking the movement of rats attached with Mica2dot nodes, along with a sensor suite comprising a microphone and an accelerometer. Johnson and Tyack [11] present DTAG, a device designed to monitor the behaviour of whales during their dive cycle. This consists of sensors for measuring in a synchronised manner the sound and the orientation of the whales. Araki et al. (United States patent [6]), present a solution for animal-herd monitoring using WSNs. Their method only tracks the location of the entire herd, and not the individual members and is more suitable for use in domestic herds. Dyo et al. [10] present a study of a wildlife monitoring network deployment meant to analyse the social co-location patterns of badgers over a period of one year. This was achieved by using collars with RFID transmitters and fixed detection nodes.

B. Animal Tracking Solutions Based on GPS

For the past three decades, ecological studies have been using terrestrial radio tracking methods [19], [16]. This has changed with the advent of GPS technology. GPS receivers are able to provide accurate location coordinates (with errors of few metres) at low power consumption and their size can be scaled down to a few millimetres (e.g. Fastrax IT430 GPS receiver: 9.6 x 9.6 x 1.85mm with a 500μA power consumption [1]). Therefore, GPS technology for wildlife tracking is a feasible option for obtaining accurate position coordinates over an extended period of time, opening new perspectives for wildlife study.

The research presented in [9] is aimed at testing the behaviour and performance of GPS receivers for wildlife monitoring applications. Previous research has concentrated on measuring the performance of GPS collars for animal tracking in terms of location accuracy, by placing them on a free-ranging moose [16], [18] and on five white-tailed deer [7]. Anderson and Lindzey [4] describe a six-to-eight months deployment of collars containing GPS receivers, which were attached to eleven cougars. The deployment had the purpose of studying predation rates and identifying the prey-selection patterns. The ZebraNet system [12] consisted of a 30-node WSN deployment for localising zebras in their natural habitat across an area of 400 squared kilometres for 1 year. The nodes were attached to the animals using collars, and established peer-to-peer connections to route information to mobile collection points (base-stations). Anthony et al. [5] present a highly scalable solution for a 5-7 year deployment for tracking migratory birds (Whooping Cranes). The solution relies on a hybrid architecture that uses cellular networks for long-range communication and ad-hoc networks for short-range (in breeding and nesting grounds).

We require the animals to be monitored in the wild for one year, and during this period we wish to record their positions (along with other sensor data) once every 20 minutes. The collected sensor information is required to be communicated to the nearest base-station. This poses a greater challenge than the applications described previously. Given that the primary goal of animal tracking is to determine their locations and this operation dominates the energy budget, a reasonable metric for comparison would be the number of GPS positions sampled during the duration of deployment. For example, the deployment for tracking migratory birds [5] is estimated to have a lifetime of 5-7 years, but they only acquire 2 GPS positions per day. This adds up to 3650 (5 years) or to 5110 (7 years) samples, which is about 5.5 times less than our chosen scenario, which requires 23890 GPS position samples (1 sample every 20-22 minutes over 1 year).

As the wild horses under study are endangered species governed by stringent conservation laws, strict limitations are imposed in terms of the weight and size of the devices that can be attached to them. A fully assembled node (without the strap) weighs 165g and is approximately 7 times lighter than the nodes deployed in ZebraNet which weighed 1151g. Despite their significant weight, ZebraNet nodes have just enough battery power to operate for only 5 full days without recharging. The entire deployment relied on solar cells, each ZebraNet node having a solar cell weighing 540g. In contrast, the nodes used in the deployments presented in this paper are expected to last around 1 year solely on battery power. Also, due to storage limitation and to the fact that one ZebraNet node may get to collect and store the data from all the other nodes in the network, data losses may occur. In this case the most recent data (according to the timestamps in the packets) is prioritized. In contrast to this approach, the solution proposed in this paper preserves all the data gathered during the experiment. Even if the base stations do not collect some of the data, all mobile nodes will store them locally in the flash memory, and as a last resort can be retrieved at the end of the deployment.

Wildlife tracking/monitoring or node localisation applications using WSNs rely on frequent exchanges of beacons or control packets over the radio to establish links between the nodes [6], [10], [12], [17], which has significant implications for the power consumption. For WSN applications which do not have the option of replacing the battery once deployed, optimising the battery consumption is essential by waking up the nodes simultaneously when required to exchange data.

III. HARDWARE

This section presents the mobile nodes that are attached to the horses and the base-station nodes, all having at their core the custom-designed hardware platform Prospeckz-5 [23] for wildlife tracking/monitoring.

The mobile nodes consist of a custom-designed strap that is placed around the horses' necks and holds the off-the-shelf NEMA 4X rated enclosure. The assembled enclosure weighs 165g and contains a Prospeckz-5 board and an enclosure-mounted antenna, two Lithium Thionyl Chloride batteries (3.6V, 2 x 2500mAh) and it is potted with re-enterable silicone compound providing vibration protection and waterproofing to IP68 standard.

Different GPS modules were selected for the two deployments presented in this paper, which offered a better understanding of the trade-offs between power consumption and position accuracy: the FGPMMOPA6H GPS module [3] and the Fastrax UC430 [2]. The long-term wildlife deployment that uses the asynchronous algorithm used the FGPMMOPA6H GPS module due to its ability to acquire a position fix very quickly (hot start ~1sec, cold start <35sec) and because its power consumption when active (Acquisition: 25mA, Tracking: 20mA) is approximately half of the UC430's power consumption (Acquisition: 47-90mA, Tracking: 27mA). As the experimental deployment on domestic horses that uses the VB-TDMA took place in a small area (approximately 500 square metres), the UC430 was selected for its higher position accuracy with observed errors of less than 2m.

The base-station node has a larger NEMA 4X rated enclosure containing three batteries (3 x 2500mAh) and an external antenna. Due to availability of 12V power and Ethernet at the towers throughout the natural reserve, the base-stations consist of a Prospeckz-5 board connected through a serial interface to a Raspberry Pi board and a 12V to 5V DC/DC converter. The range achieved between the mobile nodes and a base-station at a 2m height was approximately 550m.

IV. COMMUNICATION PROTOCOLS

This section presents the two communication protocols used in scenarios depending on the availability of power for the base-stations: an asynchronous data upload protocol with redundancy, and a synchronised Virtual-Beacon TDMA algorithm for power-constrained base-stations. These two distinct designs were tested in the field: the asynchronous protocol was deployed on the Prospeckz sensors for thirty-two Retuerta wild horses in the Donana National Park; the VB-TDMA protocol was deployed on the Prospeckz sensors for eight domesticated horses in the Veterinary School at the University of Edinburgh.

A. *Asynchronous Data Upload Protocol with Redundancy*

For the particular scenario of the horse tracking and monitoring deployment in the natural reserve, the base-station nodes could be placed on high towers in order to have access to power and internet connection, and gain better radio range. Since the base-stations can be supplied with power, they can keep the radio always on and listen for packets, having the batteries as backup in case of power drop-offs. However, the ellipsoid radio ranges of any two base-stations should not intersect in order to avoid collisions of acknowledgement packets. As a solution to this problem and to be able to deploy the base-stations at the fixed locations of the towers, the use of different radio channels was considered, with the adjacent base-stations operating at different frequencies.

The mobile nodes are programmed to upload data onto three different channels every 15 seconds. The radio transmissions use very little power, as the time required to send a packet (when the radio is kept in TX mode) is very short (less than 1ms). In contrast, if the radio were left in RX mode for extended periods of time it would draw 13.5mA. The nodes also have a fast upload channel, separate from the other three channels, in order to accommodate mobile base-stations (using UAVs and UGVs) use-cases. On this channel they upload data in short bursts of up to six packets (for each transmitted packet an acknowledgement needs to be received before transmitting the next packet). The number of packets in one burst is kept low in order to minimise possible collisions that could be caused by simultaneous bursts from different mobile nodes.

Using different channels offers redundancy in the data collection process, as on each channel, the complete set of data collected by the mobile nodes is uploaded. The packets are transmitted in chronological order (from the oldest to the newest). Packets are never dropped, and they are resent until the mobile node receives acknowledgement messages for them.

B. Virtual-Beacon TDMA Algorithm

The VB-TDMA algorithm was designed to be a low-power communication protocol for tracking applications and requires a hardware platform that contains a GPS module. When tracking mobile entities over a wide area (several tens of square kilometres), it is required to have their positions and a global clock to synchronise the communication of the mobile nodes with the base-stations. Both these functionalities can be provided by a GPS module.

The synchronisation of the nodes based on the GPS time information works as follows. The GPS module supports two protocols for communication: NMEA and SiRF. The NMEA protocol does not provide access to any of the GPS's power modes and the GPS module in SiRF mode is not able to get 1PPS time messages. The 1PPS time messages output the time associated with the current 1PPS pulse. Each message is output within a few hundred milliseconds after the 1PPS pulse is output and tells the time of the pulse that just occurred. Since both these aspects are critical to the application, it was necessary to use both protocols: SiRF was used to set the GPS module in the Micro Power Mode and NMEA to activate the ZDA messages, which enable the 1PPS time messages.

The proposed TDMA algorithm uses two types of time slots: Discovery slots and Upload slots. The Discovery slot has the purpose of determining if a certain mobile node is within range of a base-station. A mobile node sends only one packet in this slot, and if it receives an acknowledgement and if it has data to upload, it schedules an upload slot. If not, it goes into sleep mode and wakes up in 20 minutes time to try again. The base-station has the radio turned on in the receive mode for the period of all the Discovery slots. If in one of the slots it receives a packet, it acknowledges that packet and schedules to turn on the radio for the corresponding Upload slot. If a mobile node does not manage to upload all of its data in the first Upload slot (and it does not go out-of-range of the base-station during the time of the Upload slot), another Upload slot is scheduled.

For more reliability in packet delivery, the radio on the mobile node is configured to have up to 15 retransmissions of a packet in case it does not receive an acknowledgement for it. Fifteen retransmissions of a packet were timed to be slightly over 8ms, thus the Discovery time slots were configured at 10ms, and the Upload time slots at 100ms. The frequencies of the node discoveries should be chosen according to the needs of each application scenario, while considering the tradeoff between the network responsiveness and the power consumption overhead associated with keeping the radio on for 10ms during multiple Discovery slots.

The alternative approach of using a terrestrial radio beacon to synchronise a TDMA protocol would be infeasible for the given scenario. There could be one or more base-station generating beacons at regular intervals, and the mobile nodes with short listening windows for receiving the beacons and updating their internal clocks. Using such a protocol in this scenario, where mobile nodes could be out of range of the base-stations for more than one month, will lead to increasing their listening windows' size significantly to accommodate the clock drift. After a period of one month of being out of synchronisation range, the initial listening window size will be increased by approximately 52 seconds (representing the clock drift based on a 20ppm crystal over one month), which increases the total system power consumption by more than 200%.

V. WILDLIFE DEPLOYMENT

This section presents the results obtained from a wildlife deployment, where 32 wild horses (see Figure 1) of one of the oldest European breeds, were tracked and monitored for a planned duration of one year. During this year, GPS locations were gathered every 20 minutes along with the horses' activity and head angle over this time interval. This information is uploaded wirelessly from the mobile nodes attached to the horses to the base-stations dotted in the nature reserve. This section presents the results gathered using the asynchronous protocol (presented in Section IV-A) from a 2-month period from the beginning of the deployment, whereas the results obtained using the VB-TDMA are presented in Section VI.

Fig. 1. An arrangement of mobile nodes with a base-station and antenna ready for deployment (left). Wild horses being marked with sensors (right).

A. Data and Redundancy

Pre-deployment tests were performed in order to test the sanity of the collected data (head angle, activity and location accuracy). There is a trade-off between the position accuracy and the time the GPS module is on, which directly translates to power consumption. With this in mind, the accuracy obtained from the GPS module is CEP50=9.56 and CEP90=58.14.

Due to the three-way redundancy, packets are duplicated on different channels. From a total of 77285 packets, 92.59% were received on just one channel, 5.38% on two channels and 2.02% on three channels (see left-hand side of Figure 2). The low redundancy percentages are explained by the unequal volume of packets received by each base-station (most packets were received by base-station 2 on one channel).

Figure 2 (right-hand side) reveals that the base-stations that received the most packets are B1, B2 and B6, which must be in the locations visited frequently by the horses. The map presented in the left side of Figure 3 shows the locations of the base-stations and their channels, and highlights the area determined by the three base-stations with higher traffic/upload rates which is assumed to be more frequented by the horses in comparison to the other base-stations locations. This is validated by the figure on the right hand side of Figure 3, where the GPS positions are plotted in a heat map, with green indicating a low concentration of GPS locations and red signifying a high one.

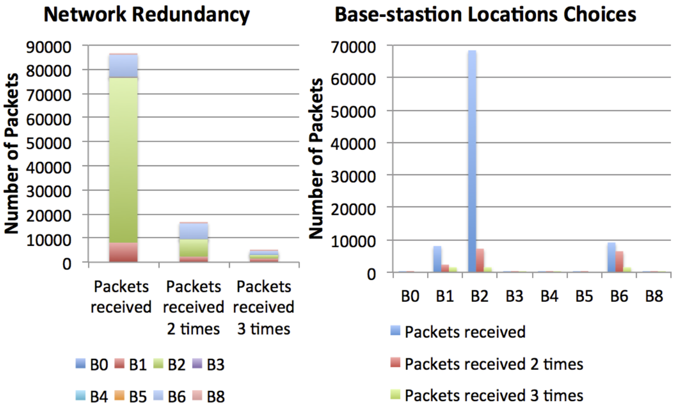

Fig. 2. Network redundancy and base-station locations choices.

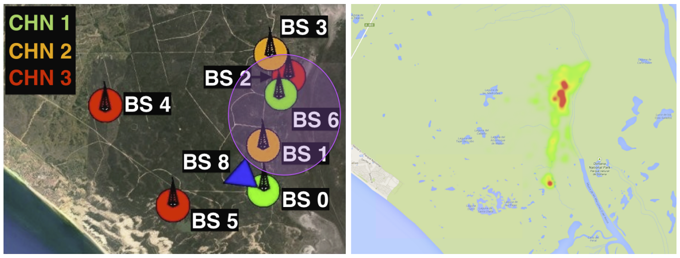

Fig. 3. Base-station locations (left); heatmap of the horses' GPS locations (right).

B. Horse Behaviour

We have explored the extent to which an asynchronous protocol can be used to infer the group behaviour of horses over an extended period of time. The results presented here are based on a longitudinal study conducted over a 2-month period. The data for each horse, gathered every 20 minutes and uploaded, includes the following information collected during the previous interval: the maximum activity based on an algorithm proposed by Mann et al. [14], the percentage of time when the head was down, and the GPS location and time stamp when the data was uploaded.

The activity and head angle data validate the known behaviour that horses rest and sleep during the night and are more active during the day.

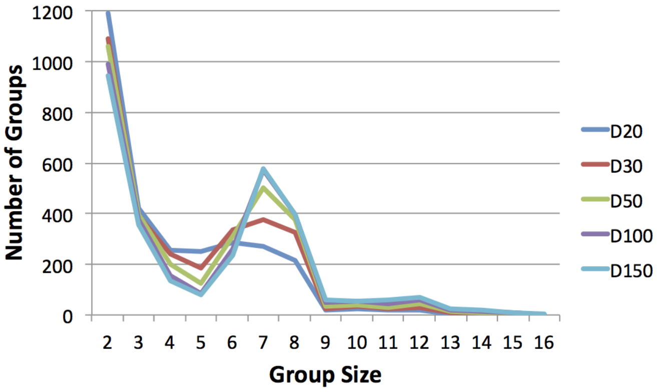

Fig. 4. Distance sensitivity analysis.

The graphs in Figures 5 - 8 illustrate the group behaviour and group dynamics of the horses under study. A horse is considered to belong to a group if it is within 100 metres of any other horse during an hourly interval. Figure 4 guided the choice of the distance of 100m based on the sensitivity analysis. Figure 5 shows the percentage of time that a horse belongs to any group. The majority of the horses belong to a group at least 60% of the time, which is in keeping with the natural herd instinct of horses in the wild.

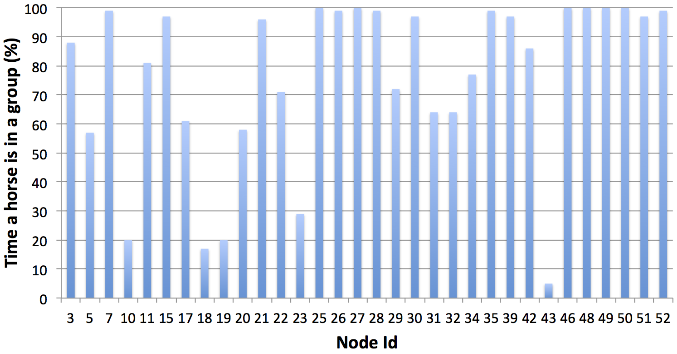

Fig. 5. The percentage of time during the two-month period when a horse is part of a group.

Figure 6 shows the number of instances of group sizes which formed during the period under study. Groups of certain sizes were more common than others, e.g. instances of groups with seven horses was the second most popular after groups with two horses in them.

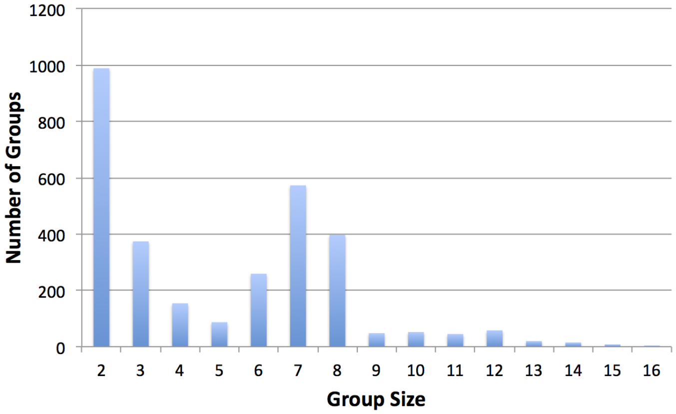

Fig. 6. Instances of group sizes over the 2-month period.

Figure 7 shows a snapshot of the horses in the different groups and their locations on a map during the first hour of the 2-month period. Group 1 was the most stable grouping over the duration of two months, and it is composed of one male (H7) and several females. We will follow Group 1 in more detail in Figure 8 to study its dynamic behaviour, with 8 horses being present in this group for a majority of the time. Figure 8 follows all the horses which had contact with Group 1 over the two-month period and shows some interesting dynamics. A core of seven horses - H7, H21, H39, H30, H35, H26 and H46 - remained together for the longest duration, with others dipping in and out. H48, for instance, started with this group in the first hour of our study (see Figure 7) but left the group after three weeks and never to re-join. The gaps in the graphs for the core horses indicate when one or more of the core horses

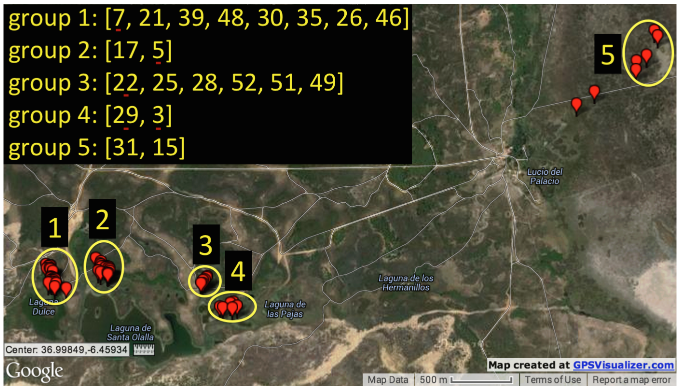

Fig. 7. A snapshot of the groups with their locations in the first hour on 19 September 2013 (Note: each horse can have up to three locations in each hour).

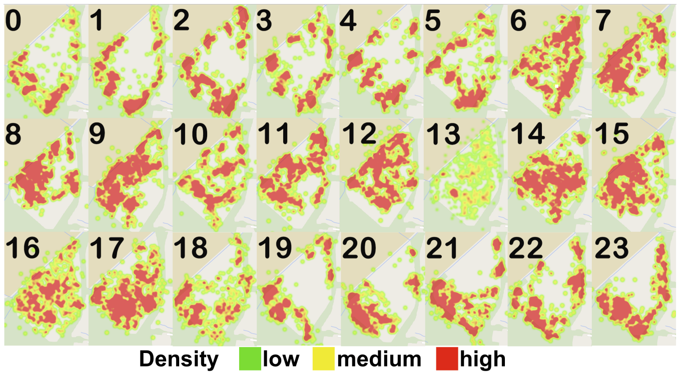

Fig. 9. Heatmaps of the hourly snapshot of a horse's location aggregated over 17 days.

left the group, even though other horses might have joined the group to increase its numbers.

The project has been an exemplar for data-driven approaches to conservation by understanding animal behaviour with a level of spatial and temporal resolution than hitherto possible for a deployment over several months. The insights obtained on the horses' behaviour could only have been possible thanks to wireless sensor networks. The current methods using satellite-based remote sensing and visual observations do not offer the same level of discrimination and efficiency. Our approach can have a considerable impact in animal behavioural sciences by extending to other species and environments where visual observation methods are currently used.

VI. BASESTATION-CONSTRAINED DEPLOYMENT

The VB-TDMA protocol was developed to extend the lifetime of the battery-powered base-stations in the absence of mains power supply in the deployment area. The testing of the protocol was conducted over a 17-day period with one base-station and eight domestic horses, which were part of a teaching herd. This deployment had the role of testing the new VB-TDMA algorithm under realistic conditions.

Our stated goal for this scenario was to obtain GPS data once every 20-22 minutes in the wild, which translates to 23,890 samples over a 12-month period for each mobile node. As the testing was intended primarily to exercise the VB-TDMA protocol, the data gathering was accelerated to once every minute over a 17-day period. The sensor node was able to record around 24,000 sets of sensor readings on a mobile node during the battery lifetime, which is more than the stated goal over the proposed 12-month duration of deployment. The deployed VB-TDMA protocol implementation had mobile nodes attempting one discovery per sampling time slot, followed by possible upload slots, and data was uploaded on only one channel (one base-station was deployed).

There is an important caveat when projecting the performance over the 12 months, based on the limited study. For a 20-minute interval the ephemeris data (used to calculate the position of each satellite in orbit) and the almanac (information about the time and status of the entire satellite constellation) of the GPS modules will not be as fresh as in the case of 1-minute intervals. Thus, the time taken to acquire a fix and to update the satellite information will be greater.

For a one-minute slot at an accuracy of less than 2m, the UC430 GPS module took about 15 seconds on average to acquire and improve a position fix, at a cost of approximately twice the power consumption of the FGPMMOPA6H GPS module. The latter as described in Section V was turned on for 25.5 seconds every 20 minutes, having a lower, albeit acceptable accuracy of less than 10m. Therefore, the overall power consumption of the UC430 aiming for a high accuracy fix every minute, is higher than the power consumption of the FGPMMOPA6H at a lower accuracy with a position fix every 20 minutes. We can therefore project that the lifetime of the deployment of nodes equipped with the FGPMMOPA6H GPS module, sampling every 20 minutes, and aiming for an accuracy of less than 10m, should be greater than one year.

Figure 9 gives an interpretation of the horses' activity and behaviour during the diurnal cycle based on the GPS location data from the test deployment. It is interesting to observe that during the night times the horses avoid the open field and prefer locations that are sheltered by trees along the periphery of their confinement area. This behaviour is noticeable in Figure 9 in the hourly snapshots of a horse's locations aggregated over the 17-day deployment period. The horse clusters around the sheltered periphery during the night times and is found in the middle of the day around the trough during feeding times. It was also observed that the horses move less during night times. During a typical night hour, a horse was located inside circles with an average radius of 23m, whereas during the day-time the average radius was 70m.

The VB-TDMA algorithm was compared in simulation [24] to other MAC protocols: S-MAC [20], which supports self-configuration, SpeckMAC-D [21] a low-power distributed, unsynchronised, random-access MAC for mobile ad-hoc WSNs, and XMAC [22] a WSNs MAC that performs low power listening by employing a shortened preamble approach. The VB-TDMA protocol performed well, leaving the mobile nodes with more than 10% of the battery after a 12-month deployment. In comparison, the other MACs completely discharged the mobile nodes' batteries during the deployment, and the amount of data collected by the network running them was less than 50% of that of the network running the VB-TDMA

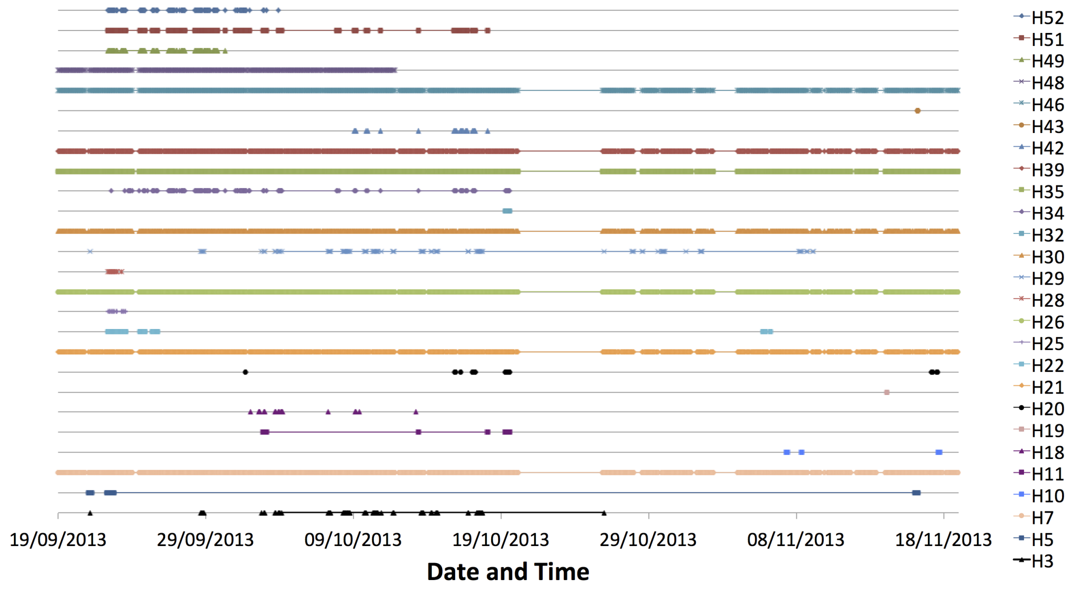

Fig. 8. Dynamics of Group 1 around the core horses - H7, H21, H39, H30, H35, H26 and H46.

[24].

VII. DESIGN TRADEOFFS AND EXPERIENCES

The Prospeckz-5 design was driven by two principal external constraints: a small enough size for use on a horse and the requirement for a battery life of at least one year. A number of battery topologies were considered, including rechargeable batteries and solar power. Relying on a solar cell/rechargeable battery combination was risky as the effective generated power was attenuated by mud coating the window of the solar cell, and rechargeable batteries have limited performance in extreme temperature conditions as encountered in Donana. It was therefore decided to use primary cells in the form of a pair of AA Lithium Thionyl Chloride batteries with the required energy density and rated for extended temperature ranges. These batteries are particularly well suited to handle the long-term low average current needs of the Prospeckz-5.

The design criteria for the microcontroller (MCU) at the heart of the Prospeckz-5 were ultra-low power operation together with a reasonable amount of RAM to allow for the use of large buffers to minimize access to the serial flash memory, which is relatively energy-intensive during each access due to the need for erasing parts of the flash. The EFM32GG990 was chosen due to the high performance of the Cortex-M3 core, which minimises the active time of the processor, and the very low current consumed during idle times. Another trade-off was the size of the MCU package in relation to the amount of RAM available, and the chosen MCU is one of the smallest with a large amount of RAM (1024KB).

The selection of a GPS module was influenced by the presence of an integrated antenna to avoid wires passing through the enclosure (with implications for water-proofing) and a small footprint. The UC430 module fitted this bill, as well as advertising support for ultra-low-power modes that should have allowed the module to operate at a very low average power. Unfortunately, in practice, due to both the mounting on a horse as well as the limited ground plane available on the space-constrained PCB, the antenna did not perform well enough to take advantage of this energy-saving feature. Therefore, the deployment in the wild used a different module, the FGPMMOPA6H, with a larger ceramic antenna which was mounted on top of the Prospeckz-5 PCB. This module does not have the ultra-low-power mode, but offered considerably superior antenna performance along with a lower current consumption when active.

The radio needed to support both reasonable range as well as low power operation. Based on our Research Centre's experience with ultra-low-power radio operation, we chose a 2.4GHz transceiver (NRF24L01+) with the option of using a relatively high signal rate of 2Mbps. It is customary to choose a transceiver with much lower signal rate but with a higher receiver sensitivity, which would allow a signal to be picked up under bad propagation conditions. In the case of Prospeckz-5, a design was favoured with an extremely low power per bit transmitted to allow "probe" packets to be sent frequently. We augmented this radio with an RFX2401C amplifier IC, which combines both a PA (power amplifier) for amplifying the transmitted signals as well as a LNA (low noise amplifier) for amplifying the received signals before processing by the radio receiver. The combination of the NRF24L01+ with the RFX2401C can offer an up to 24dBi end-to-end gain compared to the NRF24L01+ alone. We chose to use an internally-mounted antenna for the 2.4GHz radio, to keep the casing as water-tight as possible. We used an internal antenna connector rather than using a PCB-antenna or other PCB-mounted antennas to have flexibility in the choice of antennas, depending on the performance in the enclosure.

The power supply of the Prospeckz-5 had to be optimised both for extracting the maximum amount of energy out of the batteries as well as minimising the idle current drain. The batteries supply a voltage between 3 - 4.2V while the components on the system themselves operate at 1.8 - 2.2V. Using a purely linear voltage regulation strategy (using LDOs for example) nearly half the energy in the batteries would have been wasted. Typical switching DC-DC regulators, which can regulate the voltage much more efficiently, have relatively large idle currents. The Prospeckz-5 components are carefully chosen to offer an overall idle-current on the order of 10s of uA, while typical switching regulators can have idle currents in the 100s of uA. We chose the LTC3103 switching regulator, which has an idle current of only 1.8uA due to a burst mode of operation. As a result, the power from this regulator is relatively noisy so additional low-noise LDO regulators are used for the GPS module and the flash to ensure good performance.

VIII. CONCLUSIONS

This paper has presented the challenges and solutions for collecting information using collar-based sensors on the behaviour of wild horses in their natural habitat. The project has identified a number of technical issues related to power consumption for a long-term deployment. Two methods have been suggested for uploading sensor data from the mobile nodes to base-stations. A simple asynchronous data transfer protocol using acknowledgements and redundancy is currently deployed on the wild horses, which is suitable for base-stations with access to mains power and can have the radio on permanently. And, the Virtual-Beacon TDMA protocol was developed specifically for applications in monitoring and tracking mobile entities in the outdoors using GPS for scenarios involving battery-operated base-stations with limited power. A sample of results on the behaviour of the horses in the wild has for the first time provided insights at a level of granularity not hitherto seen.

Future work will involve the deployment of the VB-TDMA protocol and its evaluation in the wild. Techniques and tools are being developed to analyse the large corpus of high-resolution data, which will shine new light on the behaviour of these wild animals in their natural habitat.

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