Energy Efficiency in the Mobile Ad Hoc Networking Approach to Monitoring Farm Animals

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Abstract—**Using Mobile Ad Hoc Networks (MANETs) for monitoring bovine animals potentially offers high increase in the profitability of cattle production. In this paper we propose a formal model for the cattle monitoring system. Then we formulate the requirements for the MANET routing protocol for such systems. We identify a suitable MANET routing protocol that satisfies these requirements and adapt it to our scenario. We propose optimizations to this protocol that utilize heterogeneity of the power constrains of the wireless nodes. More precisely we make a trade-off between the power utilized by animal mounted devices and fixed sinks where they upload the collected and processed data. We also save energy on flooding based route discovery for the cost of graceful degradation of data delivery time by utilizing passive detection of temporary availability of sink routes. Finally we show in the simulation that the proposed approach is feasible and the proposed optimizations considerably decrease the energy consumption and increase scalability in terms of density and number of wireless nodes. This is important considering size and range of stocking densities of modern farming enterprises.**

Keywords-animal monitoring; MANET; routing protocol; energy efficiency; WSN

I. INTRODUCTION

The recent progress in the energy efficient wireless network interfaces, powerful, energy efficient microcontrollers and high capacity batteries provides new applications of Mobile Ad Hoc Networking approaches (MANETs). One of such applications is monitoring domestic animals, in particular diary and beef cattle [1, 2].

In countries such as UK, where the production of beef and milk has always been a major constituent of agriculture, this application offers considerable economical incentives. The total number of cattle in England in 2003 was estimated to be over 5,709,000. The beef and veal consumption in 2002 was on average 19.7kg per capita in UK and 19.6kg in EU [3]. The production of beef in UK is going to increase considerably as the ban on exporting British beef to other European Union countries, established to fight bovine spongiform encephalography (BSE), has been released [4].

There has always been a need for livestock producers to be able to 'observe' their animals as often as possible. Inattention to the wellbeing of the animals, whether it be a health or welfare issue can lead to reduced productivity and death of valuable stock [5]. The supervision of reproductive processes such as pregnancy and oestrus is essential for breeding the animals in particular when the modern farming technologies such as artificial insemination are applied [6]. It is often the case that the farmer has neither time nor resources to 'see' the animals regularly and even when she does, she may not be in a position to identify reproductive state of the individuals or some of their more deep-rooted health problems. The ability to be informed of changes of the animals' health, reproductive status and welfare can reduce the current reliance on manpower and improve the decision making process. High ratio of detecting oestrus can increase the conception rate of the cattle and allow wider application of artificial insemination, which improves the genetic quality of the calves [7]. Detecting oestrus, when reliable, can become an efficient method of detecting pregnancy, much cheaper than currently used rectal palpation, which must be performed by a veterinary [7]. These factors can considerably increase profitability of cattle farming [7, 8] and improve quality of farmer's life [8]. The simple automatic systems for detecting oestrus are already commercialized and have proven their importance for increasing profitability of farming [8].

The most challenging type of cattle production to monitor are suckler herds. Contrary to the dairy herds, suckler herds are far less handled by humans [9], which justifies use of modern wireless and wired networking. Because of their reproductive character suckler herds require much more attention in terms of monitoring and handling than other areas of beef production such as performed by finishers or store producers [6, 9].

Oestrus detection and health monitoring can be done by monitoring milk or behavior parameters [10, 11]. The major limitation of the former is suitability for dairy cows currently yielding milk (i.e. *wet*). The latter comprises monitoring walking and food intake intensity and, in case of oestrus, acceptance of mounting from males and females, i.e. 'standing-to-be-mounted' [10, 11]. Current systems monitoring animals' behavior typically have limited scope by monitoring only one parameter or relying on the animal's proximity to the milking robots, which allows monitoring only wet dairy cows. The utilized wireless technology is typically single hop communication sometimes utilizing repeaters [8].

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When MANETs are utilized for monitoring cattle, the major challenge is to minimize energy consumption of the wireless devices. It is very important as the animal mounted devices are battery powered and replacing their batteries is very work intensive. Using renewable energy sources is difficult. Solar batteries are not efficient when animals are kept indoors, may require manual cleaning and require rechargeable batteries with limited lifetime [12]. Swinging weights can compromise animals' welfare [13] and piezoelectric power sources are difficult to mount on animals [13].

In case of wireless sensor nodes most of the energy is typically consumed by wireless communication [14], in particular data transmission and reception [15]. Therefore, the most promising approaches to energy saving in mobile wireless sensor networks are energy efficient routing protocols. MANET routing protocols can generally be classified as either proactive (periodic) or reactive (on-demand). Proactive protocols (e.g. [16, 17]) try to maintain routes to all possible destinations at all times, whereas reactive protocols (e.g. [18, 19]) attempt to discover or maintain routes only when needed to destinations for current communication. The mobility of the animals carrying devices is high in relation to the predicted frequency of data exchanges [20] so using a proactive routing protocol is too expensive. In particular it would either use too much energy for significant control traffic necessary for updating topology data or be inaccurate due to outdated topology data. Because of this we aim to utilize an energy efficient on-demand MANET routing protocol.

The contributions of this paper are following: (1) we propose a formal model for a cattle monitoring system, (2) we identify the requirements for the MANET protocol for cattle monitoring, (3) we adapt a MANET routing protocol that is aware of transmission power and remaining battery capacity of the nodes to our scenario.

This paper is informed by our previous work concerning cattle monitoring [1, 2]. It has the following structure. Section II defines a formal model of a cattle monitoring system. Section III defines requirements of a MANET routing protocol for cattle monitoring. Section IV describes the selected MANET routing protocol and its proposed adaptations to our scenario. Section V presents the simulation based evaluation of the adapted MANET protocol. Section VI relates our work to the existing research. Finally, Section VII gives conclusions.

II. FORMAL MODEL

This section defines a formal model of a beef cattle monitoring system. We concentrate on monitoring walking and feed intake intensity of cattle in order to detect oestrus, pregnancy, animal diseases such as mastitis or lameness and efficiency of paddocks/pastures.

The scope of the envisaged system is a farming enterprise, which can possess several pastures and farm buildings where animals are kept. The average number of cattle held by a British enterprise in 1998 was 72 [21]. The cattle can be kept all the year on the pastures or all the year in the farm buildings but the most common practice is to keep them on the pastures in the warmer half of the year and indoors in the other [21]. Depending on the conditions stocking density of the pastures can range from 2 to 7 animals per ha [21].

Walking intensity can be measured using a pedometer mounted on the animal's leg [5, 10, 11, 22-25] and feed intake by a pedometer or accelerometer mounted on the animal's neck [5]. In both cases the impulses should be counted for two hours [10] and then processed every two or at most four hours. This way, stockmen receive the update of the status of animals at least twice during their 8 hours shifts. Both the raw and processed data should be safely retained as long as the animal stays on the farmer's hold. The access to the collected data will be provided by queries and notifications. Users should be able to query the real time and historical data, raw and processed. Querying should be possible from the farm terminals, remotely over Internet, from mobile phones, home and office PCs. Notifications should be issued to the users' mobile phones and displayed on the message boards mounted in the farm buildings. A user (i.e. a farmer, a stockman or a veterinary) should be able to query all the currently ill animals or animals which are or soon going to be ready for insemination. It should be possible for a user to retrieve data about a certain animal such as current and past diseases, oestrus, pregnancy, average frequency of oestrus and predicted next oestrus. A more advanced user such as veterinary or skilled stockman could be able to see graph of a particular factor of a particular animal together with its deviation from the average.

The system's input data can be divided into time dependant and time independent data about the animals. The time dependant data about an animal can be presented as a following vector:

$$I_{ID,t} = (w, f) \tag{1}$$

Where *ID* is an ear tag id of an animal to which the measurements refer, *t* is a timestamp of the measurements, *w* is walking intensity (i.e. number of steps made by an animal from *t*-2h to *t*), *f* is feed intake intensity (i.e. the number of times an animal rose its head from *t*-2h to *t*). The time independent data about the animal can be presented as a following vector:

$$I_{ID} = (s, N) \tag{2}$$

Where *ID* is an ear tag id of an animal to which the measurements refer, *s* is the sex of an animal (as it is not relevant to detect oestrus for bulls or steers) and *N* is a set of custom names given to an animal.

The output data of the system comprises the time dependant data about an animal and a pasture/paddock. The output data about an animal can be presented as a following vector:

$$A_{ID,t} = (d_1, d_2, f_1, \ldots, f_n) \tag{3}$$

Where *ID* is an ear tag id of an animal to which the measurements refer, *t* is a timestamp, d_1, d_2 are dates of previous and next oestrus and $f_1, \ldots, f_n$ are flags indicating

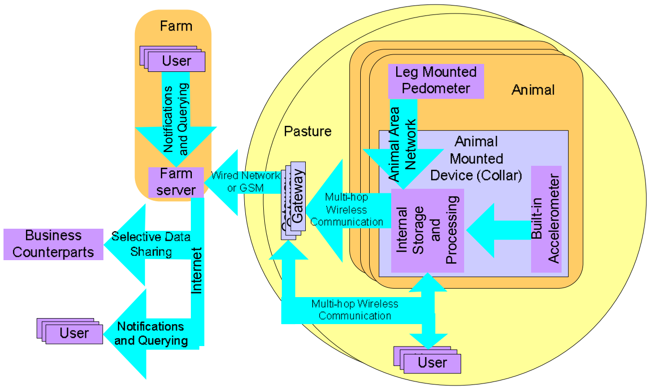

Figure 1. Architecture of the proposed system

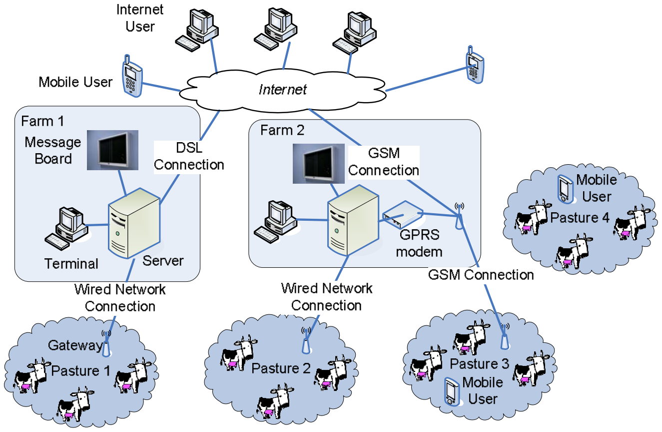

Figure 2. Example deployment

detection of pregnancy, mastitis, lameness etc. The output data about a pasture/paddock can be presented as a following vector:

$$P_{ID,t} = (e, A) \tag{4}$$

Where *ID* is an id of a pasture/paddock, *t* is a timestamp, *e* is an integer percentage of the pasture/paddock efficiency (0% meaning no feed or water – animals do not graze), *A* is a set of animal ids placed on the pasture/paddock.

A user should be able to query data about a particular animal or paddock. The most important and potentially the most often queried are the most recent results of processing ($A_{ID,t}$ and $P_{ID,t}$). A more advanced user (veterinary or a skilled stockman) can query historical input data concerning a particular animal (intensity of walking and feed intake). In certain circumstances, historical results of processing concerning a particular pasture can be utilized. They may help in assessing value of a farmland to plan purchases and sale of the properties. A user should be able to refer to an animal using its ear tag or a custom name.

The users should be able also to make 'regular queries'. The input of such query would be a logical condition referring to the most recent output data concerning animals or paddocks. The output would be a set of ids or custom nicknames referring to paddocks or animals. The example queries would be: 'Which animals are ill?', 'Which cows will have oestrus tomorrow?' or 'Which paddocks occupied currently by animals have efficiency below 10%?'.

III. REQUIREMENTS

This section defines the requirements for the wireless communication in a cattle monitoring system. The architecture for the envisaged system, described in greater detail in [2], is shown in Figure 1. An animal mounted device has a form of a collar with the built in accelerometer measuring the intensity of feed intake. The walking intensity is measured by the pedometer mounted on the animal's leg. The measurements from the pedometer are acquired by the collar over the wireless communication. The measurements from the pedometer and accelerometer are stored and processed by the collar. Both collar and the leg mounted pedometer are battery powered.

These devices have wireless network interfaces and transmit input (e.g. walking intensity, feed intake) and output (detected diseases, dates of last, next oestrus) data to the farm servers via the gateways every two hours. The typical amount of data is 32 B. The farm servers store the real time and historic data, detect the user defined events and issue notifications about these events. The users can query the data stored on servers including input and output data either locally on the farm or remotely over Internet using a PC at home or office or a WAP enabled mobile phone. The selective access to the data stored on the farm servers can be provided to business counterparts to give them the opportunity to evaluate the animals before the purchase.

The example deployment of the system is shown in Figure 2. The data is regularly transferred from the animal mounted nodes to the gateways over the wireless communication. Where possible the gateways can be connected to farm servers over a wired network connection as in Pasture 1 and 2. If a pasture is located far from farm buildings it is possible to use GSM telephony to connect pastures to farm servers as in Pasture 3. In that case, a gateway can be stationary or animal mounted. A user will be able to query the farm server using the gateway.

Users located on a pasture, dairy or in its close proximity may want to query output 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 gateways over the wireless communication. The multi hop path between a user and a gateway node may be temporarily unavailable so the sensor nodes should be able to answer the query on their own.

The tasks of wireless nodes comprise: (1) collecting, processing and storing animal related data (2) delivering input and output data for retention via gateway nodes (sinks) and (3) answering users' queries. The most important requirement for delivering the input and output data for retention is the reliability, i.e. the percentage of successfully archived data. The secondary requirement is the timeliness of the delivery necessary for availability of the data for querying by users accessing the system over Internet and issuing up to date notifications about events. We assume that at least 90% of the generated input and output data should be delivered within 4 hours. Users' queries are issued much less frequently and regularly than delivering data to sinks. The most important requirement for that task is providing a minimal percentage of successfully answered queries (e.g. 90%) with timeliness necessary for interactive work (e.g. 10 s). It is necessary to extend the uptime of nodes while preserving minimal required performance of the communicational tasks. By uptime of the nodes we mean their ability of taking the measurements and preferably also delivering data for retention and answering user's queries. This time can be limited by exhausted battery capacity so it is necessary to save energy utilized for wireless communication because changing batteries is very work demanding for stockmen.

IV. PROTOCOL

In this section we identify a suitable MANET routing protocol, briefly describe it and propose adaptations of the selected MANET routing protocol to our scenario. MANET routing protocols can generally be classified as either proactive (periodic) or reactive (on-demand). Proactive protocols (e.g. [16, 17]) try to maintain routes to all possible destinations at all times, whereas reactive protocols (e.g. [18, 19]) attempt to discover or maintain routes only when needed to destinations for current communication. The mobility of the animals carrying devices is high in relation to the predicted frequency of data exchanges [20] so using a proactive routing protocol is too expensive. In particular it would either use too much energy for significant control traffic necessary for updating topology data or be inaccurate due to outdated topology data. Because of this we aim to utilize an on-demand MANET routing protocol.

We need a routing protocol that controls power of transmitters and selects paths according to the power required for routing of the data and the remaining battery capacity of the forwarding nodes. There are many protocols that satisfy these requirements [26-29]. Some of them consider remaining capacity of the nodes only when it drops below a certain threshold [26] - in order to improve fairness of the battery capacity utilization for all the nodes throughout their whole battery life we avoid these protocols. There are several protocols that are suitable for this scenario but as an example we chose ESDSR [28] so we briefly describe it.

A. *ESDSR*

The energy efficiency in ESDSR is obtained in the following way. Senders record transmission power in packets they send. Receivers can then tell senders the minimum power level required for communication. Therefore, senders can adaptively adjust transmission power levels to suit the current need, rather than using a fixed level. More precisely, nodes upon receiving of the packets can calculate minimal energy necessary to reach their single hop neighbors (these associations are stored in power table) using the following formula:

$$P_{min} = P_{tx} - P_{recv} + P_{threshold} + P_{margin} \qquad (5)$$

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.

ESDSR has two components, route discovery and route maintenance. Route discovery is initiated when the route cache at the source node does not have any entry for the destination node. The source broadcasts a route request message. A node that receives the request can do one of two things; forward the request after appending its own id if it's not the destination, or reply using its cached routes. The destination would reply and reply messages propagate back to the source. A node ignores a request if it has already processed it.

ESDSR uses the route with maximum remaining lifetime. Remaining lifetime of a node in a route is defined as remaining node energy divided by power required to transmit packet to the next node in the route. Remaining lifetime of a route is then minimum of remaining life of nodes in the route. Following the notation used in [28],

$$\begin{aligned} C(R,t) &= \max_j R_j(t) \\ R_j(t) &= \min_i E_i(t) / P_{ij}(t) \end{aligned} \qquad (6)$$

where t is time, $E_i(t)$ is the remaining energy of node i assumed to be known from hardware and $P_{ij}(t)$ is the transmit power of node i in route j as stored in the received packet.

Route maintenance is achieved by using MAC layer acknowledgements to confirm retrieval of a packet. Information about a broken link is propagated back along the route. Nodes invalidate all routes containing the broken link. The source then tries to find the next route in the cache. If there is none, it initiates route discovery.

B. *Adaptations of ESDSR to Animal Monitoring*

We utilize ESDSR both for sending data from the animal mounted sensor devices to stationary sinks (gateways) and querying of the animal mounted devices by mobile users. Both these objectives should be achieved regardless of whether the devices are located in farm buildings or pasture.

In case of sending data to sinks at the end of the period of time over which the data is collected (in our scenario 4 hours) the devices send data to a sink using a route from the cache or a discovered one. The route to any of the deployed sinks is selected according to the cost metric from ESDSR. If the animal mounted node does not receive an acknowledgement within the selected timeout data is resent. Nodes that forward or overhear the data sent to sinks cache it according to their available storage space for the possible queries of the mobile users. Together with the cached data nodes store the timestamp of when the data was cached.

A mobile user collocated with the animals can issue regular queries and directed queries. Let us consider regular queries first. The answer to them is a group of ids (or custom nicknames) of animals that fulfill a given logical condition (e.g. all animals which are sick). The user broadcasts the query and 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. Nodes that forward the queries assemble and filter these answers according to their timestamps in order to reduce redundant traffic. The final assembling 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 query a user's device sends a broadcast to retrieve the route and 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 path selected according to ESDSR's cost metric. Finally the queried device sends the answer back along the same path.

We propose the following optimization to ESDSR that improves its energy usage in the proposed scenario. We utilize the fact that the sinks are much less energy constrained than the animal mounted devices. Animal mounted nodes calculating the minimal lifetime of a route can assume that the lifetime of the sink is infinite. This way it is possible to calculate single hop routes to the sinks from any packet received directly from the sink. The minimal lifetime (i.e. cost) of the route can be calculated using the formula

$$C(R,t) = E(t) / P_{\min}(t) \tag{7}$$

where t is time, $E(t)$ is the remaining energy of the node which received a packet from a sink and uses it to calculate the minimal lifetime of the route and $P_{min}(t)$ is the transmit power from that node to the sink.

Finally, when after data collection lasting time t (in our scenario 4 hours) a node wants to send data to a sink and it does not have any up to date path to a sink in its cache instead of immediately performing route discovery it waits for receiving a beacon from a sink or forwarding/overhearing an acknowledgment sent by a sink. A valid and recent route is obtained from this beacon or acknowledgement. Such route does not have to be as optimal as a route obtained from route discovery but spending energy on expensive flooding is avoided. If a node does not receive any beacon or acknowledgment for the time t, it sends a regular route discovery message. This way we save power on flooding necessary for route discovery for the cost of graceful degradation of data delivery to sinks. If the path from a wireless node to a sink is not constantly available because of disconnections (i.e. splitting of the topology into isolated islands of connectivity) we passively detect its temporal availability.

V. EVALUATION

A. Simulation Methodology

This section describes the methodology and results of the simulation based evaluation of the selected MANET routing protocol and our optimizations. We use the ns-2 [30] network simulator with enabled tap function, which means that the nodes process overheard packets. The medium access control (MAC) protocol is based on IEEE 802.11. Animals with wireless nodes move with the speed of 0.6 m/s (preferred walking speed of cattle [20]) according to the Random Waypoint Model [18] making stops from zero to one minute. The simulation lasts for 12 simulated hours. Animal mounted devices send 32 B of data every 4 hours. This 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. The maximal power of the transmitter is 0.85872 mW (i.e. power consumed by the transmitter and power of the transmitted signal), which gives 40 m of the maximal range of transmitters. This way we achieve parameters closer to those found in sensor radios [31]. Since the receiving power is constant and a fixed amount of energy is dissipated when a node receives the packet, we set receiving power to zero. Authors of ESDSR made a similar assumption [28]. At the beginning of simulation sinks have 1 J and animals mounted nodes have 1000 J.

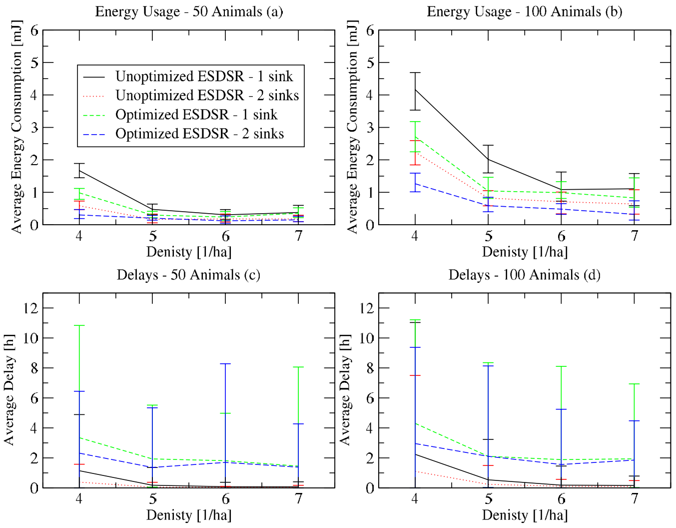

Figure 3. Simulation results

We compare ESDSR [28] with and without the optimizations proposed in Section IV.B concerning the assumptions about infinite energy of the sinks, utilization of sink beacons and saving data on route discovery. We simulate different stocking densities from the realistic range 4 to 7 animals/ha [21] for 50 and 100 animals. We use one and two sinks. Sinks are placed in the middle of the opposite sides of the simulation area. We observe minimal, average and maximal energy usage over the course of the simulation and delays. A delay here is a period of time starting when the data is ready for sending to a sink and ending when the wireless node receives an acknowledgement from the sink.

B. Simulation Resuls

Figure 3 shows the simulation results. Lines show the average values and error bars indicate the maximal and minimal values. Figure 3a and 3b show how the energy consumption depends on the number of animals and stocking density. We can see that the energy consumption grows with increasing number of animals and decreasing stocking density. The former is caused by the amounts of forwarded data and control traffic. The latter is caused by disconnections, i.e. splitting of the topology into isolated islands of connectivity. This renders some of the route discoveries and data delivery attempts unsuccessful and requires their repetition, which costs additional energy. The energy consumption can be lowered by deployment of a second sink. The proposed optimizations reduce energy consumption for all stocking densities and numbers of sinks. In particular they are most profitable for the most challenging conditions, i.e. lower stocking densities (4 and 5 animals/ha). They allow to save up to 48% of the utilized energy (100 animals, stocking density 5 animals/ha). This energy saving can be attributed to limiting broadcasts for route discovery and utilizing temporal proximity of the nodes. This means delaying data delivery until detecting availability of the path to a sink by receiving a beacon packet or overhearing/forwarding an acknowledgement from the sink.

Figure 3c and 3d show how the delays depend on the stocking density and number of animals. We can see that delays grow slightly with the increasing number of animals and considerably with decreasing socking density. The former is caused by increase in the overall traffic and the latter by the disconnections that delay data delivery until the favorable rearrangement of the topology. The energy saving achieved by our optimizations come for the cost of longer delays. The delays can be extended even by 2 hours in comparison to the original ESDSR [28].

To summarize, the proposed optimizations to ESDSR [28] considerably decrease the energy usage of the wireless nodes for the cost of higher energy usage of sinks and longer time necessary to deliver data to sinks. This fits the requirements we defined in Section III as the sinks are much less energy constrained than the animal mounted nodes and the delays of up to 4 hours are acceptable for data delivery to sinks. The increased scalability in terms of density and number of wireless nodes achieved by our optimizations is very important as the average number of cattle held by some types of British enterprises (calf-based semi intensive finishers) in 2003 [3] was as high as 147 animals. Stocking density of the pastures can range from 2 to 7 animals/ha [21].

VI. RELATED WORK

There is a considerable body of work that concerns *energy aware multi hop routing*. Initial approaches aimed at utilizing paths with the minimal energy cost [32]. Others aimed at extending lifetime of the overall system by utilizing paths that avoid, if possible, nodes with low remaining battery capacity [33]. The hybrid approaches utilized paths with minimal energy cost, which comprise only nodes with the battery level higher than a given threshold [29]. A more recent proposal [34] assumes that the amount of data to be routed is known before selecting a path. Therefore, it is possible to select a path with the lowest energy cost that utilizes only nodes with remaining battery capacity sufficient to route the required amount of data. Finally, it is also possible [35] to select the routes according to the energy cost of hops, remaining battery capacity and sending rate. In general research in this area utilizes high density of topology in order to select paths optimal for lifetime of single nodes or the overall system. None of these approaches targets at limiting control traffic necessary for route discoveries.

There have been several proposals that concern minimizing energy consumption by controlling transmitter power. In particular Kubisch et al. [36] propose several algorithms, which adjust the power and range of transceivers to achieve either the number of neighbors from a given range or a fully connected network. In many other proposals [37-40] of protocols for WSNs minimizing energy consumption is discussed only in terms of minimizing network overhead. The referenced paper considers only stationary sensor networks. In energy efficient MANET protocols [27, 28] nodes calculate the minimal power necessary to reach their neighbors from the receiving and transmitting power of the packets they receive.

Mobile wireless sensor networks for animal monitoring deployed today have typically small scale (up to tens of nodes) e.g. ZebraNet project [13] for monitoring zebras at the Mpala Research Centre in Kenya. In ZebraNet, devices mounted on zebras were transferring all their measurements to all other devices in their range. This approach was not scalable due to limited storage space of the devices and was feasible only because of the small number of monitored animals. The retrieval of the aggregated measurements from animals required approaching them by humans, which increase the maintenance costs. Another approach to retrieving data from the animal mounted sensors utilizes GSM telephony [5]. Such collars are already available on the market [41]. In case of monitoring of large number of animals this approach can be financially challenging due to the cost of GSM communication, i.e. the maintenance costs. Another disadvantage is that GSM transceivers consume large amounts of energy. That can potentially lead to a considerable effort necessary to replace the batteries every few days. These limitations were addressed [5] by installing GSM, in particular GPRS, transceivers only on a subset of animals. The devices without GPRS transceivers transfer their measurements via the GPRS-enabled devices.

There has been research done in *controlling animals* [42], which involved mounting devices on animals. These devices were producing sounds whenever an animal tried to leave a virtual paddock. The referenced paper concentrates on the automatic control aspect of the proposed application rather than on the utilized wireless communication.

VII. CONCLUSIONS

In this paper we proposed a formal model for the cattle monitoring system, then we formulated the requirements for the MANET routing protocol for such systems. We identified a MANET routing protocol that satisfies these requirements and adapted it to our scenario. We optimized this protocol for our scenario by utilizing heterogeneity of the power constrains of the nodes. We also proposed saving energy on flooding based route discovery for the cost of graceful degradation of data delivery time by utilizing passive detection of temporary availability of sink routes. Finally we showed in the simulation that the proposed optimizations considerably decrease the energy consumption and increase scalability in terms of density and number of wireless nodes.

It is possible to use a simpler approach in the described scenario, e.g. a single hop communication, where the transmission is triggered either by sink beacons or user devices. The important challenge here is providing coverage sufficient to satisfy requirements defined in Section III. This can be addressed by using for each wireless node transmitter power sufficient to cover all the area where the animals are kept or opportunistically utilize temporary proximity of the wireless nodes. In the first case the flexibility of the system is limited as the animals can be moved to a different place (e.g. a bigger pasture) and the transmitters' range can be limited by obstacles such as trees, animals, farm equipment etc. In the second case the simpler approach is potentially less efficient than the proposed approach in providing connectivity between a user's device and animal mounted devices due to the limited coverage. For the same reason the simpler approach is potentially less capable of dealing with unusual behavior of the animals such as staying far from the sink for a prolonged period of time. Such behavior can result from an injury or a disease.

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