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Dynamic Wireless Sensor Networks for Animal Behavior Research

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Introduction

Wireless sensor networks have developed into a variety of applications where data is obtained from restrictive environments. Data acquisition in biological systems is often constrained by the necessity to avoid wired connections, encouraging the use of radio communication between a mobile sensor unit and a data sink.

If several different data sources have to be surveyed simultaneously, a multitude of sensor units can be involved, this often results in wireless networks with a predictable and static structure. Changes in connectivity of these networks occur rarely and are undesirable because they slow down the data flow. However, in social networks, the dynamics in network connectivity are the actual focus of interest.

Because of their flexibility, we decided to use wireless sensor networks (i.e. radio equipped microcontrollers) to explore various aspects in the behavior of rodents nesting in subterranean habitats, such as the social structure or the structure of their burrows. Thus we model the social structure of a group of animals tagged with our sensor nodes using the changes in network topology, while, on the other hand, we use a customized sensor suite to obtain additional information about the activity of the animals in their burrows. In this contribution we will present some concepts that proved to be useful for such a network, in terms of the acquisition and pre-processing of sensor data in order to decrease the network load and the data transmission protocol that provides a good trade-off between overall data loss and redundancy, between data loss and redundancy and the post-processing of data that achieves meaningful models for animal behavior analysis.

We chose Norway rats (*Rattus norvegicus*) as a model system because they are abundant and easy to handle in laboratory and outdoor environments. Our sensor network application however, will not be limited to rats alone and our goal is to provide a system that is applicable for a broad spectrum of animal species, whenever their lifestyle requires the observation of many individuals and/or their localization is hampered due to subterranean, underwater or otherwise difficult structured habitats.

1. Norway Rat Behavior

Norway rats live closely socialized to humans, presumably since the latter began to settle down and store resources. Similar to humans they live in groups with flexible social structures, and just like them they are curious and explorative and were able to adapt to almost all terrestrial habitats worldwide. When humans discovered the utility of their rodent commensals as a model system for clinical and behavioral studies during the early 20th century, rats became one of the most abundant species in laboratories, too (see Whishaw & Kolb, 2004 for an overview over rat behavior in the laboratory). Although rats' behavior and cognitive capabilities have been studied extensively since that time in laboratory studies, only little is known about the behavior of rats in their natural habitat.

A fundamental reason for that is the fact, that rats – like many other rodents – spend a significant part of their life in burrows that are located underground, which so far could not be investigated without destroying them. The most extensive work that tried to scrutinize the community and life history of rats in their subterranean burrows is already more than 40 years old (Calhoun, 1963). In this work rats were kept in an enclosure, almost without any interferences by the observer, where they started to build burrows. In lack of better methods, observations of behavior in this study were restricted to that part of behavior that takes place over ground. Information about the behavior of the animals inside their burrows was only accessible during the final phase of the research, when the burrows were mapped and destroyed. The artifacts that were found during the excavation – like food stores, straw and droppings allowed a rough reconstruction of behavioral habits in the burrow but they only represent a snapshot of the burrow structure at the time of destruction and not much information about the social interactions between individuals that lived in the burrow.

More recent investigations of rodent ecology in the field normally use radiotelemetry but they are also limited to the observation of the animals' above ground activities. In addition, classic radiotelemetry systems require a high amount of manpower and their spatial accuracy is often appalling: Usually the results are limited to home-range analysis, overlap and population-based questions (Turchin, 1998). Sporadically researchers have started to use combinations of radiotelemetry and the aforementioned destructive methods by implanting radios into individual animals that record and transmit for example the activity cycles of the animals, whilst the burrows are only destroyed by successive digging by the researcher, keeping parts of the burrow intact during the study (Skliba et al, 2008). The radios in these kinds of studies are very simple VHF-transmitters without memory or data processing functions. Nevertheless the findings of these studies and the background of knowledge about subterranean rodents already show that there is a high frequency of social interactions in these populations with complex dynamics in group structure that hasn't been accessible to detailed research up to now (Dowding & Murphy, 1994).

The use of wireless sensor network technology for rodent observation will establish a new methodology for the investigation and mapping of subterranean burrows as well as for the observation and recording of animal behavior in species that are hard to observe, due to their lifestyle or an impenetrable habitat structure. We expect to obtain significant new insights into the natural behavior of the Norway rat, particularly about the function of its cognitive abilities and their implications for behavioral ecology.

Rodents are the largest order among mammals and the subterranean lifestyle of the Norway rat is not at all unique among rodents. In fact there are about 250 different species that live partly or even exclusively underground. They live in a variety of climates and ecosystems

(See Begall et al, 2007 for an overview). This variety is a promising basis for a series of comparative studies about social systems in rodents.
We decided to use the laboratory rat in our study, because the available breeding lines for lab use make them much easier to handle in contrast to most wild animals. Nevertheless the development of our sensor network is oriented towards a broader spectrum of applications.

2. A short presentation of the Hardware we used so far

The most stringent constraints on our hardware are the size and weight of the sensor nodes (often referred to as "motes"), which translates into a trade-off between battery size and its capacity.

Fig. 1. An example of a laboratory rat wearing a mica2dot sensor node on a removable harness

So far we have used two different kinds of commercially available motes: The Crossbow mica2dot MPR500 which uses a radio frequency of 915 MHz for data propagation and the radiocrafts RC2301 transceiver module which communicates in the 2.45 GHz ISM band. Both devices run on 3.3 V power supply which we provided either with a CR2354 Lithium battery or customized Lithium-polymer rechargeable batteries. So far the motes and the customized sensor hardware were attached to the animals using a custom leather harness, which contains the sensing equipment in a pocket (Fig. 1). Our goal is to sketch out specifications for a system-on-chip implementation and move towards an implantable solution when the development of the prototype is completed

3. Mapping network structure on social structure

Social network analysis is an upcoming domain in animal behavior research since automatic observation techniques become more and more detailed and individual-specific. In contrast to the hitherto quantitative studies of animal movements based on population statistics, social network analysis is the study of social groups as networks of nodes connected by social ties, thereby disclosing association patterns, dominance hierarchies and the fluctuations of in groups (Wey et al, 2008). The basic ideas and terminology of social network analysis are in many respects identical to the terminology used in descriptions of the topology of technical communication networks. In the following section we will therefore show that the subterranean burrows of Norway rats are suited to study social networks of animals with wireless sensor network technology.

In an underground environment the effective communication range is limited, so forwarding of measurement data can be achieved using a technique known as Delay-Tolerant Networking, or Pocket-Switched Networking. We exploit the physical meetings of different rats as opportunities to transfer data between their attached sensor nodes. These meetings are also the focus of interest in the effort to understand the social structure of the animals. Data forwarding therefore utilizes the social structure and, vice versa, the social structure of an animal community can be reconstructed by the routing data of the network.

3.1. Radio Propagation in Artificial Rat Burrows

A typical rat burrow system consists of a number of segments with a mean diameter of 8.3 cm (see Calhoun, 1963) and a mean length of 30 cm. The propagation of electromagnetic waves is very important for the adequate design of an efficient network protocol. Predicting the communication range between two nodes theoretically is difficult, as we have to assume the burrow tunnel will act as a lossy wave guide in which the conductivity of the soil depends heavily on the exact composition, humidity, and surface.

As our nodes are based on the CC2420 radio chip, we work in the 2.4 GHz ISM radio band. This chip employs direct sequence spread spectrum (DSSS) technology, which is particularly well-suited for environments suffering from a high degree of multi-path propagation.

To be able to better characterize radio propagation in rat burrows we built an artificial burrow system out of drainage pipes, depicted in Fig. 2. As a test field, we selected a 10 by 10 m field of loose ground, consisting of mold, small stones and some sand, as would be expected for a rat burrow. We selected flexible drainage pipes with a diameter of 8 cm and 10 cm and a stiff drainage pipe with a diameter of 7 cm. The drainage pipes were buried at a depth of about 1 m. We then tied a number of sensor nodes to a small rope, which allowed us to pull them through the pipe. The sensor nodes were programmed to record all received messages to flash memory, along with the received signal strength and link quality indicators. The flash memory was later read out via USB.

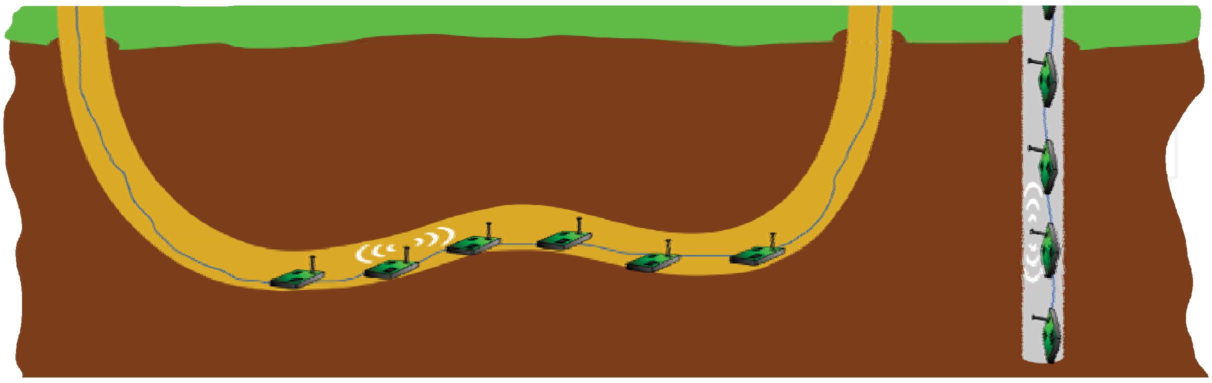

Fig. 2. Experimental setup for radio propagation measurements

The experimental results for an output power setting of 0 dBm can be found in Table 1. The packet reception rate(PRR) signifies the percentage of received packets. The received signal

strength indicator(RSSI) indicates how much the packets have been damped by the tunnel. The lowest signal strength the used hardware can still properly decode is about
-90dBm. Finally, the link quality indicator (LQI) is calculated using the number of errors in the preamble of a packet. It ranges from 55 (worst) to 110 (best). The results clearly demonstrate that the main factor limiting the range is the dampening effect of the burrow bit walls. The effective range is between 60 and 90 cm. This is significantly larger than radio propagation through solid earth, which we measured to be about 20 to 30 cm.

Tube diameter [cm]	*Distance [m]*	*PRR [%]*	*RSSI [dBm]*	*LQI*
10	0.8	0.91	-78.50 ± 0.50	105.17 ± 1.28
	0.6	0.91	-60.23 ± 0.42	106.26 ± 0.82
	0.4	0.91	-47.29 ± 0.93	106.22 ± 0.94
	0.2	0.87	-27.26 ± 0.44	106.27 ± 0.91
8	0.6	0.90	-90.09 ± 0.30	85.59 ± 4.80
	0.4	0.91	-66.05 ± 0.21	106.79 ± 0.90
	0.2	0.87	-42.39 ± 0.49	107.00 ± 0.81
7	0.6	0.92	-68.92 ± 0.27	107.00 ± 0.99
	0.4	0.92	-54.95 ± 0.79	107.36 ± 0.74
	0.2	0.92	-33.40 ± 0.85	107.26 ± 0.92

Table 1. Packet Reception Rates, Received Signal Strengths and Link Quality for different tube diameters and different distances between sender and receiver

We can thereby conclude that radio connectivity in an underground rat burrow can be used as an indicator of physical proximity. This allows us to make use of the radio as both, a method to transmit data and a proximity sensor. In the following subsections, we discuss, how this sporadic connectivity can be exploited for data forwarding, while at the same time investigating the social structure of the animals under observation.

3.2. Using Pocket Switched Networking for Data Forwarding

The term Pocket Switched Networking (PSN) was coined by Jon Crowcroft in 2005 (see Hui, 2005). PSN makes use of a nodes' local and global communication links, but also of the mobility of the nodes themselves. It is a special case of Delay/Disruption Tolerant Networking. However, it focuses on the opportunistic contacts between nodes. The key issue in the design of forwarding algorithms is to deal with and possibly foresee human - or in this case - rat mobility. In general, the complexity of this problem is strongly related to the complexity of the network, i.e. uncertainties in connectivity and movement of nodes. If the complexity of a network becomes too high, traditional routing strategies based on link-state schemes will fail due to the frequency of changes. To cope with these uncertainties in high dynamic networks we need to discover some structures that help to decide which neighbor is an appropriate next hop. An illustration of the concept of DTN can be found in Fig. 3.

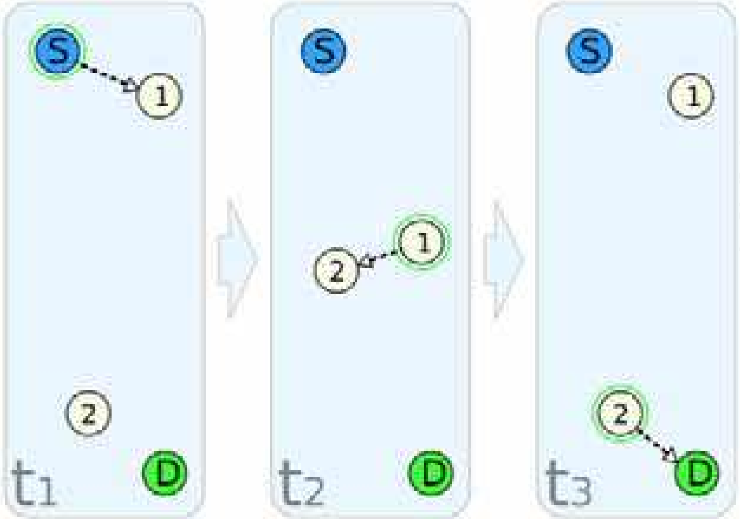

Fig. 3. A packet from S to D is forwarded via node 1 and node 2. There is no direct connection between S and D and so the packet is stored at node 1 (t1) until a connection with node 2 is available (t2). When node 2 finds a connection to D (t3), the packet is delivered.

3.3. Making Use of the Social Structure

In the field of social network analysis, a variety of measures have been defined to characterize social networks. These measures describe specific aspects of nodes in such a network. Daly et al., 2007 presented a routing strategy based similarity and betweenness centrality. We extended this routing scheme to better follow the temporal changes in social structure.

To illustrate the intuition of social network based forwarding algorithms, let us consider the following example: Alice, a student at a university wants to forward a token to Bob. If Alice meets Bob directly, she can just give the token directly; we call this simplistic approach Direct Delivery. In cases where the token is immaterial, e.g. a message, Alice could decide to give a copy of the message to anyone she meets and instruct them to do the same. This approach is called Epidemic Forwarding. Bob will eventually receive the message, but in resource constrained systems, this approach is prohibitively expensive in the number of transmissions and used buffer space.

Let us suppose, the token can only be forwarded, not copied. Alice could give the token to a person who shares many friends with Bob. This person is very likely to meet Bob, or a good friend of Bob. This metric is called similarity and we will later define it in more detail.

If Alice only knows of the existence of Bob, but doesn't know Bob directly, she may either give the token to anyone who knows of Bob or to someone who knows a lot of people in general. We call the former directed betweenness and the latter betweenness centrality.

Combining similarity, directed betweenness, and betweenness centrality, we came up with a useful forwarding strategy for this kind of opportunistic contact based networks, see (Viol, 2009).

Similarity in social networks can be defined as the number of common acquaintances of two nodes. This metric is inherently based on local knowledge. In the following, N_1 denotes the 1-hop neighborhood of a node.

$$S(u,v) = \left| N_1(u) \cap N_1(v) \right| \tag{1}$$

Betweenness centrality of a node u is generally defined as the proportion of all shortest paths in a graph from any node v to any other node w, which pass through u. Also this metric is global in principal, (Daly, 2005) showed that an ego-centric adaption considering only nodes v and w from the 1-hop neighborhood of u, does retain the necessary properties to properly route on them.

$$BC_u = \sum_{\substack{v \neq w \neq u \\ v,w \in N_1(u)}} \frac{g_{v,w}(u)}{g_{v,w}} \tag{2}$$

Classic social network analysis considers social networks binary: Either a person knows another person, or not. While this is a useful abstraction if relatively short periods of time are considered, intuition demands for dynamics and degrees in that relation: People might have been best friends in kindergarten but haven't seen each other in years now. Data from longer running traces, e.g. (Scott, 2006) show that these variations indeed reflects in the network structure, as illustrated in the next figure (Fig. 4), depicting the changing network structure of about 50 people over the course of a conference.

Fig. 4. Social structures changes over time (source data from Scott, 2006)

To better reflect these changes over time, we don't use a binary graph but assign weights to the edges. A weight of 0 signifies no acquaintance, while 1 signifies constant connection. If two nodes meet, their weight is updated using logistic growth:

$$\omega_{new} = \omega_{old} + \left(1 - \omega_{old}\right) \cdot \alpha \tag{3}$$

If nodes don't meet for a time, the weight of the edge decays exponentially:

$$\omega_{new} = \omega_{old} \cdot \gamma^{\Delta t} \tag{4}$$

Similarity, as defined above, must be adapted to reflect the weight of the edges. To do so, we define the weighted similarity as the sum of the product of the weight edges to a common neighbor.

Also, the above definition of Betweenness Centrality cannot be applied to weighted graphs without modifications. (Freeman, 1991) introduced the concept of Flow Betweenness Centrality. The intuition behind this change is realization that communication in social networks does not necessarily follow the shortest path between two nodes, but rather all links that there are with varying preference. This allows us to step back from shortest paths and consider flows on weighted edges instead. Details of this can be found in (Viol, 2009).

Furthermore, when we combine Similarity, Directed Betweenness and Betweenness Centrality, in this order of prevalence, the resulting delivery rates are significantly improved with respect to the original SimBet algorithm by (Daly, 2007), while being able to maintain a egocentric world view per node. In Fig. 5, the first 4 algorithms are trivial or taken from related work, while the last 3 are variants of the above described. SimBetAge considers Similarity and Betweenness Centrality in a weighted graph as described above, while DestSimBetAge also considers the directed betweenness. Dest2SimBetAge uses only local knowledge to calculate the directed betweenness and is thereby completely egocentric.

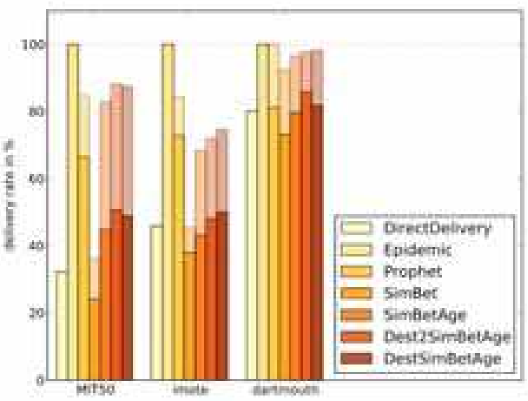

Fig. 5. Delivery rates for 3 different traces by algorithm used. Direct Delivery, Epidemic, Prophet and SimBet are taken from related work, while the remaining three are variants of our algorithm.

4. Vocalization classification

Rats share their subterranean burrows in loose assemblies of varying group size and communicate via olfactory, tactile and acoustic signals. Inter-individual rat calls are variable but can easily be classified and most of these call types are associated to a well-defined internal state of an animal and the kind of interaction between the animals emitting them. As this phenomenon is very useful to classify interactions of individuals in laboratory setups, a number of studies already bear a rich 'vocabulary' of calls and the behavioral context in which they occur - e.g. resident-intruder, mother-child interactions or post-ejaculatory and other mating sounds (e.g. Kaltwasser, 1990; Voipio 1997). An analysis of the vocalizations that occur when two rats meet in the burrow will therefore allow us to classify the kind of relationship in which the participating individuals are. This additional information should allow us to detect details of the social network inside a burrow, like dominance structures, kinship relations and hierarchies and will broaden the knowledge of social networks in addition to the network-reconstructions based on the analysis of message routing data mentioned in section 3.3.

4.1. Characterization of acoustic signals by Zero Crossing Analysis

In our aim to analyze and classify the rats’ vocalizations, we have to consider the limited computing capacities and the limitations that result from the sparse connectivity in our network. Our goal is to analyze the call structure in real-time and on the mote, in order to keep the network load for the data transmission as low as possible.

To realize that, a drastic data reduction is required.

As our hardware needs to be small and energy-efficient, we developed a classification method based on zero-crossing analysis (ZCA) as a much simpler method for the prior evaluation of call structure, compared to other common methods, like Fourier analysis. In ZCA, the ultrasonic signals of the rats, which occur predominantly in the range between 20 and 90 kHz are extensively filtered and then digitized by a comparator. The cycle period of the resulting square-wave signal is measured with a 1 MHz clock. The measured period is registered in a histogram which is updated every 15ms. The combined histogram vectors of one sound event result into a matrix that contains enough information for a final classification of the call into behaviorally relevant categories. In order to cope with ambient noise, an additional buffer holds the average for each of the histogram bins from previous measurements and compares them with the actual results in order to detect sounds of interest. Fig. 6 gives an overview over the hardware required for such pre-processing.

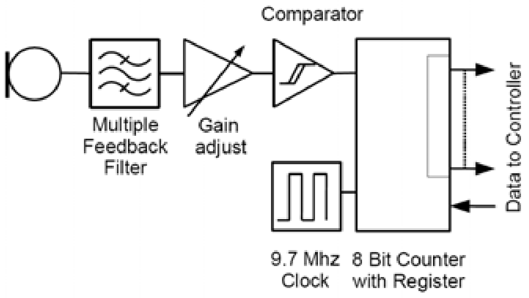

Fig. 6. Block Diagram of the ZCA sensor hardware

Fig. 7 shows examples of how different calls are represented by the ZCA algorithm in comparison with an FFT exposition. Although the ZCA is less detailed, each call type has distinctive parameters that allow a distinction between call classes. A classifier software, based on the ZCA cluster counts and temporal call parameters is under way.

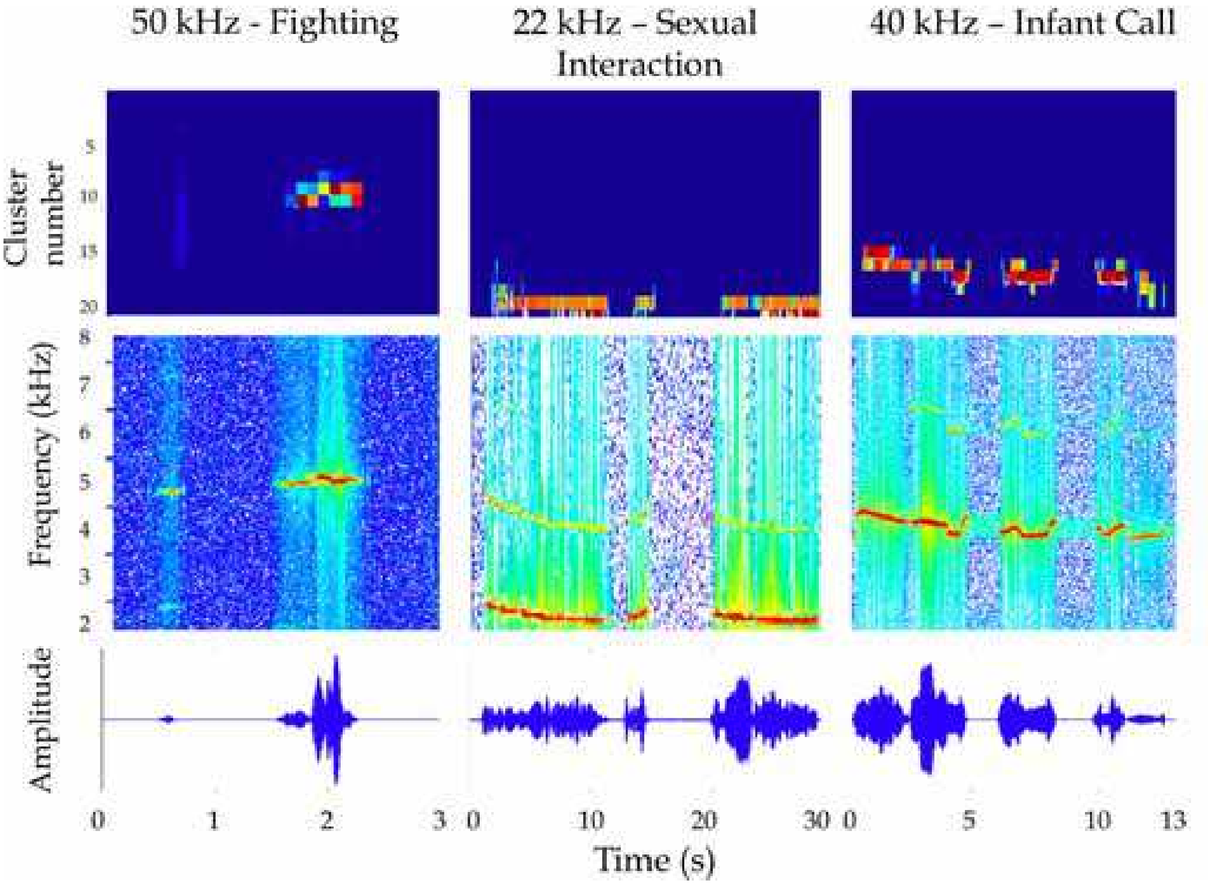

Fig. 7. Comparison between 3 rat calls that are analyzed by ZCA (upper row), by spectrograms (mid row) or by their amplitude (lower row). The behavioral classification of the calls is following (Voipio, 1997). The results shown here were realized on a test setup running on a mica2dot mote with 10 times delayed playback.

5. Position Estimation

Knowing how rats move about in the environment may enable us to describe their foraging habits, as well as the layout of their burrows. This may also allow us to draw conclusions about the actual use of different sections of the burrow in a non-destructive fashion.

Many technical systems feature pose estimation in 6 degrees of freedom, using a combination of inertial measurements, satellite navigation systems and magnetic sensors. A number of factors make 6-DOF tracking unfeasible for studying rat movement. For one, the processing power required by that method exceeds our current capabilities, as they ultimately translate on heavier and bulkier batteries, for another, and more important is, that radio signals for satellite based navigation, are not available in underground burrows. Finally, our sensor nodes are attached to rats at the torso (rather than implanted), and as a consequence the orientation of the inertial sensors may change in time, as they sag off the rats' backs, causing drift in the readings. It is currently not feasible for us to implant sensor nodes into rats.

As an alternative, we have used an approach following some ideas on pedestrian navigation(Fang 2005), to be used with rats, and allow for an estimation of their position in 2 dimensions. The original approach measures human stepping for distance measurements and combines them with azimuth measurements from a fusion of compass and gyrometer readings.

Thus we distinguish two main issues in estimating the position of a rat: Estimating the velocity at which it moves and its orientation in time. Knowledge of these two quantities would allow us to calculate the position of the rat in time, which would in turn yield important behavioral information such as activity profiles or the layout of the burrow.

5.1. Pseudo-steps

Although there are similarities between our system and existing pedestrian navigation systems, they are optimized for different scenarios, the main differences between our approach and step counting with human subjects, are:

i. Accelerometers cannot be attached to the rats' feet as they are in some pedestrian navigation systems, thus the use of the term *step* is not accurate. The periodicity of the signal does not correlate with individual steps of one paw, but with a cycle of four steps. In fact, the number of actual steps in a cycle is neither relevant, nor can it be inferred from the signals. Thus we often refer to one cycle as a pseudo-step.

ii. Our setup has a lower ratio of "*step*" time to available sample period, making period detection more difficult. In human step counting, it is possible to detect the phases of a step, with a signal that offers strong features and thus reliable time measurements and even context information. In comparison, our signal offers fewer features for time-domain measurements.

These constraints have led to a method that estimates the velocity of rats by measuring the time between peaks in the signal of the accelerometer in the transverse plane of the rat. Laboratory experiments have shown that the time between two peaks correlates with the velocity (Fig. 8), under the knowledge that the rat is actually walking (as opposed to exploratory movements that do not involve displacement).

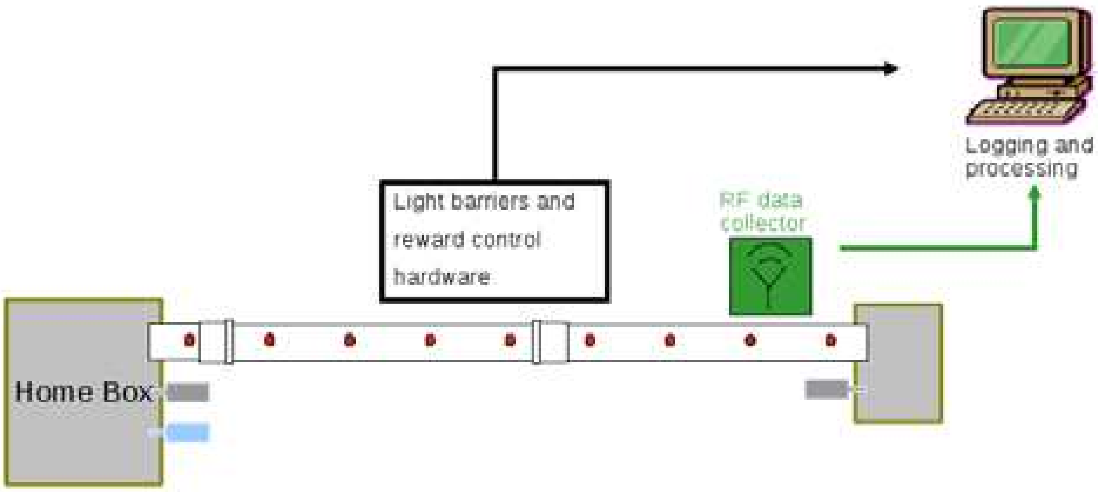

Fig. 8. Drain-pipe setup with light barriers to monitor rat movement

5.2. Implementation

The pseudo-step detection is done in hardware, using one channel of an ADXL330 accelerometer, the signal goes to an analog low-pass filter and is passed to a comparator, sampled at 10 Hz. The rats were free to move about in an artificial burrow, constructed from drain pipes and fitted with light barriers (Fig. 8), allowing to reconstruct the velocity at which the rats move.

Measuring the time between pseudo-steps, and calculating the estimated speed is done in firmware. When no stepping is measured, the system is able to record the estimated elevation (or pitch) angle relative to gravity, a feature that is useful in characterizing rats' exploratory habits.

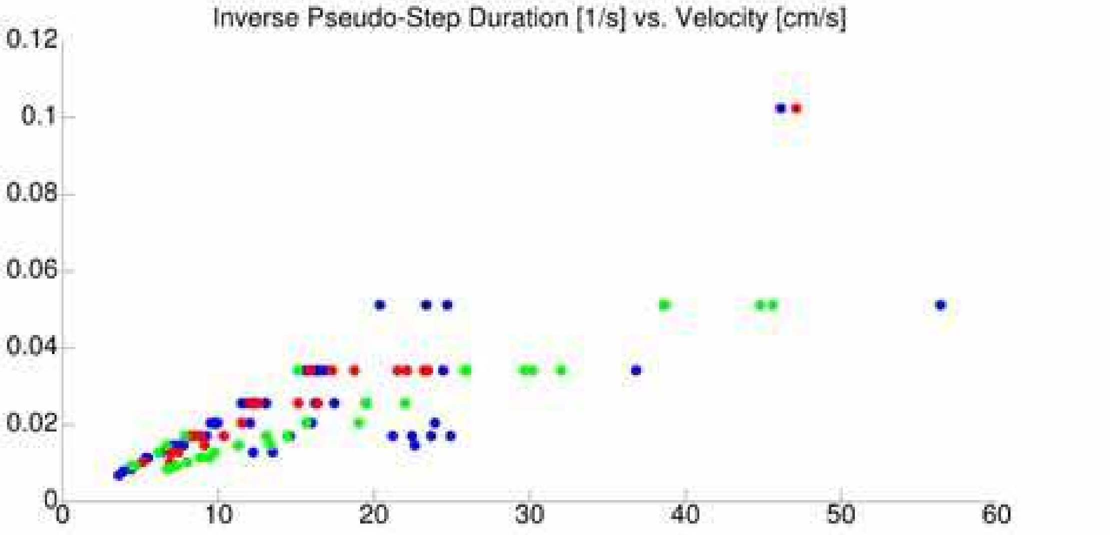

Fig. 9. The inverse of the duration of a pseudo-step correlates with the velocity of the rat

The time between two pseudo-steps has been observed to correspond with the velocity measurement obtained from the light-barrier data. Fig. 9 shows a scatter plot of the inverse of the step duration versus measured speed, with a least squares fit showing regression of $R^2 = 0.6$. This represents an improvement with respect to (Osechas et al., 2008), achieved through the exclusion of artifacts caused by insufficiencies in the light barrier setup.

5.3. Integration with Heading Estimation

It is common practice to combine gyrometer and compass readings to yield improved heading estimation (Fang 2005). In our case, the processing was simplified as much as possible, in order to save computational power, replacing the commonly used Kalman-filter-based integration by a simpler approach.

In order to prove the viability of the approach, the previously described test setup with drain pipes was expanded to include turns (Fig. 10), see also: Zeiß, 2009). Again, the pipes were fitted with light barriers to verify the rat's actual position at key points.

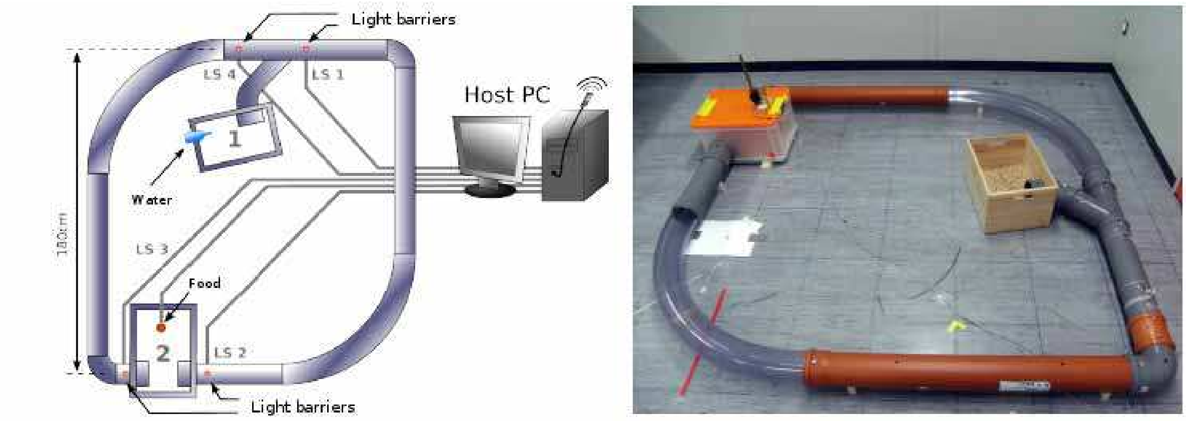

Fig. 10. Setup for testing position estimation

So far our experiments have been carried out indoors, inside a concrete building. In consequence, the earth's magnetic field is disturbed at the experiment site, in some places the disturbance is up to 55°. As the final deployment scenario is outdoors, we introduced a correction for the local disturbances of the magnetic field. The field was characterized for the whole of the experiment site and for each compass reading, the sample was corrected according to the current location. This correction would not be required in an eventual outdoor deployment.

Fig. 11 shows the average over 129 runs of two rats over 20 days in the setup. It is evident that, while there is room for improvement, the system could be used to study the layout of rat burrows, if enough data are gathered. The striking differences in accuracy on the left ($x<0$) of the setup, as compared to the right side, can be attributed to intricacies in the magnetic field disturbances that could not be corrected by our approach.

Fig. 11. Result of the 2-D position estimation

Current work is focused on context recognition, to differentiate acceleration events due to displacement, from events due to exploration. This knowledge is important to increase the reliability of the velocity estimation. Furthermore, the knowledge of when a rat is not walking enables us to analyze their exploratory behavior, as they stand on their hind legs while sniffing out unknown environments, or sleeping habits. This is the main reason for using 3-D acceleration measurements, even though lateral measurements are sufficient to characterize stepping. Measuring the pitch angle, between the gravity vector and the longitudinal axis of the rat, may yield information on the height of a chamber in a burrow.

6. Conclusion

This contribution sums up two years' development work on the RatPack project. The aim is to develop a system that will enable researchers to study the ecology of otherwise inaccessible animals, or populations, that are difficult to monitor, with a focus on animals that live in underground burrows and show social interactions. As the approach is based on dynamic wireless sensor networks, the work focused on designing sensing capabilities on the individual nodes and on data forwarding schemes on a network level.

The project has produced a set of proof-of-concept modules that provide capabilities in areas such extracting information on social structure, both from vocalizations and from the dynamic network topology, and estimating position without relying on satellite navigation, based on the animals' stepping.

On the sensing side, the working paradigm has been to trade measurement precision for simplicity, relying as much as possible on hardware pre-processing. On the networking side, the main challenge is dealing with dynamic connectivity, as the network topology is not predictable over time.

The single biggest challenge remains the envisioned outdoor deployment. It presents a major hardware challenge, as there is a trade-off between the reliability of the system and its obtrusion of the animals. Thus, efforts are focused on further miniaturization of the system, as well as on studying its behavioral disruption of the subjects.

In the long run, the RatPack should provide a tool for studying wild subterranean animal behavior, exploiting the synergy between the underlying ecology and the capabilities of disruption-tolerant networks, resulting from information fusion on various levels of abstraction, in turn yielding networking protocols that adapt to the given social scenarios to transport data efficiently and reliably from the animals to the collection stations.

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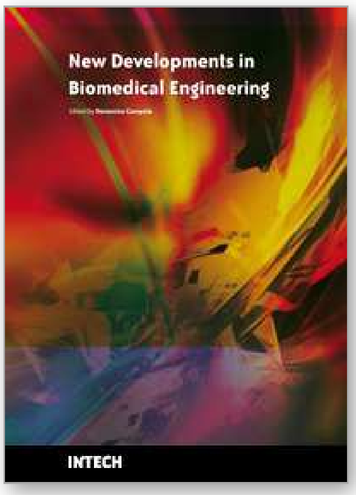

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