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# Practical MANETs for Pervasive Cattle Monitoring

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## Abstract

*The application of Mobile Ad Hoc Networks to cattle monitoring has the potential to increase the profitability of cattle production and positively impact the everyday live of farm personnel. The main research challenges are identifying and refining realistic requirements for a MANET routing protocol and designing such protocol. In this paper we report on the field experiments we performed in order to address this. Our approach builds on energy efficient MANETs to provide continuous monitoring of multidimensional parameters of animal mobility including temporal and spatial walking intensity and feed intake in order to detect oestrus, pregnancy, animal diseases and reduced efficiency of pastures. We support remote and in-situ, specific and range queries and notifications about newly detected events. Our extensive set of emulations show that we achieve lower and more balanced energy consumption while preserving the delays for increasing number of nodes within the user expected boundaries.*

## 1. Introduction

Mobile Ad Hoc Networks (MANETs) have a big potential for practical applications of considerable impact on our everyday life and economy. One such application is monitoring domestic animals, in particular dairy and beef cattle [1-4]. There is a number of existing MANET approaches, theoretical [5-13] and applied to animal monitoring [14, 15], but none that is directly suitable for this application because they are not driven by and optimized for its realistic requirements [16].

Remote and ad hoc cattle monitoring can considerably increase the profitability of cattle production and positively impact everyday live of farm personnel. The agricultural literature [3, 17, 18] and our field experiments show that there are strong demands for detecting oestrus, animal diseases and monitoring pastures' efficiency. These demands can be satisfied by continuous monitoring of multiple parameters of animal mobility and behavior [17, 18], and storing rich historical data.

Current systems for monitoring cattle behavior typically have limited scope because they mainly monitor a single parameter (e.g. [19]) or monitor only wet dairy cows due to relying on the animals' proximity to the milking robots. Wireless Sensor Networks (WSN) approaches for monitoring cattle behavior and metabolism currently use GSM telephony for most of their wireless communication [3] which is expensive or have only single hop communication [19]. Multi-hop communication is much more appropriate for this application. When animals are kept in pastures multi-hop communication allows animal mounted devices with shorter transmission range and fewer sinks (devices forwarding data from the animal mounted nodes to the farm servers) offering lower vulnerability to disconnections, i.e. splitting of the topology into separated islands of connectivity. Animal mounted devices with shorter transmission range are either smaller or characterized by longer battery life, which decreases labor intensity of their maintenance and thus makes the monitoring financially more feasible. When animals are kept in a barn multi-hop communication allows circumventing the obstacles in radio waves propagation and combat the effect of animal bodies absorbing the radio waves [20, 21]. WSN multi-hop ad hoc protocols [22-24] typically address mostly static nodes. In this paper we consider MANET routing protocols that are more suitable for this application.

An important requirement that influences profitability of deployment of the cattle monitoring

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systems is keeping the costs low and management overheads minimal (making the system more pervasive). Therefore, the practical MANET routing protocol should utilize existing infrastructure but also work in fully ad hoc infrastructureless conditions. In order to minimize the labor intensity it should minimize and balance energy consumption. It should also efficiently deal with disconnections that can happen when e.g. the herd splits into spatially separated groups.

The contributions of the paper are four fold: (1) we identify realistic requirements for a wireless routing protocol based on the performed field experiments, (2) we significantly optimize energy efficiency of control traffic by graceful degradation of data traffic energy efficiency and utilization of heterogeneity of nodes' mobility, (3) we extend the PCDI concept to utilize knowledge about heterogeneity of the nodes' mobility, (4) we describe extensive set of emulations to provide rigorous evaluation of the proposed protocol in terms of energy consumption and delays.

This paper is organized as follows. Section 2 presents a brief description of the target application. Section 3 reports on the setup and results of our field experiments. Section 4 briefly presents the related work. Section 5 proposes the novel practical protocol that provides data off-load and in-situ queries in the energy efficient manner. Section 6 reports on our evaluation of the proposed protocol. Finally, Section 7 gives conclusions.

## 2. Overview of the target cattle monitoring system

This section briefly describes the target cattle monitoring system, more fully described in [2, 4]. 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 [25]. 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.

An 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.

The typical amount of data for each update sent from animal mounted devices to sinks is 32B. 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. The detection of reduced efficiency of pastures is performed only by farm servers by aggregation of data from multiple animal mounted devices.

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.

## 3. Field experiments

In this section we describe field experiments we performed at the University of Nottingham's Dairy Centre. The purpose of these field experiments was collection of realistic parameters necessary to develop and evaluate an adequate wireless protocol. They included cattle movement and behavior monitoring as well as distributing a questionnaire to the farm personnel and researchers working on the farm.

In the first field experiment we monitored two of the cows located in one of the divisions of a modern dairy intended for about 100 animals. Cows can move freely in the area with the feeder, water tank, resting bays and milking robots available 24 hours a day. We installed on the monitored cows two collars 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

Figure 1. Cow wearing the collar

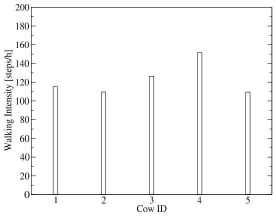

Figure 2. Walking intensity (pedometers, 2nd experiment, 4:00-22:19, 13th August '06)

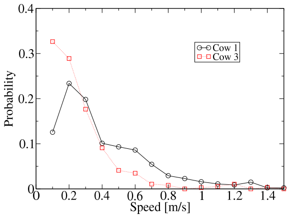

Figure 3. Probability distribution of animal speed (GPS, 2nd experiment)

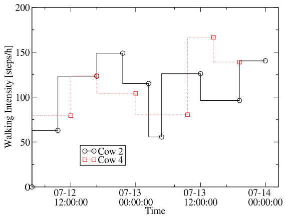

Figure 4. Activity over the day (pedometers, 2nd experiment on 13th August'06)

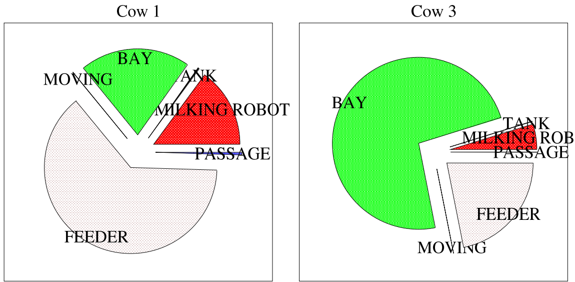

Figure 5. Activity diagrams (GPS, 2nd experiment)

the GPS receivers including positions and timestamps. All the cows in the dairy were wearing pedometers. Their measurements were automatically collected by milking robots whenever a cow was milked. The data collection started at 11:10. Both GPS receivers worked until around 14:05. Some of the collected measurements suggested that cows moved with speeds impossible for them, which suggested GPS errors. Concurrently we were filming the part of the dairy where the monitored cows were kept. We placed the camera on the ramp above this area. This location offered the most complete view but some parts of the area were obscured. GPS receivers and filming were utilized only for the purpose of our field experiments. Their utilization is not intended for the target monitoring system.

We repeated the previous experiment with five collars mounted on animals (see Fig. 1) and two cameras located at two different ramps to get a more complete view of the area where the monitored cows were kept. We had GPS receivers with better batteries than before and we were logging data about the precision of logged locations. Monitoring started at 11:10. GPS receivers worked until 18:24, 12:23 (probably jammed), 18:51, 15:09, 15:33. We received the plan of the dairy and then captured the coordinates of the characteristic locations on the plan using a handheld GPS receiver.

From the performed questionnaire we learnt that the users have to be informed about oestrus and animal diseases as soon as possible. The pregnancy should be reported within 48 hours and reduced efficiency of pastures – within 24 hours. This means that the 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 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.

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. In the Fig. 2 based on the pedometer data we can see that walking intensity of the monitored cows was sufficiently different to detect oestrus and animal diseases but too similar to influence routing. In the Fig. 3 based on the GPS data we can see that at the same time the preferred momentary walking speed significantly differs between cows, which can be utilized in the wireless protocol. The same figure shows that they rarely move faster than 0.8 m/s.

The pedometer data presented in Fig. 4 demonstrates that cows are active all the day and night including walking and milking. Their walking activity tends to be less intensive in two periods: 0-6 and 15-18. These periods can be utilized for scheduled data exchanges. Video footage and analysis of the GPS data (see Fig. 5) show no other predictable behavior patterns useful for design of the wireless protocol.

## 4. Related work

The existing Wireless Sensor Networks (WSN) for animal monitoring are either stationary (e.g. [26]), too expensive [3, 27], target small scale deployments (e.g. [14]), do not consider energy efficiency [3, 20, 21, 28, 29] or consider very different types of animals and environments [30, 31].

The existing *DTN approaches* have limited applicability to our scenario. The utilization of brute force [14] or random forwarding [32] in this scenario would introduce considerable overhead decreasing the battery life. Probabilistic approaches [33] utilize regular predictive patterns in the movement of wireless nodes which are not sufficiently reliable in case of cattle. In case of data ferries [34, 35] the only realistic candidates for ferries would be stockmen. Such an approach would be suitable for labor-intensive rearing but in this paper we address highly automated cattle production with limited and potentially irregular involvement of personnel and our objective is to further decrease it.

The classical MANET routing protocols [5-7] do not target energy efficiency and do not address disconnections. Georouting approaches [36-38] require spatial positioning not available in our scenario. The energy efficient approaches from WSN area consider static scenarios [22, 39-42], whereas energy efficient approaches from MANETs assume high data traffic and thus optimize energy efficiency of the data traffic not route discovery or broadcasting [8-10, 12, 13, 43-45]. Some other approaches propose switching off transmitters to save energy [43, 46] – we do not use them because their gain strongly depends on the characteristics of a given hardware. We utilise however in our approach energy control of transmitters [12, 45].

In our scenario we have limited amounts of data traffic so most of the energy is potentially spent on the route discovery and broadcasting of queries. Therefore we need to make broadcasts energy efficient. The probability based methods of broadcast optimization limit reachability [32, 47], which would affect negatively reliability in our scenario. The proactive neighborhood knowledge methods rely on the topology knowledge obtained from the periodic 'Hello' packets [47, 48]. Such messages due to high mobility of our scenario would have to be frequently sent which would limit energy efficiency. Area based methods often require means of geolocating not available in our scenario [47]. The passive neighborhood knowledge methods are best suited to our scenario, in particular offering best performance Passive Clustering with Delay Intelligence [49], which we adapt to our system. There is a body of work other than Passive Clustering (PC) concerning routing in MANETs relying on formation of virtual infrastructures such as clusters (e.g. [50-52]) or connected dominating sets (e.g. [53]). However they require proactive exchange of control messages to maintain the virtual infrastructure, which makes them less optimal for our scenario than PC.

PC creates soft-clusters by determining clusterhead nodes without complete neighbor knowledge. A clusterhead is a node responsible for forwarding messages to all of its neighbors. All 1-hop neighbors of a clusterhead can not be clusterheads themselves. Gateway nodes link multiple clusterheads together. If a node is neither a gateway nor a clusterhead it is an ordinary node not retransmitting broadcasts. Nodes revert to the initial state if no traffic has been seen for a defined period.

In PC the first node to broadcast itself automatically becomes the clusterhead. All other nodes within the broadcasting radius of the first clusterhead declaration broadcast must eventually declare themselves as gateways or ordinary nodes by monitoring the number of neighboring clusterheads (NC) and neighboring gateways (NG). The node can declare itself a gateway when

$$\alpha \times \mathrm{NC} + \beta > \mathrm{NG}\,, \tag{1}$$

where $\alpha$ and $\beta$ can be local parameters ($\alpha \geq 0$, $\beta \geq 0$), unique to each node.

Deliberately delaying a retransmission for a length of time (much greater than the network propagation delay) can convey information without adding additional messages, which is profitable for energy saving. In the Delayed Intelligence (DI) strategy [49] a node delays its retransmission according to the received signal power and its local remaining energy. The wait time $W$ is calculated as

$$W = \delta \times \frac{receivedPower}{localEnergy} \tag{2}$$

where $\delta$ is a constant.

## 5. Energy efficient route discovery

We propose a novel realistic MANET protocol, Energy Efficient Route Discovery (EERD), for cattle monitoring system which minimizes and balances energy consumption in the face of low data traffic and high mobility of nodes. In particular we decrease energy spent on route discovery and in-situ queries by utilization of the tailored PCDI broadcasting. We decrease the number of necessary route discoveries in a novel way by utilization of heterogeneity of nodes' mobility and selecting routes with longest lifetime. We based our approach on the established MANET routing protocol, DSR [6].

## 5.1. Decreasing and balancing energy spent on route discovery

As in ESDSR [12] 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:

$$P_{min} = P_{tx} - P_{recv} + P_{threshold} + P_{margin} \quad (3)$$

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 broadcasts are sent using the maximal power of the transmitters.

In the proposed protocol we minimize and balance energy spent on route discovery control traffic at the cost of the energy efficiency of data traffic. This novel approach is promising because the amount of exchanged data is low and we minimize power spent on sending data packets by limiting the transmitter power. The latter is possible because we know the power necessary to send data over each hop from monitoring power attenuation between neighbors. We cannot similarly decrease transmitter power in the case of the route discovery broadcasts because it would decrease the probability of finding any route.

We minimize and balance energy spent on route discovery by the novel application of Passive Clustering with Delayed Intelligence [49] (PCDI) to route request broadcasts. Broadcasts are sent using maximal transmitter power so power of the received broadcasts can still be utilized to calculate PCDI waiting time (see Formula 2). In PCDI nodes with higher battery capacity are more likely to route broadcasts so discovered routes lead through these nodes. This results in more fair energy utilization of data traffic.

## 5.2. Decreasing number of route discoveries

**5.2.1 Utilizing heterogeneity of node's mobility.** The field experiments reported in Section 3 show that there are considerable differences between typical movement speeds of wireless nodes. We decrease chances that faster wireless nodes become members of the route by delaying their forwarding of PCDI broadcasts. In this novel way we extend the lifetime of the discovered routes so repeated sending of data, route failure messages 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. In particular, animals' mobility fluctuates within 24 hour cycles (see Fig. 4), so using 24 hour time series gives more stable average values. E.g. a cow is not considered slower because she is eating at the moment. 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. We extend the PCDI formula calculating waiting time (Formula 2) by taking into account the average speed of the node in relation to average speeds of other nodes:

$$W = \delta \times \frac{receivedPower}{localEnergy} + \varepsilon \frac{V_L - V_{MIN}}{V_{MAX} - V_{MIN}}, \quad (4)$$

where $\delta$ and $\varepsilon$ 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 forward PCDI broadcasts so their probability of becoming PCDI clusterheads or gateways and later forwarding data traffic is smaller.

**5.2.2. Selecting routes with longest lifetime.** We further minimize the number of route discoveries by selecting routes with potentially longest lifetime. Because of the high mobility of the nodes we assume that 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 we monitor how the energy attenuation changes between the one hop neighbors. In this way we can count how many links within the multi-hop route are increasing their energy attenuation (deteriorating). In particular each forwarded route request and acknowledgement message contains a counter of deteriorating hops. The size of the counter is only one byte so it does not considerably increase the network overhead. This counter is incremented by the forwarding nodes which received such packet over a deteriorating link. Note that it is possible to measure changes of the energy attenuation for such link because the measuring node hears twice from the other end of the link: first time when the other end is forwarding the route request or data packet and second time when it is sending route response or acknowledgement.

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 (for route acquisition from forwarded and overheard packets).

We select routes which have (1) *the least number of hops*. For routes with the same number of hops, we choose these with (2) *the least number of deteriorating links*. If this is equal we select one with (3) *the minimal total power* (i.e. sum of the transmitter power necessary to send data over each hop). 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. We use (2) to avoid routes comprising hops between nodes moving away from each other. We motivate (3) 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.

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 could 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 forward a route request, finishes waiting enforced by Delayed Intelligence [49].

### 5.3. Saving energy on broadcasts in in-situ queries

Similarly to our previous approach [4] 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). In our new approach 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 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. Data sent to sinks is cached by the forwarding and overhearing nodes so it is possible to answer some queries in spite of disconnections.

## 6. Evaluation

### 6.1. 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 our field experiments described in Section 3 and utilizes animal movement data from these experiments.

The emulation area is similar to the dairy where we made the experiments. 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. States are associated with groups of locations within the division of the dairy and transitions between states are connected with moving between these locations.

From the GPS data we acquired speeds of cows which our emulated cows randomly select. This makes the emulated cows move with the realistic distribution of speeds. We filtered out speeds higher than 1.5 m/s, assuming they were unavailable to the bovine animals [54] and were recorded because of GPS drift. We used two different speed profiles utilizing real speeds from two different real cows (see Fig. 3). These profiles are distributed evenly between the emulated cows.

The times a cow stays at any of the locations we acquired from the video footage. These are randomly selected for the cows during the emulation to achieve the distribution close to reality. We used GPS data only 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. From the video footage we also determined the patterns of eating and drinking and the times the cows spent performing these activities. These patterns are also randomly selected for the emulation. The minimal period between milkings for a cow we calculated from the timestamps of the pedometer readings taken during the milkings.

## 6.2. Protocol emulation

We evaluate our protocol using the ns-2 [55] network simulator, the best suited for the MANET character of our application. We compare our protocol with DSR [6], a classical MANET routing protocol, and ESDSR [12], an example energy efficient MANET routing protocol. Animals with wireless nodes move according to the traces from the Bovine Movement Emulator (BME) described above (i.e. on the area 35.75m × 29.25m). We emulate two scenarios: (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. We assume that 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 2). 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 (i.e. from overheard or forwarded packets). They perform the route discovery if they do not already have a route to the sink in their cache. 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 compared 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 (we consider only the animal mounted nodes); number of nodes with exhausted battery capacity at the end of emulation; minimal, maximal and average delays; success ratio.

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 [56] 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 [12]. At the beginning of emulation the sink and the user has 1000J (effectively infinite energy) and animal mounted nodes have 1J. $P_{margin}$ in Formula 3 is 1. We use the following EERD parameters: $\alpha$=1, $\beta$=1, $\delta$=10000s, $\varepsilon$=0.5s (see Formulae 1 and 4), 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.

## 6.3. Emulation results

Emulation results are shown in Fig. 6. Points and lines show average values per node. Error bars show minimal and maximal values. In each examined case no node exhausted its battery capacity.

Fig. 6a 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. In particular the maximal values of utilized energy are 68%-87% lower in the case of EERD. These improvements can be attributed to PCDI with proposed optimizations and proposed metrics for

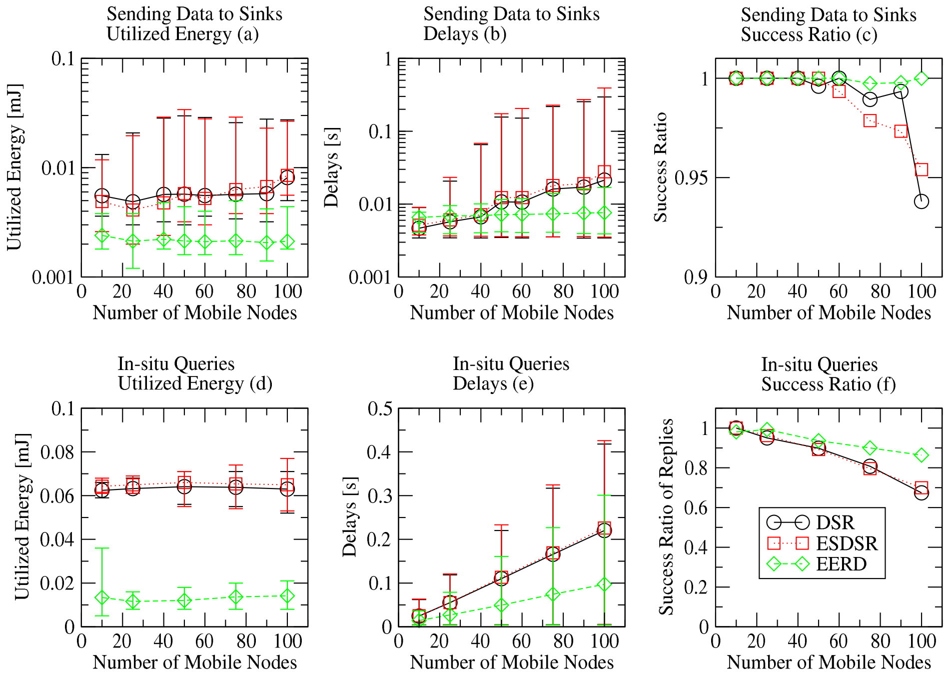

**Figure 6. Emulation results**

selecting routes.

Fig. 6b 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. EERD also offers lower maximal delays in the case of higher number of mobile nodes. 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.

Fig. 6c 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). This is not the case with EERD. This can be attributed to avoiding congestion achieved by utilization of PCDI.

Fig. 6d 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 considerable decrease of average utilized energy in relation to the existing routing protocols (by 77-82%) is achieved by optimization of broadcasting queries.

Fig. 6e shows delays in answering in-situ queries. The delays increase 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 the usability of the system.

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 Fig. 6f. We can see that this success ratio decreases 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.

## 7. Conclusions

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 utilize heterogeneity of the nodes' mobility in a novel way and give priority to discovered routes which are potentially more durable in order to minimize the number of route discoveries.

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.

Our approach can be applied not only to monitoring bovine animals. Other example applications include monitoring other domestic animals or perhaps even elderly or mentally impaired people [57].

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