An ASABE Meeting Presentation **Paper Number: 084587**

Wireless Sensor Networks for Beef and Dairy Herd Management

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Written for presentation at the
2008 ASABE Annual International Meeting
Sponsored by ASABE
Rhode Island Convention Center
Providence, Rhode Island
June 29 – July 2, 2008

Abstract *This paper reports on the application of wireless sensor technology to cattle monitoring. By monitoring and understanding cattle's individual and herd behaviour, farmers can potentially identify the onset of illness, lameness or other conditions which might benefit from early intervention. Low cost sensor network platforms show considerable potential in this context but are faced with a number of significant technical challenges before they are widely and routinely adopted. This paper focuses on challenges that relate specifically to the backhaul of data from cattle mounted sensory devices including data protocols, power consumption, mobility, operational range, data transmission volumes and herd size. The optimization of a wireless communications platform based around the IEEE 802.15.4 standard protocol from the perspective of operational battery lifetime has been analysed as a function of daily download volume and herd size. Boundary conditions are presented according to battery life expectancy. Operational issues such as the length of time grazing animals spend within range of base stations are also reported.*

Keywords antenna diversity; cattle monitoring; animals monitoring; wireless sensor networks

Introduction

Cattle production for meat and milk products is a major farming activity in UK. Operating margins within farms are low and modern farms are highly mechanized in order to minimize labour costs, which are a substantial portion of operating expense. As a result, highly labour intensive activities, such as extensive animal observation to detect and monitor illness or conditions such as calving or oestrus – are expensive to implement. In addition, the outbreak of bovine spongiform encephalography, or 'mad cow disease' in 1986 and foot-and-mouth disease in 2001 resulted in thousands of cows being culled and has driven legislation and contractual implementation of supply train traceability.

Autonomous animal monitoring through the use of sensor networks offers the potential to address both of the above and in doing so provides the farmer with the capability to optimize the farm operation without incurring excessive labour overheads. This paper looks into application of Wireless Sensor Networks (WSNs) [1-4] within the context of condition based monitoring (CBM). In general, CBM detects aspects of the physiology or behaviour of an animal and reports abnormal conditions at an early stage which will allow the farmer to take an appropriate action. Various systems of animal instrumentation have been patented (Oliver & Doughty, 1999, Davies, 2004) or reported in scientific literature such as the proceedings of the European Conference for Precision Livestock Farming, ECPLF in 2007. A few partial systems have been marketed without wide take up (Table 1). However, changes in the availability of wireless technologies (such as the Zigbee alliance) and reductions in the cost of components make it likely that cost of implementation will reduce rapidly. It is timely to review the options for the design and operations of these systems. This paper aims to identify some issues in the design and operations of wireless sensor networks for CBM of cattle.

Comment [kwong1]:

Manufacturer	Frequency	Location/ Attachment	Condition of Interest	Protocol
DeLaval		Neck	ID & estrus	
Westfalia		Neck or leg	ID & estrus	
Heattime/SCR	InfraRed	Neck	Estrus	
Fullwood	na	leg	Estrus	
Well Cow	433 MHz	Rumen	Acidosis	
TenXsys	na	Rumen	Temp, estrus, calving	
SAE AfiAct	na	Leg	Estrus	
Magiix	RFID	Rumen	Temp & ID	
Zigbeef	Zigbee	Ear	ID	802.15.4

Table 1 Wireless Dairy Cow Monitoring Systems available for sale

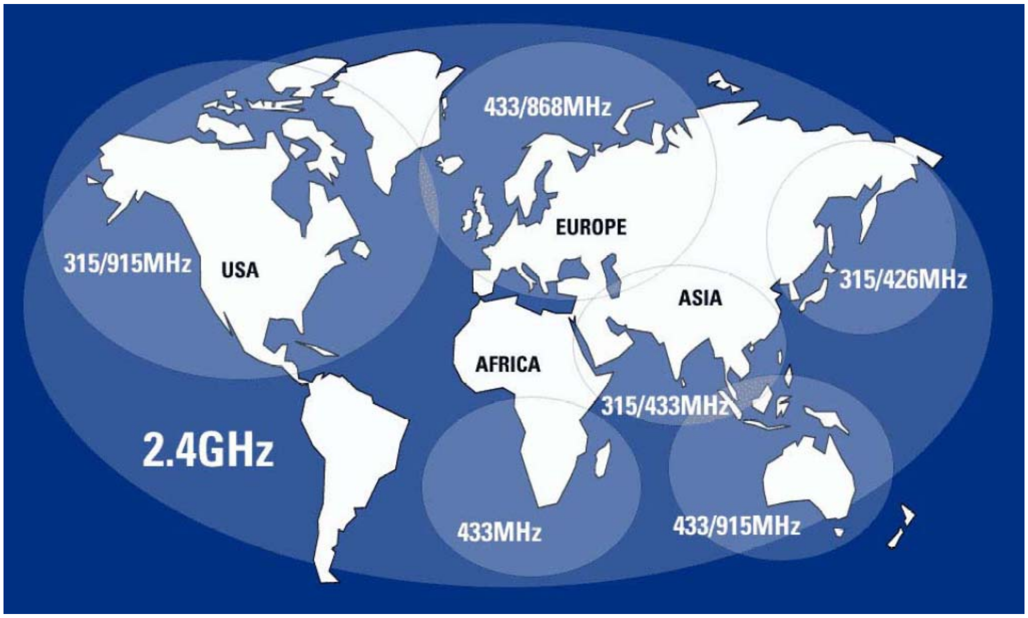


Figure 1 Freely available frequency bands worldwide (TI http://focus.ti.com/lit/ml/slap128/slap128.pdf)

There are major differences in the availability of frequencies below 1 GHz in different territories worldwide (Figure 1) and thus organisations designing integrated circuits for world markets are tending towards unifying around 2.4 GHz as a carrier frequency and the Zigbee alliance was formed to aid the creation of a de facto standard that covers not only frequency but also handshaking protocols and packet design. To the designer, the advantage of a standard is that hardware costs are driven down. The implementation of software stacks targeted at the most complex systems may not be necessary however, within agricultural applications. The Bluetooth protocol for example, limits the number of devices to 8 and requires many seconds of handshaking time.

Most RF sensor technologies are aimed at mass markets that have characteristics that differ from those in agriculture. Devices will often have access to mains electrical power, be relatively static relative to each other and operate within buildings in a noisy environment. In agriculture, particularly in livestock monitoring, power is limited. Devices will be constantly mobile and transmission may have to penetrate through heavy rain, and although the background radio noise may be less than in an urban environment, there may be hundreds if not thousands of nodes within a network. As an exemplar, consider a muster of cattle each wearing a radio sensor device. If each animal occupies 2 sq m there could be 3900 animals within a 50 m range of a base station all attempting to download data or even just to register with the base station.

The weight of a device attached to an animal is also constrained. The weight limit for a neck based device is likely to be constrained by the pressure and irritation it may cause and a reasonable limit for permanent mounting should not exceed 1 kg. This severely limits the amount of battery power available, and robust environmental power harvesting technologies are not yet available.

Our team has been investigating the constraints imposed both by the engineering limitations (power, weight, radio frequency) and also by the animal behaviour and operations.

Materials and Methods

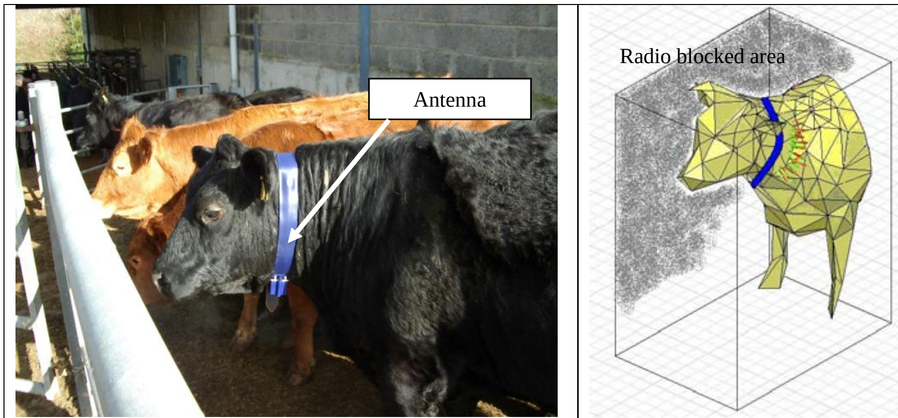
The CBM technology has been based on a collar mounted wireless and sensor platform. This offers greater capacity in terms of battery weight and mounting position of antenna compared with other mounting positions on an animal. The collar can act as a hub for other sensors mounted elsewhere on the animal and which may use the collar to process or re-transmit data. The communication between collar and base station has been implemented using the 802.15.4 standard without implementing the full ZigBee stack.
When a collar is ready to transmit data it will attempt to communicate with a base station. Acknowledgement signals are sent from the base station to ensure that the data transfer has been effective. If the collar fails to communicate with the base station it will sleep for a pre-determined period and then retry. If the collar has been successful in transmitting the data, it will enter sleep mode for an extended period in order to conserve battery lifetime. In addition to acknowledgements, antenna diversity is also implemented, to achieve multiple signal propagation paths, and hence optimise the likelihood of a successful transmission.

Wireless Communication

Frequency Selection

In the CBM system, the animal is free to roam around and wireless methods are considered the only feasible option to establish and maintain communications between a base station and collar attached on cattle. Access to the range of radio frequency bands is regulated by various standards bodies such as International Telecommunication Union (ITU). WSNs use unlicensed bands, which are the ISM – industrial, scientific and medical radio bands, originally reserved internationally for non-commercial use of radio frequency (RF) electromagnetic fields. In this paper, most of the trials are conducted using 2.4 GHz ISM band, as this is available globally.

The effective range of communication coverage and physical locations of individual collars define the connectivity of a network. The connectivity of CBM is assumed to be sporadic, where most of the collars are out of the coverage range periodically. Connectivity is mainly influenced by the farm size, animal movement and environment (i.e. noise, building structure and material). These factors are usually fixed and difficult to be removed. For example, it is unlikely to be possible to set up a full coverage network in an open farm sized over 100 sq. km.Fig 2 shows a common antenna placement on a collar and the resultant impact that the cow has on the transmission capability. Essentially, the collar can only successfully transmit a packet if the antenna is facing to the base station since the signal can not penetrate animal’s body.



(a) antenna placement on collar.

(b) radio signal can only propagate to one side.

Figure 2 Influence of antenna placement on radio transmission

An estimation of signal penetration rate through an animal's body can be made using data obtained from a detailed study of dielectric properties of body tissues [8]. While this is not completely accurate, the electric properties of mammalian tissue are expected to be reasonably similar between species. Table 2 summarises penetration depth of common ISM band frequencies, and shows that the penetration rate is less than 2.5 cm in fleshy tissues (skin/muscle) when transmitting at 2.4 GHz. The lower frequency band of 315 MHz has a better penetration depth but the width of cow neck is approximately 0.25m, and therefore it is not possible for any radio signal to reliably penetrate through the animal's body and establish network connectivity.

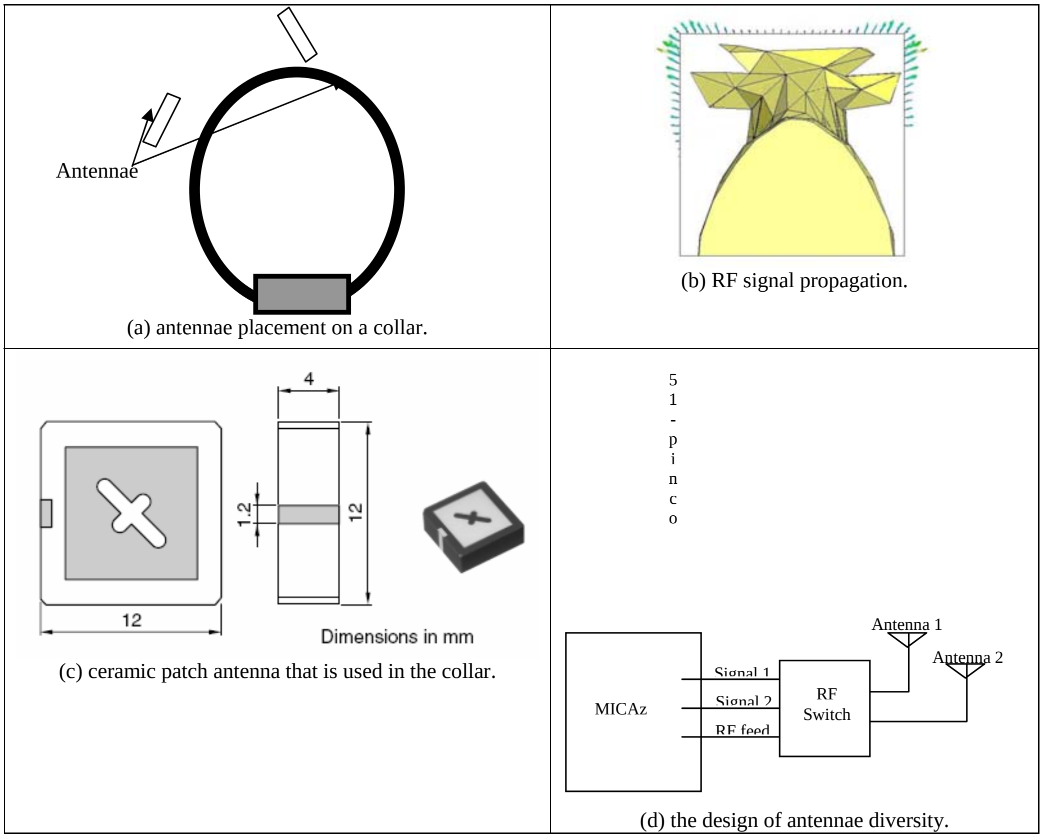
	315 MHz			868 MHz			2.4 GHz		
	Conductivity (S/m)	Relative permittivity	Penetration depth (m)	Conductivity (S/m)	Relative permittivity	Penetration depth (m)	Conductivity (S/m)	Relative permittivity	Penetration depth (m)
Blood	1.3212	65.375	0.03651	1.5241	61.463	0.028143	2.5024	58.347	0.016407

Body fluid	1.5192	69.014	0.33134	1.6269	68.91	0.027843	2.4392	68.24	0.018137
Bone cortical	0.083944	13.386	0.23495	0.1395	12.484	0.13535	0.38459	11.41	0.046992
Bone marrow	0.027655	5.7424	0.46425	0.039407	5.5109	0.31711	0.092834	5.3024	0.13196
Fat	0.039795	5.6239	0.3225	0.050289	5.467	0.24793	0.10235	5.2853	0.11956
Muscle	0.77442	58.001	0.055463	0.93213	55.109	0.042904	1.705	52.791	0.022785
Skin (dry)	0.64898	49.249	0.060904	0.85617	41.576	0.040842	1.4407	38.063	0.022956
Skin (wet)	0.63677	51.53	0.063104	0.83301	46.212	0.044047	1.5618	42.923	0.022471

Table 2 Frequencies and tissue penetration depth [9].

Antenna design and collar location

An antenna diversity scheme was examined, in which two antennae (placed at top left and top right of the collar) can be used to optimise the collar radio coverage. The locations of the antennae are carefully considered so that signal propagates efficiently outward with fewer impediments from the other cattle in the proximity. Figure 3a illustrates positions of the antennae and Figure 3b shows how the signal propagates outward in a desired fashion.



(a) antennae placement on a collar.

(b) RF signal propagation.

(c) ceramic patch antenna that is used in the collar.

(d) the design of antennae diversity.

Figure 3 Antenna design of a collar

In the case where only a single antenna is incorporated into the collar, an animal may be in range of a base station, but the collar may not be able to relay information as the antenna may be facing in the wrong direction. Having two antennae on a single collar enables diversity in radio propagation paths. The antennae chosen for the collar assembly were ceramic patch antenna (CABPB1240A) [10] which are small in size but also have a good directional radiation pattern and a gain of 2 dBi. The dimensions of ceramic patch antenna are shown in figure **Error! Reference source not found.**3c. The wireless communication platform used to implement the communication link was MICAz. Figure **Error! Reference source not found.**3d illustrates an RF switch (HMC197) [11] that is connected to the MICAz. The MICAz controls the RF switch to select one of the antennae for transmission thereby facilitating the implementation of antenna diversity.

Farm trials of antenna diversity enabled collars were carried out at a research farm. A single antenna diversity collar was mounted on a dairy cow placed within a small herd of 14 cows in a 12m x 20m collecting yard. A base station was placed at one end of the yard. In the trial, the collar was set to transmit a packet every second using the right and left antenna in turn. Figure 4 illustrates the received signal strength indicator (RSSI) extracted by the reception point from packets transmitted by the collar. A set of RSSI was collected for each collar during a pre-set time interval. Figure 4 shows how the RSSIs vary for both antennae over time. The received RSSI is consistently 10 to 15 dB higher for one antenna.
The impact that this has on the transmission of data is demonstrated in the following graph, **Error! Reference source not found.**Figure 5. This figure shows how the RSSI varies as a function of packet count depending on whether a packet was transmitted from an antenna located on the right hand side or the left hand side of a cow. Antenna 1 is oriented with the antenna in the line of sight of the base station whereas antenna 2 is oriented away from the base station. As a consequence, antenna 1 records a consistently higher received signal strength and a greater number of packets are received during the same time interval.
It can thus be deduced that the transmission path is strongly influenced by the orientation of the animal.

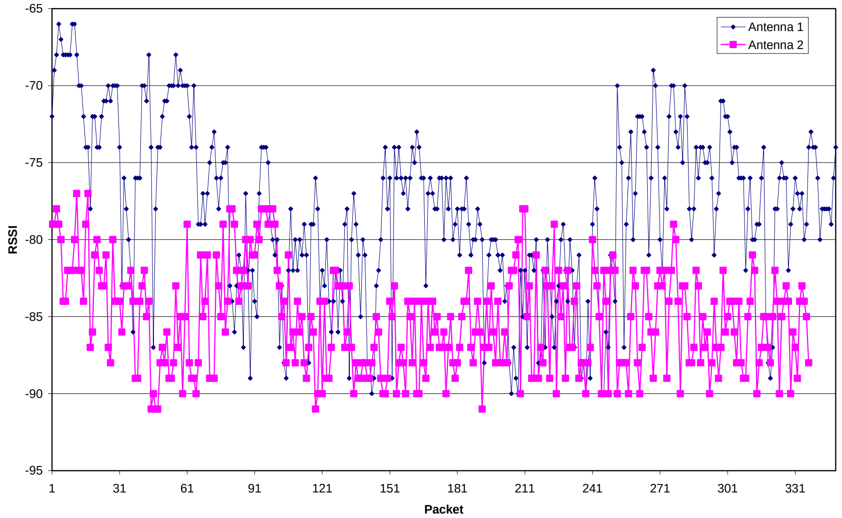


Figure 4 RSSI from the both antennae with -10dBm power transmission.

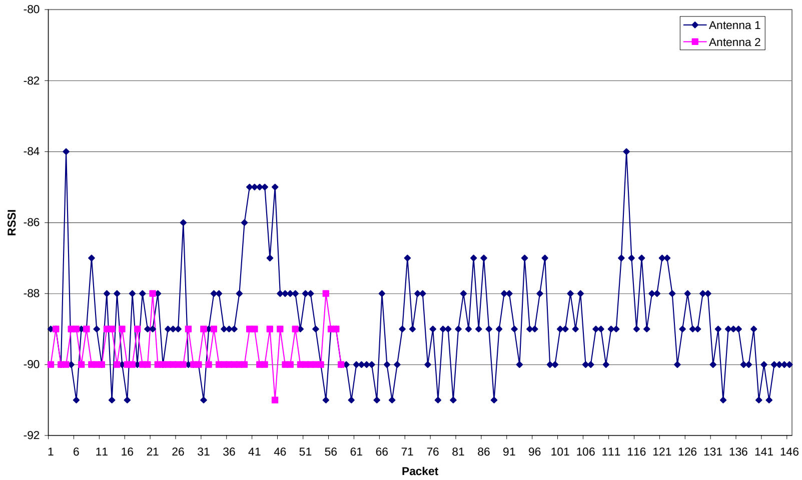


Figure 5 RSSI and received packet count for a cow at the edge of the network.

The power required by the wireless sensor platform to transmit data varies according to the output power that is required from the transmitter. Generally however, transmitter current drain of somewhere between 20 mA and 30 mA can be assumed and these values can be used to give reasonable design guidelines. **Error! Reference source not found.** Figure 6 shows the allowable daily communications time such that the current drain levels described above are maintained. The graph shows the case again for two scenarios, namely 20 mA and 30 mA current drain during transmission. Also assumed in the graph below is the constraint that the communications portion of the power consumption is less than 10% of the overall amount. Hence the times shown below represent 10% of the duty cycle times as calculated previously.

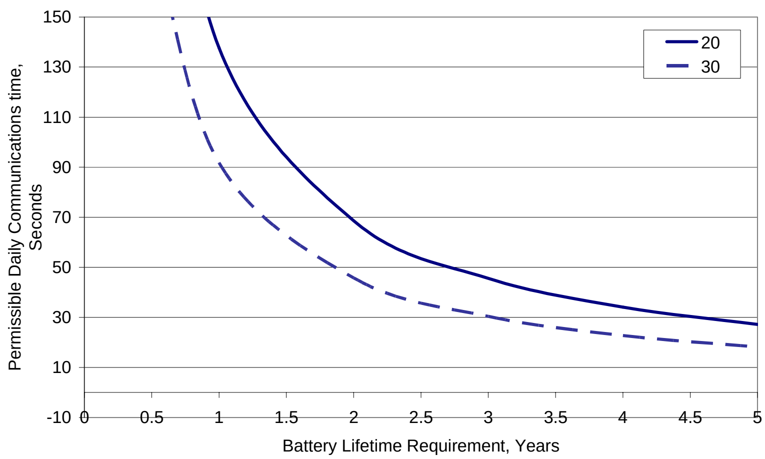


Figure 6 Allowable Daily Communication time versus Battery Lifetime

It is clear from the above analysis that the operational time allocated to the communications portion of collar should be around 20 seconds per day (or less) to maintain an operational battery lifetime of five years. While this is a small fraction of the operational time, it should be sufficient to permit the required data upload needs. However, a light weight communications protocol is essential. In the present application it was assumed that the network will not be congested, an assumption which is valid since, given the fact that the data load is low . At a data load of 100bytes per day a herd of 1000 animals seeking to download data at the same time would be readily accommodated within minutes. Hence over the period of several hours the network loading will be minimal. The timing of the interval between transmissions can be varied and can be adjusted in accordance with knowledge of the animal's movements, for example dairy cows will be milked at least twice a day at set times. Figure 7 shows the worst possible case, where no intelligence is applied to the timing of transmission. In this case they are evenly spaced over the day such that the average power constraints are met.

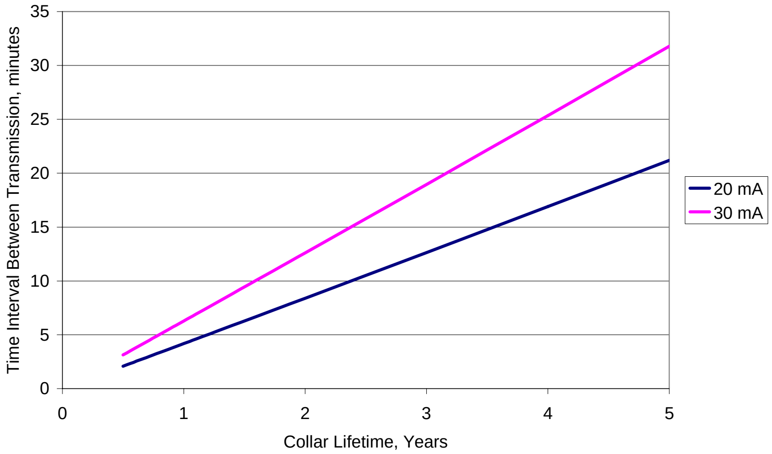


Figure 7 Time Interval between Transmissions

Figure 7 shows that, without any intelligent processing, the time interval between transmissions can extend to tens of minutes (assuming that they are spread evenly throughout the 24 hours). Within these constraints, battery lifetimes of 5 years are feasible, given known power consumption values during transmission. Hence the probability of a collar coming within range of a base station is increased to the point where successful data download is guaranteed, if it is known an animal will require to be in a certain vicinity at least once during a normal 24 period . Furthermore, it should be remembered that these time intervals can be reduced. The power consumption will increase but since the above calculation allocates only 10% of the overall power budget to the communications platform, further gains are possible with some careful tradeoffs.

(a) collar with sensors on the cow.

(b) Base station.

Figure 8: Farm Trials, collar and base station installation.

Figure 8 Figure shows the base station that has been deployed in the farm. Since space is not critical at the base station, a high gain (6dBi) omni-directional antenna can be employed (HGV-2406U) [14] . Base station placement and transmission issues are discussed in a separate paper to be presented at the ASABE 2008 meeting.

Animal Behaviour

In the dairy herd, cows visit a milking facility two or more times per day, therefore positioning of antennae in the collecting yard will almost certainly enable a daily or twice daily download of information. However, systems are also required for non-lactating animals to predict calving or in beef animals that have no regular handling.

Animals have other needs beside milking (drinking, grooming, eating) and so it is proposed that antennae could be placed close to watering points, which then asks the question how much time do they spend within range of an antenna so placed. A study was conducted with cows with GPS collars to determine how much time cows spent per day within range of an antenna.

Forty beef cows monitored at a research farm (altitude 210 m above sea level) were kept in two different fields at grazing densities commensurate with commercial practice. Field 1 contained two drinking troughs (‘Trough 1’ and ‘Trough 3’) while field 2 contained one drinking trough (‘Trough 2’). Field 2 also contained a small stream from which cows may drink.

To calculate the proximities of the cows to the nearest water trough, the Cartesian co-ordinates were calculated for all available records on a selected date, or between two given dates with logged GPS data. Collars attached to cows recorded GPS data for each animal at pre-set temporal intervals of either 3 minutes or 30 minutes. Reliability issues with collars did mean that portions of data were not collected on some animals, however this was taken into account in the analysis below, as only complete daily records for each cow were included in this analysis. The percentage figures given in the following tables are the proportion of available records that fall into the three proximity bands with respect to the total number of records that day. The distance between the point for each record and the position of the nearest of the following troughs is used:

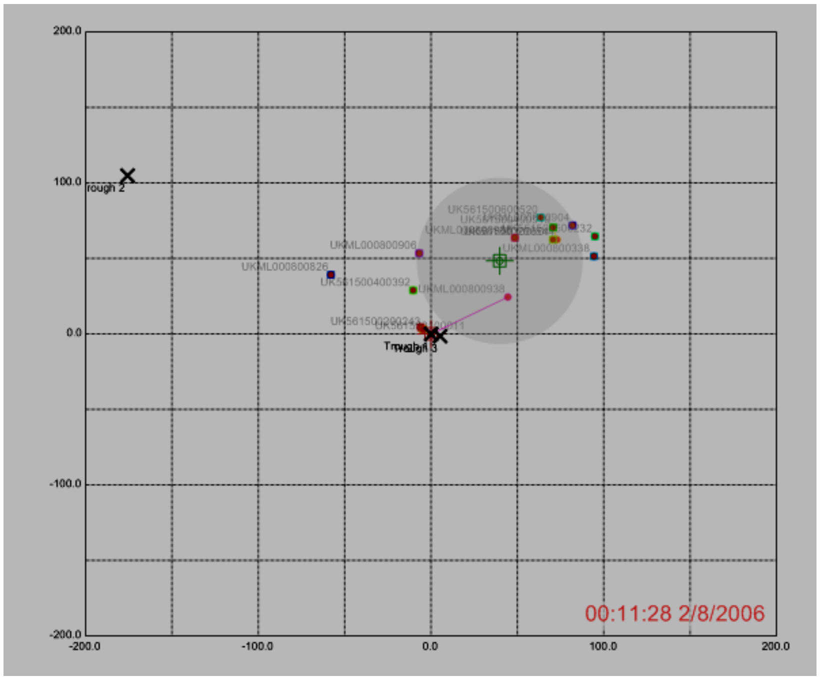


Figure **9. P**ositions of cows and water troughs

Figure 9 shows a snapshot of cattle positioning at grass in Cartesian co-ordinates. The area represented is 200m square with the positions of the three troughs marked with crosses. Left to right, these are: trough 2 (in field 2), trough 1 and trough 3 (both in field 1) which were positioned as follows:

- Trough 1: N 55 degrees 51.758 minutes, W 003 degrees 13.095 minutes, height 719 feet
- Trough 2: N 55 degrees 51.877 minutes, W 003 degrees 13.004 minutes, height 726 feet
- Trough 3: N 55 degrees 51.754 minutes, W 003 degrees 13.096 minutes, height 714 feet

The shaded circle represents the degree of dispersion of the herd given by the average distance of animals from the geometric centroid of the herd which is shown on the above figure as a crosshair. The animals are marked as red filled circles labelled with their ear tag identifier. At this point in time, very few animals are within 50m of any trough. Lengths of time spent near a water trough depend on seasonal, environmental and social factors. For example, cows may also drink from a small stream that flows through Field 2 – as a result there can be entire days when there are no cows within 50m of a drinking trough. Whereas during warm weather, animals may congregate around a trough as the following figure shows:

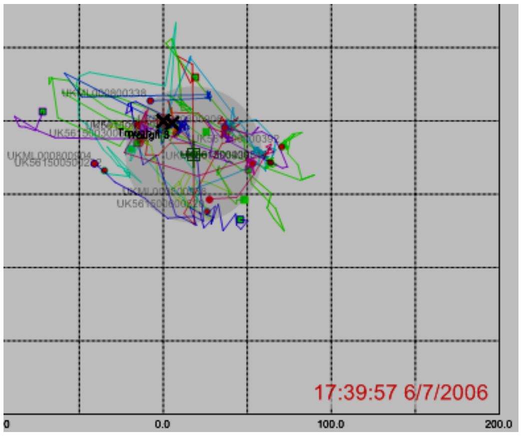


Figure 10 Dispersion of cows from antennae located at drinking troughs

The traces show the paths taken by the cattle over 40 minutes. At the time this data was collected the outdoor temperature was between 26 and 30 degrees Celsius consequently, most of the animals are less than 100m away from the trough and have clearly been closer at various points. In order to calculate the proximities of the cows to the nearest water trough, the Cartesian co-ordinates are calculated for all records on a selected date or between two given dates with GPS contact and the distance between the point for each record and the position of the nearest trough.

Table 3 records the proportion of position samples that fall into the three proximity bands with respect to the total number of samples that day implying the time spent by cattle in the herd near a trough:

Monitoring Period	% of time within 5m	% of time between 5-25m	% of time between 25-50m	Max T (˚C)	Avg T (˚C)
26th May 2006 to 4th June 2006	0.176%	3.3075%	9.641%	23.3	11.8
22nd June 2006 to 2nd July 2006	0.472%	5.4847%	14.242%	33.7	15.4
21st July 2006 to 23rd July 2006	0.1455%	2.241%	7.867%	26.4	18.2[1]
25th July 2006 to 27th July 2006	0.436%	4.5023%	11.3112%	34.8	22.2[2]
29th July 2006 to 30th July 2006	0.0827%	4.326%	14.377%	30.1	19
1st August 2006	0.318%	5.523%	21.757%	21.4	14.6
3rd August 2006	0.0895%	2.722%	16.801%	30.4	16.7
6th August 2006 to 10th August 2006	0.185%	3.757%	10.887%	24.6	15

Table 3 Cattle localisation close to water troughs

On the dates between 26th May 2006 and 4th June 2006 the cows were undisturbed and in field 1 with collars sampling at 30 minute intervals while at all other times they were in field 1 with the collars sampling at 3 minute intervals. From these data it is apparent that the cows will be within range of a single base

1 Incomplete meteorological records for this period

2 Incomplete meteorological records for this period

station for a sufficient period. However, a very different protocol of sleeping and waking will be necessary unless further work shows that cows have a predictable time pattern of activity through the day.

These data are summarised in Table 4.

Distance from trough	% Time spent	Daily Time
0-5m	0.25	5 mins
5-25m	3.3	50 mins
25-50m	11.43	3 hrs

Table 4 Cow Trough Proximity Summary

From these data it is apparent that, given a base station range of around 30m, the cows will be within range of a single base station for a sufficient period. Hence a collar programmed to attempt to transmit every 5 to 10 minutes will have a high probability of success during the course of a day while maintaining a low battery usage.

Conclusions

An overview of a couple of issues relating to condition based monitoring of cattle have been reported. It is proposed that 2.4 GHz is adopted as the radio frequency of choice on cost grounds. However, the full implementation of the Zigbee protocol will add unnecessary overhead. Parsimonious use of transmission time (less than 20 s per day) will permit long battery life. Cows were within range of base stations even in grazing situations for several minutes per day and thus long enough to download data daily although robust protocols still need to be developed for non-milking animals. Further work is required to enable protocols to be optimised for cattle monitoring and to allow interoperability.

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