Implementation of herd management system with wireless sensor networks

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Abstract
This paper investigates an adaptation of Wireless Sensor Networks (WSNs) to cattle monitoring applications. The proposed solution facilitates the requirement for continuously assessing the condition of individual animals, aggregating and reporting this data to the farm manager. There are several existing approaches to achieving animal monitoring, ranging from using a store and forward mechanism to employing GSM-based techniques; these approaches only provide sporadic information and introduce a considerable cost in staffing and physical hardware. The core of this study is to overcome the aforementioned drawbacks by using alternative cheap, low power consumption sensor nodes capable of providing real-time communication at a reasonable hardware cost. In this paper, both the hardware and software has been designed to provide a solution which can obtain real-time data from dairy cattle whilst conforming to the limitations associated with WSNs implementations.

Keywords: cattle monitoring, routing, data collector, real-time communications

1. Introduction

The challenges faced by modern agriculture have never been greater. With feedstock and labour prices increasing and constant pressure from retailers to keep food prices low, profit margins are at a point where farmers cannot grow their business to an economic size. Recent high profile welfare threats such as the BSE and Foot and Mouth outbreaks in the UK have further weakened the financial positions of many in the industry. More recently, technology has indicated potential solutions to common problems in livestock farming with applications of both Expert System and Machine Learning technologies in agriculture and animal welfare becoming increasingly prevalent [1, 2]. Given the current cost and availability of digital storage and communication, it has become easier to monitor and capture representations of the condition of individual systems or processes in levels of detail previously unknown. Mobile wireless sensors allow welfare monitoring to take place with greater regularity than would be practical with farm staff. The nature of these sensors permits remote access, removing the need for expensive specialised husbandry to collect data. The application of GPS technology is one such example; with the continual capture of the grazing habits of free ranging cattle [3, 4], farmers can now make more informed decisions on the efficient use of land and the preferred habitats of livestock.

Although real-time communications is not preferable for several reasons, most notably battery conservation, many welfare threatening conditions require timely notification of prognoses as a consequence of the rate at which deterioration can occur. In Mayer et al. [4] this problem is circumvented by retrieving data from the animal mounted devices via the GSM infrastructure which facilitates real-time communication. Battery life concerns aside, this approach becomes prohibitively expensive when monitoring large numbers of animals i.e. the typical cost of a collar is approximately 1700 Euros [3, 4].

Thus this paper will detail the design of a solution that implements real-time health monitoring using alternative low-cost, low power consumption wireless sensor nodes. To achieve this goal, firstly, an antenna diversity collar is designed to improve the performance of radio coverage in typical farming environments. Secondly, in contrast to the traditional store and forward mechanism, a routing protocol is presented to facilitate multi-hop connectivity. The protocol obviates the time spent in creating and maintaining an explicit routing path that results in shorter packet delay. To the best of our knowledge, no routing scheme is currently developed for supporting animal monitoring. An alternative approach utilises a portable device mounted on to a vehicle or a trained dog that can be used to collect data.

2. Challenges

Wireless sensor nodes are known for their constrained capacities in terms of energy, limited computational power and low memory capability e.g. a MICAz node [5] is powered by two alkaline AA batteries and has one 4MHz processor with 128kB of memory and 4kB of RAM. Given these inherent limited capacities, the implementation of a cattle monitoring solution raises specific and severe challenges;

- ***Radio interference caused by animals;*** cattle are generally fed in herds, massively increases the surface area, which in turn seriously affects radio performance as a consequence of signal absorption by animals [6, 7]. The hardware design should thus take into consideration this interference issue and this will be addressed in Section 3.
- ***Memory limitations;*** since sensor networks normally operate with limited data storage memory the traditional store and forward approach is often not feasible. A robust routing protocol is needed to instantly forward the measured data back to base station.
- ***Mobility.*** In most WSN monitoring applications, for example that described in [8], sensor nodes are assumed to be static. One of the major design issues raised when the sensor nodes are mounted on cattle is that the location of sensor nodes changes frequently. The network topology and routing path configurations should be therefore be dynamic in responding to frequent animal movement and take into consideration the impact on the packet delivery performance.

3. Wireless communications

In the cattle monitoring system, the animal is free to roam and wireless technology is considered the only feasible method to establish and maintain communications between a base station and collars attached to the cattle. Access to the majority of radio frequency bands is constrained by various standards and regulatory bodies (e.g. the radio section of the International Telecommunication Union (ITU-R) and Ofcom). Consequently WSNs tend to use unlicensed bands and, in particular, the Industrial, Scientific and Medical (ISM) bands, originally reserved internationally for non-commercial use. In this paper, most of the trials are thus conducted using the 2.4GHz ISM band which is freely available globally.

An estimate of signal penetration through an animal can be made using the electrical properties of body tissues [6, 7]. The properties of mammalian tissue are expected to be similar between species. Table 1 summarises the penetration depth at two ISM-band frequencies. Penetration at 2.4GHz is less than 2.5cm in fleshy tissues (skin/muscle). Although there is better penetration at 315MHz, the width of a cow’s neck is approximately 0.25m. It is unlikely, therefore, that there will be sufficient penetration of radio signals to maintain reliable network connectivity.

	315MHz			2.4GHz		
	Conductivity (S/m)	Relative permittivity	Penetration depth (m)	Conductivity (S/m)	Relative permittivity	Penetration depth (m)
Blood	1.3212	65.375	0.03651	2.5024	58.347	0.016407
Bone cortical	0.083944	13.386	0.23495	0.38459	11.41	0.046992
Fat	0.039795	5.6239	0.3225	0.10235	5.2853	0.11956
Muscle	0.77442	58.001	0.055463	1.705	52.791	0.022785
Skin (dry)	0.64898	49.249	0.060904	1.4407	38.063	0.022956

Table 1: Tissue penetration depth at two frequencies [7].

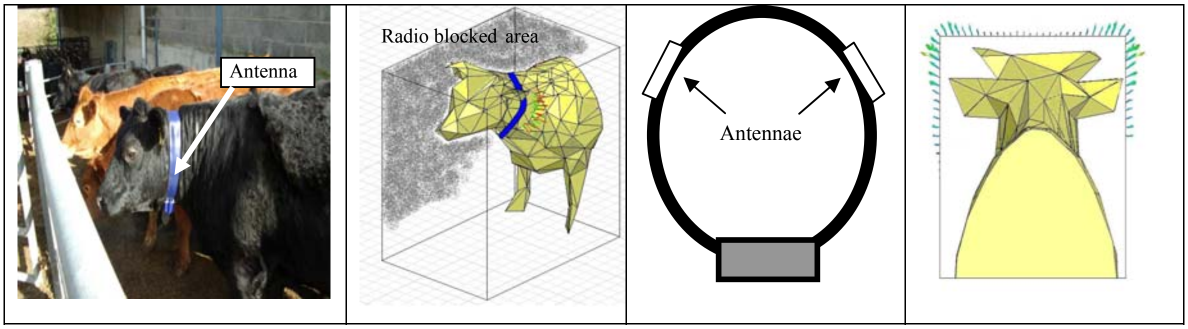

Figure 1: (a) Antenna location on collar; (b) Radio shadow cast by animal; (c) enhanced collar design with two antennas; (d) RF propagation from redesigned collar.

If a single antenna is attached to the collar, an animal may be in-range of a base station, but the collar may not be able to relay information due to shadowing (by the animal itself). Attaching two antennas to a collar creates spatial diversity. A diversity scheme was examined in which a pair of antennas (located at top left and top right of the collar) are used to improve radio coverage. The locations on the collar represent a compromise. Locations on the side of the neck would minimise the effect of shadowing by the animal wearing the collar. However, it also would be susceptible to shadowing from other animals in the immediate vicinity. The locations chosen allow energy to propagate over the top of near-by animals. Figure 1(c) shows the antenna locations on the collar and Figure 1(d) illustrates, schematically, the favoured directions of signal propagation. The antennas chosen for the collar assembly were ceramic patches (CABPB1240A) [9]. These are small, low directivity, antennas with a gain of about 2 dBi. The wireless communication platform used to implement the communication link was the MICAz. The RF switch (HMC197) [10] selects one of the antennas under MICAz control thereby realising classical selection diversity advantage.

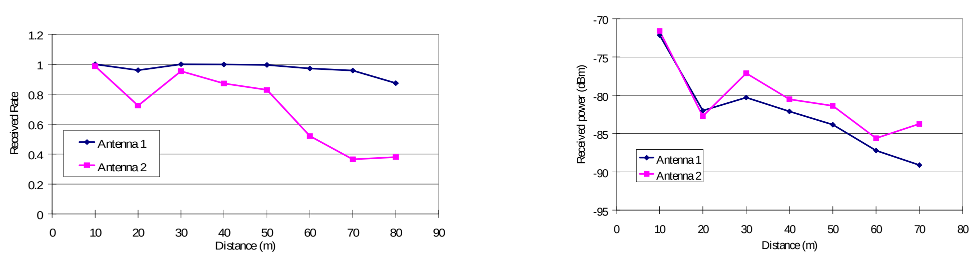

Figure 2: (a) Antenna 1 faces towards base station vs. Antenna 2 faces away from base station; (b) Antenna 1 faces to right perpendicular angle vs. Antenna 2 faces left perpendicular angle.

An experiment with diversity-equipped collars was carried out in an open environment. Figure 2(a) shows received packet rate versus distance from the base station. The collar is oriented such that Antenna 1 is faces towards the base station and Antenna 2 is faces away from the base station. In another experiment, the collar was oriented such that both antennas faced in a direction perpendicular to that of the base station (Antenna 1 to the right and Antenna 2 to the left). Figure 2(b) shows the received power at the base station.

3.1 Base Station Antenna Optimization

Radio link quality between transceiver and receiver plays a major role in the performance of any radio network. The radio connectivity range is determined by frequency, transmitted power, antenna characteristics and the radio propagation channel. A single, line-of-sight, path between transmitter and receiver seldom exists in a real world environment. In an open environment received signal strength may be very sensitive to the strength of the ground reflected propagation path. In the case of a strong ground reflection receive, and transmit, antenna heights (above ground level) will have a large impact on received signal strength depending on whether interference between direct and reflected paths is constructive or destructive. A simple two-path model can be used to describe (and predict) this effect [11]. Using this model the received signal power, P_r, at distance d is given by:

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \qquad (1)[11]$$

where P_t is transmitted power, G_t and G_r are transmit and receive antenna gains (as ratios, not in dBi), h_t and h_r are the heights of transmit and receive antennas above the ground, d is the distance between transmit and receive antennas and L accounts for any losses not represented by the two-path model. P_t, h_r, G_t and G_r are determined by selection and configuration of the communications hardware whereas h_t varies according to animal size. On a farm the transmit antenna height is approximately 1.2 m (for a standing animal of average height). In principal the height for the base station (h_r) antenna could be optimised (for the expected value range of d providing this range is not too large) to ensure close to constructive interference between direct and ground reflected signals. This optimum height is given by:

$$h_r = n\frac{\lambda d}{4h_t} \qquad (2)[11]$$

where λ is wavelength and n is an odd integer which would normally be chosen to 1. Choosing a value of n > 1 would mean a taller and therefore more expensive antenna tower [11]. This is unlikely to be advantageous unless, for example, greater antenna elevation resulted in a significantly reduced probability of shadowing.

Measurements of received power have been made and compared power predicted by Equations 1 and 2. Assuming that the animals are roaming in an area within 40 m of the base station. The transmit antenna height was 1.2 m consistent with the collar being worn by an animal of average size. Figure 3(a) shows a comparison of theoretical values (two-ray model) with experimental results of received signal power at the receiver. In the figure the height of receiver's antenna is varied from 0.25 to 2.25 meters and the best received signal strength is when the receiver's antenna is set at 1 meter. The terrain, on which the experiments were conducted, was on an open ground with grass surface (approximately 5cm tall). 95 % confidence intervals for mean received power have been calculated using 300 RSSI samples. The prediction assumes terrain permittivity and conductivity values of 6 and 0.1 respectively which is typical of grassland used for grazing cattle. Please refer to Fresnel reflection equation [12] for more information regarding the impact of ground surface on signal propagation and reflection. Figure 3(b) shows the (theoretical) base station antenna height for three (optimum values of *n*).

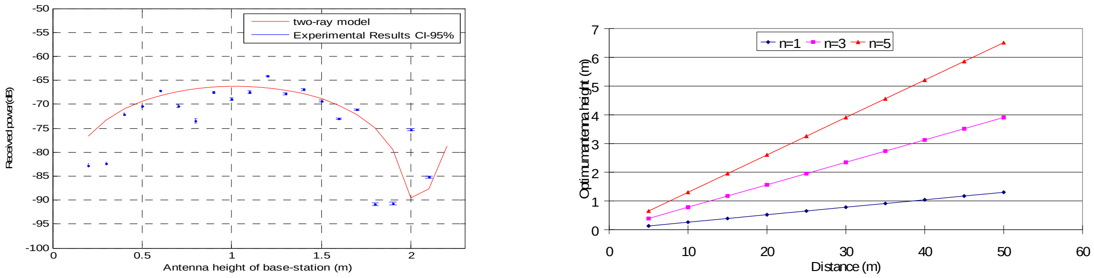

Figure 3: (a) Optimum antenna height at base station; (b) optimum antenna height (*n*=1, 2, 5).

4. Cattle mobility

Domestic cattle are essentially descended from prey species from which they inherit herding traits that benefit them both socially and from a general welfare perspective. However, herds are not uniformly spaced and do not always move as a single collective. Individual animals have different social standings within herds which will influence the animals they are most likely to associate with. As a consequence, the herd may break up into independent sub-herds. This raises an additional question for a WSN which is how rapidly network topologies are likely to change and the possibilities of the nodes moving out of range of each other and of base stations. In order to anticipate the extent and rate of such changes, the behaviour of the herd needs to be captured and modelled. In previous works this has been attempted using collar mounted GPS transponders, for example [3], used GPS to assess the behaviours of 14 free ranging Zebu cows in western Niger. Samples of position were taken at 0.1Hz so that displacement and rate of position change could be used to determine grazing coverage.

With this work in mind, two 24 hour periods of GPS fixes taken at 3 minute intervals from a herd of 14 Limousin and Angus crosses free-ranging on a farm in West Lothian, equipped with collar mounted transponders were used [13]. Days from summer 2006 were selected at random from a set where the herd had good satellite coverage and there were no major interventions from farm staff. This data set is used to answer two questions that relate to the viability of the WSN: firstly, what is the range between the animals and a base station and secondly, what are the distances between animals most likely to be.

To answer these, it is better to examine the way the quantities of interest are distributed rather than to use point estimate statistics since they may be skewed or multimodal. The best way of producing an accurate picture of a probability density function is to use a kernel density estimator such as a Parzen Window [4]. In the kernel density estimates shown below, the probability distribution of the distance of herd from base station on 4th August is shown in Figure 4(a) and distance of herd from base station on 8th August is shown in Figure 4(b). On the 4th of August, the most likely distance from the base-station is around 50m with a second, smaller mode at around 90m. On the 8th this is entirely concentrated around the 80m mark.

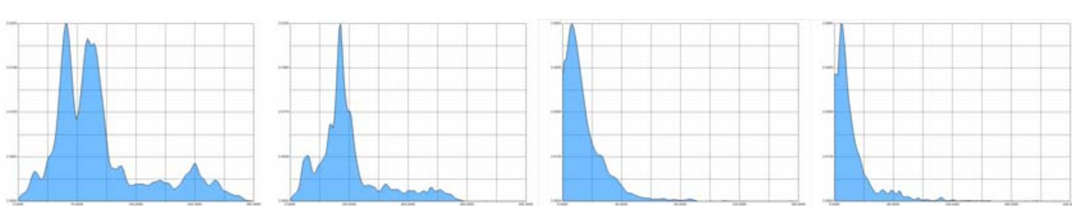

Figure 4: (a) probability distribution of the distance of herd from base station 4th August; (b) probability distribution of the distance of herd from base station 8th August; (c) minimum inter-cow distance 8th August; (d) minimum inter-cow distance 8th August.

With low power wireless sensor networks, range from the base station can be an issue even in fields of the size of those on UK farms. Although animals have been found to stray to ranges of up to 300m from a base station, the most likely distances they are to be found at are between 50-90m [13]. The above density functions show the minimum inter-cow distance on 4th August in Figure 4(c) with the minimum inter-cow distance from the 8th August given in Figure 4(d). In both cases the majority of observations are below 40m with the maximally likely distance being at around 10m [13].

5. Dynamic routing scheme

The connectivity between each collar is often sporadic leading to an unstable routing path and resulting in increased packet delay. To diminish the impact of mobility, an Implicit Routing Protocol (IRP) was designed for cattle monitoring systems. The proposed IRP operates according to the following two phases: the configuration phase and the data forwarding phase. During the configuration phase, the base station (BS) periodically floods a TIER message throughout the entire network. This TIER message contains a BS's ID field, and a hop count field. The hop count field is used to track the number of hops the TIER message has traversed from the base station, the TIERS being numbered starting from the base station. A collar in a given tier, *n,* represents the *n*-th tier away from the BS. This critical information is the *TIER ID.* As animals freely to move, the BS is required to send TIER messages periodically at intervals of T_s to maintain the correct configuration. At the data forwarding phase, if the collar is required to report its measured data back to the BS, it will form a packet containing its current *TIER ID* and measurement data. This packet is then broadcasted. Only receiving collars with lower *TIER IDs* are required to respond with an acknowledgment (ACK) packet. These collars, after acknowledging the source collar, will broadcast the packet. Conversely, receiving collars with equal or higher *TIER IDs* will discard the received data immediately. This forwarding rule will then repeat until the data arrives at the BS. Thus the measured data will move one hop closer to the BS at each forwarding stage.

The performance IRP was further investigated through experiments. The IRP was implemented on the MICAz node using TinyOS [14]; the test-bed was a 3-hop network with one source node, one base station (BS) and N pairs of intermediate relay nodes. Figure 5(a) depicts the average packet delay and Figure 5(b) the received packet rate of test bed configuration N = 4, and in each tier there are 4 relay nodes. During each experiment, the source node generates 10,000 packets at an interval of 250ms, each packet containing 85 bytes in the payload. In order to simulate movement, an asynchronous random "on/off" mechanism was implemented. A sensor node in "off" mode represents a cow movement out of communication range; and when a sensor node is switched to "on" mode, it represented a cow entering the communication range. This "on/off mechanism" was characterised by an "off" probability P_{off} which determined the probability the sensor node's stay in "off" mode. Figure 5(a) and (b) both show that network performance is severely impacted as P_{off} increases. However, performance is improved when the number of sensor nodes in each tier increases.

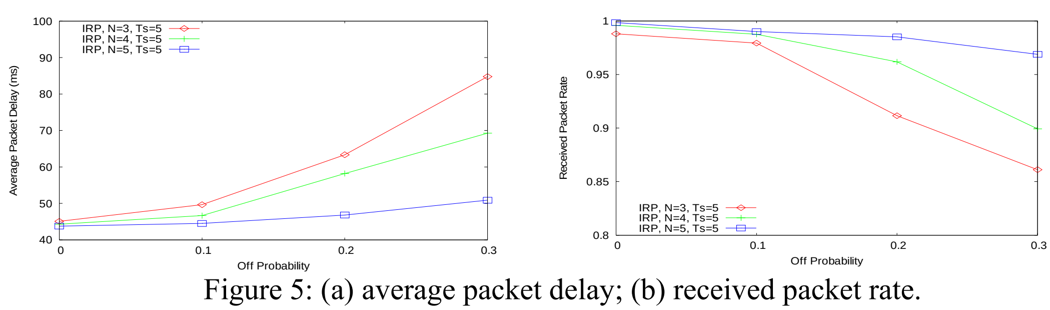

Figure 5: (a) average packet delay; (b) received packet rate.

6. Data Collector

Data collector, also known as data mule, which is a mobile/portable device that can be brought in to the field where the cattle gathered to collect data [15]. This scheme is useful when the IPR cannot establish a path. This will happen when there is a big gap in between two groups of animal. The hardware structure of a data collector is essentially identical to a normal sensor node but with additional memory and power capacities. These additional add-ons allow the data collector constantly scans for new sensor node which comes in contact and downloads stored data from the sensor node. In the farm environment, the collector can be carried by a well-trained dog or mounted on to a tracker and sent out into the farm. After data has been collected from the field the data collector can be connected to a pc directly for data downloading.

The communication protocol of data collector can be divided into two parts: discovery process and data transfer process. During the discovery process the data collector determines if there are any animals in the vicinity by periodically broadcasting a beacon. This beacon will be acknowledged by the sensor node that receives it. When the collector receives a response back from a sensor node it will send out an acknowledgement to the sensor node and the discovery process will be terminated at this point. Data transfer process will be initial after the discover process in which data is exchanged between sensor node and data collector. Each of the packets sent by the sensor node will be acknowledge by the collector hence by receiving an acknowledgement from the collector the sensor node can remove this stored data from its memory and safely know that this data has successfully transmitted. Figure 6 shows the protocol flowchart.

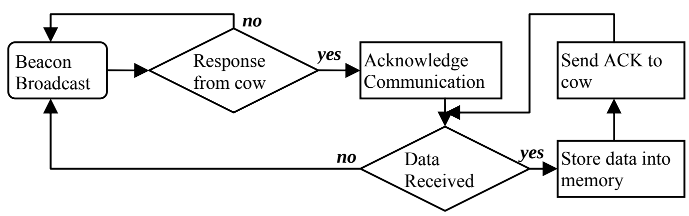

Figure 6: Data collector flow chart diagram

The performance of data collector can be improved by reducing the duty cycle of the sensor node. By reducing the sleep period the sensor node is more likely to hear the beacon sent out by the collector hence data can be transmitted before the collector move away. Of course, by reducing the duty cycle the sensor node will increase its power consumption level. Figure 7 shows collector in action.

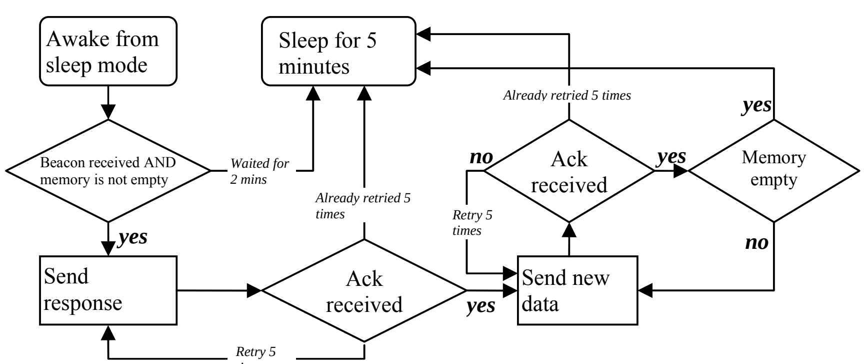

Figure 7: Senor node operational protocol.

7. Conclusions

Challenges imposed from adaptation of wireless sensor networks in agriculture and farming have been studied and evaluated. The main difficulty of adapting wireless sensor network into cattle monitoring is to support node's mobility that is caused by animal movements. A detail analysis of herd distribution based on 14 Limosin and Angus crosses in a working farm is provided. With the knowledge of the herd mobility two tailored networking schemes are proposed facilitating real-time data download. These schemes enable up-to-date animal statuses being feedback to farm manager, with the goal of improving animal welfare and operational efficiency via more informed decision-making.

8. References

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