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AUTO-ID CENTRE

WHITE PAPER

A Study of Factors Affecting the Design of EPC Antennas & Readers for Supermarket Shelves

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ABSTRACT

The factors which govern the design of antennas and readers for EPC labels attached to objects in supermarket shelves are identified and analysed.

Because it is desired to give the results as far as possible both a theoretical and an experimental basis, and because many of these factors arise from fundamental properties of electromagnetic fields, a review of fundamental aspects of both electromagnetic theory and of RFID theory is given.

Experimental results to establish (a) the nature of u.h.f. fields in supermarket shelves, and (b) the feasibility of reading u.h.f. RFID tags in supermarket shelves, and are described. The importance of field stirring or antenna multiplexing is clearly established.

Feasible antenna configurations for reading h.f. tags in supermarket shelves are derived from fundamental theory. Future work will be concerned with the experimental evaluation of such fields for a range of HF antennas in supermarket shelves, and will also involve demonstrations of successful reading of multiple read h.f. tags.

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Biography

Peter Cole
Research Director

Dr. Cole, Professor of Radio Frequency Identification (RFID) systems in the Department of Electrical and Electronic Engineering at the University of Adelaide, has been selected to head a new RFID study in Australia. Dr. Cole's current research covers the industrial applications of electromagnetic identification and tracking systems, the design of multi-function microcircuits, the design of signaling methodologies for simultaneous high-speed reading of multiple electronic labels, and the development of international standards for RFID systems. Dr. Cole will be working closely with both the MIT and Cambridge Labs. He will be focusing his research and expertise on the EPC concept within the silicon chips currently being prototyped by Center sponsors.

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1. OBJECTIVES

The objectives of this paper are:

- To provide an understanding of the nature of the electromagnetic fields that can be created at both high frequencies (HF) and ultra high frequencies (UHF) in the vicinity of supermarket shelves.

- To guide designers of antenna systems for coupling to EPC labelled products in supermarket shelving using either UHF or HF EPC labelling systems.

- To describe aspects of interrogator architecture which are relevant to performance in the shelf context.

This paper is not intended to be the last word on the design of interrogators and antennas for supermarket shelves. Rather, it describes the beginnings of work on the subject, and is intended to stimulate discussion on an improving sequence of designs.

It does provide an explanation of important physical principles that must be taken into account in the supermarket shelf antenna design problem.

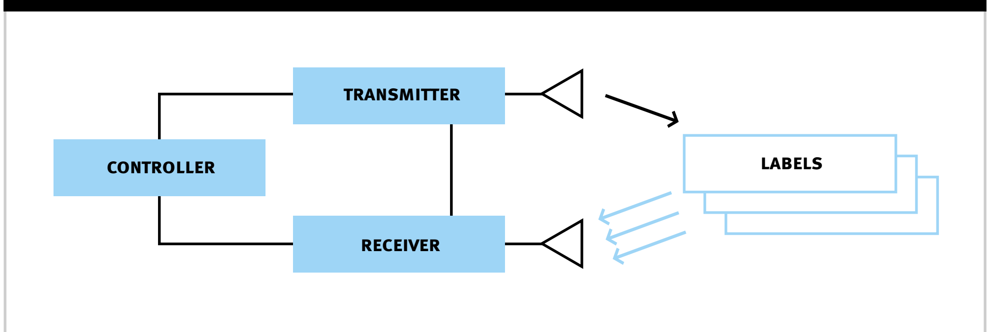
It also contains some very encouraging results which have been obtained with the deployment of very simple equipment of not particularly recent vintage.

2. CONTEXT

An illustration of some aspects of EPC label reading is provided in Figure 1. As the diagram suggests, there is transmission of an interrogation signal from an interrogator to a label, and separately transmission of a reply signal from a label to a receiver.

Figure 1

MULTIPLE LABEL READING



As labels are almost invariably passive, some conversion of interrogation energy to electrical energy within the tag must take place, and only this energy is available for forming of the reply. Thus the label reply is weak. It must be detected in the presence of environmental noise or extraneous signals, some of which may come from the interrogator, or from other interrogators.

In contradiction of the impression which might be gained from the diagram of Figure 1, a single antenna is normally used within the interrogator for both transmission of the interrogation signal and reception of the reply signal. Thus the interrogator normally includes means for **separation of the interrogation and reply signals**.

In order to understand how we can best design systems of this nature, will have to begin with a discussion of the nature of the electromagnetic fields which are used to communicate to and from the label.

3. THE NATURE OF ELECTROMAGNETIC FIELDS

3.1. Introduction

In this section we will consider the nature of electromagnetic fields that are **changing in time**, as unchanging fields are not suitable for the transmission of information to or from electronic labels.

We will consider fields in both the HF (3 to 30 MHz) region and the UHF (300 to 3000 MHz) region.

We will use the names for electric and magnetic field quantities as specified in ISO 1000 [1] and as appear below.

ELECTROMAGNETIC FIELD VECTORS		
Electric field	**E**	Volts per metre
Electric flux density	**D**	Coulombs per square metre
Magnetic field	**H**	Amperes per meter
Magnetic flux density	**B**	Webers per square meter

The font chosen here is intended to carry the implication that the fields are oscillating in the sinusoidal steady state and are represented by time independent phasors of which the magnitude is equal to the **peak value** (not the r.m.s. value) of the oscillation. A different font will be employed below when time varying fields are considered.

The real distinctions, apart for the difference in units, between the electric field **E** and the electric flux density **D**, and between the magnetic field **H** and magnetic flux density **B** are only apparent when dielectric and magnetic media are present. In our context such media are absent from the propagation region between the interrogator and the labels, so what we say in Section 3.4 about the electric field **E** applies also to the electric flux density **D** and vice versa; and what we say about the magnetic field **H** applies also to the magnetic flux density **B** and vice versa.

3.2. Frequency – Wavelength Relation

Important properties of electromagnetic fields when they are propagating between an interrogator and the label are the frequency **f** and wavelength **λ** which are related by

$$\mathbf{c} = \mathbf{f}\,\lambda$$

Where **c** is the velocity of electromagnetic propagation in free space, and has the value 300,000,000 m/s.

Particular frequencies of interest are 13.56 MHz in the HF region, at which frequency the wavelength is 22 m, and 915 MHz in the UHF region, at which frequency the wavelength is 328 mm.

Knowing the wavelength for the frequency in use is very important, as we shall see Section 4.2 that it establishes the boundary between the **near field**, in which the fields behave in one way, and the **far field**, in which the fields behave in quite another way, although both fields are useful in RFID systems.

3.3. Electrodynamic Laws

The basic laws of microscopic electrodynamics are Maxwell's equations [2], which are most economically written as

$$\nabla \times \mathsf{E} = -\frac{\partial \mathsf{B}}{\partial t} \qquad \nabla \times \mathsf{H} = \mathsf{J} + \frac{\partial \mathsf{D}}{\partial t} \qquad \nabla \cdot \mathsf{D} = \rho \qquad \nabla \cdot \mathsf{B} = 0$$

where a font different from that used in Section 3.1 has been chosen for the field vectors to signify that in these equations the fields are not restricted to the sinusoidal steady state, but can have any time variation, including none.

Fortunately, one does not have to be expert in vector calculus to extract significance from these equations. The significance for RFID systems, and in particular for the fields which couple to labels on products on supermarket shelves, are developed in the next two sections.

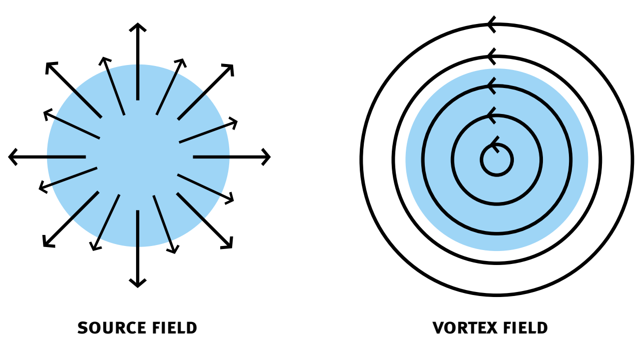
3.4. Source and Vortex Fields

Although the laws of electrodynamics come from Maxwell, they are most readily comprehended in terms of the **source and vortex interpretation** of Helmholtz, and in terms of the **field pictures** of Michael Faraday.

Helmholtz has shown that vector fields may be regarded as the superposition of two different basic field types, known as source type and vortex type, both of which are illustrated in Figure 2.

Figure 2

SOURCE AND VORTEX FIELDS



In the illustration of a **purely source field**, we see field lines of electric field originating in a region of positive charge. If those field lines terminate somewhere, it will be in a region of negative charge. These source type field lines never intersect, nor close upon themselves.

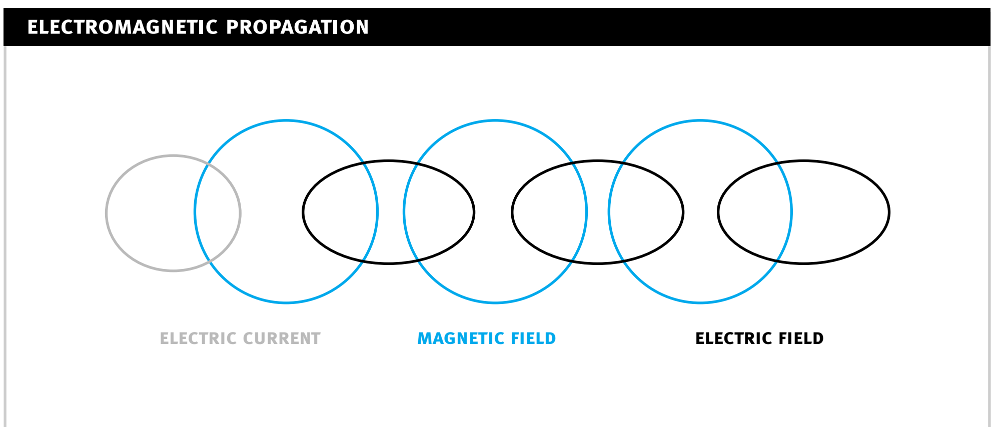
In the illustration of a **purely vortex field**, we see field lines of magnetic field surrounding a wire carrying a current. These vortex field lines are always in the form of closed curves, and never have a starting point or an ending point.

What we learn about electric fields from Maxwell's equations is that the electric field **E** can be either **source type** or can be **vortex type**, or can be a **mixture of both**. The regions of space providing sources of E can be charges on conductors. The regions of space providing vortices of **E** are regions where there is a time varying magnetic flux density.

What we learn about magnetic fields from Maxwell's equations is that the magnetic field **H** can, in the absence of magnetic media, be only **vortex type**. The regions of space providing vortices of **H** are regions where there is either an electric current, or **a time varying electric flux density**. For the latter quantity, Maxwell coined the term "displacement current" once he recognised that it fulfilled a role very similar to actual electric current in many aspects of electrodynamics, and in particular in its ability to create a magnetic field.

When electromagnetic fields propagate to a significant distance from their originating antenna, it is the property of time varying electric fields to create surrounding vortices of magnetic field, and time varying magnetic fields to create surrounding vortices of electric field that might be regarded as providing the mechanism for further and further propagation, such as is illustrated in Figure 3 below.

Figure 3: Illustration of electromagnetic propagation.



3.5. Boundary Conditions

When one is faced with the task of picturing a possible electromagnetic field that can exist in the vicinity of material objects, it is extremely useful to make use of some **boundary conditions** that time varying electric and magnetic fields must satisfy in the vicinity of **metallic conductors**. These boundary conditions are readily derivable from a combination of Maxwell's equations and the properties of metallic conductors. We are not, however, concerned here with their derivation, but with their use.

The boundary condition for **electric fields** states that such fields must **always meet a conductor at right angles**.

There may easily be a component of electric field normal to the surface, but there will never be a component of electric field tangential to the surface. This restriction is illustrated in Figure 4.

The boundary condition for **magnetic fields** states that such fields must **always approach a conductor tangentially**. There may easily be a component of magnetic field tangential to the surface, but there will never be a component of magnetic field normal to the surface. This restriction is illustrated in Figure 5.

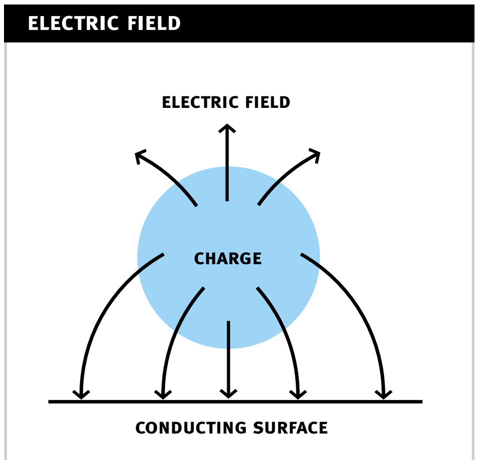


Figure 4: Boundary condition for electric fields.

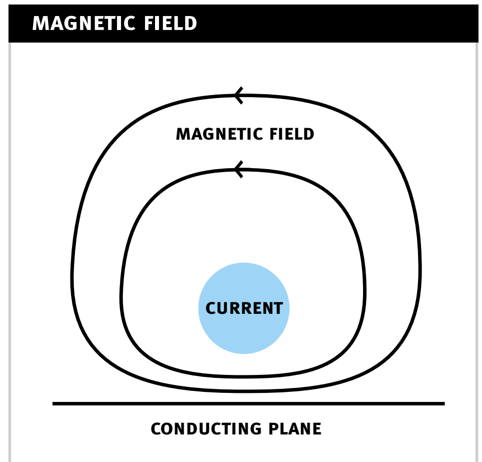


Figure 5: Boundary condition for magnetic fields.

3.6. More about Magnetic Fields

There are in fact three important things that are illustrated by Figure 5. One is the boundary condition just stated. Another is the previously stated fact that the magnetic field lines must flow in closed loops. The third is that they must always enclose either a region of electric current, or what Maxwell has called a **displacement current**, that is a region of time varying electric field of flux density.

One aspect of this last statement which will become important later is that it is only at very high frequencies, such as at UHF, and where the electromagnetic propagation is occurring, that it is practicable for displacement current to take on the role of creating magnetic field. At lower frequencies, and in particular at HF, and with non-propagating fields, only electric current has a sufficient strength to create a worthwhile magnetic field.

4. PROPERTIES OF ELECTROMAGNETIC COUPLING LINKS

4.1. Introduction

We intend in this section to provide a summary of two mathematical formulations of the energy transfer which can take place between an interrogation antenna and the label antenna in an RFID system.

But before we begin this study will need to know more about the properties of near and far fields such as can be created by the electromagnetic antennas in an interrogation system.

4.2. Near and Far Fields

In considering the electromagnetic fields generated by a transmitting antenna, it is useful to distinguish between what is called the **near field**, which is the field within a distance of about **$\lambda/2\pi$** of the antenna, and what is called the **far field,** which is the field at a distance greater than about **$\lambda/2\pi$** from the antenna.

The near field is basically an **energy storage field**. It is concerned with the storage of energy per unit volume in electromagnetic form in the region close to the antenna, and is not concerned to any significant degree with the propagation of energy away from the antenna. It can be regarded as intimately associated with the charges on the antenna or the currents within it. Twice per cycle of oscillation, the energy stored in that field disappears from space and re-enters the antenna.

In contrast, the far field is basically an **energy propagation** field. It is concerned with a propagation of energy per unit area per unit time in electromagnetic form away from the antenna. It is no longer intimately associated with the charges and currents in the antenna, but can be thought of as generated by the electromagnetic fields that stand between the antenna and the far field point. This aspect was illustrated in Figure 3.

At any point of space, there is really a mixture of the near field and the far field, but within the near field-far field boundary, the near field is by far the greatest, and outside of the near field-far field boundary, the far field is by far the greatest.

These differences come about because the energy density per unit volume in the near field diminishes as the inverse sixth power of distance from the antenna, whereas the energy density per unit area in the far field diminishes only as the inverse second power of distance from the antenna. The far field is therefore the field that tends to dominate at large distance.

The relations just stated apply to idealised forms of antenna which are physically small. When we are speaking of the distance from the antenna that is not large compared to the size of the antenna itself, those statements need to be modified. Generally the rate of variation of energy density with position close to the antenna is less than in the previously quoted simple relations.

The significance of the near field-far field distinction can be best appreciated by reciting the value of the boundary distance **$\lambda/2\pi$** for the most common frequencies used for RFID systems. At 13.56 MHz, **λ** is about 22 m, so the boundary distance is about 3.5 m. At 915 MHz, **λ** is about 328 mm, so the boundary distance is about 50 mm.

Our conclusion is that HF systems operate in the near field, while UHF systems operate in the far field.

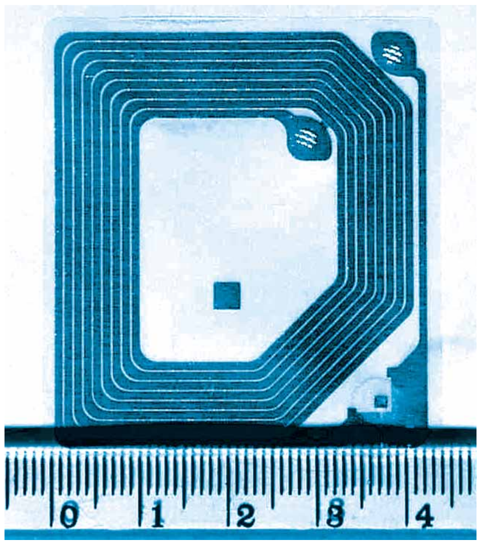
4.3. Relation between Fields

In the near field, the electric field and the magnetic field have a degree of independence. It is possible to design antennas which create, in the near field, largely electric field **E** and very little magnetic field **H**, and different antennas which create, in the near field, largely magnetic field **H** and very little electric field **E**.

As electric field **E** is easily stopped by many materials, most interrogation systems operating at HF seek to generate mostly magnetic field **H**. As a consequence, the label antennas for these systems seek to couple to magnetic field.

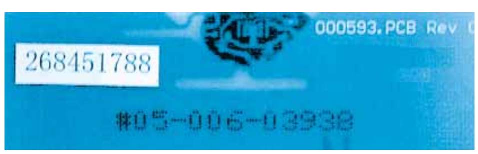
Such an antenna normally takes the form of a multi-turn planar coil such as is illustrated in Figure 6. The label can be regarded as excited by an induced voltage created, through Faraday's law of electromagnetic induction, by the time rate of change of magnetic flux which links the coil. This being the case, the label receives maximum excitation when the magnetic field meets the plane of the label, which is made on a plastic or paper substrate, at right angles. If the magnetic field is in the plane of the label, there is no coupling.

Figure 6: Example of an HF magnetic field antenna.



An illustration of the label antenna for coupling at UHF is provided in Figure 7. A simple description of coupling to this antenna, corresponding to that for coupling to the antenna shown in Figure 6, cannot be given, for the reason that near field creation and exploitation can be described in terms of lumped circuit theory, in which the full set of Maxwell's equations are not required, whereas radiation between antennas which are large enough to be regarded as good radiators in the far field, requires all four Maxwell equations to be employed, and the analysis proceeds to greater length, and involves some advanced theorems, such as the Lorenz reciprocity theorem.

Figure 7: Example of a UHF electromagnetic antenna.



However, some simple statements can still be made. One is that in the far field, electric field **E** and magnetic field **H** have a fixed ratio η, which has the value 377 ohms. Another is that it does not matter if the label seeks the couple to one field or the other field, as long as it does so efficiently.

An exception to this statement can be found when the label antenna which is very tiny is placed in the far field of an interrogation antenna. It is possible then to use a hybrid of radiation antenna theory and coupling volume theory [3], both of which are explained in sections following shortly below, to determine the coupled power.

4.4. What the Interrogator Fields do

In both HF and UHF systems the effect that any activity, within the label, has within the interrogator antenna, is very small. Thus in seeking to understand how good an interrogation antenna is at either frequency we can usefully focus our attention on what the fields surrounding that antenna really do.
In the near field it is, as already discussed, energy storage. In the far field it is energy propagation away from the antenna. These differences lead to different conceptual schemes which have been found fruitful for the calculation of energy transferred from the interrogator to the label.

At HF, where coupling is in the near field, we employ **coupling volume theory**, and focus attention on the **energy stored per unit volume** in the region occupied by the label.

At UHF, where coupling is to the far field, we use **radiating antenna theory**, and focus attention on the **electromagnetic power flow per area** flowing past label.

4.5. Coupling Volume Theory

It is practicable here to give only an outline of coupling volume theory. It is left to the reader to complete the algebraic steps that have been omitted between the equations below.

In near field RFID systems, coupling is almost always via magnetic field. Such magnetic field is created by an interrogation antenna that has the form of a large coil having either a single turn or a plurality of turns. In order to couple to this magnetic field, the label antenna normally takes the form of a small planar coil, normally with a plurality of turns.

The energy transfer is provided by the magnetic field of the interrogator coil creating, via Faraday's law, an induced voltage in the label coil. The situation can be analysed by lumped circuit theory. No radiation theory is in fact required.

From the equations of lumped circuit theory applied to mutually coupled coils, it is easy to show that the ratio of the power $\mathbf{P_r}$ dissipated in the loss resistance of the label coil to the power $\mathbf{P_t}$ which must be supplied to the loss resistance of the interrogator coil is given by

$$\frac{P_r}{P_t} = k^2 Q_1 Q_2$$

where $\mathbf{Q_1}$ and $\mathbf{Q_2}$ are the quality factors of the resonances of the interrogator and the label coils respectively, both of which are assumed to have been tuned to resonance at the interrogation frequency, and **k** is the coefficient of coupling between the coils. The coefficient of coupling **k** is a dimensionless ratio defined in terms of the mutual inductance **M** between the coils and the self inductances $\mathbf{L_1}$ and $\mathbf{L_1}$ of the coils as

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

The power ratio relationship shows the importance of employing high quality factors in the resonances of each of the participating coils, and the importance of achieving a good coupling factor between the coils, but it does not point directly to optimisation procedures which may be applied separately to the interrogator and label coils, although intuition suggests that such procedures should exist.

To derive such optimisation procedures, it is first shown that the power transfer relation may be re-written as

$$\frac{P_r}{P_t} = \frac{V_c}{V_d} Q_1 Q_2$$

in which new quantities known as coupling volume $\mathbf{V_c}$ and dispersal volume $\mathbf{V_d}$ appear. Their formal definitions are

$$V_c = \frac{\text{Reactive power in the label inductor when short circuit}}{\text{Reactive power density per unit volume at the label position}}$$

and

$$V_d = \frac{\text{Reactive power flowing in the interrogator transmitter coil}}{\text{Reactive power density per unit volume at the label position}}$$

The benefit of this formulation is that the two quantities just defined are capable of individual optimisation. As an example, it may be shown that the coupling volume for a planar label or of **N** turns, each of which has cross sectional area **A**, and label self inductance **L** is given by

$$V_c = \frac{\mu_0 N^2 A^2}{L}$$

When the coil turns do not have all the same area, as is common in a spiral coil such as was illustrated in Figure 6, the factor **NA** in the above formula is replaced by the sum of the flux collecting areas of the individual turns.

We emphasise again that coupling volume theory shows that the principal role of an interrogation antenna is to create an **energy storage** field within which the label sits. There is no need at all for the interrogator to radiate energy to the far field. Indeed, as electromagnetic compatibility regulations are enforced in the far field, it is desirable to construct HF antennas which create energy storage fields but from which minimal radiation occurs.

Simple coils which are small enough to have, despite the requirements of Pocklington’s theorem [4], a uniform current distribution around their periphery, have less radiation than larger coils, in which the non-uniform current distribution around the periphery causes those coils to take on some of the properties of electric dipole radiators, which have greater radiation to the far field.

So from the point of view of minimisation of radiation, small coil antennas may be desirable for use at high frequencies. However, the variation of field with distance from such small coil antennas can be quite severe, and can unduly tax the dynamic range of correct and safe operation provided in the label. This issue represents one of the complications which enter into the design of shelf antennas at high frequencies.

4.6. Radiating Antenna Theory

As the theory of coupling between antennas placed in the far field of one another [5] is much better known than the theory outlined in the previous section, only a brief outline of the principal results will be presented here.

For the determination of the power which may be extracted by a label antenna which is placed in the far field of an interrogator antenna it is logical first to calculate, at the label position, the power flow per unit area caused by the interrogator transmitter antenna. The power flow per unit area is given by

$$\text{Power flow per unit area} = \frac{g_t P_t}{4\pi r^2}$$

wherein $\mathbf{g_t}$ is a gain of the transmitter antenna and $\mathbf{P_t}$ the power which it transmits, and **r** is the distance from the transmitter antenna to the label position. In using this formula, we are implicitly assuming that the label has been placed in the direction of strongest radiation from the interrogator antenna.

The power $\mathbf{P_r}$ which may be extracted under optimum conditions of tuning and matching by a lossless label antenna placed at the above position is given by

$$P_r = A_{er} \times \text{Power flow per unite area}$$

wherein $\mathbf{A_{er}}$ is a property of the label known as its **effective area**. It is unrelated to the physical area of the antenna, (which if it is just piece of thin wire, does not have a physical area), but has the desirable property that we may imagine the label antenna collects all of the radiated power which flows through that effective area which may be thought of as surrounding the label antenna.

The **Lorenz reciprocity theorem** of electrodynamics may be used to show that the effective area of a receiving antenna is related to the gain $\mathbf{g_r}$ it would have in a transmitting role by the equation

$$A_{er} = \frac{g_r \lambda^2}{4\pi}$$

Label antennas are normally electrically small, that is dimensions are small compared with wavelength. It is a consequence of this fact that the gain of such antennas is always about 1.5, and the effective area of those antennas is not much influenced by their design.

What is influenced by their design is firstly whether they are sensitive to electric or magnetic fields, and secondly whether they have internal reactances or internal losses that make the extraction of the theoretically achievable received power difficult. These two issues play a big part in the design of suitable label antennas for use at ultra high frequencies. But since this paper is substantially about interrogator antennas rather than label antennas, we will not consider these issues further here.

Before leaving this section we produce two results which are simply rearrangements of the several relations above. These are

$$\frac{P_r}{P_t} = g_r \, g_t \left(\frac{\lambda}{4\pi r}\right)^2$$

and

$$\frac{P_r}{P_t} = \frac{A_{et} \, A_{er}}{\lambda^2 \, r^2}$$

These two results have the benefit of showing clearly the equal contribution that the transmitter antenna gain and receiver antenna gain make towards the power transfer, and of emphasising the reciprocity property that the two antennas could be interchanged without changing the optimum power transfer ratio.

4.7. Properties in Common

We now list the properties which coupling volume theory and radiating antenna theory have in common.

The first is that they both exhibit a **reciprocity property**, which indicates that, when a single pair of terminals is used for connection to each of the interrogator and label antennas, the propagation loss in the direction from the interrogator antenna to the label antenna is the same as the propagation loss in the direction from the label antenna to the interrogator antenna.

This conclusion is relevant to the question of whether a label can be strongly excited but its reply could be too weak to be heard.

4.8. Properties in Contrast

We now list the properties of the two formulations which stand in contrast to one another.

4.8.1. Losses in antennas

The first of these is the extent to which losses in each of the antennas has been considered. In coupling volume theory, the quality factor of the transmitter antenna is entirely due to its intrinsic losses. The effect of any radiation resistance in this antenna is assumed to be negligibly small. There does not seem to be a practical situation in which this policy needs to be varied. In near field coupling therefore, most of the power delivered to the transmitter antenna is converted to heat.

These facts may not matter, as what we are seeking to do is to create energy storage fields close to the transmitter antenna, not generate radiation there from, which radiation is in fact unwelcome, as it is subject to electromagnetic compatibility regulation.

In the coupling volume theory, at the label end, the quality factor of the label antenna is caused by both its intrinsic losses and by power which may be drawn from the label circuit. If one is interested in the question of how to deliver the maximum power to the label circuit, this result may be obtained when the power to the label circuit is equal to the power lost in the intrinsic resonance circuit losses, and the quality factor of the label circuit at which this occurs is just half of the quality factor which occurs when no power is delivered to the label circuit.

So it may also be that a significant amount of power which reaches the label is also converted to heat. Such powers should not necessarily be regarded as wasted. The label makes its reply felt back at the interrogator through having a significant amount of reactive power flowing in the label circuit, and any power necessarily dissipated in sustaining the oscillation within the label circuit may be regarded as usefully expended. It does not follow that we require the label circuit to consume as much power as is dissipated in sustaining the tuned circuit losses. Provided we can establish a large amount of reactive power in the label circuit, and successfully modulate it, we are entirely happy if the control circuit that accomplishes this consumes very little power.

In radiating antenna theory, we have avoided the question of whether or not of the interrogator transmitting antenna is efficient by simply defining $\mathbf{P_t}$ as the actual power which is radiated. In practical situations there will be some small loss in the transmitter antenna, and because of this the transmitter will have to supply a power slightly in excess of what is radiated. There is no practical difficulty in taking this into account.

In far field coupling, it is generally true that the transmitter antenna is reasonably efficient, in that most of the power delivered to it is actually radiated, which is what we want to have happen, as the fields to which the label couples are inextricably linked with radiation. It is also true that most of the power that we can potentially extract from the label antenna can really be extracted without the losses in the label antenna intruding too much. Achieving this result does require that we achieve reasonably low loss matching to the very small radiation resistance of the label antenna and the very much greater reactance which stands between that radiation resistance and the terminals of an equivalent circuit for that antenna. It is a standard result of antenna theory that as the antenna is becoming electrically small this problem begins to become acute, but for UHF antennas of a credit card size it is not particularly severe.

When, however, label antennas become very small, the extraction of the theoretically available source power for a lossless antenna becomes an impracticable aim, and coupling volume theory may usefully be employed at the site of the label antenna.

4.8.2. Bandwidth

The second distinction we would make between near field coupling and far field coupling systems is that there is a contrast in relation to bandwidth. In near field coupling, the creation of stored energy in the vicinity of the transmitting antenna is enhanced by having high quality factors, but unfortunately high-quality factor antennas become finicky. They are easily detuned by environmental changes and the benefit of their high-quality factor becomes lost. There is also the question of whether in the high-quality factor combined with the relatively low centre frequency will provide an adequate bandwidth within the antenna for communication at the rate designed.

In the far field, of these two things happen much less. But it does happen that as far field label antennas are made smaller, a number of factors limit their performance. One is that they too develop a small bandwidth and also become finicky. Another is that losses, which are not significant with larger antennas, begin to intrude. Both of these factors have been alluded to above.

4.8.3. Label orientation effects

At HF, it has already been indicated that the basic coupling mechanism is through magnetic flux linking the coil of the label antenna. Mostly the magnetic field oscillates in a single direction, but with difficulty we can make it move around so that it oscillates with different phases into directions, but those two directions are still confined to lie in a single plane. It is impossible with a signal of the bandwidth required by regulators to move the field around in all three directions of space – two is the limit. Thus there are null coupling orientations for the label antenna. The only way to overcome this is to be energise the transmitter antenna generating one field shape, and later to energise another transmitting antenna generating a different field shape.

This happens in principle also at UHF, but in practice it seems to matter less, probably because a number of factors at UHF, such as movement of labels or nearby objects, can produce field stirring without any deliberate changes being made in the interrogator configurations. When, however, labels do not move and the environment does not change, field stirring that can be achieved through multiplexing between different antennas is needed.

4.8.4. Boundary conditions

In both cases fields are shaped by the **boundary conditions** described earlier. The boundary conditions introduce significant restrictions on label orientation in HF systems. If the label shelves are metallic, any magnetic field close to such a shelf will be parallel to that shelf, and an electronic label lying in the plane will be very weakly excited as compared with a label in an appropriate perpendicular direction.

While this is true also to some extent for UHF systems, there is a difference deriving from the fact that fields vary with distance at a rate determined by the propagation constant $\boldsymbol{\beta = 2\pi / \lambda}$.

The result is that the effect of the boundary condition at HF is felt at a considerable distance from the boundary, whereas at UHF effect of the boundary condition is true at that boundary, but rapidly changes as we move away from the boundary.

As an example, at UHF, a metal boundary can cause extinguishment of the tangential component of the electric field **E** (and a doubling of the tangential component of the magnetic field **H**) as compared with the fields that will have existed at the boundary if it were not present, but 80 mm from the boundary, it is the tangential component of the magnetic field **H** which is extinguished while the tangential component of the electric field **E** is doubled.

This gives UHF systems some interesting properties. If we can make the labels, or the boundaries, move, we can produces some situations in which there is considerable reinforcement of the electromagnetic fields, and labels which would not have read without the movement become good responders.

4.9. Reciprocity

Reciprocity is a fundamental property of electromagnetic fields subject to a static environment and where a single pair of terminals is used to energise whatever transmitter and receiver system is in use in the interrogator, and another single pair of terminals is used to deliver signals from whatever label antennas system is used in the label circuit. This is the normal arrangement.

Basically, the reciprocity theorem states that in the circumstances described above the coupling from the interrogator to the label is equal to the coupling back from the label to the interrogator.

The theorem allows us to expect that a strongly excited label will give a strong reply. Also we do not expect a label to be able to give a strong reply and not be able to clearly receive command signals from the interrogator.

5. ELECTROMAGNETIC COMPATIBILITY ISSUES

5.1. Introduction

We will have space in this report to make only a few remarks about this very large subject.

5.2. Enforcement

It is noted that at both UHF and HF, electromagnetic compatibility regulations are enforced in the far field.

In the measurements, reflections from the environment, at least from a ground plane, must be allowed for, in the sense that when such reflections occur, a reduction in the radiated power is required.

5.3. Remarks for UHF Systems

At UHF use of interrogator transmitter antennas with high gain is self-defeating, as the regulations are usually written in terms of the radiated power density per unit area, with the result that the use of high gain transmitter antennas requires a corresponding reduction in transmitter power.

Thus quite low gain UHF antennas, i.e. with broad angular coverage are preferred.

5.4. Remarks for HF Systems

The way to obtain good spatial coverage with HF antennas without excessive variation in the amplitude of the field produced over the range of space intended to be occupied by product is to use antennas with physically large areas.

Such antennas are more likely to radiate to the far field, and a compromise on antennas size is required. Some antenna configurations suitable for use at HF can create strong local fields and diminished radiation to the far field, and should be considered if other aspects of their product coverage is satisfactory.

6. SHELF ANTENNA DESIGN

6.1. Introduction

In the design of antennas for supermarket shelves we need to achieve the following

- Create fields of appropriate orientation.
- Create fields of reasonable uniformity, so that the dynamic range of labels is not overtaxed.
- Our antennas should not be too finicky because they are of too high a quality factor.
- The labels should be easy to manufacture.
- This probably means that they should fit in easily with existing shelf design.
- The labels on products should be placed where the best parts of the field are.
- For HF systems the antenna and shelf design must allow for a complete flux path, and must surround conduction current, not merely displacement current.

6.2. Standard Shelving

For the purpose of experimentation, a brief survey of shelving found in supermarkets was carried out, and some standard shelving materials were obtained from suppliers for erection in one of our laboratories.

A common shelf arrangement found in major chains of supermarkets is illustrated in skeletal form in the figure below, which provides an illustration of the shelf arrangement which we purchased.

Figure 8: A form of standard shelving

For simplicity in the laboratory, the shelves are single sided, but mostly in supermarkets a single spine supports shelves on two sides. In addition, there are supports provided on each of the front sides, as well as the supports that are provided at the spine.

The uprights supporting the shelves at the front, absent in our structure, were generally found to be at 1800 mm spacings. The upright supports at the spine, as in our structure, are generally found to be at 900 mm spacings. Most shelves were 550 mm deep from front to back. Many shelves had a vertical separation of 420 mm. An exception can be found for paper goods such as tissues or toilet paper, in which case a vertical shelf spacing of 660 mm was noted.

Most of the shelves were constructed from nickel or chromium plated mesh made from round steel bars separated 20 mm in the width direction and 90 mm in the depth direction. It is assumed that the very common mesh construction has been adopted so that extraneous materials may fall to the floor which is the only surface requiring frequent cleaning. In one of the major chains the mesh gaps were reduced from 20 mm as mentioned above to 10 mm as present in our structure.

However, the shelves not always wire. Some supermarkets employ a small proportion of flat metal shelving, and some use that extensively.

Sometimes shelving is sloped downward to the front edge in order to improve product visibility. A feature of the shelf vertical spacing which was noted was that it was frequently variable and suited to product height, thus obviating the need for unstable stacking of products in order to achieve high display density.

In fact the only products that we found stacked were those for which little damage to people or the products will occur if the products tumbled to the floor.

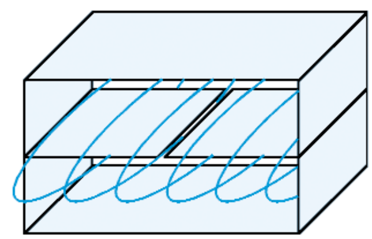
It is a fortunate fact that such products, such as tissues and toilet rolls, are normally electromagnetically highly transparent.

6.3. Case Study at HF – The Quadruple Shelf Pair

The structure we consider here is shown in outline form in Figure 9 below. The magnetic field lines, which are shown in blue are created by current which flows horizontally along the central shelf, and returned via the upright sections to flow in the opposite direction of the topmost and bottom most shelves.

Figure 9

THE QUADRUPOLE SHELF PAIR



The diagram shows a single feed point space for the injection of current in the centre of the metal shelf, but appropriately phased feed points in all shelves may be considered.

The structure has the advantage that the field lines are reasonably uniform throughout the region that will be occupied by product, and are totally compatible with a shelf structure in which all horizontal and vertical elements other than the central spine are conducting.

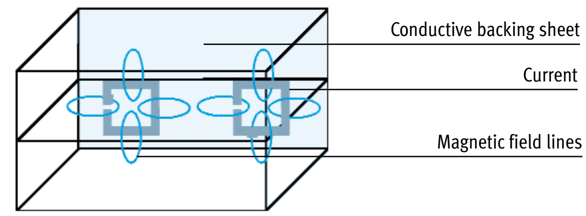
The structure has, however, the disadvantage that the magnetic flux path involves not only the shelves facing one supermarket aisle, but also the shelf at corresponding height facing a neighbouring aisle. This simple field configurations precludes the use of the conducting mesh back plane almost always present in supermarket shelf configuration, and is for that reason considered to be unlikely to be adopted.

6.4. Case study at HF – The Forward Facing Loop

An option that can be considered for operation at HF is the installation of a number of loop antennas towards the rear of each shelf, but sufficiently spaced from the conductive mesh which separates the shelves facing one aisle from those facing another, such as is shown in Figure 10 below.

Figure 10

FORWARD FACING LOOPS



Several things become clear from examining the figure. One is that a return flux path must be provided behind the conductive loops. Allowing too small space for this flux path will create oppositely phased images of the antennas behind the backing sheet with the result that the field variation in front of the antennas, already substantial, becomes even greater. It is true that the effect can be mitigated to an extent by the use of ferrite material within the return flux path, but this is regarded as a costly solution.

Another thing that becomes evident is that the field varies not only significantly in magnitude, but also in direction from point to point, and coupling to product labels that are in a consistent direction cannot always be an assured.

We have conducted so far no experiments on this type of structure.

6.5 Case Study at HF – The Shelf Loop

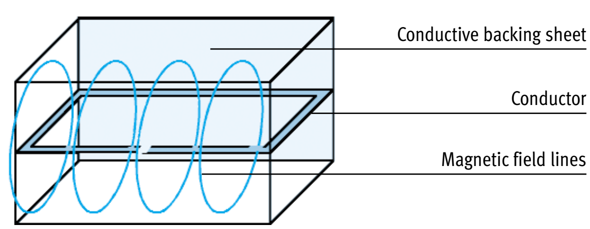
This antenna structure is suitable for non-metallic shelving. It consists of metallic loop which occupies the underside edges of a 900 mm wide and 550 mm deep shelf.

A simplified view of this structure and of the magnetic field pattern which results is shown in Figure 11 below.

A single feed point at the front may be readily tuned and matched to 50 ohms, and a coaxial cable may make connection with the strip and lead to the point of symmetry at the centre of the back of the shelf. Such an arrangement maximises the uniformity of current within the loop.

Figure 11

THE HORIZONTAL SHELF LOOP



Experiments on this structure will be reported in Section 9.

6.6. Issues at HF

It is the intention here to list some of the difficulties that can be expected in the construction and use of HF labelling systems in the supermarket context. Provided however, these issues are recognised in design, HF labelling systems appear to be usable, at least for a substantial number of products. The issues to be considered are:

- HF antennas are expected to be resonant, and significant detuning must be avoided.

- In the detuning process, the separation between transmit and receive signals, which may depend upon good antenna matching, begins to diminish. In consequence, phase noise present in the output of the transmitter may be deflected into the receiver. Fortunately, the development of low phase noise transmitter signals for HF operation seems to be a reasonably soluble problem.

- If the antennas become large, then three things relevant to far field radiation begin to occur. Firstly the driving power must be increased, as a larger region of space must now be filled with a reactive power density. Secondly the parameter known as the radiation resistance will increase (which actually promotes radiation), and will do so as a fourth power of antenna size. Thirdly, the current distribution becomes non-uniform, and radiation will further increase as a consequence of the structure's taking on some aspects of an electric dipole rather than simply a magnetic dipole radiator.

6.7. Issues at UHF

It is the intention here to list some of the difficulties that can be expected in the construction and use of UHF labelling systems in the supermarket context. Provided however, these issues are recognised in design, and the note is taken of current or feasible shelf stacking policies, UHF labelling systems appear to be eminently usable. The issues to be considered are:

- Some objects are readily transparent to UHF fields while others would exhibit significant absorption. The placement of labels on objects should be in positions in which the interrogator signals will readily reach them. The previously mentioned shelf stacking policies which have been observed in existing supermarket practices lead to the conclusion that antennas placed immediately below one shelf will readily illuminate the products in the space below, provided the labels are placed at the top of products that are likely to be highly absorptive.

- Multipath propagation is strongly present in UHF systems, and field stirring through the use of multiplexed antennas is essential.

- What is known as the null position problem of homodyne receivers is particularly relevant at UHF where a label may move only a distance of 40 mm for the phase of its reply signal returned to the interrogator to change by 90 degrees. These matters will become clear in a later section which discusses interrogator architectures, but may be readily handled through the use of UHF interrogators with a capacity to detect both in phase and quadrature components of label replies.

- In the design of highly sensitive interrogators, the effect of transmitter phase noise entering the receiver must always be considered. The extent to which this can occur depends upon isolation achievable between signal paths in the interrogators. Some of these paths involve reflection from the environment. It is fortunate that the desire to be able to identify product location with reasonable accuracy produces situations in which extreme interrogator sensitivity is not required, and the phase noise problem, which is quite notable with long-range UHF interrogators, does not appear to be highly significant in our experiments.

7. LABEL ARCHITECTURE

7.1. Introduction

Our aim in this section is to provide some idea of the internal structure of some common designs of RFID labels. Although there will not be important conclusions drawn about the design of shelf antennas from this section, it is believed that readers will be more comfortable with reading the paper as a whole if some idea of a possible internal structure of labels is presented.

We will not attempt to cover all possible label architectures, just the simpler ones.

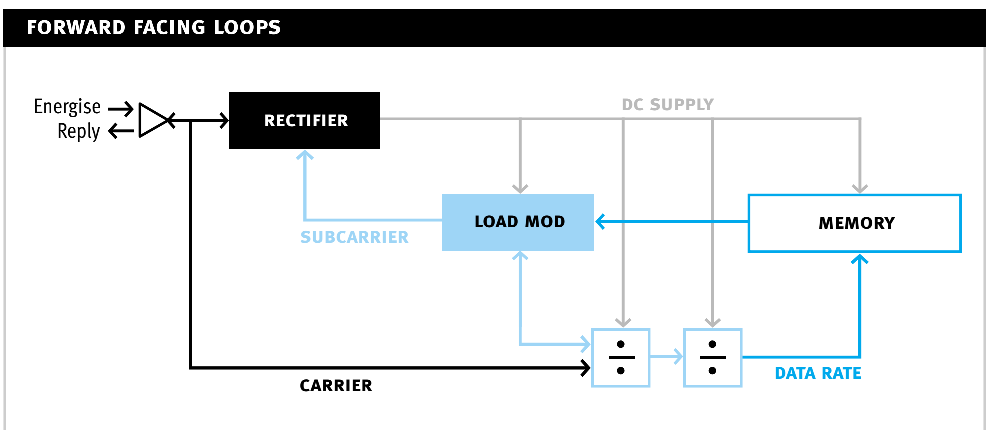
7.2. A Traditional Architecture

A traditional passive RFID label architecture [6] is shown in Figure 12 below. Important aspects illustrated by this figure are that a direct current supply for all circuits is provided by rectification of the incoming signal, and that the reply signal is often generated by periodically leading this rectifier, rather than directly modulating the received signal.

Also shown is that the reply is generally modulated upon a sub-carrier signal whose frequency is small in relation to the interrogation signal, and is itself several times the data rate.

One of the implications of the figure is that both the sub-carrier and carrier are synchronously generated by counting down from the carrier, but this practice is by no means universal, and is not practical to employ in UHF labels. In those cases on-chip oscillators generally play a role in establishing the sub-carrier frequency and the data rate. In jurisdictions which allow substantial modulation of the interrogation carrier, however, timing signals can come to the label via that route.

Figure 12: Traditional label architecture.



For the labels for which experimental results will be reported later in this paper, the reply sub carriers have always been generated asynchronously. The method by which the reply data has been modulated on those sub-carriers has included both phase modulation and frequency modulation, in the latter case in an unusual version in which four cycles of sub-carrier are always used for each bit of data, irrespective of the sub-carrier frequency in use.

Another aspect of label design not captured in the figure is that at HF, the label antenna is the inductor of a tuned circuit. Yet another aspect of label design not captured in the figure is that at UHF, high sensitivity may be obtained with small labels by having the junction capacitance of the rectifier system a significant component of a resonance involving the label antenna. Both of these aspects will be referred to in sections below.

7.3. Desirable Characteristics

7.3.1. HF labels

At HF losses in an unmodulated label are small. To avoid finicky labels, it is desirable to keep the quality factor at a sensible level. With that quality factor, we should aim to employ as high a self-inductance and as low a capacitance as is practicable, given the label antenna size.

When the label quality factor is kept to a sensible level, there is some influence on label operating power.

Another issue affecting label design is that of providing adequate dynamic range over which the label will operate successfully, or will not suffer damage. Once this issue is recognised, it has implications for interrogator antenna design. The implications are that conducting surfaces should be made sufficiently large that high current densities, and the associated adjacent high magnetic fields, are avoided. Another implication is that the extreme variation with distance of the magnetic field from a small dipole should where possible be avoided through making the label excitation structures of significant size.

7.3.2. UHF labels

For UHF labels, we have the possibility of designing a label antenna that responds either to electromagnetic fields (this being the case when the label antenna is reasonably efficient), or primarily to electric field or to magnetic field, (this being possible when the label is very small indeed).

In the normal situation, labels which are to be placed on products will be electrically small (this means of a dimension substantially less than a half wavelength), and will only operate with reasonable efficiency over a narrow bandwidth. It is again a consequence that we may wish to avoid labels which are finicky because they are easily mistuned. This objective has two consequences. One is that we should avoid making labels excessively small. The other is that the labels need to be designed with the knowledge of the immediate environment in which they will be placed, particularly if they are to be placed close to metal surfaces on a product. In the latter case they must be designed so that they will couple well to the magnetic fields which will be tangential to such surfaces. Fortunately, all this is possible, but such labels will occupy volume, rather than be of negligible thickness.

It is also a notable characteristic that at UHF, the capacitance of the rectifier junction plays an important role in any matching circuit that attempts to optimise the extraction of power from the label antenna. Very good performance can be obtained when this issue is recognised and exploited.

The question of label dynamic range is, as with HF labels, also important.

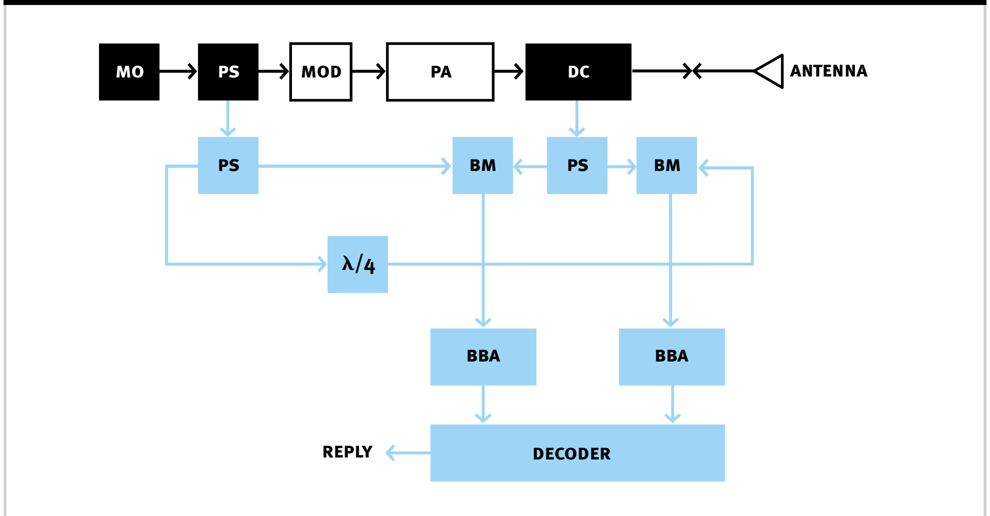
8. INTERROGATOR ARCHITECTURES

8.1. Introduction

A traditional architecture for a good quality RFID interrogator is shown in Figure 13 below. The design is that of a homodyne transmitter-receiver combination in which a single master oscillator generates the interrogator carrier and also serves as a local oscillator for the receiver.

Figure 13

A TRADITIONAL INTERROGATOR ARCHITECTURE



A single antenna is used for both the transmitter and receiver, and a directional coupler is used for separating transmitter and reply signals. Separate channels for in phase and quadrature signal detection deal at UHF with substantial, and effectively uncontrollable, phase shifts in the reply signal as a label position is varied.

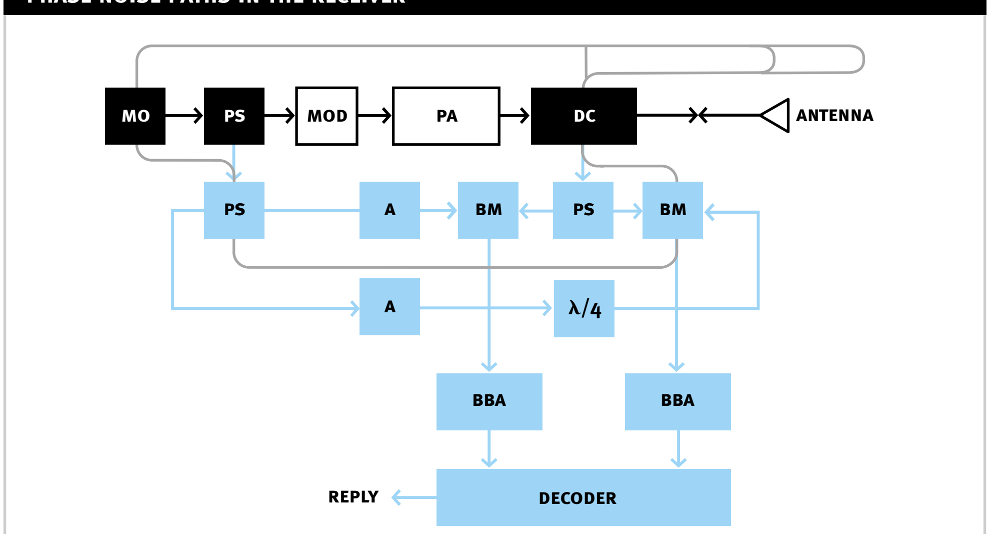
It has been found in the design of sensitive, long-range UHF labelling systems that one of the factors limiting range is phase noise in the transmitted signal [7] which may leak into the receiver.

The two techniques for keeping phase noise of the transmitter out of the receiver are to use a well-matched antenna and a directional coupler of high directivity, or to use separate transmitter and receive antennas which are uncoupled from one another. In the latter case, in HF designs, a high-quality factor transmitter antenna is advantageous.

The pathways by means of which phase noise from the transmitter may reach the receiver are illustrated in Figure 14 below.

Figure 14

PHASE NOISE PATHS IN THE RECEIVER



8.2. Problems with Unmatched Interrogator Antennas

Analysis of the effects of phase noise shows that it depends upon the strength of the directly scattered signal into the receiver, as illustrated by the grey pathway in Figure 14, and the amount of a shift involved in the paths shown in the diagram, both at the carrier frequency of the interrogator, and at the sub-carrier frequencies employed in the label reply, as well, of course, on the strength of the signal scattered into the receiver from pathways not involving the label.

As many of the amplifiers used in the architecture have significant group delay, phase noise is a concern, particularly when we expect the shelf antenna environment to not permit consistently low antenna reflection.

8.3. Other Interrogator Architectures

Variations on this traditional interrogator architecture can be found in the industry.

In one variation, suited to economical manufacture, the directional coupler, balanced mixer, power splitter and local oscillator phase shifter which provide for both in the phase and quadrature reply signal detection are replaced by a pair of amplitude detectors spaced one eighth for the wavelength apart on the antenna feed line.

In another variation, the reply from many labels is systematically built up from the number of partial replies elicited from labels through a number of short interrogator transmissions.

Despite these variations, it is not believed any significant change to label readability, relative to that provided by the architecture described in Section 8.1, will result.

9. EXPERIMENTAL WORK

9.1. Objectives

The objectives of experimental work reported here were:

- To see whether clear label replies could be obtained from labels placed in the supermarket shelf environment with interrogation systems of the type which will satisfy electromagnetic compatibility regulations.

- To obtain some idea of the field coverage which could be obtained with various interrogator antenna designs.

9.2. Available Equipment

The equipment which could be assembled in a short time and the minimum cost consisted of

– The supermarket shelving system previously illustrated in Figure 8 above.

– An early model (vintage 1990) UHF interrogator system [6] with prototype labels designed for a waste management system. This system employed labels with asynchronous on chip oscillators designed to operate at a frequency in the vicinity of 200 kHz, and to employ binary phase shift keying to modulate its reply onto the sub-carrier. The label operating power is high by current technology standards, so whatever performance we see here is certain to be exceeded by current technology. Appropriate modifications to the system were made so that its peak power output was within current FCC regulations for frequency hopping equipment.

  The antenna system successfully employed with this equipment consisted of a circularly polarised patch antenna with an overall gain of about 5 dB, or 2 dB if one considers the gain from the input terminal to each of the output polarisations.

– A more recent model multiple read HF interrogator system with prototype labels designed for a document management system. In this system a power output of 800 mW to an antenna of quality factor 14 was employed. This system also employed labels with asynchronous on-chip oscillators designed to operate at sub carrier frequencies of 250 kHz and 400 kHz, in which the label reply is provided by frequency modulation of the sub-carrier between those two values. The label operating voltage is high by current technology standards, and EPC labels under development are expected to have performance exceeding those used here.

  The extent of far field radiation from the loop antennas used in the experiments has not yet been determined.

9.3. Illustration of Waveforms

9.3.1. UHF system

The baseband signals observed in the UHF system when labels were moved generally over the field of illumination of UHF system, which was one shelf bay, are shown in Figure 15 below. Both in phase and quadrature baseband signals are shown.

Clearly the baseband signals have a very high signal to noise ratio. The intervals of the phase change are very clearly discernible.

9.3.2. HF system

The baseband signals observed in the HF system when labels were moved generally over the field of illumination of HF system, which was one shelf bay, are shown in Figure 16.
Again both in phase and quadrature signals are shown.

Figure 15: Illustration of baseband signals showing phase modulation.

BASEBAND SIGNALS SHOWING PHASE MODULATION

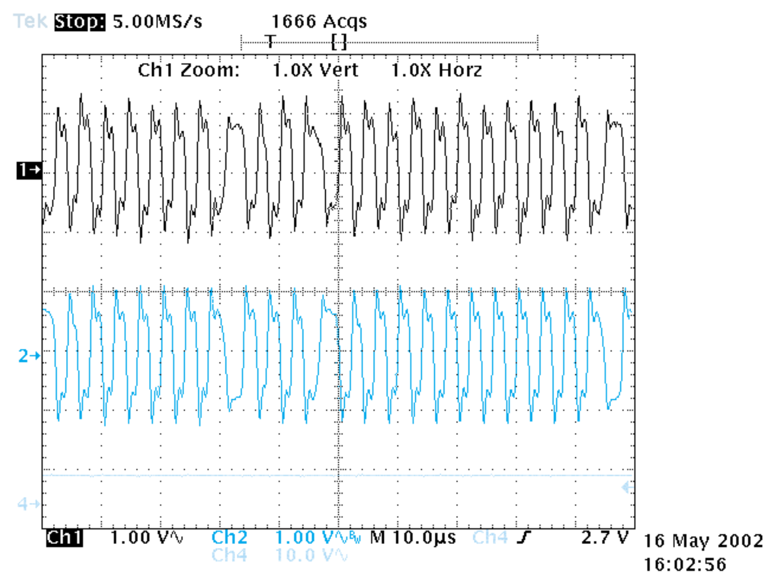
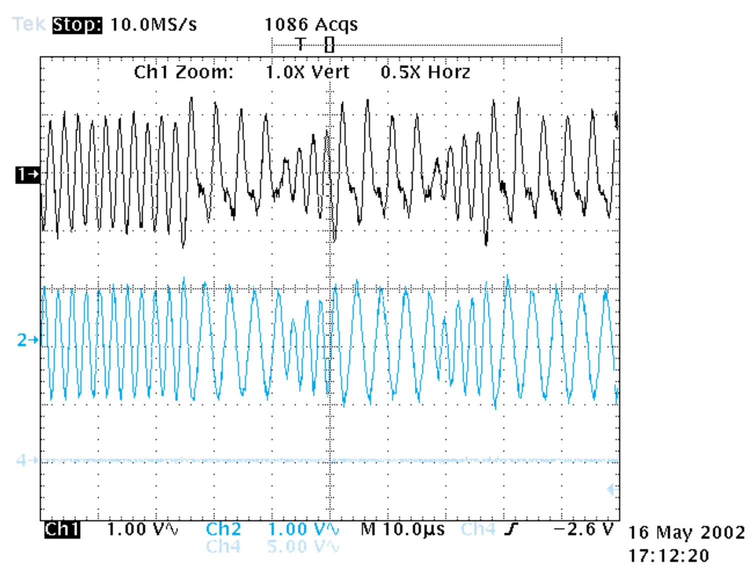


Figure 16: Illustration of baseband signals showing frequency modulation.

BASEBAND SIGNALS SHOWING FREQUENCY MODULATION



9.4. Simple Wire Antenna

Because it is a well-known that almost any piece of wire that has dimensions comparable with or larger than half a wavelength will radiate copiously, an initial exploration using a network analyser of the field distribution which is obtained beneath the simple wire slung underneath one shelf, as shown in Figure 17, was made.

For convenience the wire consisted of an approximately 3 mm diameter aluminium rod and which was fastened by means of an alligator clip to a coaxial connector passing through one of the mounting holes of the shelf bracket.

The results were very much as expected. The wire continues to radiate over its whole length, but in a very irregular way. The field distribution beneath the wire shows the characteristics of a many path electromagnetic propagation situation, in which there are both deep nulls and corresponding peaks in the field intensity.

This antenna configurations was regarded as useful for confirming expectations, but not highly useful for practical application in the shelf reading context. It provides for no field stirring, so that labels and some locations would not be read. Moreover, some of the radiation is to large volumes of space in which the energy density is too low to be usefully used, even though the total energy radiated thereto is significant.

What is needed is a more deliberately focused antenna that would radiate over an appropriately large beam to the shelf region below it, and that can be multiplexed with similar antennas so that null positions can be avoided.

Such an antenna is the circularly polarised patch antenna which is normally employed with a model of UHF interrogator used in our experiments.

Figure 17: Illustration of simple wire antenna.

9.5. Operation with Patch Antenna

When the patch antenna previously described in Section 9.2 and normally used with the UHF interrogator was slung beneath the centre of an upper shelf, it was found that labels could be read in almost all regions above the shelf below, with baseband signals as previously illustrated in Figure 15. Only at the extreme edges and high up, that is in regions which would be substantially outside of the beam of the antenna, presented any difficulty.

These good results were obtained with labels with their long axis parallel to be mesh back plane of the shelf structure, and also with their long axis perpendicular to that plane. This latter result appears to provide confirmation that the use of a circularly polarised interrogation antenna is beneficial.
Our conclusion is that multiplexed patch antennas slung underneath upper shelves will provide a very good reading mechanism for UHF labels, but more than one patch antenna per metre of shelf length may be required.

In multiplexing a single transmission line to several patch antennas we do not require the usual design of high isolation multiplexer. Only a moderate level of isolation will be required, and economy of manufacture will result.

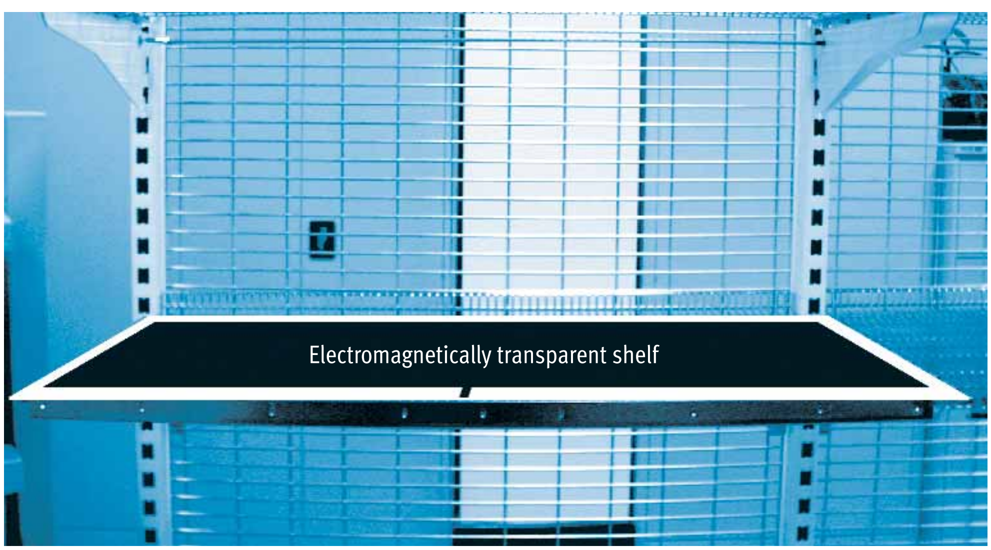
9.6. Use of HF Loop Antenna

For the evaluation of label reading at HF, the grid-like metal shelves were removed from the upright supports of the shelf structure, and electromagnetically transparent shelves (made from particle board) with a single turn rectangular peripheral metal strip antenna, such as is illustrated in the doctored photograph of Figure 19, connected to the interrogator described in Section 9.2, was used.

It should be emphasised that the drawing lacks reality in that the drawn in antenna appears to be sitting on the existing rectangular grid metal shelf, but in the experiments the metal shelf had been removed.

It was found that HF label antennas oriented parallel to the back plane off-the-shelf structure could be read at all positions across the shelf below.

Figure 18: A drawing of a shelf loop antenna.

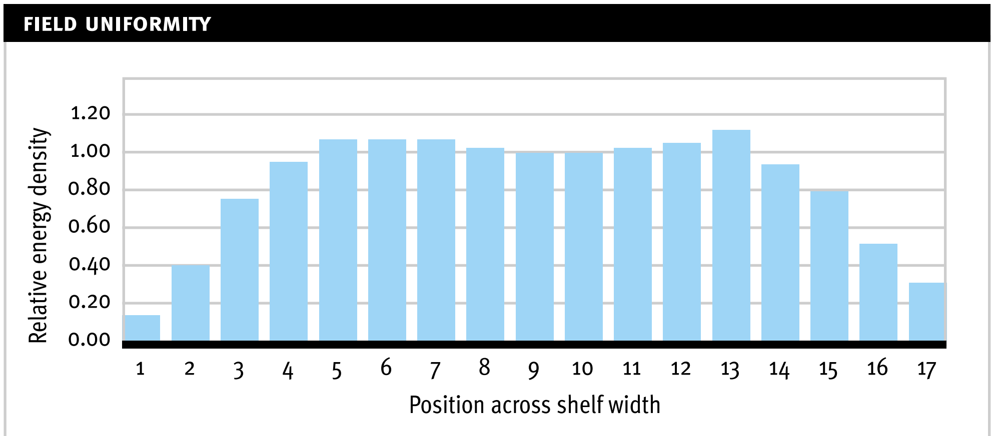


9.7. Shelf Field Uniformity

The results of a measurement by means of the network analyser of the uniformity of the field created by the shelf loop antenna at the height of 160 mm above the shelf appear below.

In interpreting this graph, we note that the vertical axis is linear in reactive power density per unit volume. The range of values from about 1 down to about 0.2 is only about 5 dB, and is very much less than the expected dynamic operating range of the label, for which a value of 40 dB is a reasonable aim.

Figure 19: Field uniformity in a shelf loop antenna.



10. CONCLUSIONS

The basic principles of electromagnetic theory relevant to the design of readers and antennas for RFID labels for products on the supermarket shelves have been explained. Of particular importance is the understanding of both near field and far field coupling, and of the boundary conditions that electromagnetic fields must obey in proximity to metal structures.

A comprehensive list of issues in RFID reader design and label antenna design has been identified. Some simple interrogator architectures have been described. More complex architectures are acknowledged without detailed description.

Suitable objectives for antenna design for UHF Systems include the achievement of uniform direct interrogation signal illumination of labels without undue dispersal of interrogation energy to areas where it is not useful, and the provision of suitable field stirring to deal with field nulls arising from multipath propagation. Circularly polarised interrogation antennas have been shown to be helpful, and in phase and quadrature detection of reply signals is regarded as essential.

Suitable objectives for antenna designed for HF systems include the planning of closed flux paths that surround antenna current, and the achievement of field uniformity in magnitude and direction so that dynamic range demands on label performance are minimised. Techniques whereby these desirable results can be achieved have been described.

Experimental tests of these principles on standard supermarket shelving using fairly ordinary RFID systems has showed that the good coverage of the volume of a standard shelf bay could be obtained with a single antenna in each frequency range.

Interrogator transmitter phase noise, known to be of concern for long-range UHF interrogation systems, and did not seem to pose a problem in the supermarket shelf context.

REFERENCES

1. **International Organisation for Standardisation, "SI units and recommendations for the use of their multiples and of certain other units"**
   International Standard ISO 1000 (1992).

2. **Sadiku, M.N.O., "Elements of Electromagnetics"**
   Saunders Publishing, (1989).

3. **Cole, P.H., Eshraghian, K and Roy, A.K. "Theory and Operation of a Passive Subharmonic Transponder"**
   I.R.E.E. International Electronics Convention, August 1979.

4. **Werner, D.H., Werner, P.L., and Breakall, J.K. "Some computational aspects of Pocklington's electric field integral equation for thin wires,"**
   IEEE Trans. Antennas Propagation., vol. 42, 4, pp. 561-563, (1994).

5. **Ramo, S. Whinnery, J.R. and van Duzer, T., "Fields and Waves in Communication Electronics"**
   John Wiley and Sons.

6. **Cole, P.H., Hall, D.M., Loukine, M, and Werner, C.D. "Fundamental Constraints on rf Tagging Systems",**
   Third Annual Wireless Symposium and Exhibition, Santa Clara, February 1995, pp 294-303.

7. **Rohde, U.L. and Hagemayer, F., "Feedback technique improves oscillator phase noise",**
   Microwaves and RF, November 1968, pp 61-69.

8. **Turner, L.H. and Cole, P.H., "Transponder system"**
   U.S. Patent 5,305,008. (1994).

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