Realistic Large Scale ad hoc Animal Monitoring

Bartosz Wietrzyk, Milena Radenkovic
School of Computer Science
University of Nottingham
Nottingham, NG8 1BB, UK
e-mail: bartosz@wietrzyk.name, mvr@cs.nott.ac.uk

***Abstract*— Automated cattle monitoring with wireless devices installed on animals is important for profitability of animal production as well as welfare of animals and farmers. In this paper we define requirements for such monitoring on the basis of questionnaires distributed to potential users and processing data from long term animal monitoring. Then we discuss a practical store and forward architecture that allows data retention, issuing notifications and answering remote as well as in situ queries. The core of this architecture - disruption tolerant mobile ad hoc routing protocols allows minimizing and balancing energy utilization, which is crucial for labor intensity of animal monitoring. We achieved that by dynamic adaptation to the behavior of monitored animals, in particular utilization of heterogeneity of nodes' mobility. We evaluate the proposed protocol to show how it satisfies our requirements and then discuss precautions against security threats, which are essential for feasibility of the deployment of the proposed architecture.**

Keywords- Animal Monitoring, DTN, Energy Conservation, Wireless Routing, Security

I. INTRODUCTION

There is a proliferation of interest in using wireless ad hoc technologies to monitor health and behavior parameters of wild as well as domestic animals [2-8] and the environment as a whole [9]. This paper focuses on cattle monitoring because timely detection of cattle health problems can prevent spread of diseases such as mastitis and other infection diseases, metabolic diseases and lameness, which can lead to decreased productivity and death of valuable stock [3], as well as endanger health of the humans. The productivity of a farming enterprise can be also extended by timely detection of the oestrus in order to efficiently perform insemination of cows. Currently most of the farms practice manual observation, whereas the most advanced enterprises utilize milk monitoring by stationary sensors, or animal mounted sensors read over a single hop communication having very short [10] to medium range [11] leading to disconnections. These solutions are simple and easy to implement but require expensive infrastructure to provide full coverage or they offer only limited reliability. Current state of the art research for monitoring cattle behavior and metabolism in the Wireless Sensor Networking (WSN) research community are largely pragmatic proofs of concepts [12]. More precisely they utilize single hop [5, 6] or GSM communication [3]. The latter is expensive and not reliable in agricultural areas, where GSM operators have limited incentives to provide complete coverage.

In this paper, we discuss practical feasibility of the deployment of the delay store and forward architecture introduced in [8, 13], that provides data retention, detecting custom events, notification issuing, remote and in-situ queries answering. The core of this architecture, a novel energy efficient, disruption tolerant Mobile Ad Hoc Network (MANET) routing protocol provides offloading data for long term storage by sending data to farm servers via sinks that are a part of a MANET and handles in-situ queries issued by users collocated with the animals. The advantages of this protocol are following: (1) we significantly optimize energy efficiency of control traffic by identification and utilization of animal movement patterns as well as graceful degradation of data traffic energy efficiency, (2) the protocol can dynamically adapt to the current behavior of the animals carrying the mobile devices by utilizing heterogeneity of nodes' mobility, (3) it can work with any type of bovine animals. Reducing and balancing energy utilization of the mobile nodes is essential from the perspective of farming industry because it allows decreasing labor necessary for changing the batteries installed in the animal mounted devices.

In this paper, we demonstrate practical feasibility of this algorithm by extended monitoring of behavior of 5 animals over 1 year. Our results are based on significantly larger data set than normally used for this kind of application domain. The usual data size would sometimes include a somewhat bigger number of nodes but would in turn have much shorter time span of the data capture (weeks rather than months or years). Finally we address the challenges of the practical deployment of the proposed algorithm by proposing mechanism for dealing with disconnections and discussing the security issues. We argue that security issues are at the core of allowing deployment of the cattle monitoring in the commercial environment. Competitors are likely to disrupt functioning of the target farming enterprise or put it into a less favorable position. Buyers of the animal products (e.g., supermarkets) may want to lower the price of the products they buy or gather intelligence about the sellers to better evaluate their offer. The impact of the utilized security precautions on the energy efficiency of the animal mounted devices should be minimized.

This paper is an extended version of [1]. More precisely, it gives more information about the proposed algorithm and also provides its detailed evaluation. The paper is organized as follows. Section II discusses and categorizes related work. Section III presents the proposed architecture. Section IV reports on the setup and results of our field experiments we performed to collect realistic data sets and requirements necessary to evaluate the proposed architecture and the MANET routing protocol. The cattle movement data from these experiments was uploaded [14] to the Community Resource for Archiving Wireless Data At Dartmouth (CRAWDAD). Section V presents our practical protocol that provides data off-load and in-situ queries extending the discussion about combating disconnections. Section VI reports on our evaluation of the proposed protocol. Section VII identifies potential security threats, proposes feasible precautions against them and discusses impact of these precautions on the proposed protocol. Finally, Section VIII identifies future challenges.

II. RELATED WORK

This Section reports and classifies the existing work related to cattle monitoring.

A. Criteria

We begin with defining and motivating the set of criteria used for reviewing existing work. They can be divided into satisfying user requirements and addressing environmental constrains. Satisfying user requirements includes: (1) increasing reliability, (2) managing delays, (3) increasing scalability, (4) lowering costs. Addressing environmental constrains means handling high mobility of nodes. Further within this section we discus each of these criteria in a greater detail.

a) Increasing Reliability. This is an important requirement that affects the usability of the monitoring system and should not be limited to the best effort level due to the nature of ad hoc type of communication. We target to increase the reliability by applying the appropriate techniques such as extending range of transmitters with multi-hop communication, utilizing redundant data storage and feedback. Due to lower time constraints it is easier to increase reliability of sending data for retention and delivering notifications about detected events than answering in-situ queries.

b) Managing Delays. Different types of traffic have different time constrains. According to the users' requirements the acceptable delays for sending data from animal mounted devices to farm servers via sinks depend on the type of data. The urgent data includes for example information about the detected oestrus or an animal disease. Such events should be reported as quickly as possible. Non-urgent data is for example a periodic update necessary for detecting the reduced efficiency of pastures. Reduced efficiency of pastures should be reported within 24 hours. Delays for answering in-situ queries should allow the users to work interactively.

c) Increasing Scalability. The target system should comprise multiple MANETs where each MANET can comprise from several up to approximately hundred of animal mounted devices. We consider scalability in terms of the number of MANETs in the overall topology, the number of animal mounted nodes within each of the MANETs and of the density of the topology of a single MANET. The system should maintain the required parameters such as delays and energy efficiency within the dynamic range of topology size and density. In the case of lower densities of the topologies the major challenge are disconnections because the topology can split into separated islands of connectivity, e.g., this may happen when an animal becomes ill or injured or the herd splits into separate groups. Such disconnections are challenging for the wireless communications because the multi-hop path between a pair of nodes does not necessarily always exist. Handling disconnections means thus detecting the existence of the multi-hop path and when it appears, performing necessary data exchanges or routing the data in the store and forward manner or caching data and answering queries within the network partition. In the case of higher densities of topologies or higher numbers of nodes the major challenge is combating network congestion that is usually caused by broadcasts. Therefore the most promising approach to combating congestion is optimizing the broadcasts by differentiating the roles of nodes in rebroadcasting packets.

d) Lowering Costs. This refers to lowering the financial and labor costs of installation and maintenance of the target cattle monitoring system. More specifically, we focus on lowering the costs of utilizing the third party communication services such as GSM, satellite telephony or human labor. The major constituent of maintenance costs of the target system is replacing batteries of the animal mounted nodes and we aim to minimize and balance energy utilized for wireless communication by animal mounted nodes.

e) Handling High Mobility. Animal mounted nodes have movement patterns that are difficult to predict and this results in frequent changes of topology. Handling high mobility thus means using soft state topology data, which is collected in the demand driven way, i.e., when there is data to be routed and the topologies change in the self organized fashion.

B. Existing Approaches to Animal Monitoring

This section discusses existing Wireless Sensor Networks (WSNs) for animal monitoring. The WSNs [15] consist of hundreds to thousands of inexpensive wireless nodes, each with some computational power and sensing capability, operating in an unattended mode. The hardware technology for these networks are low cost processors, miniature sensing and radio modules. Sensor data includes continuous sensor readings of physical phenomena, audio and video streams.

a) Stationary Wireless Sensor Networks. The initial WSNs were purely stationary. The sensor data was archived in a powerful server geographically collocated with the sensors (usually referred to as a base station) that was usually fully replicated on the pre-determined powerful servers in the labs. Users could query the databases to get information about sensor data. An example stationary WSN was the WSN deployed on the Great Duck Island [16] to monitor the ecology of Leach's Storm Petrel. It used single-hop communication and had a multi-layer architecture. The fist layer consisted of multiple sensor networks that were deployed in dense patches that were widely separated and measured various physical phenomena and had cameras and microphones. Each sensor patch had sensor motes that were capable of various forms of filtering, sharing and combining sensor measurements. Sensor motes transmitted sensor data to the second layer that is referred to as a gateway. A gateway was then responsible for transmitting the packets to the third level referred to as the base station and some further data processing. The base station in the third level provided full database services and connectivity to the database replicas across the Internet. Fourth layer usually refers to services that provide multi-user access to sensor data including services for supporting analysis, visualization and web content. Once deployed, most base stations are intended to remain stationary and in a densely packed configuration. WSN deployed on the Great Duck Island comprised 43 sensor nodes and its maintenance was characterized by low labor intensity. Its stationary character allowed simplification of the routing and avoiding problems with mobility and disconnections. The simple routing and lack of disconnections helped in avoiding problems with energy saving. Lack of disconnections and problems with energy saving allowed short delays. This approach because of its stationary character does not apply to our scenario.

b) Animal Mounted. In a typical animal mounted WSN mobile nodes send measurements to a centralized server over a GSM or satellite network. Alternatively the measurements are collected by a mobile base station carried by a human or mounted on a vehicle and then manually processed [2]. The oldest form of animal mounted wireless sensors are radio tags, which send VHF beacons [17]. Their measurements are retrieved by a base station, which can be fixed, carried by a human or mounted on a vehicle. This approach is not optimal for our scenario because using fixed base stations is expensive in the case of covering larger areas. Using base stations carried by humans or mounted on vehicles is very labor intensive. In both cases potentially data from only a subset of tagged animals can be retrieved. The more recent variant of this method [17] is using satellite telephony instead of VHF beacons. This is much less labor intensive and more reliable but also very expensive and energy inefficient. One of the first examples of animal mounted WSNs was ZebraNet [2] that consisted of animal mounted collars collecting and exchanging GPS locations, which were retrieved by a mobile base station. The collars, were opportunistically exchanging all stored measurements with all encountered nodes. This addressed disconnection but had low scalability – the maximal envisaged number of the deployed animal mounted nodes was 30 and involved human labor. The authors of [3] mounted various sensors on a single steer to monitor temperature inside its rumen, location, acceleration, as well as external temperature, humidity and pressure. The measurements from the sensors were transmitted to the gateway mounted on the animal, which forwarded them on via GPRS. The presented approach was expensive and not energy efficient because of extensive utilization of GPRS. Low energy efficiency increased the labor intensity of its maintenance. The GSM telephony can have limited coverage in rural areas where the cattle is kept [3]. This approach does not address our requirements because due to heavy utilization of GSM it has high costs and low energy efficiency. Butler et al. [4] proposed using animal mounted devices to force bovine animals to move or stay within virtual fences but did not address the energy efficiency of the wireless communication. Researchers at CSIRO [5, 6] fitted 13 cows with collars containing accelerometers, GPS receivers and wireless networking interfaces in order to examine reliability of the communication and usability of the data collected by GPS receivers and accelerometers. The authors did not give the details about the utilized routing protocol and did not consider the energy efficiency. The later work of these researchers [7] concerns using animal mounted devices to prevent bulls from fighting with each other. The animal mounted collars have GPS receivers, wireless network interfaces and are capable to apply electric shocks to the animals wearing them. The utilized wireless communication is a simple single-hop one without considering energy efficiency. Small et al. [18-20] proposed using whale mounted sensors to collect data about whales and their habitat. They utilized a combination of the Infostation [21, 22] paradigm and a DTN approach similar to Gossiping [23]. This work is similar the ZebraNet [2] but limits the probability of forwarding data to other nodes. In our scenario animal mounted devices form a much denser topology than in the case of whale monitoring. Therefore, gossiping would increase the network overhead and thus affect energy efficiency.

c) DTN networks for rural areas. There is intensive ongoing research in DTN networks for rural developing areas [24-27]. However, this research typically concerns providing connectivity between villagers or between villagers and local authorities rather than monitoring farm animals and does not consider energy efficiency.

III. ARCHITECTURE OF THE CATTLE MONITORING SYSTEM

This section describes the architecture of the target cattle monitoring system, more fully described in [13, 28]. The scope of the monitoring system is a farming enterprise, which comprises several pastures and barns where animals are kept. The cattle can be kept all the year continuously in the pastures or all the year in the barns but the most common practice is to keep them in the pastures during the warmer half of the year and indoors during the other [29]. The proposed system can be used to monitor animals regardless if they are kept continuously in the pastures or in the barn and regardless if they currently yield milk or not.

Oestrus, animal diseases, reduced efficiency of pastures can be detected by measuring, collecting, and analyzing walking and feed intake intensity [10, 30]. Relying on both factors can decrease the number of false positive errors [30, 31]. In the proposed system, animal mounted device has the form of a collar with a built-in accelerometer measuring the intensity of feed intake. Walking intensity is measured by a pedometer mounted on the animal's leg. Measurements from the pedometer are acquired by the collar over wireless communication. Measurements from the pedometer and accelerometer are stored and processed by the collar. Both the collar and the leg mounted pedometer are battery powered. Data processing performed by animal mounted devices aims to detect oestrus, pregnancy, animal diseases etc. They have wireless network interfaces and regularly transmit raw and processed data to the farm servers over the sinks. Sinks are members of the MANET, which forward the data collected and processed by animal mounted devices to farm servers. Animals wear the same devices regardless if they are kept in pastures or barns.

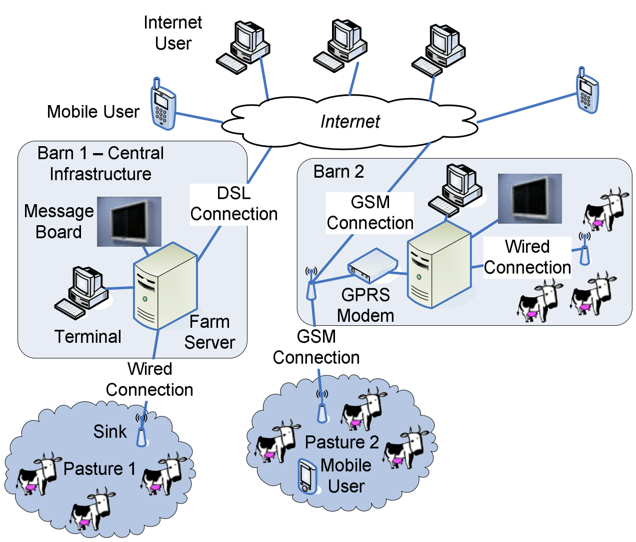

Figure 1. Example deployment

The typical amount of data for each update sent from animal mounted devices to sinks is 32B. As shown in Figure 1, sinks can be connected to farm servers over a wired network connection or GSM telephony. In the latter case, the sink can be stationary or animal mounted. The farm servers store the real time and historic data, detect the user defined events and issue notifications about these events.

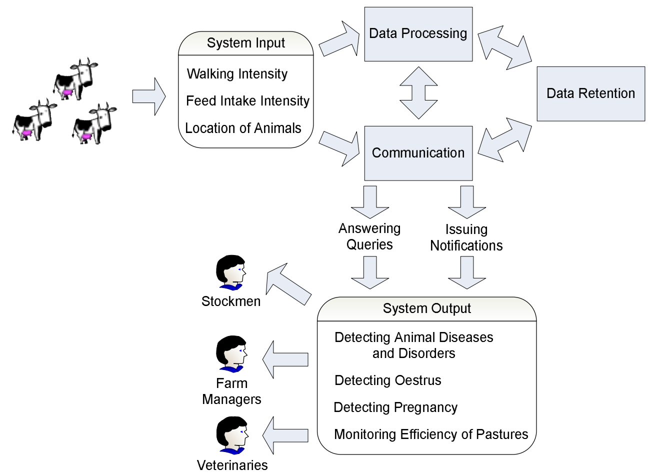

Figure 2. Functional overview of the cattle monitoring system

As shown in Figure 2, the users can query the data stored on the servers, including raw and processed data, either locally at the farm or remotely over the Internet. Users located in a pasture, stall or in its close proximity may want to query data about the animals located there. This can be achieved by querying the data from a PDA or a smart phone connecting directly to the animal mounted devices, or via the sinks over the wireless communication.

IV. FIELD EXPERIMENTS

In this section we describe field experiments we performed at the University of Nottingham's Dairy Centre in collaboration with School of Biosciences. The purpose of these field experiments was collection of realistic data sets and requirements necessary to design, develop and evaluate the delay tolerant architecture and the energy efficient MANET routing protocol for the cattle monitoring system. The cattle movement data from these experiments was submitted [14] to the Community Resource for Archiving Wireless Data At Dartmouth (CRAWDAD). CROWDAD is an international repository of real wireless data for wireless network research community.

A. *Quantitative Experiments*

Quantitative experiments comprised cattle movement and behavior monitoring in order to gather the realistic environmental constrains.

1) *Experiment Setup*

We received one year long walking intensity data from 5 pedometers mounted on the cows located in the division of a modern dairy housing 100 animals, shown in Figure 3. One year length of the pedometer data allows for enough variability of continuing patterns that could be used by our algorithm to enhance its performance. Cows could move freely in the area with feeder, water tank, resting bays and milking robots available 24 hours a day. Their measurements were automatically collected by milking robots whenever a cow was milked.

We also monitored behavior of the animals using animal mounted GPS receivers and cameras. In particular we mounted on the monitored cows five collars, each comprising a neck strap and an aluminum instrument enclosure containing a Bluetooth GPS and a Bluetooth enabled mobile phone. Mobile phones were logging data from the GPS receivers including positions and timestamps. Monitoring started at 11:10. The collars were removed at 18:10. GPS receivers worked until 18:24 (manually turned off), 12:23 (probably jammed), 18:51 (manually turned off), 15:09 (exhausted battery), 15:33 (exhausted battery). Later we submitted [14] the collected GPS and pedometer data to the Community Resource for Archiving Wireless Data At Dartmouth (CRAWDAD). Concurrently we were filming the part of the dairy where the monitored cows were kept. We placed the camera on two ramps above this area. These locations offered the most complete view. We received the plan of the dairy and then captured the coordinates of the characteristic locations on the plan using a handheld GPS receiver. GPS receivers and filming were utilized only for the purpose of our field experiments. Their utilization is not intended for the target monitoring system.

2) Results

Our field experiments show that cows typically react well to the animal mounted collars weighting 1075g. This is very promising for the practical feasibility of the target cattle monitoring system. Figure 4 shows the average daily walking intensity of five cows, calculated from the one year long pedometer data as arithmetic weighted mean of walking intensities per each cow and each day. We can see that the animals' mobility can differ significantly among different animals and for each animal among different days. However, from this picture we cannot judge how the walking intensity is reflected in the spatial mobility. Figure 5 shows probability distribution of speeds for a subset of cows wearing GPS receivers. They were calculated by dividing the time a cow used the given speed range by the length of time the GPS receiver was enabled. We can see that not only walking intensity but also the preferred spatial movement speed can significantly differ among animals. These considerable differences in the animals' walking speed can be utilized in the routing protocol. Figure 5 also shows that the animals rarely move faster than 0.8 m/s, which is important for the wireless communication.

Figure 6 shows average walking intensity over the day for five different animals, each average walking intensity was calculated as a weighted arithmetic mean for each animal and for each hour of the day (i.e., one hour time frame) throughout all the days for which we had pedometer data (one year). Figure 7 shows the probabilities of milking happening at a given hour, calculated as a ratio of milkings number at given hour of the day to the number of all recorded milkings. We can see that cows are active all the day and night including walking and milking but they show similar 24 hours patterns. In particular, walking and milking activities tend to be less intensive between 0 and 6 a.m. These periods can be utilized for scheduled data exchanges.

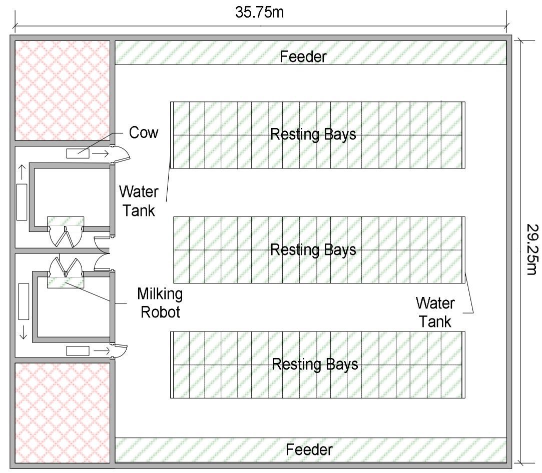

Figure 3. Layout of the dairy division

The quantitative experiments were performed in the dairy but this is only an example deployment scenario of the target monitoring system. The target monitoring system is also intended to monitor beef cattle animals kept continuously on the pastures even all the year. Such cattle may never be taken to the farm buildings.

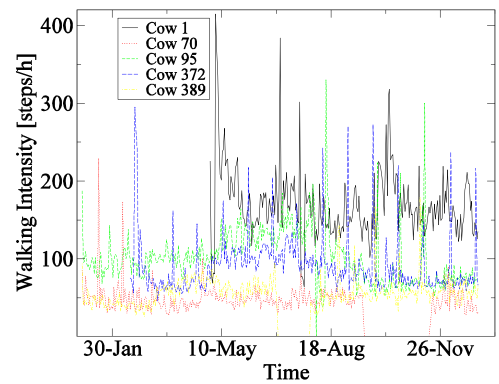

Figure 4. Walking intensity (pedometers)

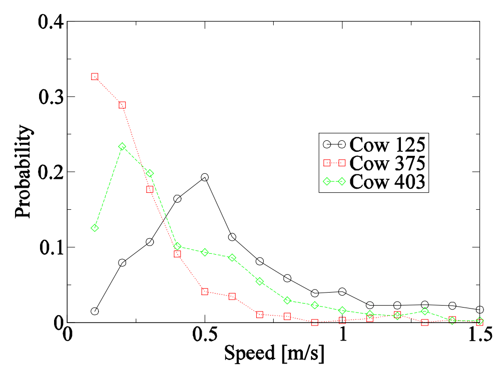

Figure 5. Probability distribution of animal speed (GPS receivers)

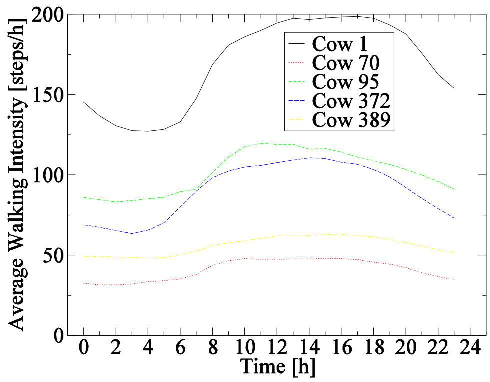

Figure 6. Activity over the day (pedometers)

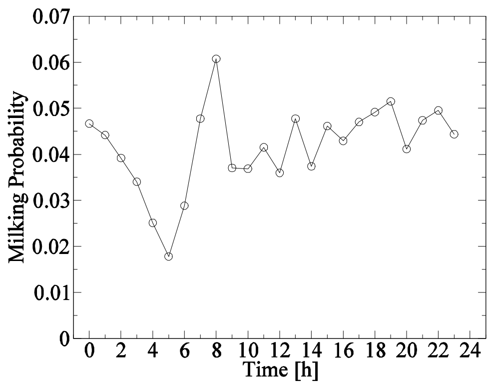

Figure 7. Milking probability (pedometers)

B. *Qualitative Experiments*

The objective of the qualitative experiments was gathering of the realistic user requirements.

1) Experiment Setup

Our qualitative experiments comprised distributing an anonymous questionnaire to the farm personnel and researchers working on the farm. We received four filled questionnaires. One of them was filled by a regular herdsman, one by the head herdsman (farm manager) and two by researchers working on the farm.

2) Results

From the performed questionnaire we learnt that the most required functionality of the system is detection of oestrus, pregnancy and animal diseases. Users have to be informed about oestrus and a newly detected disease as quickly as possible. The pregnancy should be reported within 48 hours from detection. Detection of reduced efficiency of pastures is less essential but more urgent – it should be reported to users within 24 hours from detection.

In order to inform users about the detected oestrus and animal diseases as quickly as possible, animal mounted nodes should be able to detect oestrus and animal diseases on their own and send this information over the sink as soon as it is detected. When no particular event is detected, data from collars should be transmitted via sink at least every 24 hours to allow server its aggregation and detection of reduced performance of pastures.

The users recognize sending notifications to their mobile phones as very useful and have to receive them any time, not only when they are collocated with the animals. This requires sending the notifications using the GSM network as, e.g., SMS messages. The users need to perform in-situ queries up to several times a day. This means that energy saving is relevant not only for sending data to sinks but also in-situ queries.

The head herdsman recognized also as useful measuring body temperature of the animals. This however requires using sensors mounted inside animal body because externally mounted sensors do not provide reliable measurements [3]. The regular herdsman recognized as useful detection of calving but feasibility of this requires further research in animal physiology.

V. ENERGY EFFICIENT ROUTE DISCOVERY

This section describes realistic, energy efficient MANET routing protocol, Energy Efficient Route Discovery (EERD), for the cattle monitoring system we introduced in [8, 13] and proposes energy efficient mechanism for dealing with disconnections. EERD concerns sending data from animal mounted nodes to sinks and performing in-situ queries. It significantly optimizes energy efficiency of control traffic by identification and utilization of animal movement patterns as well as graceful degradation of data traffic energy efficiency. We concentrate on energy utilized for wireless communication because the progress in the energy efficient microcontrollers with high computation power made the energy utilized for data processing negligible [32] in relation to energy spent on wireless communication. Simulation based analysis of delays, latency and package loss are presented in Section VI. They show that EERD not only decreases energy utilization but also improves success ratio of packet delivery in relation to DSR [33] and a generic routing protocol ESDSR [34]. This is achieved by decreasing packet loss caused by congestion.

A. *Design Space*

In order to allow extending coverage while preserving energy efficiency (i.e., low transmission power) and to allow circumventing of obstacles in radio propagation we need the multi-hop ad hoc connectivity between mobile nodes. This can be achieved by a MANET routing protocol. Due to characteristics of our scenario such protocol should be optimized for energy efficiency and handling disconnections.

The design space for the energy efficiency of the routing protocol is shown in Figure 8. The Broadcast Optimization axis represent saving energy on broadcasting queries and route discovery control packets. The relevant approaches here include Passive Clustering with Delayed Intelligence [35] and utilization of heterogeneity of nodes' mobility we propose. The Route Selection Axis represents proposed selecting routes, which potentially have the maximal lifetime. The vertical axis, Transmitter Power Control represents saving energy by minimizing transmitter power. The relevant approach here is similar to the transmitter power control utilized in Energy Saving Dynamic Source Routing (ESDSR) [34] or Distributed Power Control (DPC)

[36]. The proposed routing protocol is a combination of these techniques.

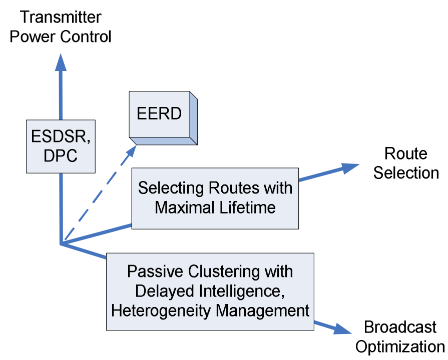

Figure 8. Energy efficiency design space

B. Overview

Energy Efficient Route Discovery (EERD), for cattle monitoring system minimizes and balances energy consumption in the face of low data traffic and high mobility of nodes. It decreases energy spent on route discovery and in-situ queries by utilization of the tailored PCDI broadcasting. The number of necessary route discoveries is decreased by utilization of heterogeneity of nodes' mobility, selecting routes with longest lifetime and opportunistic route discovery. This protocol also deals with disconnections by cooperative detection of route availability. It is based on the established MANET routing protocol, DSR [33]. DSR was selected instead of Ad-hoc On-demand Distance Vector Routing (AODV) [37] because due to the application of PCDI the duration of the route discovery is difficult to estimate, which collides with expiry times of AODV dynamic routing table entries. Too long expiry time of these entries would highly increase the amount of soft state maintained by the nodes. In contrast too short expiry time would prevent routes with higher number of hops from working. The only advantage of AODV over DSR are shorter control packages in the case of routes with higher number of hops [37], which were not experienced in the evaluation reported in Section VI.

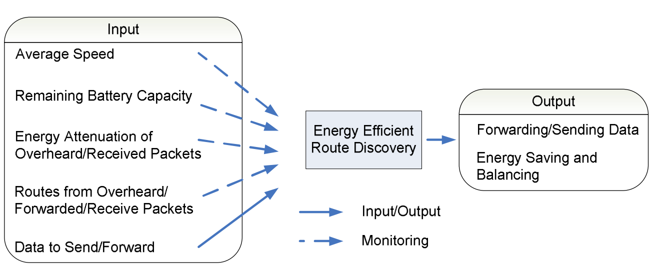

Figure 9. Input and output of the Energy Efficient Route Discovery

Figure 9 shows that EERD balances and saves energy on routing data by monitoring average speed of the nodes, remaining battery capacity of the local node, energy attenuation of the received and overheard packets, as well as acquiring routes from overheard and forwarded packets.

C. Energy Saving and Route Discovery Techniques

This subsection describes energy saving and route discovery techniques utilized in EERD.

1) Decreasing and Balancing Energy Spent on Route Discovery

As in ESDSR [34] nodes put the utilized transmitter power in the packets so that each node can track power necessary to contact its single-hop neighbors using the following formula:

$$P_{min} = P_{tx} - P_{recv} + P_{threshold} + P_{margin} \tag{1}$$

where P_{min} is the minimal required power for the sender to use, P_{tx} is the current transmit power, P_{recv} is the current received power, $P_{threshold}$ is the threshold power level for the application, and P_{margin} is the margin to safeguard against changes such as channel fluctuation and mobility. All the values are in dBm. Note that only route requests and other broadcasted packets are sent using the maximal power of the transmitters.

The proposed protocol minimizes and balances energy spent on route discovery control traffic at the cost of the energy efficiency of data traffic. This is promising because the amount of exchanged data is low and power spent on sending data packets is minimized by limiting the transmitter power. The latter is possible because the power necessary to send data over each hop is known from monitoring power attenuation between neighbors. The power of route discovery broadcasts cannot be similarly decreased because it would decrease the probability of finding any route.

Energy spent on route discovery is minimized and balanced by applying Passive Clustering with Delayed Intelligence (PCDI) [35] to route request broadcasts. Note that broadcasted packets are sent using maximal transmitter power so power of the received broadcasts can still be utilized to calculate PCDI waiting time. In PCDI nodes with higher battery capacity are more likely to route broadcasted packets so discovered routes lead through these nodes. This results in more fair energy utilization of data traffic.

2) Decreasing Number of Route Discoveries

Energy spent on route discovery is further minimized by decreasing number of route discoveries achieved by utilization of the following techniques.

a) Utilizing Heterogeneity of Node's Mobility. The field experiments reported in Section IV show that there are considerable differences between typical movement speeds and typical walking intensities of animals carrying wireless nodes. The proposed protocol decreases chances that faster wireless nodes become members of the route by delaying their rebroadcasting of PCDI broadcasts. In this way the lifetime of the discovered routes is extended so repeated sending of data, route failure packets and route discovery broadcasts can be minimized.

Each mobile node stores the 24 hour time series of its momentary speed received from the pedometer – expressed as number of steps per time unit. An average speed is calculated over this time series discarding time when an animal did not move. The 24 hour time period is motivated by limited resources of the nodes and the 24 hour movement pattern cycle of the animals indicated by the pedometer data (see Figure 6). Each transmitted packet has a piggybacked maximal and minimal average speed of a node. These values are updated and stored by the forwarding nodes. Each node resets these stored values after a timeout to account for the changing conditions. This data allows nodes to asses their mobility in relation to other nodes. In EERD the PCDI formula calculating waiting time is extended by taking into account the average speed of the node in relation to average speeds of other nodes:

$$W = \delta \times \frac{receivedPower}{localEnergy} + \varepsilon \times \frac{V_L - V_{MIN}}{V_{MAX} - V_{MIN}} \qquad (2)$$

where δ and ε are constants adjusted for the particular hardware, V_L is the average speed of the local node, V_{MIN} and V_{MAX} are minimal and maximal average speeds of the neighborhood nodes. In this way, relatively faster nodes wait longer to rebroadcast PCDI broadcasts so their probability of becoming PCDI clusterheads or gateways and later forwarding data traffic is smaller.

b) Selecting Routes with Longest Lifetime. The number of route discoveries is further minimized by selecting routes with potentially longest lifetime. Because of the high mobility of the nodes the life of a route is typically terminated not by the exhausted battery capacity but by the change of the topology.

Utilizing received, forwarded and overheard packets a node monitors how the energy attenuation changes between the one hop neighbors. In this way a node can count how many links within the multi-hop route are increasing their energy attenuation (deteriorating). In particular each forwarded route request and acknowledgement packet contains a counter of deteriorating hops.

Finally, as shown in Figure 10, a node selects routes, which have (1) *the least number of hops*. For routes with the same number of hops, a node chooses these with (2) *the least number of deteriorating links*. If this is equal one with (3) *the minimal total power* (i.e., sum of the transmitter power necessary to send data over each hop) is selected. The rationale behind (1) is that on average the fewer nodes are required to take part in routing the longer it takes before one of them moves out of the wireless range of its neighbors. (2) is used to avoid routes comprising hops between nodes moving away from each other. (3) is motivated by assuming that the power attenuation between two nodes is in most cases proportional to square distance between them. Therefore, selecting routes with minimal total power tends to select the routes leading through nodes, which are closer together. Such nodes are likely to need more time to leave each other's range.

Note that selecting a more optimal route does not involve exchanging additional packets. The selection of a route is performed in two cases. The first case is when a node wants to send data and finds multiple routes to the target node – one of them can have been acquired from a route discovery and the rest from forwarding or overhearing packets. The second case is when a node, which is due to rebroadcast a route request, finishes waiting enforced by Delayed Intelligence [35].

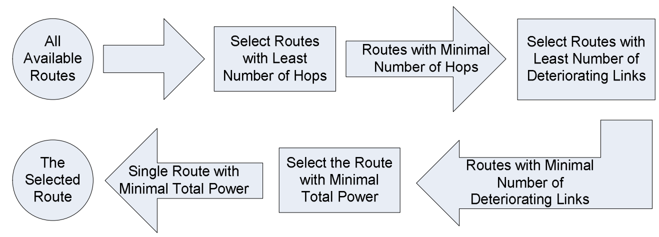

Figure 10. Route selection algorithm

Overall power of a route is calculated incrementally by adding the power necessary for sending data over subsequent hops. The partial result is carried by packets such as route requests, route replies and acknowledgements. In the case of route requests this is necessary for selecting the optimal route for further forwarding. In the case of route replies and acknowledgements this is necessary for opportunistic route acquisition from forwarded and overheard packets. A node rebroadcasts more than one route reply for a single route discovery attempt only if subsequent replies contain better routes.

c) Opportunistic Route Acquisition. An important way of limiting the number of route discoveries is collecting routes from overheard and forwarded packets such as route replies and data traffic. The gain from overhearing depends on the utilized wireless networking interface, in particular how much the power consumed by transmitting is greater than the power consumed by receiving and what is the difference in power consumption between promiscuous and non-promiscuous mode.

The sink always acknowledges receiving data. In order to account for possible disconnections, if no acknowledgement is received delivery is repeated after a timeout. In this way it is possible to opportunistically collect routes not only from forwarded or overheard route replies but also acknowledgements. For that purpose acknowledgements similarly to route replies carry aggregated power of the route and the counter of deteriorating links.

3) Saving Energy on Broadcasts in In-situ Queries

A mobile user collocated with the animals can issue both regular queries and directed queries. The answer to a regular query is a group of animal ids (or their custom nicknames) that fulfill a given logical condition (e.g., all animals, which are sick). The user broadcasts the query using PCDI with the proposed optimizations. All the nodes that know any partial answer to the query send the answer back to the user, together with the timestamp of the data based on which the answer was generated. The answer is sent back along the route traversed by the query. Nodes that forward the queries assemble and filter these answers according to their timestamps in order to reduce redundant traffic. The final assembly is performed by the user's device.

Directed queries concern data about a particular animal (e.g., predicted date of the next oestrus). To receive the answer to such a query a user's device sends a broadcast using PCDI with the proposed optimizations to retrieve the route and the hardware address of the node that has the most recent data about the animal of interest if the user's device does not already have this information in its cache. This node could be a device that produced or caches the required data, or a sink, which can retrieve this data from a server. Then the user's device sends the query along the discovered route selected according to the cost metric proposed above. Finally, the queried device sends the answer back along the same route.

D. *Handling Disconnections*

We propose extending EERD with the following mechanism for handling disconnections, which within this paper mean splitting of the network topology into separated islands of connectivity. The proposed protocol is intended to adapt to different environments, where the cattle is kept, dairy, pasture, etc. Therefore, it is not possible to present fixed boundaries of disconnection time.

In the case of sending data to sinks the data is sent only when the multi-hop path between an animal mounted node and any of the sinks exists. It is detected using the proposed *cooperative detection of route availability*, shown in Figure 11. More precisely, if the route discovery is unsuccessful it is repeated after a certain timeout with a small random delay. The purpose of the random delay is preventing the broadcast storm caused by multiple nodes initiating route discovery at the same time. In order to save energy on the repeated unsuccessful route discoveries if the route discovery is unsuccessful the node that initiated it broadcasts a negative acknowledgement. In this way all the nodes within its island of connectivity know that the route to the sink is not available and the route discovery should be repeated no sooner than after the predefined timeout. Otherwise if a node receives a route request packet but no negative acknowledgement, this means that a route to a sink exists so the node can try to discover it. The negative acknowledgements are preferred here over positive ones to save energy in circumstances when no disconnections take place – e.g., animals are located in a barn.

When a sink receives data from an animal mounted node it sends an acknowledgement. If no acknowledgement is received the animal mounted node resends the data over a different path and if it does not know any alternative path it initiates route discovery.

In order to answer the in-situ queries in the face of disconnections the animal mounted nodes should be able to answer the query within the island of connectivity (network partition). To achieve that, nodes cache data sent to sinks, which they forward or overhear. This caching is performed according to their available storage space. The proactive caching, i.e., the proactive exchange of the data for the purpose of caching, is not advisable here due to the energy constrains [38]. If the sink is connected to the farm server over an expensive third party connection such as GPRS, it may also cache the data forwarded to farm servers. In this way the sink can support answering in-situ queries without the need to query the farm server.

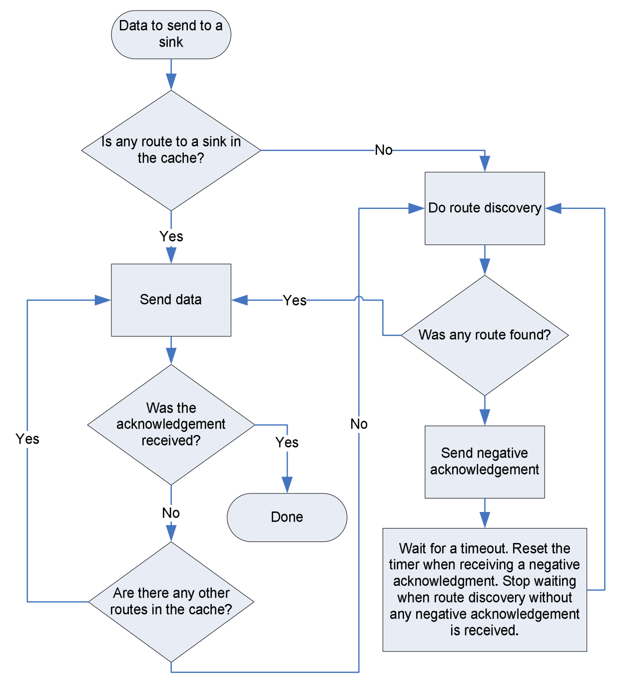

Figure 11. Cooperative detection of route availability

Nodes receiving an in-situ query answer it whenever they have at least a partial answer to this query. This answer can come from locally produced or cached data. If the in-situ query is received by the sinks, the sink may answer it after fetching appropriate data from the farm server or its local cache. In the case of direct queries nodes forward the answers to the queries only when the answer was based on the data, which is newer than in the case of answers already forwarded.

E. *Sending Data from Farm Servers to Animal Mounted Nodes*

Sporadically the farm servers may need to send data to the selected or all animal mounted nodes. This data can be for example a firmware or configuration update. Such communication is similar to sending data from animal mounted nodes to farm servers. In particular the farm servers keep track of associations between the animals and pastures or barns where they are kept so they know to which sinks data should be forwarded. After receiving this data a sink performs route discovery (similarly as an animal mounted node) and sends the data to the given animal mounted nodes. If a route does not exist it retries after a timeout.

If there is more than one sink collocated with the target animal mounted node, the first sink, which manages to successfully deliver data to the target node can inform about this other collocated sinks so that the target node does not receive duplicates. To prevent duplicates being delivered at the same time each sink can wait a random delay before sending the data. If the instant communication between sinks is not possible, e.g., they are connected to farm servers by data couriers or GSM then the animal mounted nodes may receive duplicates but this type of communication is sporadic so these duplicates do not make a considerable difference for energy efficiency.

VI. EVALUATION

This section reports on the evaluation of the proposed architecture for the cattle monitoring system, and its core, MANET routing protocol - EERD. As the method of evaluation we selected emulation, i.e., simulation utilizing data from the real experiments. This approach offers a satisfactory compromise between realism, variety of examined conditions, number of observed parameters and utilization of resources. In particular it offers higher realism than the purely stochastic simulation. Whereas in comparison to purely experimental evaluation emulation offers higher variety of examined conditions and more observed parameters for the same constraints (i.e., time and funds). We compared the proposed routing protocol with DSR [33] – a classical MANET routing protocol and ESDSR [34] – an example energy efficient routing protocol. We emulated the communication scenarios, which are realistic for the proposed cattle monitoring system but also sufficiently challenging for the emulated protocols to demonstrate benefits of the proposed protocol. In order to increase realism of the simulation the movement patterns of mobile nodes are emulated utilizing data from the field experiments instead of utilization of generic stochastic models such as Random Waypoint Model [33] or Reference Point Group Mobility Model [39]. These models were devised to simulate mobility of people and it is very difficult to adjust their parameters to make them reflect mobility of bovine animals.

A. *Bovine Movement Emulator*

In order to make a realistic packet level emulation involving up to 100 nodes we implemented an emulator of bovine movements. This emulator is informed by field experiments described in Section IV and utilizes animal movement data from these experiments.

The emulation area is similar to the dairy where the field experiments were performed (see Figure 3). Each of the emulated cows is for most of the time in one of three states: (1) resting in a bay, (2) eating/drinking, (3) being milked. These states are associated with groups of locations within the division of the dairy and transitions between the states are connected with moving between locations. Selecting the next state is restricted in the following way. There is a minimal period allowed between milkings and a cow goes to a milking robot only when any of them has a queue shorter than three animals. If after reaching the robot the queue is longer than two animals, the cow changes the target state.

Speeds, which the emulated cows randomly select, were acquired from the GPS data. This makes the emulated cows move with similar distribution of speeds as the real animals. Speeds higher than 1.5 m/s were filtered out under the assumption that they were unavailable to the bovine animals [40] and were recorded because of GPS drift. Two different speed profiles utilizing real speeds from cows 375 and 403 were utilized (see Figure 5). These profiles are distributed evenly between the emulated cows.

The times a cow stays at any of the locations were acquired from the video footage. These are randomly selected for the cows during the emulation to achieve the distribution close to reality. GPS data is only utilized for acquiring resting times because in other cases the accuracy of GPS data is too low in relation to the distances between different types of locations such as feeder, water tanks, milking robots and bays. The patterns of eating and drinking and the times the cows spent performing these activities were also determined from the video footage. These patterns are also randomly selected during the emulation. The minimal period between milkings for a cow we calculated from the timestamps of the pedometer readings taken during the milkings.

B. *Comparison with Existing Approaches*

The proposed MANET routing protocol was compared with the existing approaches including DSR [33] and ESDSR [34]. DSR was selected as a classical MANET routing protocol and ESDSR as an example energy efficient MANET routing protocol.

1) *Emulation Setup*

The proposed protocol was evaluated using the ns-2 [41] network simulator, best suited for the MANET character of our scenario. The protocol was implemented in C++ as a wireless routing agent [42]. In order to allow processing of the packets overheard by nodes the tap function was enabled.

As shown in Figure 12, Bovine Movement Emulator (BME) described earlier was utilized to generate mobility traces for ns-2. Ns-2 generated wireless traces, which were then processed using Python scripts to measure the observed parameters. Then in the case of one of the emulated scenarios, which were emulated in several iterations to average the results, statistics from all the iterations were aggregated.

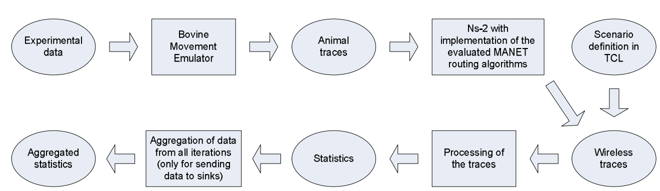

Figure 12. Emulation environment

We emulated two scenarios, which reflect realistic communication patterns within the proposed cattle monitoring system and are sufficiently challenging for the simulated routing protocols to demonstrate differences in their performance: (1) animal mounted nodes sending data to a sink, (2) one stationary user querying animal mounted nodes. In both cases data traffic starts after 1 hour to let the emulated animals leave their initial positions. At the beginning of simulation the animal mounted nodes already know their average speed in relation to the maximal and minimal average speed of the other nodes.

In the first scenario animal mounted devices try to send once 32B of data to the stationary sink, which models the regular daily update sent to the farm servers (see Section III). 32B reflects the amount of data from animal mounted pedometer, accelerometer and results of processing made by animal mounted nodes such as detected animal diseases, date of last oestrus etc. They start after 1 hour, randomly distributed over 5s to take advantage of passive acquisition of routes. They perform the route discovery if they do not already have a route to the sink in their cache (from overheard or forwarded packets). The whole emulation lasts for 3 emulated hours. In this scenario for each set of parameters we repeat the emulation 5 times with different random values for BME and ns-2 and then average the results. In the second case the user broadcasts 20 queries. Each node replies to the query with probability 0.25 with 32B of data. This emulates range queries. Each subsequent query is submitted 10s after receiving the last answer to the previous query.

To evaluate the scalability of the evaluated routing protocols the number of animals was altered. The observed parameters include: minimal, average and maximal energy usage per node over the course of the emulation and its standard deviation (we consider only the animal mounted nodes); number of nodes with exhausted battery capacity at the end of emulation; minimal, maximal and average delays and their standard deviation; success ratio.

Delays mean here in the case of sending data to sinks the time from the moment when data is sent until successful receiving of the acknowledgement by an animal mounted node. In the case of in-situ queries delays mean time from sending the query to receiving the answer. Success ratio means in the case of sending data to a sink the fraction of nodes that successfully delivered data to sinks. In the case of in-situ queries we measured two different success ratios. Success ratio for queries is calculated using the following formula:

$$SR = \frac{N_{RQ}}{N_Q \cdot N_A} \tag{3}$$

where N_{RQ} is the number of receptions of a query by an animal mounted node, N_Q is a number of issued queries and N_A is a number of animal mounted nodes. If the animal mounted node receives the same query more than once only the first case is considered. Success ratio of responses is the fraction of responses that were successfully returned to the user. The standard deviation was calculated using the following formula:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{4}$$

where N is the number of samples, x_i is the sample value and $\bar{x}$ is the value of the arithmetic average.

The maximal power of the transmitter is 0.85872mW (i.e., power consumed by the transmitter and power of the transmitted signal), which gives the maximum transmission range of 40m. According to [43] this gives parameters closer to those found in sensor radios. Since the receiving power is constant and a fixed amount of energy is dissipated when a node receives a packet, receiving power is ignored (modeled as zero). The authors of ESDSR made a similar assumption [34]. At the beginning of emulation the sink and the user have 1000J each (effectively infinite energy) and animal mounted nodes have 1J each. P_{margin} in Formula 1 is 1. We use the following EERD parameters: α=1, β=1, δ=10000s, ε=0.5s (see Formula 2), reverting to the initial state and discarding received states of neighbors after 60s. The route validity period is 60s and waiting for route replies lasts 1s. We used Two Ray Ground propagation model, IEEE 802.11 MAC layer and standard ns-2's implementation of priority queue and omni-directional antenna.

2) Emulation Results

Emulation results are shown in Figure 13 and 14. Points and lines show average values per node or standard deviation. Error bars show minimal and maximal values. In each examined case no node exhausted its battery capacity.

Figure 13a shows energy utilized by animal mounted nodes for sending data to the sink. EERD considerably decreases average energy usage in comparison to DSR and ESDSR (48%-75%). The proposed protocol considerably balances energy utilization compared to DSR and ESDSR. Figure 13b shows that EERD has standard deviation of energy utilization by 76%-91% smaller than DSR and ESDSR. These improvements can be attributed to PCDI with proposed optimizations and proposed metrics for selecting routes.

Figure 13c shows delays for sending data to the sink. We can see that in the case of DSR and ESDSR the delays grow with the number of nodes, whereas in the case of EERD the delays are almost constant. Figure 13d shows the average deviation of delays. In the case of DSR and ESDSR it grows much faster with the increasing number of nodes than in the case of EERD. This means better scalability of the EERD in comparison to DSR and ESDSR, which can be attributed to reduced network overhead achieved by utilization of PCDI.

Figure 13e shows the success ratio (SR) for delivering data to sinks. We can see that in all examined cases the SR is very high. Nodes do not repeat failed attempts otherwise the SR would be even higher. In the case of DSR and ESDSR SR drops slightly for the higher numbers of nodes (to 0.94 and 0.95 respectively for 100 nodes). It is not the case with EERD. This can be attributed to avoiding congestion achieved by utilization of PCDI.

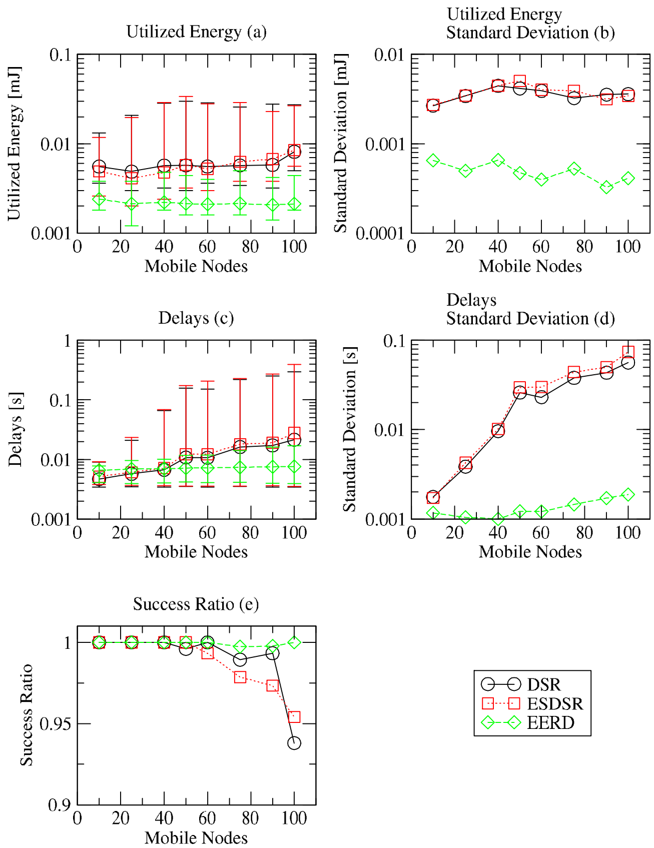

Figure 13. Comparison with existing approaches – statistics for sending data to sinks

Figure 14a shows the energy utilized by animal mounted nodes for answering in-situ queries. The amount of utilized energy is comparable to the case of communication with the sink, which justifies optimization of this type of communication. The amount of utilized energy is almost constant for each of the protocols regardless of the number of nodes. The considerable decrease of average energy utilized by the proposed protocol in relation to the existing routing protocols (by 77-82%) is achieved by optimization of broadcasting queries. Figure 14b shows that the standard deviation of utilized energy is much higher for EERD than for other compared protocols for the very sparse topology (10 nodes). Then the EERD's standard deviation drops sharply for 25 nodes and stays almost constant. In contrast the standard deviation of DSR and ESDSR grows with the number of nodes. This demonstrates better scalability of EERD in terms of energy usage achieved by optimized broadcasting.

Figure 14c shows delays in answering in-situ queries. The delays grow linearly with the number of animals. In the case of the proposed routing protocol this increase is lower, which means better scalability. This can be attributed to the decreased network congestion caused by the proposed optimization of broadcasting. For 100 mobile nodes EERD achieves up to 57% of decrease in average delays and up to 29% in maximal delays. The decrease of delays in answering in-situ queries is very important as this improves usability of the system. Figure 14d shows the average deviation of delays. It grows linearly with the number of nodes but this growth is much higher in the case of DSR and ESDSR than in the case of EERD. This gain is achieved by utilization of Passive Clustering and is very important for scalability.

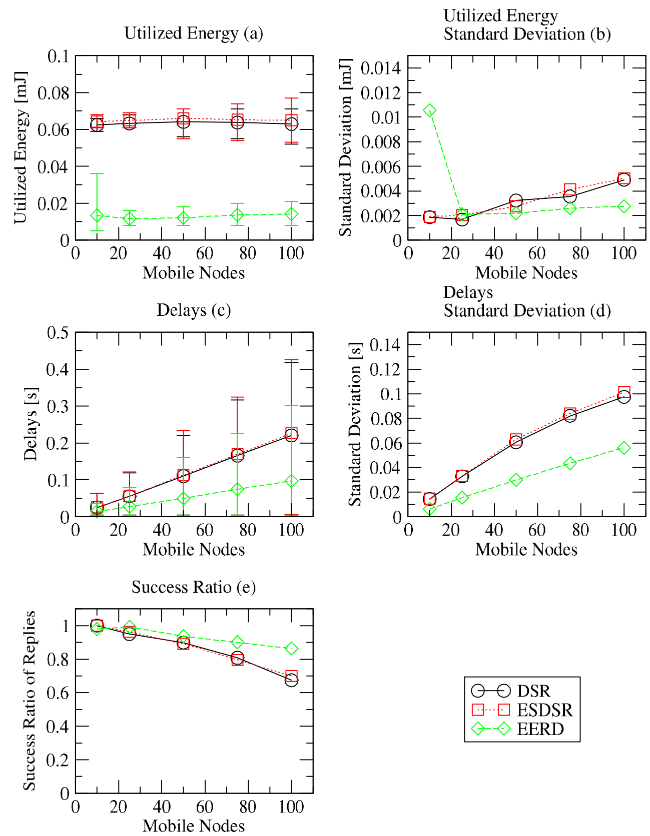

Figure 14. Comparison with existing approaches – statistics for in-situ queries

For all examined number of nodes and routing protocols the in-situ queries were delivered to all mobile nodes. The success ratio of delivering answers to the user's device is shown in Figure 14e. We can see that this success ratio decreases almost linearly with the increasing number of animals, which can be attributed to the network congestion. The proposed protocol offers however a higher success ratio for higher numbers of animal mounted nodes. This is due to the decrease in network traffic achieved by utilization of Passive Clustering. For 100 nodes the proposed protocol has success ratio higher than DSR by 22% and higher than ESDSR by 19%.

To summarize, the proposed MANET routing protocol has lower and more balanced utilization of energy than the other compared routing protocols. In the case of in-situ queries it also offers better scalability in terms of delays and success ratio.

C. Evaluation of the Specific Techniques Utilized in EERD

In order to better understand the influence of the specific techniques utilized in the proposed MANET routing protocol on its performance, the protocol was emulated with certain its features disabled.

1) Emulation Setup

The simulation setup was similar to the one described in Section VI.B.1. Instead of comparing the proposed protocol with the existing approaches, the performance of the fully functional protocol was compared with the performance of the same protocol with certain its features disabled, including:

- Power control – all packets are sent with the maximal power
- PCDI [35] – the flooding similar as in DSR [33] is utilized instead
- Utilization of heterogeneity of the nodes' mobility – the original PCDI formula [35] for calculating delays is utilized instead of the one we propose (Formula 2)

2) Emulation Results

Emulation results are shown Figure 15 and Figure 16. Points and lines show average values per node or standard deviation. Error bars show minimal and maximal values. In each examined case no node exhausted its battery capacity.

Figure 15a shows energy utilized by animal mounted nodes for sending data to the sink. We can see that without PCDI the utilized energy grows with the number of nodes. Utilization of PCDI makes the energy consumption almost independent of the number of nodes. This can be attributed to the energy saved on route discovery broadcasting. Utilization of transmitter power control gives the constant advantage in average utilized energy of 22% to 31%. Heterogeneity management extension to PCDI does not make any considerable difference here. Figure 15b show standard deviation of the average utilized energy. Utilization of PCDI and transmitter power control increases standard deviation. This is the cost of achieving lower average energy usage.

Figure 15c shows delays for sending data to sinks. Without utilization of PCDI delays grow slightly with the number of nodes otherwise their average is almost constant. Figure 15d shows standard deviation of delays. We can see that utilization of PCDI make it grow slower with the number of nodes.

Figure 15e shows the Success Ratio (SR) for delivering data to sinks. The SR is very high. The nodes do not repeat failed attempts otherwise the SR would be even higher. We can see that utilization of PCDI slightly improves SR.

Figure 16a shows the energy utilized by animal mounted nodes for in-situ queries. For all the examined cases the amount of utilized energy hardly depends on the number of mobile nodes. We can see that the most important decrease of energy utilization results from using PCDI and transmitter power control. PCDI decreases average energy utilization by 57-64% and transmitter power control by 33-40%. Figure 16b shows the standard deviation of the energy utilised for answering in-situ queries. We can see that PCDI highly increases this deviation for small topologies (10 nodes) but decreases it for topologies of medium size (25-75 nodes). The reason of high influence of PCDI on limiting utilized energy is decreasing network overhead caused by broadcasting of queries.

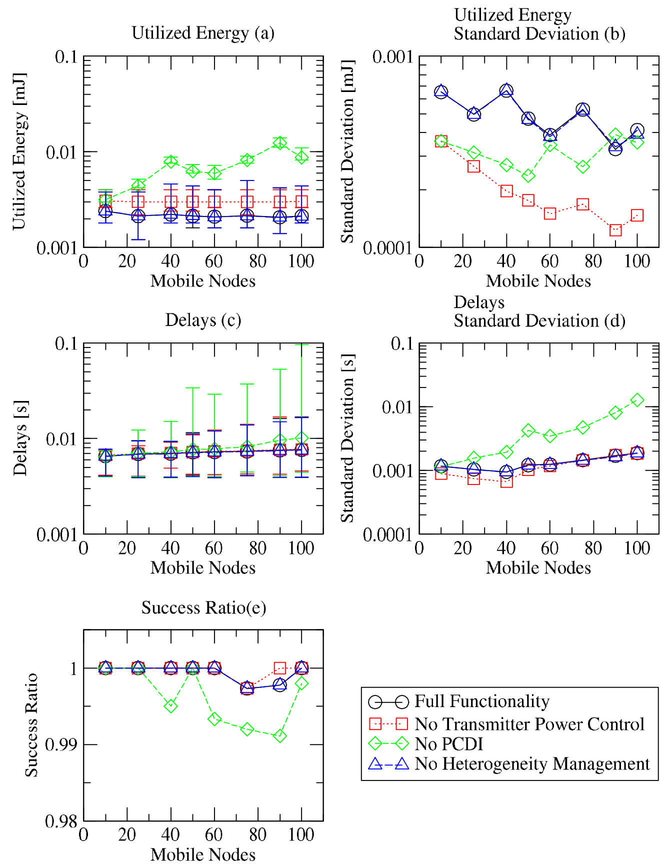

Figure 15. Evaluation of the utilized techniques – statistics for sending data to sinks

Figure 16c shows the delays of answering in-situ queries. We can see that they grow linearly with the increasing number of nodes but utilization of PCDI makes this growth smaller. Figure 16d shows that PCDI also decreases the standard deviation of the delays. These gains can be attributed to the decreased network congestion resulting from optimization of broadcasting.

For all examined cases the in-situ queries were delivered to all mobile nodes. The success ratio of delivering answers to the user's device is shown in Figure 16e. We can see that this success ratio decreases with the increasing number of animals, which can be attributed to the network congestion. Utilization of PCDI decreases the network congestion and thus improves the success ratio.

To summarize, the proposed MANET routing protocol EERD provides lower and more balanced energy usage than the classic, non-energy aware DSR and the more generic existing energy aware routing protocol ESDSR. In the case of in-situ queries EERD makes success ratio and delays deteriorate slower with the increasing number of nodes thus improving the scalability in comparison to DSR and ESDSR.

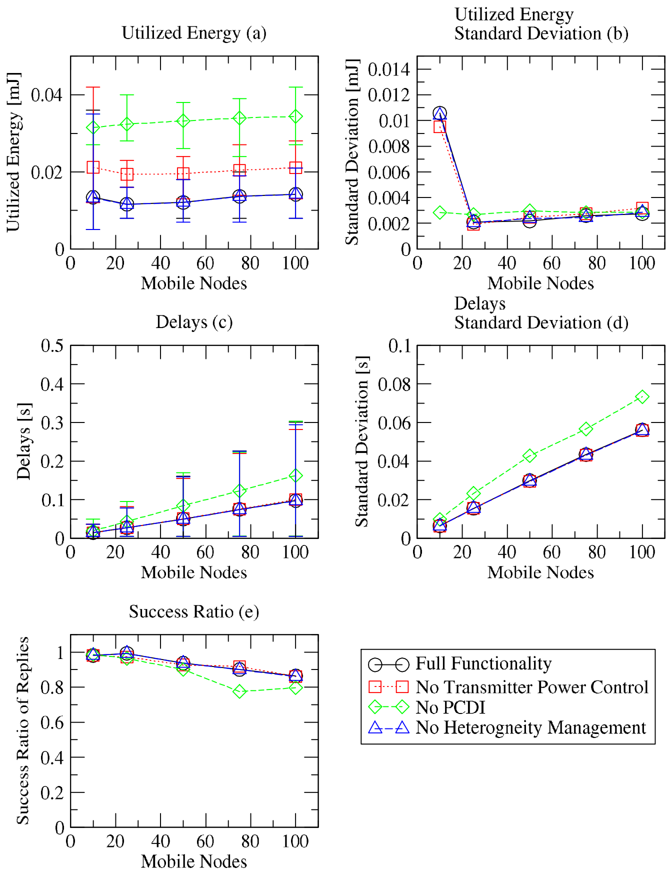

Figure 16. Evaluation of the utilized techniques – statistics for in-situ queries

The most important impact on saving and balancing energy has utilization of PCDI to optimize broadcasting of route discovery packets and in-situ queries. In the case of in-situ queries PCDI provides shorter and more stable delays as well as higher success ratio.

VII. SECURITY

This section discusses possible security threats to the target cattle monitoring system including unauthorized retrieval, modification and generation of data as well as denial of service attacks (DoS). We propose ways how the security of the system can be improved and describe how the improved security affects the energy efficiency of animal mounted devices.

Due to the nature of cattle monitoring these solutions employ wireless sensor and mobile ad-hoc networks. They are therefore open to the all types of attacks typical for wireless networks and mobile ad-hoc networks as shown in Table 1.

Farmers who are owners of the system are likely to modify or fabricate data to put their products ahead of competition. They are also likely to suppress the data collection and event detection process, i.e., perform denial of service (DOS) attacks, in order to hide information such as spread of animal diseases.

They are most likely to target data collection process as they have unrestricted and unmonitored access to their animals and sensing equipment. Methods can involve taking animals out of range, temporary or permanently, so that their sensors can not send data to farm servers, refraining from changing batteries or changing data directly on farm servers. They can also perform DOS attacks that would globally disable the functionality of the system during the spread of animal disease. This involves physical layer attacks such as radio jamming.

Protecting the system against its potential owners may be risky because they may assume that introducing the system is against their business and thus they can be reluctant to that. Therefore, we do not consider this in a greater detail within this paper. The possible approach for creating incentives of such security against the owners' tampering would be granting quality certificates to the farmers who decide to adopt it. Potentially a greater awareness of security issues from farmers, retailers and consumers would be required for this model to be realistic.

Farm workers may want to tamper with the collected data to hide from management their misconduct - e.g., leaving animals on a pasture for too long or not providing them with water. This tampering will involve changing the collected data already stored on the farm servers. This form of attack can be avoided by appropriate securing the access to the databases storing this data, which is outside the scope of this paper.

Competitors are likely to disrupt functioning of the target farming enterprise or put it into a less favorable position. They are likely to modify or fabricate the data as well as perform various DOS attacks. They will perform attacks on physical layer (e.g., radio jamming) or network layer. The latter involves deploying hostile nodes or modifying existing nodes in order to make them send incorrect route request or route reply messages in order to disrupt data delivery to sinks, answering in-situ queries or cause faster battery depletion. The hostile nodes can also send fabricated data or modify forwarded data to disrupt working of the farm. The precautions against these attacks are easier to introduce because owners of the system have strong incentives to support it. These attacks can be prevented by utilization of cryptographic primitives to encrypt and authenticate the exchanged data [44], which can increase energy consumption due to higher computational complexity and increased data traffic. Using cryptography in many cases requires public key infrastructure (PKI), which bares the infrastructureless mode that is otherwise feasible to our system. In the infrastructureless mode the sinks and farm servers are not deployed and users can only access the measurements via in-situ queries.

The deployment of hostile nodes can be detected using intrusion detection methods [45, 46]. Such nodes can be excluded from the system and reported to the personnel. Intrusion detection potentially requires no configuration during the deployment or maintenance, so its utilization would not increase management costs. There are well researched methods of detecting routing attacks within MANETs [46]. They usually rely on continuous analyzing of network traffic by mobile nodes and looking for known types of attacks. It is considerably more challenging to use intrusion detection methods against application layer attacks such as intercepting or fabricating data. Detecting such attacks would require detecting changes in the typical communication patterns, which can be caused by legitimate events that the monitoring system is meant to detect such as an occurrence of an animal disease.

Excluding hostile nodes from the system can be done in completely decentralized manner as proposed in [45]. In particular a node can only communicate with others if it possesses a token granted and periodically renewed by its neighbors. The disadvantage of this approach is that its performance may be affected by disconnections.

Another stakeholder, who may want to attack the cattle monitoring system are buyers of the animal products (e.g., supermarkets), who may want to lower the price of the products they buy or gather intelligence about the sellers to better evaluate their offer. Similarly as competitors they can perform DOS attacks, as well as modification or fabrication of data. They can also get unauthorized access to data by deploying passive nodes that would perform overhearing or active nodes that would forward the data and collect it. Passive overhearing can be only addressed by encryption of the exchanged data. Deployment of active spying nodes can be prevented by encrypting data or cooperative appraisal [45].

To summarize, there are numerous security threats against the proposed cattle monitoring system. Main feasible precautions include encryption, cryptographic authentication and intrusion detection – all of them are expensive in terms of processing and network traffic. Moreover, cryptographic methods typically require infrastructure, which increases management costs.

VIII. CONCLUSIONS AND FUTURE WORK

In this paper we proposed the novel practical MANET approach for scalable cattle monitoring system. Ease of use, cheap deployment and maintenance allow its pervasiveness. More precisely, it utilizes the available infrastructure but also works in the fully ad hoc infrastructureless conditions by supporting in-situ queries. The labor intensity of its maintenance is reduced by minimizing and balancing energy consumption in the face of low data traffic and high mobility of the nodes. The proposed routing protocol satisfies the requirements we define basing on literature and our field experiments. In particular we proposed a novel approach of minimizing and balancing energy spent on route discovery at the cost of energy efficiency of data traffic. We significantly optimize energy efficiency of control traffic by identification and utilization of animal movement patterns as well as graceful degradation of data traffic energy efficiency. We also deal with the disconnections in the energy efficient manner.

We evaluate the proposed protocol over an extensive emulation utilizing movement patterns collected during our field experiments. We demonstrate that this protocol offers lower and more balanced energy consumption than the other evaluated protocols. We show that our approach is suitable for high and low densities of topologies. Our field experiments, which produced data for the emulation of the proposed protocol, were performed in a dairy. The proposed protocol however is intended also for monitoring animals kept continuously in the pastures.

Although in this paper we concentrate on the cattle monitoring, the approach presented here can be also utilized for designing other application specific monitoring systems and MANET/DTN protocols. The proposed protocol with some customizations can be used for other applications with high mobility, limited speed of wireless nodes, low data traffic and disconnections including monitoring welfare and behavior of other animals as well as health of people [47, 48].

The results from the experiments presented in this paper are encouraging, validating the efficiency of the proposed routing protocol in terms of energy utilization, delays and success ratio. However there are still issues that have not been fully addressed. They are identified below.

The movement patterns used for simulation were based on real data and observations and thus are close to reality. We tested the correctness of the protocol implementation by analyzing the simulation traces. The potential weak point of our simulation is the validity of the utilized radio propagation model (i.e., two-ray ground reflection model from ns-2 [49]) for the dairy environment. In particular all simulation models make simplifying assumptions about radio propagation, which do not have to apply for all types of environment [50]. The typical method of validating these assumptions and simulation models in general for the given type of environment is comparing the parameters of radio propagation form the model with the measurements from the real environment [50, 51]. Such measurements have to be performed to validate our simulation.

The efficiency of the proposed MANET routing protocol can be further validated by the real world large scale deployment of the devices utilizing this protocol. This will allow considering some parameters that were not considered during emulation such as absorption of radio frequency waves by animal and human bodies [4, 5] or propagation of radio waves in relation to position of the animal and its collar. This will require design of the hardware appropriate for installing on the animals. Such hardware will have to be sufficiently robust not to be destroyed by the animals and will have to provide adequate radio connectivity.

ACKNOWLEDGEMENTS

The authors would like to thank the members of the School of Biosciences for their help and support in performing field experiments presented in Section IV.

REFERENCES

[1] B. Wietrzyk and M. Radenkovic, "Enabling Large Scale Ad hoc Animal Welfare Monitoring", in *The Fifth International Conference on Wireless and Mobile Communications (ICWMC 2009)*, Cannes/La Bocca, French Riviera, France: IEEE Computer Society, 2009, Available.

[2] P. Zhang, C. M. Sadler, S. A. Lyon, and M. Martonosi, "Hardware Design Experiences in ZebraNet", In *Proc. of SenSys*, Baltimore, Maryland, USA, 2004.

[3] K. Mayer, K. Ellis, and K. Taylor, "Cattle Health Monitoring Using Wireless Sensor Networks", In *Proc. of CCN*, Cambridge, Massachusetts, USA, 2004.

[4] Z. Butler, P. Corke, R. Peterson, and D. Rus, "Dynamic Virtual fences for Controlling Cows", In *Proc. of ISER*, Marina Mandarin Hotel, Singapore, 2004.

[5] T. Wark, et al., "Transforming Agriculture through Pervasive Wireless Sensor Networks", *Pervasive Computing, IEEE*, April-June 2007, 6 (2), pp. 50-57.

[6] P. Corke and P. Sikka, "Results from the Farm", In *Proc. of EmNets*, Harvard University, Cambridge, MA, USA, 2006.

[7] T. Wark, et al., "The design and evaluation of a mobile sensor/actuator network for autonomous animal control", In *Proc. of International Conference on Information Processing In Sensor Networks (IPSN)*, Cambridge, Massachusetts, USA, 2007, pp. 206-215.

[8] B. Wietrzyk, M. Radenkovic, and I. Kostadinov, "Practical MANETs for Pervasive Cattle Monitoring", In *Proc. of the Seventh International Conference on Networking*, Cancun, Mexico, 2008.

[9] M. Radenkovic and T. Lodge, "Engaging the public through mass-scale multimedia networks", *IEEE Multimedia*, 2006, 13 (3), pp. 12-15.

[10] K. Maatje, R. M. d. Mol, and W. Rossing, "Cow status monitoring (health and oestrus) using detection sensors", *Computers and Electronics in Agriculture*, 1997, 16 (3), pp. 245-254(10).

[11] "HeatWatch® Estrus Detection System", CowChips, LLC, Available: http://www.cowchips.net/. [June 27, 2010]

[12] A. Chaintreau, et al., "Pocket Switched Networks: Real-world mobility and its consequences for opportunistic forwarding", Computer Laboratory, University of Cambridge, Cambridge, UK, Technical Report 617, 2005.

[13] B. Wietrzyk and M. Radenkovic, "Energy Efficiency in the Mobile Ad Hoc Networking Approach to Monitoring Farm Animals", In *Proc. of the Sixth International Conference on Networking*, Sainte-Luce, Martinique, 2007.

[14] B. Wietrzyk and M. Radenkovic, "CRAWDAD data set nottingham/cattle", Available: http://www.crawdad.org/nottingham/cattle. [June 27, 2010]

[15] B. Krishnamachari, D. Estrin, and S. Wicker, "The impact of data aggregation in wireless sensor networks", In *Proc. of ICDCS*, 2002, pp. 575-578.

[16] R. Szewczyk, J. Polastre, A. Mainwaring, and D. Culler, "Lessons from a Sensor Network Expedition", In *Proc. of EWSN*, 2004.

[17] R. E. Kenward, *A Manual for Wildlife Radio Tagging*, Academic Press, 2001.

[18] T. Small and Z. J. Haas, "The shared wireless infostation model: a new ad hoc networking paradigm (or where there is a whale, there is a way)", In *Proc. of MobiHoc*, Annapolis, Maryland, USA, 2003.

[19] T. Small, Z. J. Haas, A. Purgue, and K. Fristrup, "A Sensor Network for Biological Data Acquisition", *Handbook on Sensor Networks*, 2004.

[20] Z. J. Hass and T. Small, "A New Networking Model for Biological Applications of Ad Hoc Sensor Networks".

[21] A. L. Iacono and C. Rose, "Infostations: New Perspectives on Wireless Data Network", in *Next Generation Wireless Networks*, vol. 598: Springer Netherlands, 2002, pp. 3-63.

[22] D. J. Goodman, J. Borras, N. B. Mandayam, and R. D. Yates, "INFOSTATIONS: a new system model for data and messaging services", In *Proc. of Vehicular Technology Conference*, Phoenix, AZ, USA, 1997, pp. 969-973.

[23] Z. J. Haas, J. Y. Halpern, and L. Li, "Gossip-based ad hoc routing", *IEEE/ACM Trans. Netw.*, 2006, 14 (3), pp. 479-491.

[24] M. Demmer and K. Fall, "DTLSR: delay tolerant routing for developing regions", In *Proc. of Applications, Technologies, Architectures, and Protocols for Computer Communication*, Kyoto, Japan, 2007.

[25] A. Lindgren, A. Doria, J. Lindblom, and M. Ek, "Networking in the land of northern lights: two years of experiences from DTN system deployments", In *Proc. of International Conference on Mobile Computing and Networking*, San Francisco, California, USA 2008.

[26] A. Seth, D. Kroeker, M. Zaharia, S. Guo, and S. Keshav, "Low-cost communication for rural internet kiosks using mechanical backhaul", In *Proc. of International Conference on Mobile Computing and Networking*, Los Angeles, CA, USA 2006, pp. 334 - 345.

[27] X. Zhang, J. Kurose, B. N. Levine, D. Towsley, and H. Zhang, "Study of a bus-based disruption-tolerant network: mobility modeling and impact on routing", In *Proc. of International Conference on Mobile Computing and Networking*, Montréal, Québec, Canada, 2007, pp. 195 - 206.

[28] M. Radenkovic and B. Wietrzyk, "Mobile Ad Hoc Networking Approach to Detecting and Querying Events Related to Farm Animals", In *Proc. of ICNS*, Santa Clara, California, USA, 2006, pp. 109-115.

[29] C. J. C. Phillips, *Principles of cattle production*, CABI Publishing, Oxon, UK, 2001.

[30] R. M. d. Mol, A. Keen, G. H. Kroeze, and J. M. F. H. Achten, "Description of a detection model for oestrus and diseases in dairy cattle based on time series analysis combined with a Kalman filter", *Computers and Electronics in Agriculture*, April 1999, 22 (2), pp. 171-185(15).

[31] R. Firk, E. Stamer, W. Junge, and J. Krieter, "Automation of oestrus detection in dairy cows: a review", *Livestock Production Science*, July 2002, 75 (3), pp. 219-232(14).

[32] E. J. Riedy and R. Szewczyk, "Power and Control in Networked Sensors", 2000.

[33] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks": Kluwer Academic, 1996.

[34] M. Tarique, K. E. Tepe, and M. Naserian, "Energy Saving Dynamic Source Routing for Ad HocWireless Networks", In *Proc. of WIOPT*, 2005.

[35] M. R. Gosnell, R. Albarelli, M. X. Cheng, and B. McMillin, "Energy Balanced Broadcasting Through Delayed Intelligence", In *Proc. of ITCC*, 2005, pp. 627-632.

[36] P. Bergamo, et al., "Distributed Power Control for Energy Efficient Routing in Ad Hoc Networks", *Wireless Networks*, 2004, 10 (1), pp. 1572-8196.

[37] C. E. Perkins and E. M. Royer, "Ad-hoc on-demand distance vector routing", In *Proc. of WMCSA*, 1999.

[38] M. Radenkovic and B. Wietrzyk, "Wireless mobile ad-hoc sensor networks for very large scale cattle monitoring", In *Proc. of ASWN*, Berlin, Germany, 2006, pp. 47-58.

[39] X. Hong, M. Gerla, G. Pei, and C.-C. Chiang, "A group mobility model for ad hoc wireless networks", In *Proc. of 2nd ACM International Workshop on Modeling Analysis and Simulation of Wireless and Mobile Systems*, Seattle, Washington, United States, 1999, pp. 53-60.

[40] C. J. C. Phillips, *Cattle behaviour*, Farming Press, Ipswich, UK, 1993.

[41] L. Breslau, et al., "Advances in network simulation", *IEEE Computer*, 2000, 33 (5), pp. 59-67.

[42] F. J. Ros and P. M. Ruiz, "Implementing a New Manet Unicast Routing Protocol in NS2", Dept. of Information and Communications Engineering University of Murcia, 2004.

[43] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks", In *Proc. of MOBICOM*, Boston, MA, USA, 2000, pp. 56-67.

[44] M. G. Zapata and N. Asokan, "Securing Ad hoc Routing Protocols", In *Proc. of WiSe*, Atlanta, Giorgia, USA, 2002.

[45] H. Yang, J. Shu, X. Meng, and S. Lu, "SCAN: self-organized network-layer security in mobile ad hoc networks", *IEEE Jurnal on Selected Areas in Communications*, 2006, 24 (2), pp. 261-273.

[46] Y.-a. Huang and W. Lee, "A cooperative intrusion detection system for ad hoc networks", In *Proc. of 1st ACM workshop on Security of ad hoc and sensor networks*, Fairfax, Virginia, 2003, pp. 135-147.

[47] I. Mohomed, A. Misra, M. Ebling, and W. Jerome, "HARMONI: Context-aware Filtering of Sensor Data for Continuous Remote Health Monitoring", in *Sixth Annual IEEE International Conference on Pervasive Computing and Communications*, Hong Kong: IEEE, 2008, pp. 248-251, Available.

[48] W. D. Jones, "Taking Body Temperature, Inside Out", *IEEE Spectrum*, 2006, 1, pp. 11-13.

[49] K. Fall and K. Varadhan, *The ns Manual*, 2008.

[50] D. Kotz, et al., "Experimental Evaluation of Wireless Simulation Assumptions", In *Proc. of MSWiM*, Venezia, Italy, 2004.

[51] J. Liu, et al., "Simulation Validation Using Direct Execution ofWireless Ad-Hoc Routing Protocols", In *Proc. of 18th Workshop o Parallel and Distributed Simulation (PADS'04)*, 2004.

TABLE I. POTENTIAL ATTACKERS

Location\Attacker	**Owners**	**Competitors, buyers**
Individual animal being monitored, monitoring hardware	Tampering with monitoring hardware, removing or disabling sensors to change sensed data	
Radio waves communication (physical layers)	Signal jamming, moving devices or animals out of network coverage.	Signal jamming, modification and fabrication of data by deploying malicious devices or modifying existing devices
Link Layer		Illegitimate access and fabricating or modifying data
Network Layer		Illegitimate access and fabricating or modifying data, routing attacks