Cattle-Powered Node Experience in a Heterogeneous Network for Localization of Herds

Álvaro Gutiérrez, *Member, IEEE*, Nelson I. Dopico, Carlos González, Santiago Zazo, Javier Jiménez-Leube, and Ivana Raos

***Abstract*—A heterogeneous network, mainly based on nodes that use harvested energy to self-energize, is presented, and its use is demonstrated. The network, mostly kinetically powered, has been used for the localization of herds in grazing areas under extreme climate conditions. The network consists of secondary and primary nodes. The former, powered by a kinetic generator, take advantage of animal movements to broadcast a unique identifier. The latter are battery-powered and gather secondary-node-transmitted information to provide it, along with position and time data, to a final base station in charge of the animal monitoring. Because a limited human interaction is desirable, the aim of this network is to reduce the battery count of the system.**

***Index Terms*—Energy harvesting, energy-aware network, ubiquitous systems, wireless sensor networks.**

I. Introduction

ANIMAL localization [1], animal behavioral studies [2], cattle monitoring [3], or the improvement of livestock techniques [4] have been active research areas for years. The use of mobile sensor networks promises a fruitful future for animal behavioral sciences, although some difficulties arise when trying to deploy electronic devices in a natural environment. In these networks, energy and power supplies are both technological and ecological constraints. On the one hand, power supply is needed for a long lifetime directly related to the battery lifetime. Moreover, in an animal-tracking scenario, if thousands of animals must be monitored, thousands of nodes must be battery operated. Therefore, high maintenance costs are reached, and a tedious task of battery replacement comes up. On the other hand, the use of batteries might turn out to be polluting in outdoor environments. As any system deployed in natural environments, environmental impact plays a relevant role and should be minimized.

The primary goal of our research is to track herds' movements in challenged areas at a very low cost and to reduce the environmental impact with unattended operation. Typically, animal movements do not need to be accurately tracked, but enough to monitor their presence in a certain area a number of times per day. In this way, a herder may know where the herd is, if any animal has left, or where it was lately around. This paper presents a self-powered heterogeneous network to locate herds and individual animals tested with semidomesticated Scandinavian reindeer. Previous works that focused on system architecture and simulations rather than real operating conditions and deployments can be found in [5]–[7].

There are several systems proposed in the literature which have been applied to animal localization. However, systems that are proposed so far make use of battery-power nodes which diverge from the primary goal of this paper. Most of them make use of satellites to locate animals' position [8]. They have been widely used in moose [9], camel [10], goat [11], turtle [12], duck [13], or whale [14] tracking. However, its use is extremely expensive and requires all the satellite transmitters on the animals to be updated in the satellite database. Moreover, the Global Positioning System (GPS) system must be powered, and once exhausted, batteries must be replaced.

In order to decrease the maintenance of the power supply, some approaches make use of storage systems based on solar energy as environmental energy source [15], [16]. In [17], for example, a single-storage energy harvesting based on solar energy is built. In [18], the authors presented a system based on a double-storage method. The primary system is recharged using a solar cell. If there is an excess of energy in the primary system, it recharges the secondary system and vice versa. In [19], a nonbattery-powered node is presented. It uses a supercapacitor which is recharged by means of solar energy. In [20], the authors make use of a supercapacitor which is recharged when some of the photodiodes are enabled. Some of the previous implementations have been used for animal tracking, as in the *ZebraNet* project [21] or the *TurtleNet* project [22]. However, solar energy is severely limited for latitudes where daily sunlight may be short in some seasons or the irradiance is not enough to power systems.

In order to overcome solar energy restrictions, many different techniques have been studied. In [23], the authors describe a system which takes advantage of human motion and obtains enough energy for transmitting information. However, the

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The authors are with Escuela Técnica Superior de Ingenieros de Telecomunicación, Universidad Politécnica de Madrid, 28040 Madrid, Spain (e-mail: aguti@etsit.upm.es; nelson@gaps.ssr.upm.es; cgonzale@etsit.upm.es; santiago@gaps.ssr.upm.es; jleube@etsit.upm.es; ivana@gaps.ssr.upm.es).

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communication is based on a transmitter which does not allow to reach farther than just a few meters. In [24], the authors follow the same principle by taking advantage of finger motion. A piezoelectric system based on a push button is presented in [25]. Other strategies make use of wind energy [26] or radio frequency energy [27]. However, while the former is not useful for animal-tracking systems because animals avoid wind flows, the latter suffers from poor emission ranges which make such systems unsuitable for large herds of animals.

Kinetic energy harvesting is, in turn, a good candidate for wearable electronic devices and wireless sensor networks [28], [29]. Kinetic energy harvesting devices are typically based on electric or electromagnetic transducers. However, they are mainly based on regular or random vibrations or displacements which provide a low-power generation insufficient in some applications. Moreover, the smaller the size of the object, the higher its resonant frequency. Therefore, it is difficult to design a miniature resonant generator to work on animals because they move randomly and, in some periods, they rest still. On the other hand, a thermoelectric converter, as the one presented in [30], could be a good candidate for humans depending on the climate regions. However, in general, they are not suitable for animals because the skin insulation does not provide enough thermal gradient.

Given the aforementioned constraints, this paper presents a system along with its testing and conclusions all based on a kinetic harvester module. Such module powers up batteryless nodes of a heterogeneous network which enables the transmission of reduced information to the rest of the network. The goal of the wireless sensor network is to endow each animal in a herd with a unique identification (ID) code that could be read within a range of tens to a hundred meters. Since limited human interaction is desirable, the aim of this network is to reduce the battery count of the system.

Upcoming sections are structured as follows. Section II describes the heterogeneous wireless sensor network that constitutes the localization system. Section III shows hardware and simulation experimental results. Section IV focuses on the experiments and tests that the prototypes underwent in different European locations. Section V summarizes the outcomes of the proof of concept and its tests and concludes this paper.

II. WIRELESS SENSOR NETWORK

The developed system is made up of primary and secondary nodes. Secondary nodes are the simplest elements in the network. They take kinetic energy from animal movements which produce just enough power to create and broadcast a unique ID to the environment without confirmation of its reception. If a primary node is within the transmission range, it receives and stores the transmitted ID. Moreover, primary nodes are able to obtain their global position owing to a GPS. Therefore, a primary node, which receives a transmission from a secondary node, approximates the aforementioned secondary node's position through its last acquired location.

Furthermore, the system includes repeaters and a base station. A repeater is a static battery-powered node which is able to communicate with other repeaters and the base station. The base station is a static battery-powered node which has access to the Internet and is able to offer data to a final monitoring system. Therefore, when a primary node enters within the range of communication of a repeater, it transmits all the information obtained from the secondary nodes as well as its own GPS positions along the time. Repeaters communicate with the base station which merges the data provided by the repeaters and extract the trajectories of the different primary and secondary nodes.

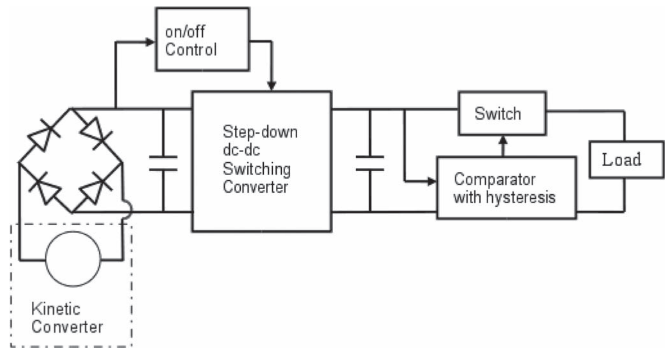


Fig. 1. Secondary node harvester block diagram.

A. Secondary Node

The secondary node (see Fig. 1) is made up of a kinetic-to-electric energy converter (energy source), followed by a rectifier, a step-down converter (including the inductor and the freewheeling diode), a storage capacitor, and a supply management circuit with hysteresis (see [5] for detailed information). The load is a 433-MHz radio transmitter which broadcasts a unique ID previously configured.

A 20-cm magnet/coil generator has been used as the kinetic-to-electric energy converter. Two generators can be connected to the harvester input. The generated voltage follows Lenz law. For a given magnet polarity, as the magnet enters the coil, a positive voltage cycle results and a negative cycle is obtained when the magnet moves out of the coil, so that there is no dc component. The waveform at the output of the coil in a swing of the magnet is a sine wave

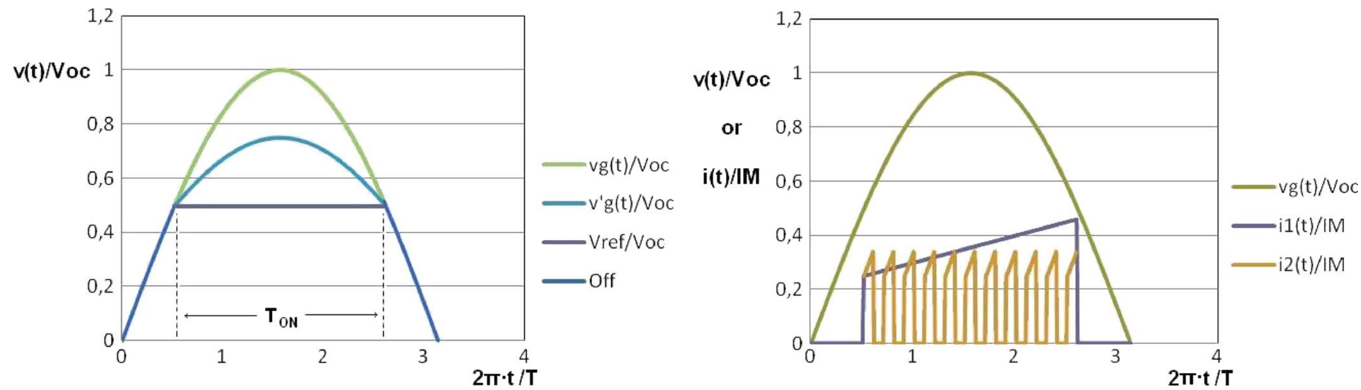
$$v_g(t) = V_{\text{oc}} \sin(2\pi f t) \tag{1}$$

where V_{oc} is the open-circuit voltage, f is the frequency, and t is time. The observed frequencies are in the range of 5–10 Hz.

However, the observed waveform is not an exact sine wave. The positive and the negative semicycles slightly differ in voltage peak value and duration because their values depend on the speed at which the magnet passes through the coil. This speed may be slightly different when the magnet enters or leaves the coil if it is accelerated.

A full-bridge configuration is selected for rectification. Contrary to a single diode or a voltage doubler, in a full-bridge configuration, each diode must withstand $V_{\text{oc}}/2$ when they are reverse biased so that low forward drop diodes with low reverse voltage can be used.

A commercial step-down dc–dc converter was chosen because the voltage provided by the generator/rectifier must be



(a) (b)

Fig. 2. Typical converter normalized input current waveform as a function of normalized time under different load conditions. (a) $T_{\rm on}$ is the normalized time during which the converter is on per semicycle. (b) Normalized open-circuit generator voltage in a semicycle is given as a reference.

reduced to the level required by the electronic load. In order to avoid uncontrolled on and off cycles of the step-down converter, a simple on/off control scheme [31] is used to obtain power from the generator and assure clean start-ups and shutdowns. A reference voltage $V_{\rm ref}$, above the minimum operating voltage of the converter, is selected as a voltage threshold. When the rectifier output voltage is lower than the reference voltage, $v_i(t) < V_{\rm ref}$, the converter is kept shut down by the on/off control. When $v_i(t) > V_{\rm ref}$, the converter turns on in a short time (tens of microseconds), much shorter than the semiperiod of the input signal, and then operates in standard converter condition. The reference voltage condition sets a converter operating window of duration $t_{\rm ON}$ in each semicycle given by

$$t_1 < t_{\rm ON} < \left(\frac{T}{2} - t_1\right). \tag{2}$$

If the forward voltage drop V_f of the rectifying diodes is neglected, $v_i(t) = v_g(t)$ (otherwise, $v_i(t) = v_g(t) - 2V_f$), and setting $v_g(t_1) = V_{\rm ref}$

$$t_1 = \frac{T}{2\pi} \arcsin\left(\frac{V_{\rm ref}}{V_{\rm oc}}\right) \tag{3}$$

where $t_1 < (T/4)$.

The power dissipated by the load (W_o) is slightly lower than the power provided by the generator (W_g) because the step-down converter also consumes some energy (W_c). Nevertheless, usually, $W_c \ll W_o$. Therefore

$$W_g = v_i(t)i_i(t) = W_o + W_c \approx W_o = V_o I_o. \tag{4}$$

Fig. 2(a) shows the converter input voltage patterns; $V_{\rm ref} = V_{\rm oc}/2$ is assumed in the figure as an example. If the generator is able to supply the demanded current at any time during the converter operation period, then the converter input voltage $v_i(t) = v_g(t) > V_{\rm ref}$. Such behavior corresponds to the upper and middle curves of voltage in Fig. 2(a). Input current is turned on and off to adjust the power delivered to the load

$$W_0 = V_0 I_0 = \frac{2}{T} \int_{t_1}^{\frac{T}{2}-t_1} v_g(t) i_i(t)\, dt. \tag{5}$$

The current flowing through the converter to the load I_C follows the pattern shown in Fig. 2(b). The regulator switches on and off to control the delivered power. The output current is a nearly steady current with a small ripple which depends on the output low-pass filter. Neglecting the current drawn by the converter itself, the output current I_o is the average value of the input current $I_o \approx I_C \approx \langle i_i(t) \rangle$. If I_C is uninterrupted, the power delivered to the load is exactly the maximum that the generator can provide [$IM(t)$ in Fig. 2(b)]. If it discontinues, the generator could deliver more power than that required by the load.

In our target application, the regulator operates in bursts because the input wave, assumed to be a sine wave of period T with a long trailing time of zero voltage, has an expected repetition period (T_r) much larger than the period of the input wave (T). Even if all the power available at the input $(V_{\rm ref} = 0)$, given by its rms value $V_{\rm oc}/\sqrt{2}$, is delivered at the output at a constant load, the repetition period has to comply with

$$V_0^2 T_r \le \left(\frac{V_{\rm oc}}{\sqrt{2}}\right)^2 T \Rightarrow T_r \le \left(\frac{V_{\rm oc}}{V_0\sqrt{2}}\right)^2 T. \tag{6}$$

The available power is reduced when a minimum voltage $V_{\rm ref} \neq 0$ is set in order to ensure clean converter start-ups and shutdowns. In this case, the available input power in a semicycle can be estimated as

$$\begin{aligned} V_{\rm rms}^2 &= \frac{V_{\rm oc}^2}{2} - 2\left[\frac{2}{T}\int_0^{t_1} (V_{\rm oc}\sin(\omega t))^2\, dt\right] \\ &= \frac{V_{\rm oc}^2}{2} - \frac{2V_{\rm oc}^2}{T}\left(t_1 - \frac{1}{2\omega}\sin(2\omega t_1)\right). \end{aligned} \tag{7}$$

In our application, not only the frequency and $V_{\rm oc}$ are variable but also the repetition period. Under this condition, the design aims at obtain an output time window of constant regulated voltage in a swing of the generator.

The output of the comparator controls a pMOS that acts as a switch. Once the supply is turned on, it remains on until the output voltage reaches a minimum threshold voltage.

When the kinetic converter is swung by hand and the harvester is loaded with 330 Ω, a pulse of 3 V and duration of

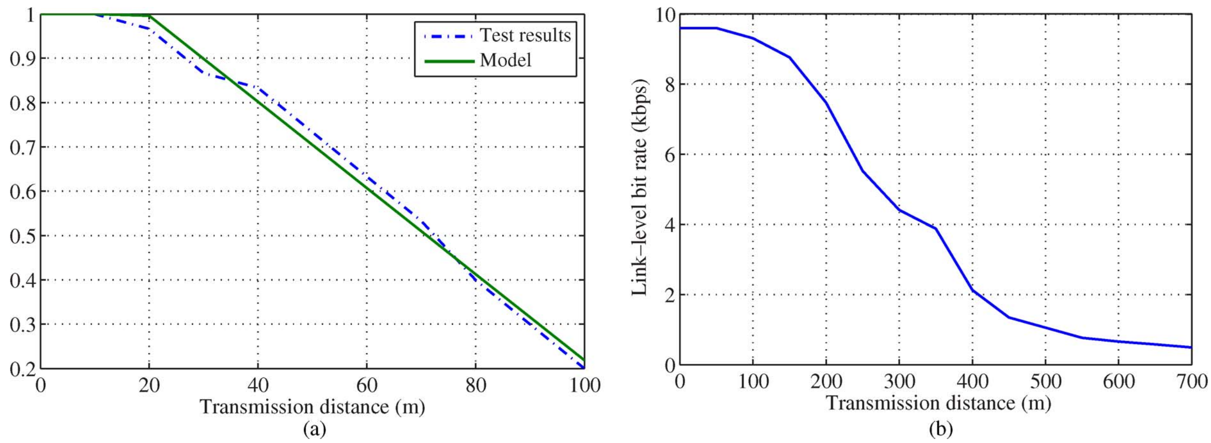


Fig. 3. Radio-link hardware tests. (a) Secondary-link probability of successful reception. (b) Repeater-link throughput.

about 40 ms are observed. It is within this period in particular in which a frame containing a unique ID is broadcast. In the last 5 ms, the voltage evolves from 3 to 2.2 V as the current is drained and the generator does not supply power anymore. At this voltage, the power supply is switched off.

The remainder of the secondary node is the ID transmitter which is made up of an MCU/UHF processor and an ID selector [5]. When the power burst is available, the MCU initializes, loads the ID, turns on the UHF transmitter, and broadcasts the ID frame.

B. Primary Node

Primary nodes are autonomous battery-powered devices specifically designed with an ARM-7 processor which controls the power supply of their four peripherals: a GPS module, a 433-MHz receiver, a 166-MHz transceiver, and a 64-Mb Flash memory [5].

Primary-to-secondary unidirectional communication is achieved by means of the 433-MHz receiver, whereas communication with repeaters and base stations is operated by the 166-MHz transceiver. A file system is designed specifically taking into account the application scenario. Hence, it enables fast writing to Flash memory in order to reduce the probability of power lost by the time data are written. Every file is named after its corresponding secondary-node ID. Data stored in every file comprise latitude, longitude, and time provided by the GPS module along with the corresponding primary-node ID number.

Primary nodes transmit contents from their file system as they connect with a repeater or base station. Transmitted frames include additionally the primary-node number and a frame number in order to support synchronization tasks on the receiver side—i.e., a repeater or base station.

C. Repeaters and Base Station

Driven by design simplicity, repeaters, base stations, and primary nodes are implemented on the same printed circuit board. Differences between them lay on their respective software implementation and the GPS module—not integrated neither by repeaters nor base stations since they are not intended to support additional localization facilities. Therefore, repeaters, as static network elements, have their predetermined position stored rather than read from a GPS module, thus saving costs and energy.

Repeaters and base stations always keep their 166-MHz transceiver on awaiting primary-node transmissions. Primary links operate a light media access control (MAC) protocol on both sides which allows for collisions, losses, and retransmissions in order to enable concurrent communications.

Finally, a computer must be connected to the base-station node. As information is received from a primary node, it is sent to the computer for its processing.

III. Laboratory and Simulation Evaluation

A. Hardware Evaluation

Different tests were developed in order to assess link performance. The two most meaningful links are referred hereafter: secondary links (secondary to primary) and repeater links (primary–repeater or repeater–base station). Further information about the hardware evaluation can be found in [5].

Secondary links are modeled based on the probability of successful reception by a primary node for a frame broadcast from a secondary node—frames include a CRC. The test was conducted in an obstacle-free environment and consisted of one secondary node and one primary node placed on 10-m steps from 0 to 120 m; nevertheless, frames were not received farther than 100 m. Fig. 3(a) shows the test results and a model fitted. Transmissions within 20 m are considered to be always successful, whereas from 20 to 100 m, the model is fitted by means of the minimum least square method.

Repeater links are characterized by means of their throughput since they operate a MAC protocol. The maximum communication distance was 720 m. See Fig. 3(b) for details.

B. Simulation Evaluation

Simulations may aid in system evaluation, particularly during prototype development. Otherwise, some analyses would become too expensive either in terms of cost or time. Localization error, latency, and system scalability are assessed hereafter

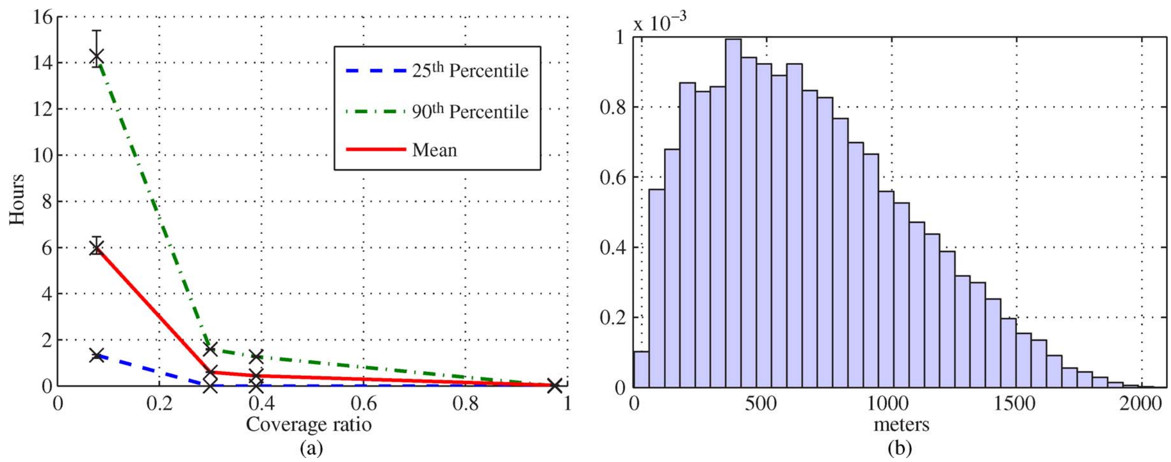


Fig. 4. System simulation results. (a) Delay statistics. (b) Error histogram.

based on simulation results which cover a wide range of system setups—interested readers may find in [6] an extended review of simulated behavior.

Simulations model repeater links as disks of radius 600 m wherein communication is always successful. Reception probability over secondary links is fitted as in Fig. 3(a). The animal mobility pattern makes individuals move on straight lines over variable time periods $[U(30\ \text{s}, 300\ \text{s})]$ finishing each one with a turn $[U(-\pi, \pi)]$. Instantaneous speed is 2 km/h. Such definitions are plausible according to the observations reported in [32]. The localization error is liable to be considered as a worst case (see below) since most mean speeds in [32] were lower.

1) Localization Error: Since primary nodes integrate a GPS module, their self-localization error depends merely on GPS accuracy. Error in primary GPS readings is thus neglected. However, secondary-node positions are approximated by the last GPS reading of the primary node receiving their secondary ID frame. Secondary-node error depends on the ID propagation distance and the net displacement of the receiving primary node since its last GPS update. The worst case arises if the primary-node trajectory is aligned with the secondary-node position—therefore, such primary node should have followed a straight line since its last GPS reading. Given a GPS duty cycle of 1 h, such worst case would turn out to be 2.1 km: 2 km traversed by the primary node and 100 m by the secondary frame. Fig. 4(b) shows the histogram of the secondary-node error as simulated over 10 days—results are the same regardless of the number of primary or secondary nodes. Although some (few) errors are beyond 2 km, 90% of them are less or equal than 1.24 km, whereas their mean is 665 m. Such duty cycle aims at extending primary-node lifetime, but the error can be still lowered to the extent imposed by the secondary-link probability of successful reception—in such case, error probability density function would be given by Fig. 3(a) properly scaled on its y-axis.

2) Localization Delay: The system becomes aware of secondary-node detections recorded by primary nodes as soon as the latter enter a repeater communication range. Detections that occurred within repeater communication range have, therefore, zero notification delay, whereas those off repeater range are affected by the primary-node trajectory until connection can be established with a repeater. Overall, localization delay depends on the repeater coverage ratio over the area where reindeer are roaming as well as their mobility pattern. If there is full coverage, delay will be zero regardless of animal movements.

Three statistics (25th percentile, mean, and 90th percentile) are plotted over different coverage ratios in Fig. 4(a). They correspond to four repeater setups (1, 4, 5, and 16) with six primary-to-secondary ratios each in a square arena of 3.8 km $\times$ 3.8 km. The monotonically decreasing dependence on the coverage ratio is evident. Further details on system latency are subject to coverage geometry with respect to the overall arena. Simulations have accounted for equiprobability of every spot to host animals; however, in real scenarios, knowledge of frequent animal paths may enable cost-effective repeater deployments.

3) Scalability: As the number of heads of herd rises, so does collision probability on communication links. Let secondary IDs be 10 b long $(N = 1024)$; then, frames last for 6.72 ms (T_f). Given a mean transmission period of 5 min per source (T_p) and assuming synchronized time slots $(T_f \ll T_p)$, the collision probability over secondary links would be given by $1 - Np(1-(T_f/T_p))^{N-1}p(T_f/T_p) + p(1-(T_f/T_p))^N$ which is $2.6 \cdot 10^{-4}$ for the given scenario—and it is even less likely to affect system performance if we recall Fig. 3(a) which limits the previous scenario to (unlikely) happen within a radius of 100 m. Furthermore, primary nodes are expected to be fewer than secondary nodes and run a MAC protocol; hence, scalability issues should not arise at this point.

In addition, a number of simulations were run with a variable animal population (90–360) and different secondary-to-primary ratios $(9:1$ to $1:2)$ in order to assess any unforeseen behavior. In either case, information flowed in the network as expected, and localization error and delay behaved regardless of the number of primary nodes or animal population.

Animal population might impact on system performance only if trajectories were affected (simulations took into account possible animal collisions by changing their paths). However, such an effect is not noticeable even in densities as of 85 reindeer/km^2—that was tested additionally by shortening the simulation arena systematically.

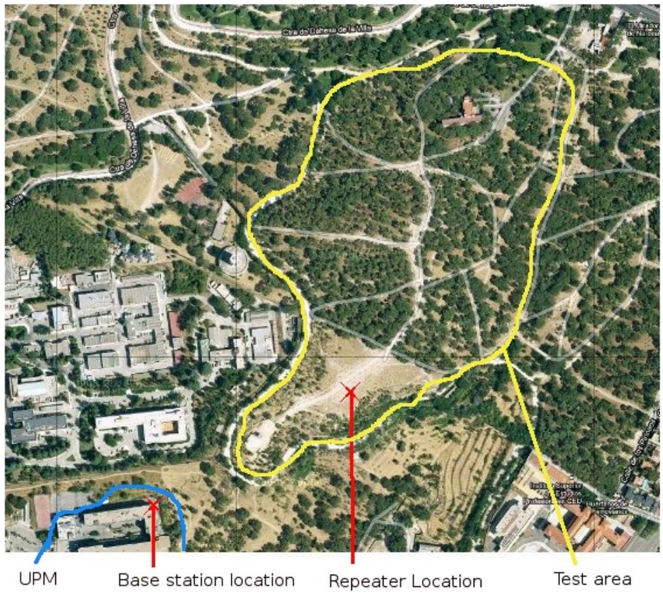


Fig. 5. Area map of the tests carried out in Madrid.

IV. Test-Bed Experiments

Two different experimental setups have been performed in order to validate the heterogeneous network. The first setup was carried out in Madrid with students in which the hardware and architecture were tested. The second one was carried out in Lapland in order to test the network viability in a real scenario with animals and extreme climate conditions.

A. *Test in Madrid*

The test in Madrid was carried out with students in a forest environment near the campus in January 2011. Each individual had a primary node, a secondary node, and a generator. Every 30 s, the generator was swung twice, mimicking the expected grazing movement—i.e., head moving up and down searching for food. The experiment was tested for 1 h in an area of 200 m $\times$ 500 m.

One repeater node with its antenna was placed in the forest, while the base station was on the roof of the school building. The distance between the repeater and the base station was about 200 m (see Fig. 5).

Eight primary and secondary nodes were used during the experiments. Students were allowed to move within the test area freely; they could walk alone or in groups. After 45 min, the students were asked to walk alone for 15 min in the neighborhood of the repeaters.

The primary nodes transmitted, to the repeater, their trajectories and the information obtained from secondary nodes. The repeater forwarded all this information to the base station. All the information presented in this section was obtained from the computer connected to the base station.

From the extracted results, it is observed that, at first, the students created two different groups, according to their friendship. These groups were moving independently, and not much information was transmitted between them because the paths traversed by the groups were completely different. Later on, once they were asked to move alone in a smaller area, more interactions between all individuals arose.

TABLE I
Reception's Relation Between Primary and Secondary Nodes in the Test Performed in Madrid

	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
S_1	80	0	20	40	5	60	20	110
S_2	1	114	87	6	24	51	92	58
S_3	0	0	132	26	11	97	130	35
S_4	45	86	37	108	21	63	22	31
S_5	8	32	21	11	151	31	153	113
S_6	42	52	7	12	32	141	98	76
S_7	6	5	13	2	128	24	113	54
S_8	95	44	24	11	3	34	91	111

Table I shows information about the number of localizations achieved by each primary node (P_i) for each secondary node (S_i). Because each individual has a primary and a secondary node with the same number, both nodes are considered to be in the same position. Therefore, receptions obtained by a primary node (P_i) represent the transmissions done by the secondary node on the same individual (S_i)—the diagonal. This is self-localization. Notice that, in such 1-h experiment, the generator was supposed to be swung a total of 120 times. Only an average of 118.75 self-localizations were achieved. However, some secondary nodes (S3, S5, and S6) were self-located more than 120 times, because the double swing provided enough energy to transmit a second frame in sporadic cases. On the other hand, some nodes did not receive all the frames transmitted. This is because of the following: 1) some movements of the generator were not producing a transmission; 2) some transmissions were not correctly decoded; and 3) some transmissions were lost. If this average (118.77 self-localizations) is considered as the total number of correct frames transmitted, each secondary node (S_i) was located by a primary node different from the one on the same individual $(P_j, i \neq j)$, an average of 37.5 times.

Moreover, the different groups created during the first phase of the experiment can be extracted. Individuals 2, 3, 5, and 7 were moving together, while 1, 6, and 8 were doing it too. Individual number 4, carried out by a professor, seems to be moving more independently and joining and leaving the groups during the tests.

Finally, Fig. 6 shows tracking results for one secondary node. It shows the trajectory performed. The real trajectory is provided by the corresponding primary node GPS. The figure shows that the trajectory extracted from the network is noisier than the real trajectory because not all transmissions were received by other primary nodes and some transmissions were duplicated on the network because they were received by different primary nodes. Moreover, notice that, at the beginning of the experiment, there are some coordinates which clearly deviate from the real trajectory. This is because of the start-up of the GPS, which takes some measures to stabilize.

B. *Test in Lapland*

Tests in Jokkmokk (Lapland) were carried out with reindeer in a bounded arena of 100 m $\times$ 100 m for 5 days. The week

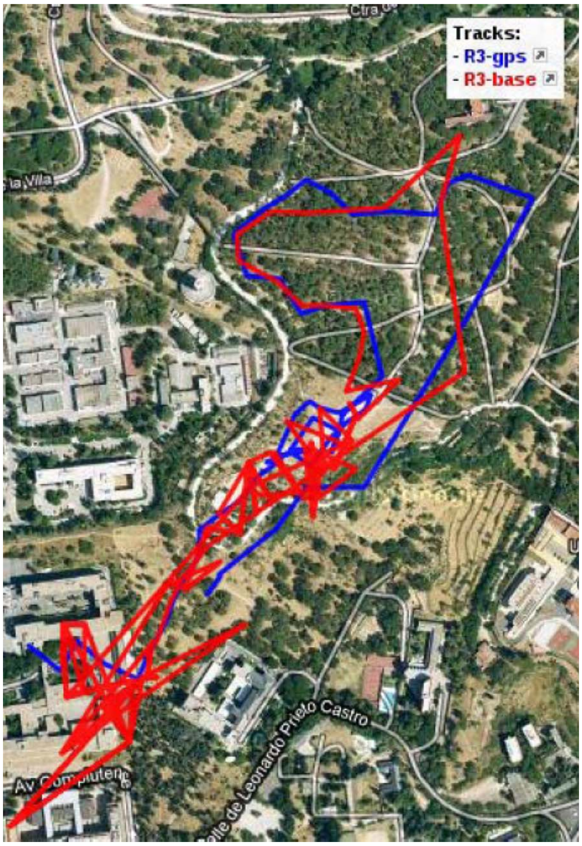


Fig. 6. Tracking results of a secondary node. (Blue in online version) Real trajectory as retrieved from the GPS module and (red in online version) trajectory reported by the base station.

chosen was from February 21 to 25, 2011. Climate conditions, as low as −37 °C during the week test, were one of the biggest constraints because of some mechanical issues and energy considerations. Different experiments, described hereafter, were carried out during this week. Some of them intended to verify mechanical parts and climate conditions, while the others aimed at verifying the correct working of network.

1) Electronic Test: On Day 1, all the electronics mounted on reindeer were tested. The goal of this test was to check that problems due to transportation and climate conditions were not present. Because of the weather conditions, all the electronics were not tested at the same time, just in case some of them broke.

Two primary nodes and two secondary nodes were mounted on two different reindeer. Primary nodes were expected to be tracked by means of the GPS, whereas the secondary nodes were only mounted to test their adaptiveness to the weather conditions. All the electronics were operative during the test—which lasted for 5 hours over daylight.

Results were very satisfactory since all the electronics behaved as the experiments in Madrid had anticipated, but with more than 40 °C of difference.

2) Mechanical Test: The mechanical test was the most complex. Finding out the best placement and setup of both primary nodes and secondary nodes on collars mounted on reindeer turned out to be very difficult because of missing practical knowledge on reindeer behavior and because of the extreme climate conditions. During Day 2 and Day 3, different collar configurations were tested—see Fig. 7.

(a) (b)

Fig. 7. Two secondary nodes with their collars mounted on reindeer. (a) Double-collar configuration with two generators. (b) Single-collar configuration with one generator.

1) **One collar with one primary node, one secondary node, and two generators mounted on the same reindeer**: It was a configuration similar to the one tested in Madrid. We intended to obtain the real position of the reindeer owing to the primary node and the extracted information of the same reindeer from the network in order to compare them. However, such configuration was not a good solution from a mechanical point of view as two different problems came up. The first one was that reindeer were very uncomfortable with so much electronics on their neck. The second one was that the kinetic generator was rotated around the reindeer neck; hence, no transmissions were received after a short period of time, and the reindeer, in turn, felt so uncomfortable that they tried to modify the collar position.
2) **One secondary node and one generator mounted on a reindeer with a single collar**: With this solution, the aforementioned problems were avoided. However, because of the height of the snow in the environment, reindeer moved their head slower than expected. Therefore, not every time a reindeer moved its head to find food the generator supplied enough energy to the secondary node; and consequently, not many transmissions were observed.
3) **One secondary node and two generators mounted on a reindeer with a double collar**: This solution was the best one tested. Although the reindeer moved slowly its head, generators mounted on the collar were able to supply enough energy to the secondary node to transmit a frame every time the reindeer moved its head.

Finally, reindeer were not moving around as much as expected. Moreover, they sometimes rested still for hours without any kind of movement. Furthermore, the mechanical position of the generator on the collar was very critical regarding energy generation. A particular position of the generator could permit reindeer to generate energy not only while eating but also when moving.

3) Antenna Test: This test was carried out on Day 3 at the same time as the mechanical test. Its objective was to test the transmission link of both the repeater and the base station at

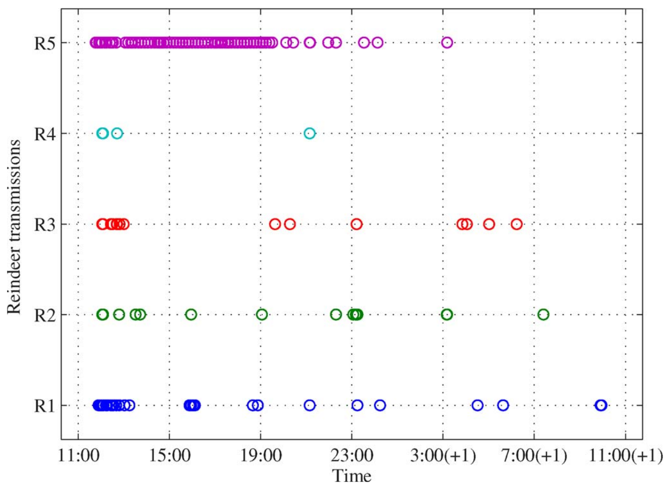


Fig. 8. Secondary frames received by the base station in the 24-h experiment. R1 and R5 used double collars, whereas R2, R3, and R4 used single ones.

the adverse climate conditions during a whole day. For this test, one antenna was placed in the middle of the corral where reindeer were located, and the second one was situated inside a cabin. The base station was programmed to transmit frames, and the repeater node was programmed to acknowledge them. For the distance at which the test was performed (≈300 m), 100% of the transmissions were acknowledged.

Given this new configuration, the system was left operating over a complete day. No problem with transmissions was detected even at −32 °C reached during the night.

4) Network Test: Once all the different parts were tested, the whole network test was run for one complete day. Collars were mounted on reindeer at 11:00 A.M. on Day 4 and removed at 11:00 A.M. on Day 5. Two primary nodes were mounted on reindeer, and three more nodes were mounted as static nodes in trees around the corral. Five secondary nodes were mounted on reindeer—two with a double-collar configuration and three with a single-collar one.

Fig. 8 shows secondary-node reception results for the five different nodes extracted from the base station. It can be observed that reindeer were able to transmit many frames while mounting the collars on their necks—see beginning of the graph. This is because reindeer were moving fast trying to escape. Later on, reindeer calmed down, and thus, transmissions occurred sporadically. Attention should be drawn to reindeer 5 (R5) which was carrying a double collar in a perfectly horizontal position. Such configuration allowed the two generators to provide enough energy for transmission (actually, in excess) while the reindeer was moving, what is translated into many frames was transmitted and *retrieved* by the network. However, because of the mechanical problems already mentioned, after some time, the collar moved from its original position, and the frames continued with the standard behavior observed by the rest of the nodes.

V. Conclusion

Experimental results that validate the proof of concept of a heterogeneous network for animal tracking made up of kinetic-powered secondary nodes and battery-powered primary nodes have been reported. Secondary nodes include a 433-MHz transmitter powered by a kinetic converter system made with coils and magnets. The regulated voltage necessary to operate the transmitter is provided by a harvester in a time window. Primary nodes implement a 433-MHz receiver to gather secondary-node information. The system has been tested both in a simulated case, in which students behaved as target animals, and in a real scenario, with reindeer under extreme climate conditions. Results show a satisfactory system performance. Secondary nodes, mounted on animals, were able to transmit and be detected more than three times per hour in average without the need of any battery. This is a good step forward in terms of scalability and maintenance of the network. Therefore, we conclude that the validation of this heterogeneous network allows to envision an interesting potential for harvesting and scavenging systems based on kinetic energy generated by animals.

However, some constraints have been observed which are a starting point to continue with the research on the system. There are several mechanical problems which should be addressed in the future. The first one is related to the design and position of the kinetic generator which should be more rigid in order to keep the initial setup and therefore obtain an enhanced transfer function between movement and transmissions. The second one is related to the collar packaging. Since reindeer fight from time to time and they sleep on the snow or the terrain, a more robust encapsulation for the electronics is needed if a long term experiment is intended. Also, a redesign of the generator could be addressed using *ad hoc* molds to build it if the budged allows it.

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Authors' photographs and biographies not available at the time of publication.