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WSN: Modelling the Attenuation of Radio Signals by Bovines

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Abstract. *The use of wireless sensor networks to monitor the health status of animals has been widely proposed but there are considerable technical challenges to practical implementation. For reasons of cost reduction is likely that ISM bands will be favoured in practice and this limits the available frequencies of interest. We have modelled the electromagnetic environment associated with the monitoring of the bovine health. In this environment, each animal wears a collar-mounted radio system that transmits data from health monitoring devices to a fixed base station. We developed detailed models of the proposed antenna of the radio system, metal elements of the collar and a fully grown animal in five different poses. Using a finite element method we extracted the radiation patterns of the animal-collar-antenna combination at the 2.4GHz operating frequency of the radio system. We applied these extracted radiation patterns to large area environments using a ray tracing tool that has been validated for mobile phone applications at similar frequencies. We modelled two typical environments each containing a number of cows: first, an outdoor field of typical soil conditions, a metallic trough and a telephone pole; second, a 32 m by 3 m indoor barn with concrete floor, metal roof (8m high), walls and partitions. We will present results of the models and their practical implications for those considering the application of radio transmission systems in the bovine environment*

Keywords. Wireless Sensor Networks, Automatic Health Monitoring, Bovine Environment, 2.4 GHz

Introduction

Modern livestock farming is characterized by continually increasing herd sizes and increased costs of labour and veterinary services. The technology of monitoring animal health and status with sensors and transmitting information by wireless will allow the health status of large numbers of animals to be monitored continuously at very low cost. The Condition Based Monitoring Programme commissioned by ITITechmedia, Glasgow, Scotland, UK aims to develop new techniques for monitoring of cattle, where low cost remote mobile sensor platforms can be applied to enable herdsmen and farm managers to continuously monitor and assess animals for a variety of conditions.

Good radio communications underpins any such system, and requires a thorough understanding of the associated electromagnetic environment. There are a number of potentially difficult challenges that must be overcome. High data rate requirements and low cost limitations encourage the use of commercial off-the-shelf 2.4 GHz communications modules. From mobile communications work, it can be reasonably expected that signals at these frequencies will suffer from shadowing, reflection and diffraction by obstacles. These obstacles include the animals themselves, their enclosures, and farm machinery and buildings. Predicting the available signal power in any given location in a farm environment becomes a non-trivial problem, but one that must be solved if the base stations are to be sited for minimum signal attenuation, and hence maximum collar battery life, under typical operating conditions without a labor intensive and time consuming trial and error approach. That is the problem that we tackle in this paper, from a predictive, simulation-based viewpoint using a two-step approach. The rest of the Paper is arranged as follows. In the first section, we predict the radiation pattern of the antenna in the bovine collars, using a full-vector frequency domain electromagnetic solver tool to allow us to take into account the detailed design of the antenna as well as modifying factors such as the metal portions of the collar and the cow itself. In the second section, we predict the signal strength generated by this antenna throughout typical indoor and outdoor bovine environments by using an advanced ray-tracing methodology validated in mobile telecommunications applications. In the third section, we discuss the implications of these results for base station installation and provide guidelines for choosing the base station sites.

In-situ Antenna Simulation

The first step in our approach is to model the radiation pattern of the antenna in-situ, including the collar and the animal. An example of one of the final simulation model meshes is shown in Fig. 1, with a view of the front portion of the cow, collar and antenna in Fig. 1(a) and a close up showing detail in the antenna mesh in Fig. 1(b). We developed five different bovine meshes, as summarized in Table I, by modifying a 3-D computer aided design (CAD) model of a cow that was freely available from an academic repository [1][1]. In order to inform our modifications, we gathered data on the typical size of a cow, yielding an estimate of the overall length of 2.39 m, a neck depth of 0.48 m and neck width of 0.25m. Each mesh represents a typical 'pose', including the cow looking straight ahead, turning its head to right (45^o and 90^o), head down (looking straight ahead) and head raised (looking straight ahead). Due to the small wavelength at 2.4 GHz (λ_0 = 12.5 mm) relative to the size of the cow, it is not practical (or even necessary due to the strong absorption) to mesh the entire volume of the cow for accurate simulation results.

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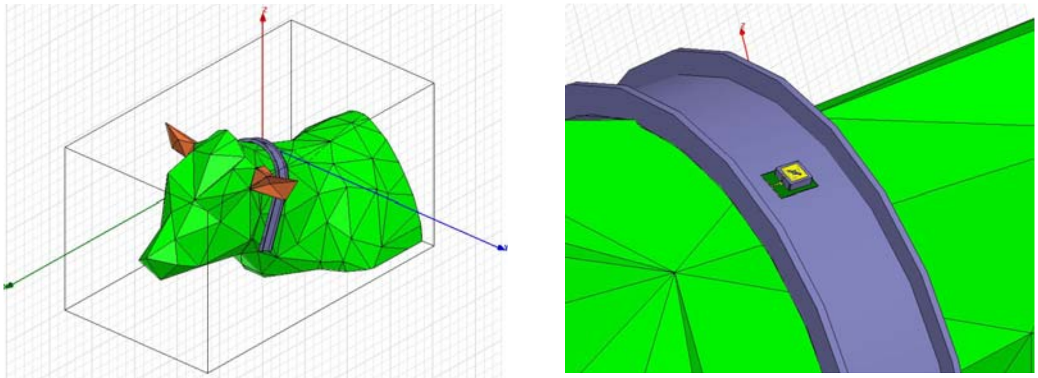
Instead, we employed the much more efficient surface impedance boundary condition, using the average of the appropriate tissue types (permittivity ε_r = 43.4, conductivity σ = 1.67Sm^{-1}) [2]. The ears were sufficiently thin that a signal could pass through, albeit with some attenuation, and hence were modeled without this approximation. After extensive validation, including evaluation of surface current plots on the surface of the cow, we were able to remove the rear and lower portion of the cow from the model without affecting the antenna response.

Table I. Summary of the poses modeled in the cow meshes

Cow Model	**Head turn**	**Head lift**
#1	0^o (straight ahead)	Normal
#2	45^o (half right)	Normal
#3	90^o (full right)	Normal
#4	0^o	Lower (feeding)
#5	0^o	Higher

We developed a mesh for the metal portion of the cow collar comprising a 4 mm thick stainless steel band of circumference 950 mm, width 60 mm and with 14 mm high flanges on both sides. Dielectric portions of the collar were omitted due to their negligible influence on the results. The collar-mounted antenna model was closely based on the a ceramic patch antenna specifically designed for 2.4 GHz communications applications (CABPB1240A, TDK Corporation) with outer dimensions 12 mm by 12 mm by 4 mm. A small section of printed circuit board, including the recommended electrode layout, was also included so that the antenna could be correctly excited by microstrip feedline.



(a) (b)

Figure 1. 3D rendering of optimised cow, collar and antenna model mesh for electromagnetic simulation purposes: (a) the head neck and shoulders cow model are sufficient for accurate modelling (b) detailed view of the patch antenna located at the top of a metal collar with flanges.

We calculated the 3-D radiation pattern of the collar antenna in the bovine environment using a full 3-D electromagnetic solver tool, Ansoft's High Frequency Structure Simulator (HFSS). All simulations were conducted using HFSS v10.1, running on a workstation with dual 64-bit Opteron 2218 processors, 32 GB of RAM and Windows XP64. An example of the far field radiation pattern obtained from the models is shown in Fig. 2, for the same mesh that is presented in Fig 1. The graph uses spherical polar coordinates. The further from the axis, or the hotter the colour, the stronger the radiated field in that direction. There is a single main lobe that is directed predominantly upwards, indicating that the strongest radiated signal is above the cow. The collar acts as a ground plane for the antenna, and simulations (not shown here) indicate the flanges significantly influence the direction of the main lobe, partly compensating for the slight backward tilt of the collar.

In order to provide data that could be used in the next step, the far field magnitude of the radiation pattern was calculated with units of volts (V), and is plotted in Fig. 4.1, with the vertical patterns in Fig. 3(a) and the horizontal patterns in Fig. 3(b). All of the vertical patterns are of similar shape, but the magnitude of the main lobe (that points upwards) varies by 0.5V (45%), with the strongest main lobe occurring when the cow has its head turned 90^o to the right and the weakest when the head is down. The difference arises as a consequence of the main lobe shape. When the cow's head is down, the energy in the main lobe is spread over a wider solid angle than that of the cow with its head turned 90^o to the right. The horizontal patterns all indicate that the pattern is wider in the lateral direction (i.e. the peaks at 110^0 and 240^0) than in the front to back direction (i.e. the dips at 0^o and 180^o). When the cow's head is turned 90^o to the right, there are two additional minor lobes between 300^o and 360^o and the strongest emission is at 180^o. The apparent increase in emission at 180^o is because the cow's body is no longer partly obscuring this direction, due to the head rotation. The effect of these differences on the received signal strength is analyzed in the next section.

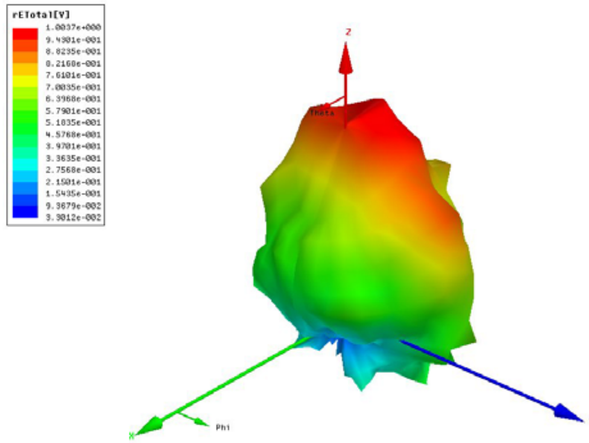


Figure 2. 3D plot of the radiated far field intensity of the cow mounted collar antenna in-situ with the cow in the nominal pose. The axis is the same as for Fig. 1(a) with the cow's head pointing in the positive x-*direction. Most of the radiation is directed upwards.*

(a)

(b)

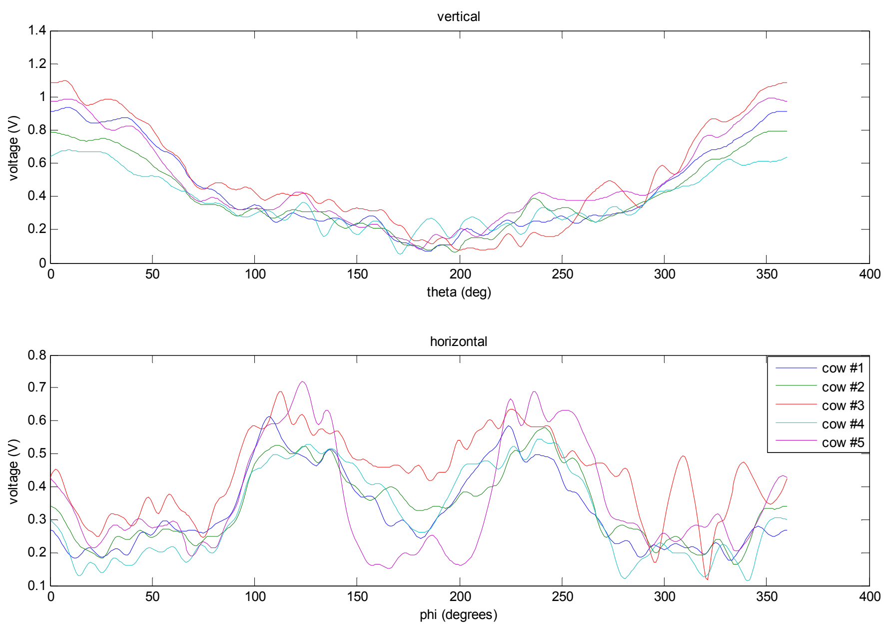


Figure. 3. Magnitude of the far field patterns calculated by HFSS: (a) vertical (b) horizontal.

WSN performance prediction

In order to predict the performance of the WSN, it is necessary to account for a variety of electromagnetic effects such as signals being shadowed by obstacles, reflected from surfaces and diffracted by edges. It is impractical to employ full vector electromagnetic solver tools in such a large simulation domain, but can easily be solved using geometric optics, or ray tracing. Such methods are often used for mobile phone or wireless local area network planning and provide good agreement to measurements [3]. In the following simulations, we used Radioplan's RPS v5.3 software.

Indoors

We constructed a model of a typical byre (loose house barn) that was 36 m by 36 m and 8 m high at its highest point, with a concrete floor, concrete walls, metal gables and a metal roof. Five metal fences running the length of the byre create separate rectangular pens. We created a small herd of 20 cows (the maximum possible within the RPS license limitation of 750 polygons per simulation) as shown in Fig. 4. In order to have enough spare polygons to include the cows, it was necessary to remove the lower portion of the fences as we do not expect them to have a significant impact upon the results, yet they consumed most of the polygon allowance. For the concrete floor, we chose the value of the permittivity to be $\varepsilon_r = 6.5 - j1$ [4], corresponding to well cured concrete at 2.4 GHz since this is most likely to correspond to the state of concrete in pre-existing buildings found upon a farm.

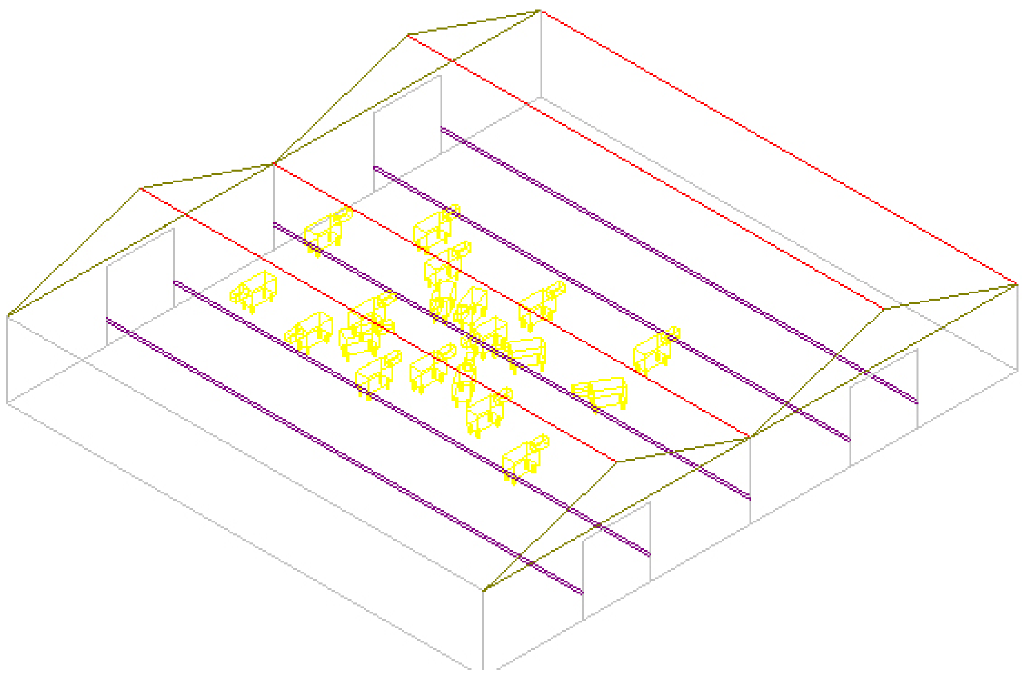


Figure 4. Wireframe rendering of the simulation setup in RPS for modelling an entire byre complete with a small herd of 20 cows. The byre is 36 m long, 36 m wide and 8 m high at the highest point. The cows are shown in yellow. The fences are shown in purple. The roof is shown in red and the gables in green. The floor and walls are shown in grey.

The signal coverage plots are presented in Fig. 5 for best (cow model #5), worst (cow model #2) and typical cases (cow model #1), at three heights above the floor: 1.5m, 3m and 5m. For heights above 5 m, the base station would have to be placed into one or other of the sloping roof areas, drastically reducing the field of view. The cows and fences cause significant shadowing for all three cases when the receivers are located at 1.5m off the ground. The shadowing reduces significantly in all three cases when the receivers are raised to 3m. A further increase in height to 5m provides further minor improvement however there are still areas of slightly weaker signal in all three cases. The worst case shows slightly weaker signal over a third to a half of the byre, while for the typical and best cases the area of weaker signal is limited to approximately an ninth of the area. Raising the height of receivers does not seem to improve the reception in areas that are strongly shadowed. Therefore, it could be reasonably expected that the ability to receive signals from a cow that is feeding or otherwise transmitting from near the floor (e.g. when lying down) will be partly dependent on the position of the base station antenna and not just the height. In that case, several receive antennas distributed through the byre would be beneficial as this would increase the chance of good line of sight without increasing the power consumption of the animal-worn collar.

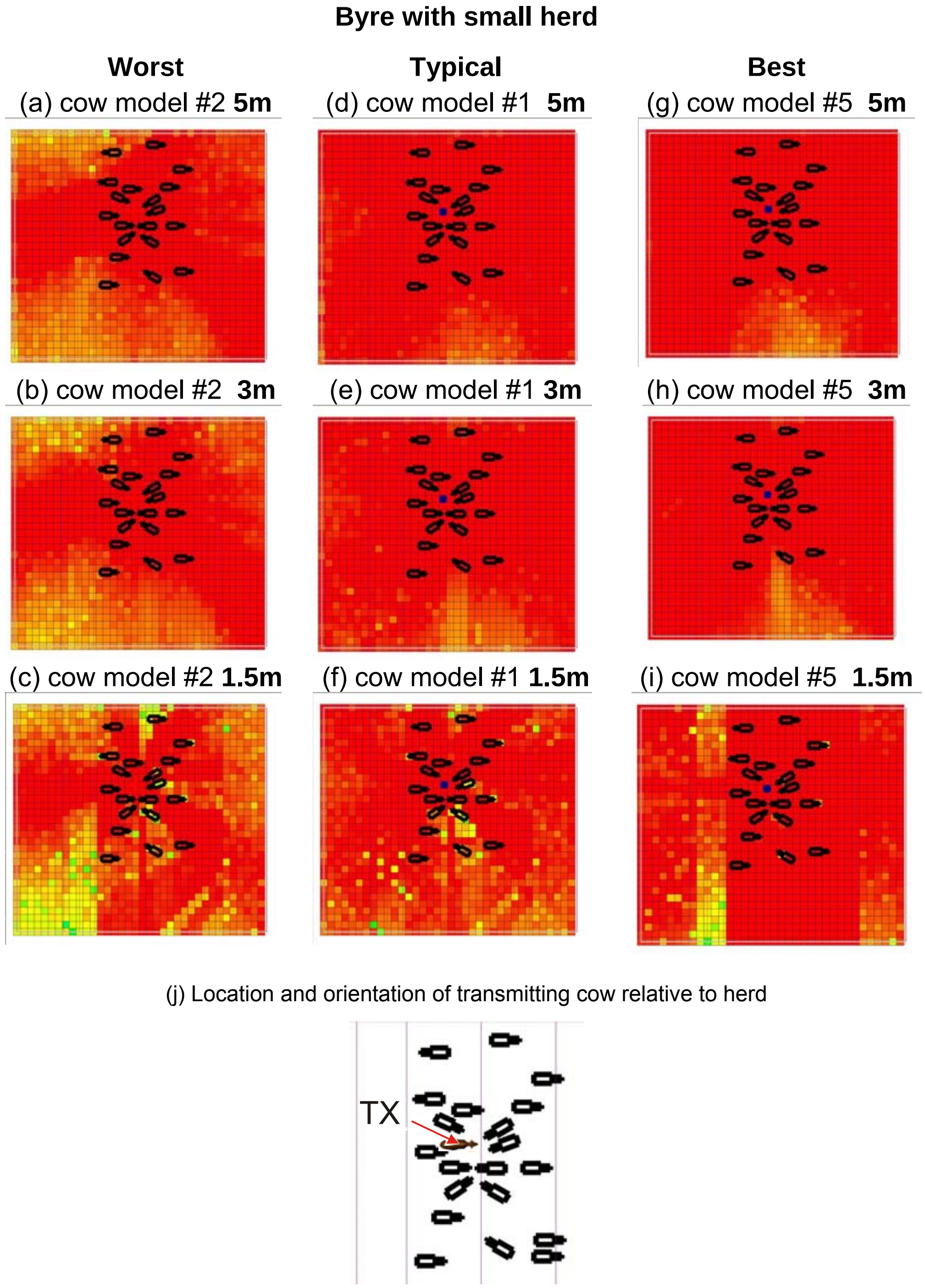


Figure 5. *Horizontal signal coverage (plan view) for receivers located at a height of 1.5m – 5m in a whole byre with a small herd of cows: (a-c) worst case, (d-f) typical case, (g-i) best case, (j) location and orientation of the transmitting cow in these plots. The blue dots in the centre of each plot should be ignored. Red squares indicates the strongest signals (-70dBm), green the midstrength (-86 dBm) and blue the weakest (-110dBm). Each square represents an area of one metre.*

Outdoors

We constructed a pasture model, as shown in Fig. 6, that was the same size as the byre with the same number and location of cows so that the difference between the indoor and outdoor environments could be evaluated. The wooden post and wire fences surrounding the pasture are not included in this outdoor model, so that it is applicable to much larger pastures and free-roaming cattle as well. We modeled the water trough as a 2m long by 1m wide by 0.75m high box of water having dielectric constant ε_r=76.7 –j9.4 [5]. We modeled the telephone pole as a 0.2m by 0.2m by 8m high box having dielectric constant ε_r=1.5 –j0.03 [6].

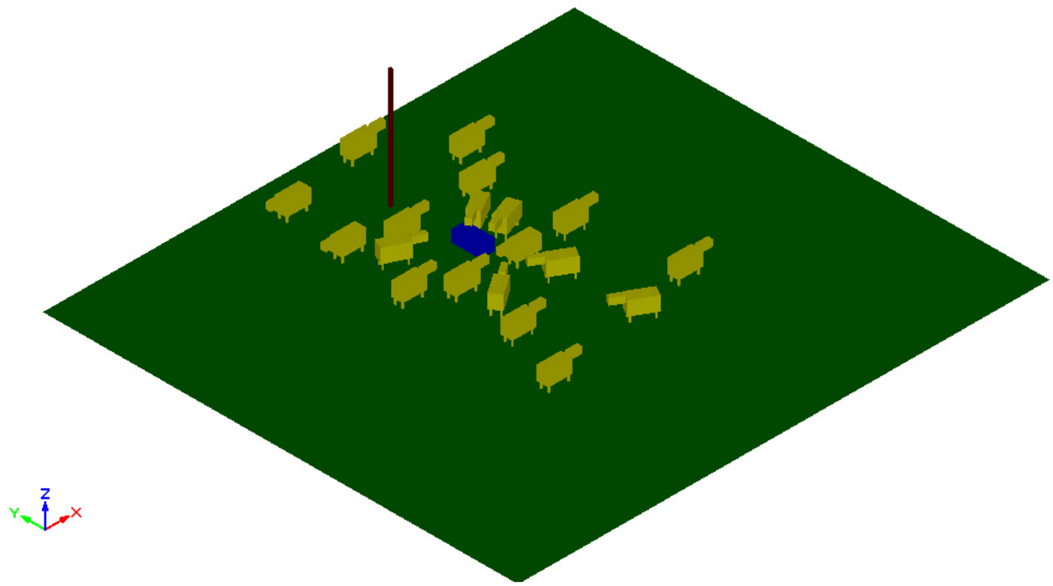


Figure 6. Rendering of the simulation setup in RPS for modelling a pasture with a small herd of 20 cows. The pasture is 36m long and 36m wide. The telephone pole is 8m high. The cows are shown in yellow. A plastic water trough, filled with water, is shown in blue.

The signal coverage plots are presented in Fig. 7 for the same best (cow model #5), worst (cow model #2) and typical cases (cow model #1) used for the outdoor model. The cows cause severe shadowing for all three cases when the receivers are located at 1.5m off the ground. The shadowing is so severe that in each case some receivers do not receive any signal at all (white squares); however this is less pronounced for the best case. Raising the receivers to 3m reduces the shadowing to that caused by the transmitting cow's poll. Further increase in the elevation of the receivers results in a slight further improvement that can be seen as a reduction in the size of the shadowed regions. While not shown, raising the receivers to 8m (the height of the telephone pole) results in further slight improvements.

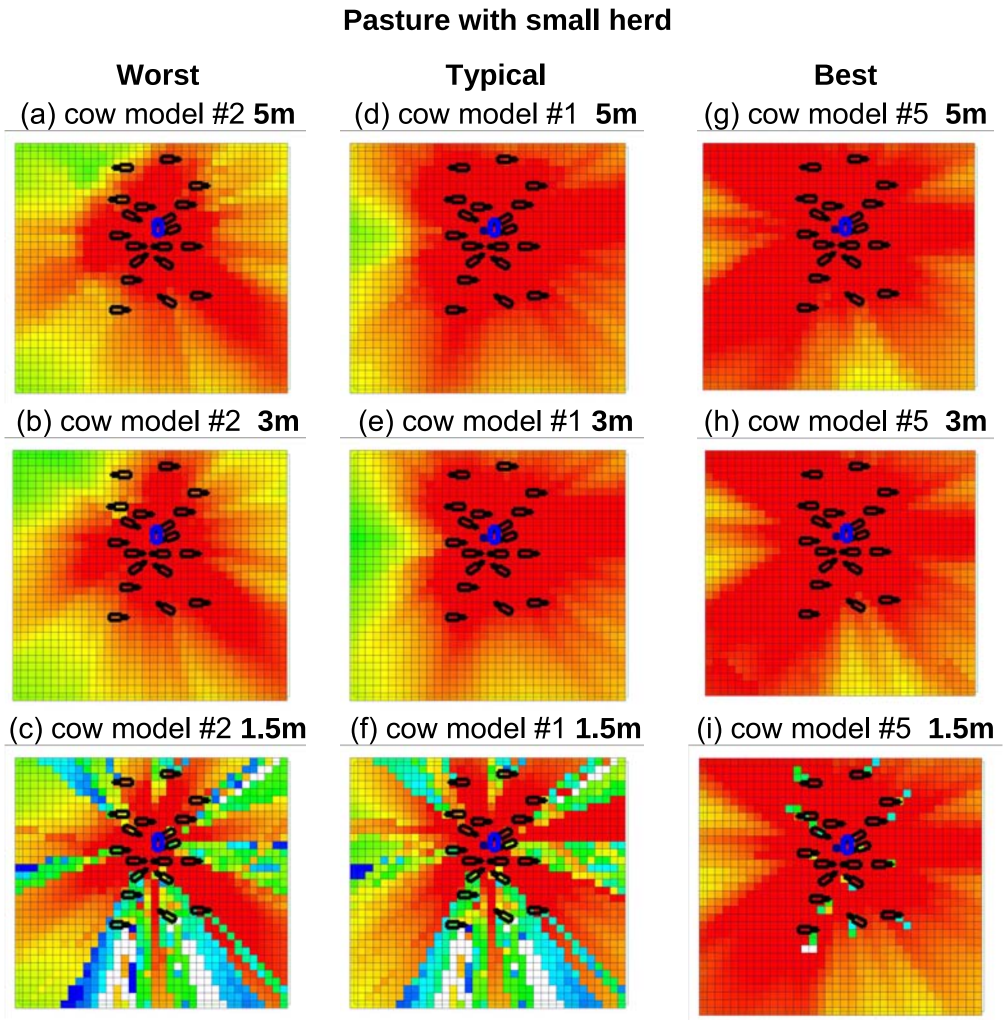


Figure 7 *Horizontal signal coverage (plan view) for receivers located at a height of 1.5m – 5m in a pasture with a small herd of cows: (a-c) worst case, (d-f) typical case, (g-i) best case, Red squares indicates the strongest signals (-70dBm), green the midstrength (-86 dBm) and blue the weakest (-110dBm). Each square represents an area of one metre.*

Conclusion

We have studied the bovine electromagnetic environment as it relates to radio signal propagation in WSN. Using a fullwave electromagnetic solver and detailed meshes, we predicted in the in-situ radiation pattern of a ceramic patch antenna mounted on a metal collar on a cow in five different poses. In all cases, the radiation was largely directed upwards, although the main lobe was broadest when the cow had its head down. We extracted vertical and horizontal far field radiation patterns and used these as the input to a geometrical optics package to study the transmitted signal strength in both an indoor (byre) and outdoor (pasture) environment. Our results show that the base station antenna should be mounted as high as possible whilst still maintaining a full field of view. Multiple base station antenna are likely to be required if the byre is populated to capacity because sitting animals will be shadowed by those standing, and will result in increased system performance without affecting battery life. Since we used a standard commercially available patch antenna for the collar, and do not assume a specific type of antenna for the base station, these results are widely applicable.

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