Potential Uses of Embedded RFID for Appliance Identification

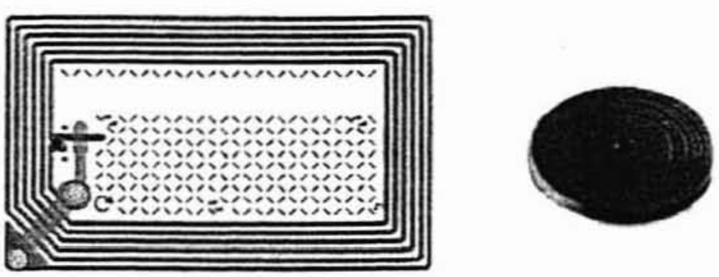
Richard McWilliam, Alan Purvis
Durham University, School of Engineering

Radio Frequency Identification (RFID) has become a pervasive technology for the purpose of tracking goods through the supply chain. It is possible to adapt this radio technology such that remote identification is possible using the electrical power cable as a communication channel in place of the inductive coils used by most RFID tags. Furthermore, passive transponders which do not require a local power source may be used. This opens up several interesting possibilities for automatic appliance identification during manufacture, test and in general use.

RFID for Appliance Identification

Conventional RFID tags are used in many application areas wherever it is convenient to place tags on the goods such that they may be detected by proximity Read-Write Devices (RWD). These devices are placed at strategic locations in the supply chain and can detect tags in close proximity. Read range is typically a few centimetres – possibly up to one metre – and line of sight is not required to detect the tag. Another distinct advantage is the possibility to detect many tags concurrently within the field of the RWD.

When considering RFID for the purpose of appliance identification, some drawbacks become apparent. Firstly, it may not be appropriate to attach the tag to the external casing of an appliance for the entire lifetime of the product as it may become dislodged or damaged. Secondly, if the tag is placed inside the product problems can occur with metallic casings due to severe dampening of the magnetic field used to energise the tag. This is a common problem in RFID applications and is often the culprit when read range does not meet expectations. For this reason, reading a tag placed inside the product becomes more challenging unless one know exactly where the tag is located.



(a) (b)

Figure 1: Conventional RFID tags (a) a typical inductive antenna for' label' style tags – the chip is marked red, (b) a packaged 'button' style tag in which the antenna coil and chip are sealed.

Using the power cable: offline communication

As an attempt to solve these challenges, we have developed a novel RFID system which electrically conducts signals along the appliance power lead rather than between coils through the air. The appliance is recognised when the power lead is plugged into a special RWD, providing a consistent method for identifying different types of appliances. This method was originally devised for the electrical safety test market, whereby appliances in the workplace must be identified and given an electrical safety test on regular basis. This becomes an considerable task on large commercial and educational sites. As shown in figure 2, a tag is located inside the appliance and is read as soon as the appliance is plugged into the Portable Appliance Tester (PAT). The correct test parameters are automatically determined before proceeding. Important results from the test can then be written back to the tag for future reference.

The key component in this system is the inductive coupler (described below) which enables communication between the RFID chip and the RWD via the power cable. This coupler is simply fastened around the power cable and requires no galvanic connection. This is an example of an 'offline' system i.e., one that operates whilst the appliance is unplugged from the live mains. Another example of an offline application is storage and retrieval of data during manufacture. Such data may be for example describe the exact required configuration of the appliance which may be needed during assembly or testing. Pertinent data is then permanently stored in the tag for retrieval by the manufacturer or service engineer to help diagnose failures or perhaps even faulty batches.

Using the power line: online communication

The concept can be expanded to the power line itself, whereupon RFID communication takes place across the live mains network. This is called an 'online' system, with potential applications in real-time appliance monitoring. It would enable for example the detection and recall of an appliance which has elapsed its prescribed safety test date, but which is still in active use. A further application is device power monitoring, whereby the RFID inductive coupler also behaves as a current transformer and can therefore be used to monitor and report current consumed by the device over time.

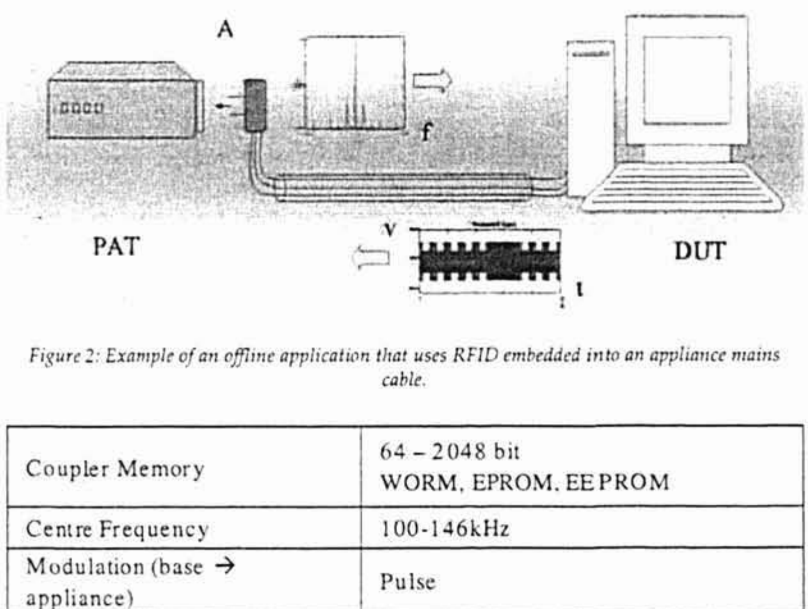


Figure 2: Example of an offline application that uses RFID embedded into an appliance mains cable.

Coupler Memory	64 – 2048 bit WORM, EPROM, EEPROM
Centre Frequency	100-146kHz
Modulation (base → appliance)	Pulse
Modulation (appliance → base)	ASK, FSK, PSK on sub-carrier
Data Rate	Typically 2-4kbit/s
Minimum Line Carrier Current	40mA typical
Chip power requirements	100µW minimum
Chip Activation Voltage	2.8-5.5V, 3.5V typical

Table 1: Features of a typical RFID tag ASICs.

Operation of the Offline System

As illustrated in figure 2, we utilise the appliance mains lead as a communication channel. A Strong-Carrier Double Sideband (SC-DSB) signal is injected at point A which excites an inductive coupler placed around the cable. The strong carrier provides remote power to the passive ASIC inside the coupler and modulation of the carrier allows simple communication by backscatter, generally using Amplitude Shift Keying (ASK), although other schemes can be used. A natural return path for the electrical current exists when the appliance is fitted with a mains inlet filter, which usually incorporates large line to line capacitors.

An EEPROM with 2kbit capacity is integrated within the ASIC for flexible memory organisation, including parameterised memory maps which cater for the client's data storage requirements. For less

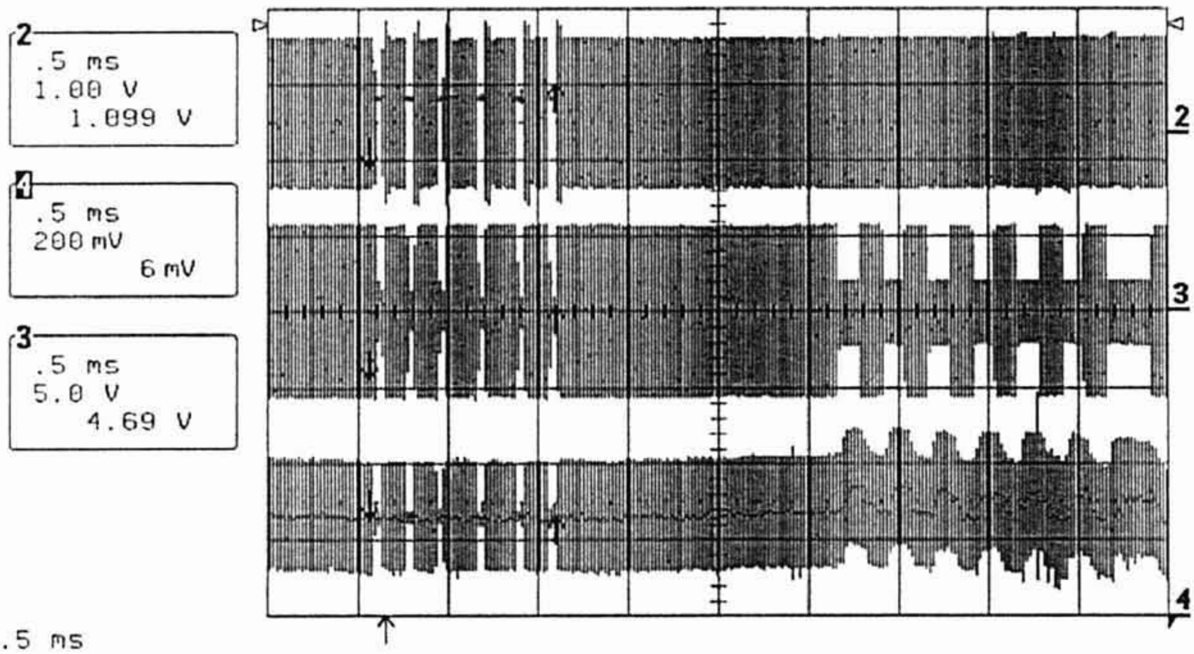


Figure 3: Electrical waveforms for offline RFID system. Top trace: energising carrier generated by the RWD; middle trace: signal produced by RFID tag chip; bottom trace: signal received by RWD when RFID tag is transmitting.

demanding applications, 96 or 128 bit WORM memories such as those used in ePC applications may be used to store a unique identifier. Table 1 gives a summary of further technical features of the tag ASIC. A consequence of the low data rates used is that it becomes possible to implement the Read-Write Device modem and protocol functions in software such that firmware updates can be used to make the RWD compatible with new ASICs as they become available to the RFID market.

The Inductive Coupler

The coupler should have the following properties:

1. It must transfer sufficient electrical power from the power cable to activate the tag ASIC. This is typically expressed as a minimum activation voltage (around 2.8 V for our prototype);
2. It must enable impedance modulation, which is the mechanism by which the tag communicates with the RWD;
3. It should fit within a specified volume as determined by the application requirements.

The basic coupler geometry is shown in figure 4. It consists of a toroidal copper winding disposed around a cylindrical ferrite core. A ferrite core is required to achieve sufficient winding inductance. A capacitor is generally placed across the winding terminals such that resonance is achieved at the operational frequency.

Various fitment options are possible with single-wire coupling giving best performance. We have investigated miniaturisation of this design in order to allow more convenient fitting, for example inside the metal end-cap of a standard electrical fuse, rendering retrofitting of older appliances a simple procedure. Finding the smallest volume for a given frequency requires that the reactive

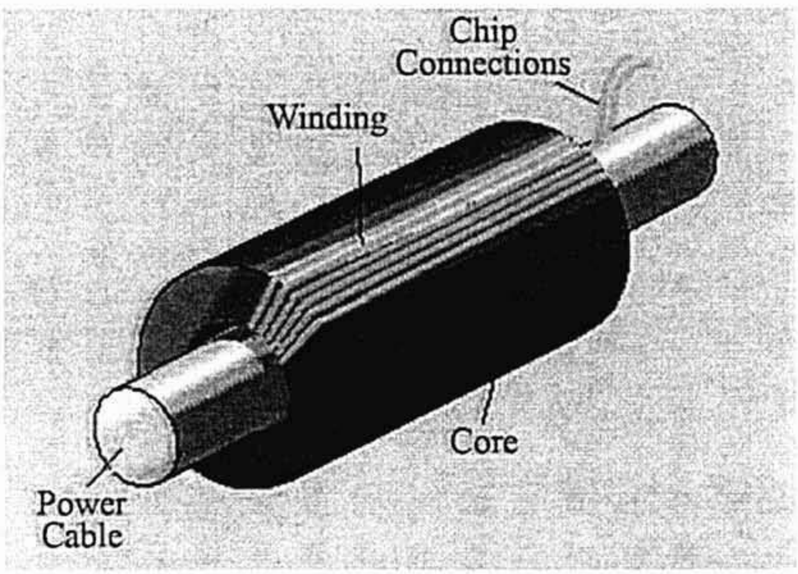


Figure 4: The coupler is simply composed of a copper winding around a ferrite core, to which an RFID chip is attached.

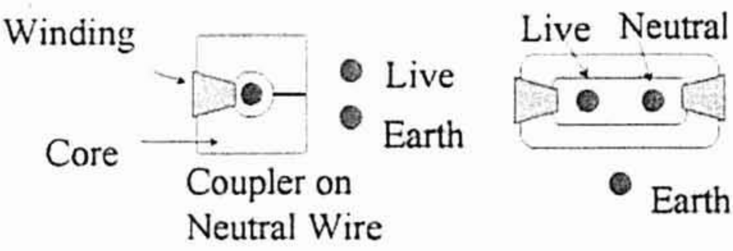


Figure 5: Two possible coupler configurations

components (core winding and capacitor) occupy minimum space.

Two-wire coupling is possible, see figure 5, but there is significant attenuation due to an effective air gap that appears in the magnetic coupling circuit between the wires, rendering the design of such a coupler of convenient size very challenging.

Design constraints

The primary limiting physical parameters of the coupler design include range, size and the physical coupling arrangement, each of which is subject to constraints.

In terms of range, our tests have extended over 100 meters of standard triplex mains cable (assumed to be greater than any common appliance power lead) with only minor impact on performance. For a given channel frequency range is ultimately limited by the signal wavelength, for which limitations have been suggested [2]. This limits usable range to around 400m at 125kHz in order to avoid possible standing wave effects. Line impedance (determined mainly by the mains inlet filter of the DUT) also has an impact on range.

The total volume occupied by the coupler assembly can be expressed as a sum of the space occupied by the core (V_{core}), winding (V_{wind}), resonating capacitor (V_{cap}) and ASIC (V_{chip}):

$$Volume_{total} = V_{core} + V_{wind} + V_{cap} + V_{chip}$$

The first three terms in equation 1 are interdependent. For example, to establish a given inductance we could choose the following parameters: N (number of turns), h core length, r_1 (inner core radius), r_2 (outer core radius) and μ (core permeability). The resulting inductance is found using:

$$L = \frac{\mu_o \mu N^2 h}{2\pi} \ln\left(\frac{r_2}{r_1}\right)$$

The effective core volume (V_{core}) can then be found from [1]:

$$V_{core} = \frac{4\pi^2 L \ln^2\left(\frac{r_2}{r_1}\right)}{\mu_o \mu N^2 \left(\frac{1}{r_1} - \frac{1}{r_2}\right)^2}$$

Given that the coupler must resonate at the chosen frequency, w, the necessary capacitance, C, is found from the resonance equation:

$$C = \frac{1}{\omega^2 L}$$

If we wish to minimise V_{total} (the total volume) then main constraints become μ, N, r_2, h and w. For example in choosing N, it is important to consider the compromise between power matching to the carrier signal coming from the RWD and providing sufficient modulation index (defined here as the change in line current), since the power and communication signals are coupled. Figure 6 shows design graphs gathered from prototype couplers. The RFID chip impedance is programmed to vary in order to modulate the carrier signal and we wish to ensure that, in doing so, the chip voltage remains in its operating region (between 2 V and 5 V in this case) and that the received power does not dip. The couplers are tolerant to variations in chip impedance between 1kΩ and 10kΩ for various windings (between 20 and 40 turns), as shown in the boxed regions. Note that the coupler which has 10 turns does not meet the voltage or power requirements. These results also depend on the power line impedance, which was set to 50 Ω in this example.

Using this result we may configure appropriate cores that will meet the specification. We summarise two actual configurations in Table 2, in which both designs were permitted 20 winding turns. Core 1 is relatively large and dominates the overall coupler volume while core 2 is of similar dimensions to the capacitor and chip. Core 2 is suitable for fitment inside a fuse cap (see figure 7) while core 1 is intended for 6A and 12A triplex.

	Core Volume, mm^3	Calculated Inductance	Measured Inductance (@10kHz, 500mV)	Equivalent Parallel Resistance	Required Capacitance for Resonance
Core 1	6302	1.23mH	2.03mH	1.45kΩ	1.3nF
Core 2	19.7	268μH	520μH	450Ω	3.1nF

Table 2: Two examples of passive coupler design.

Detecting the Message

Since the energising carrier signal is generated by the RWD, coherent demodulation is possible with precise phase synchronisation. A product detector can be used whose output is represented by:

$$V_{out}(t) = \frac{1}{2} A_r \mathrm{Re}\left\{R(t) e^{j(\theta_c(t) - \theta_r)}\right\}$$

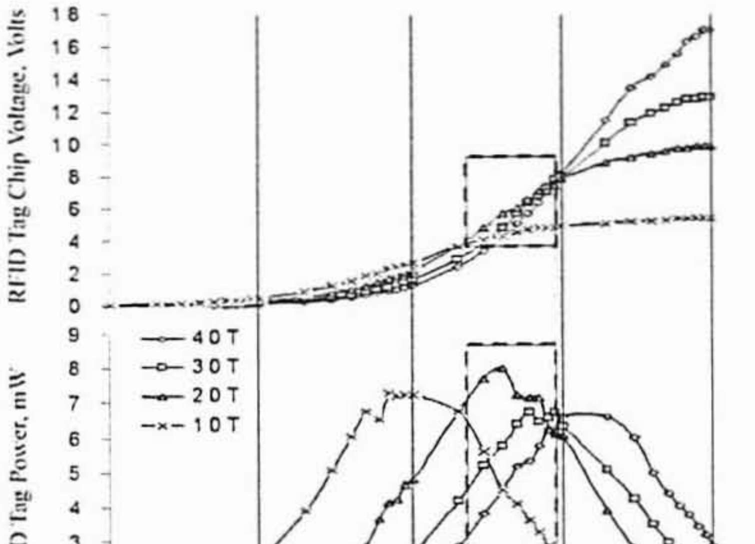


Figure 6: Design graphs showing measured voltage and power available at the coupler as a function of connected load. Boxed regions indicate suitable conditions for transponder chip operation.

where Ar is receiver gain, Θ_0 demodulator phase offset, $R(t)$, $\Theta_r(t)$ are amplitude and phase variation of modulated signal respectively. Once energised by inductive coupling the transponder modulates its terminal impedance to effect a combination of amplitude and phase modulation at the RWD ($V_{out}(t)$). Depending on system tuning and line loads adjustment of the demodulator phase offset may be required to maximise received signal strength. This can be achieved in real time by software control.

Integrity on the Live Power Line

When live mains is present the coupler must not be damaged by the presence of the either 50 / 60 Hz mains or energy spikes. We have observed that suitable transient voltage suppressors can offer protection against large momentary currents as depicted in figure 8, where the suppressor has maintained a safe voltage across the chip. In addition the junction capacitance of the suppressor directly contributes towards coupler resonance.

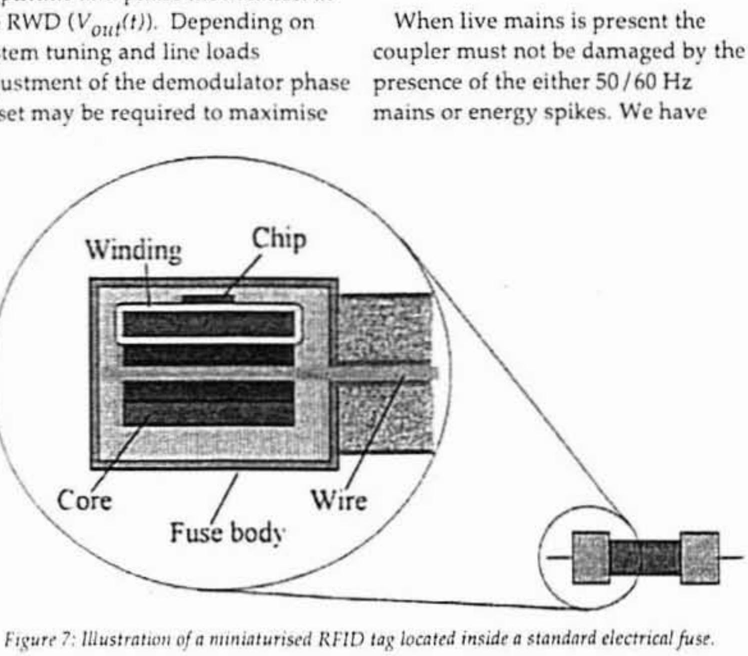


Figure 7: Illustration of a miniaturised RFID tag located inside a standard electrical fuse.

Operation of the Online System

There are well known issues associated with power line communication, including: severe attenuation, variable line impedance [2,3] and limited permitted signalling levels [4]. This is compounded by the fact that it is preferable to use passive RFID tags which have to extract sufficient energy from the power line to operate. We consider results from passive communication tests and speculate on the possibilities for active communication.

Passive Operation

In passive mode the RWD supplies all energy to the transponder. We must reflect part of the energy incident on the receiver back to the RWD in order to communicate. Our experimental system achieves this by modulating the quality factor of the resonant pickup circuit attached to the inductive coupler and so altering the impedance of the coupler as seen by the power line. A sensitive resonant circuit in the RWD detects these changes using a resonant circuit to detect variations in the line current, then feeds a voltage signal to a sensitive receiver. An alternative form of tag communication is 'cloaking', whereby the transponder alters its self resonant frequency. This approach has the disadvantage of reducing power coupled to the tag when detuned. Although this is a convenient form of passive signalling (due to low transponder complexity), system performance is dominated

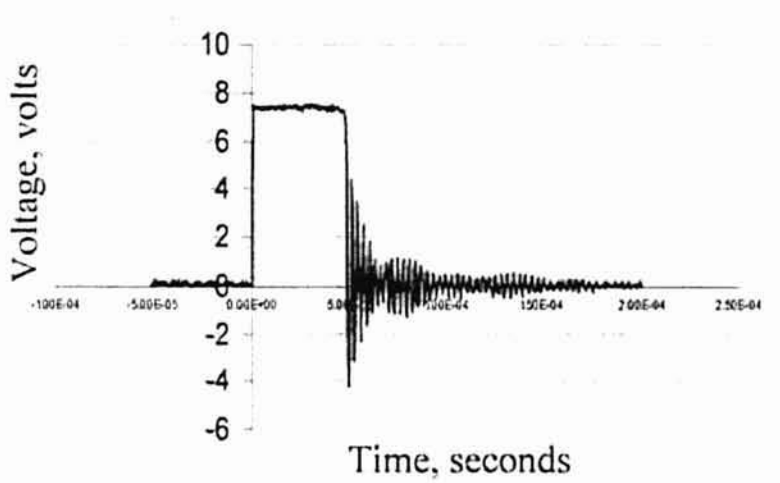


Figure 8: Coupler protection by transient voltage suppressor.

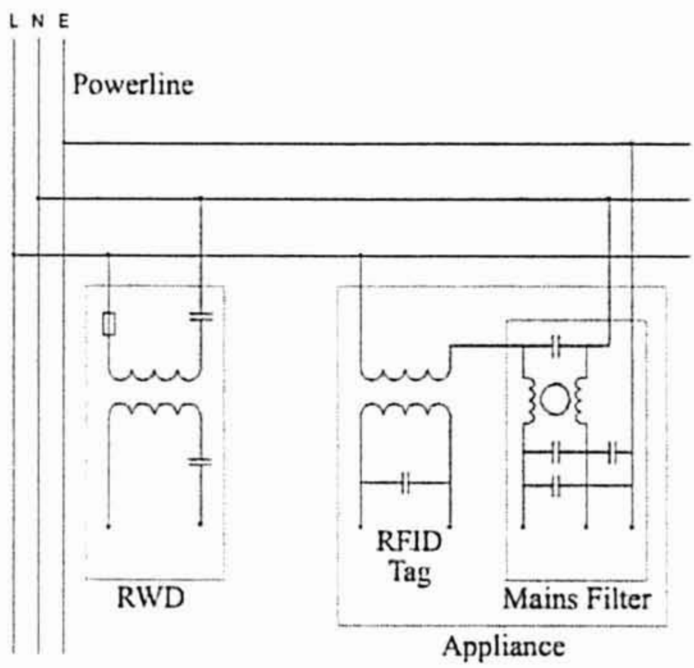


Figure 9: Experimental passive system showing coupling of RFID tag and RWD. Utilisation of a typical appliance mains filter is also shown.

largely by line impedance. Real loads in the line attenuate power received at the transponder while reactive loads appear at the RWD and transponder due to inductive coupling which can disturb the modulated carrier signal. Thus power line impedance variations affect both power transmission and communication.

Using the experimental system shown in figure 9 passive communication has been found to be possible across the live mains network. 32bit ID numbers are retrieved from the passive transponder by the RWD.

To further assess the viability of communication across the live power line network a model of the mains network has been devised. It incorporates a transmission line model (TLM) into a transmission matrix representation and includes accurate models of the RWD, RFID transponder and various mains inlet filters. Using this model, we can simulate several important characteristics of the system. We may, for example, calculate the expected signal attenuation between the RFID tag and RWD as they are spaced further apart on the power network (see figure 10). Another important assessment is the variation of RWD sensitivity (i.e., the ability to recognise the RFID tag) as the distance is increased (see figure 11). This was accompanied by a practical investigation whereby RFID tagging was tested using the power network in a busy laboratory at Durham University.

From this investigation, the following observations were made:

- Communication is possible over the power line using the resonant power line couplers.
- As expected, power line impedance has a large impact on performance. This is determined by the length of cabling between outlet sockets and loads present on the line. The tagged appliance itself can also assert a fluctuation in line impedance.
- A high degree of current coupling is required at the appliance inlet i.e., line-line capacitors present in mains inlet filters are necessary.
- An adaptive coherent detector (as outlined earlier) is essential in order to compensate for fluctuations in power line impedance.

An example of main-induced disturbance is shown in figure 12 where the received message is clearly affected (compare with figure 3).

Active Operation

For our prototype RFID system the RWD coupler supplies around 235

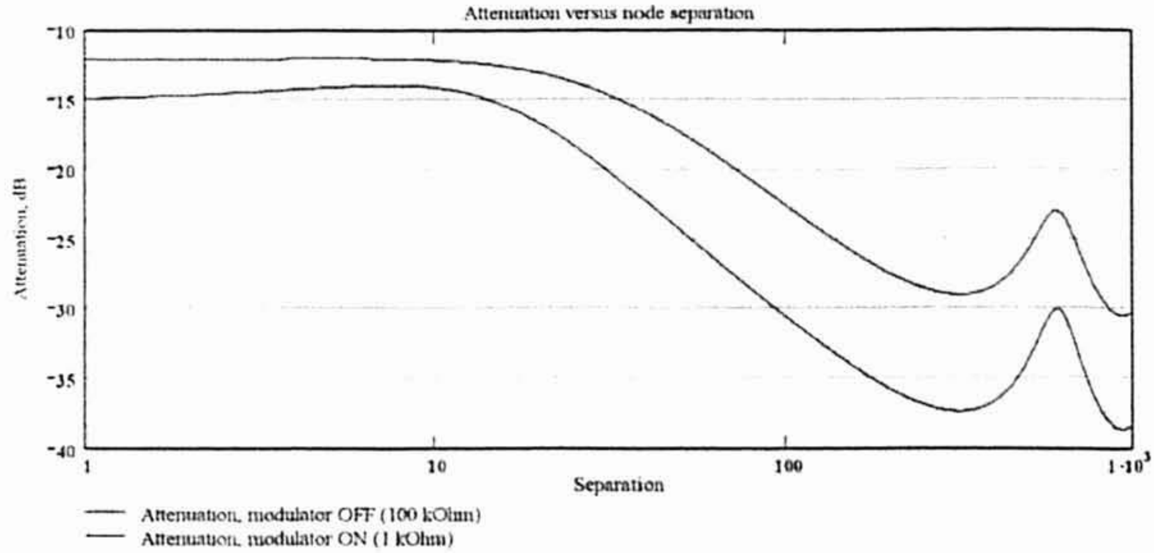


Figure 10: Calculated attenuation between RFID tag and RWD versus their separation distance. Modulator ON/OFF conditions occur during communication.

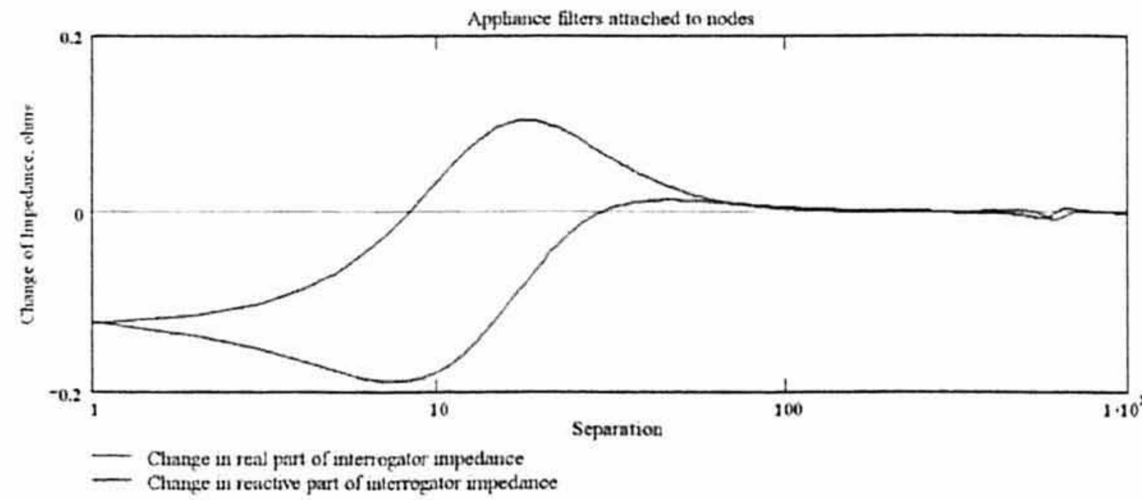


Figure 11: RWD modulation sensitivity versus distance between RWD and RFID tag. Non-zero values on either the red or blue trace indicate potential for receiving data from the tag.

mW to the power line in order to energise the tag and establish communication. In practice, restrictions apply to the signalling levels that can be used [4].

An alternative online method is active signalling, where the RFID tag possesses its own power source for transmission. Although this would provide greater allowance for attenuation between RWD and tag, additional requirements on tag ASIC include:

- Higher receiver sensitivity (due to reception of weaker transmissions;
- Independent transmit circuitry (not backscatter);
- Signal processing.
  Several possible sources of energy are explored in table 3.

Further Work

Further characterisation of the online system is required which is the focus of our current research work. We are also investigating a test system that uses a software-defined radio [5] to explore methods for active tagging. This will allow us to develop and test signalling protocols and radio structures implemented in reconfigurable hardware.

Of particular interest is the possibility of event monitoring on the mains network, for example, when an appliance has been switched on causing a message to be sent from the RFID tag. This would improve identification of potential hazards on the mains system, for example, if an appliance is being

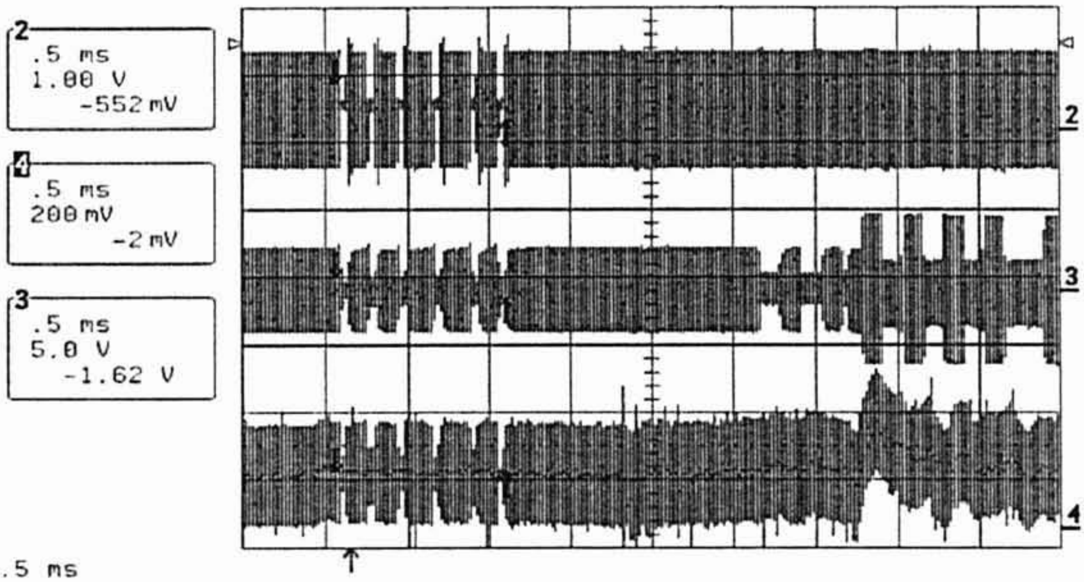


Figure 12: Effect of a disturbance in the mains network on RFID frequency signalling (key same as figure 3). Disturbances may originate from the power network or from the appliance itself, when it is switched on.

Source	Advantages	Disadvantages
50/60 Hz mains	Potentially high energy available	Inductive coupling difficult; mains must be live at appliance.
'Random' harmonic noise, impulsive spikes present on power line	High frequency content easier to extract	Dependability and consistency of noise signals; wideband pickup required
Energising pilot tone (independent from communication carrier)	Energy is present when required; optimal inductive coupling	Pilot must be injected into mains; regulatory restrictions
Internal battery	Guaranteed energy source	Finite energy reservoir; lifetime depends on regularity of use

Table 3: Potential energy sources for an active transponder.

used past its test date as discussed earlier. By matching the appliance's noise waveform (as seen by the RWD) with the transmitted RFID signal, we aim to determine the on/off status of the appliance.

Conclusion

This project has discussed the potential for embedded RFID tags which use inductive coupling to the mains cable in order to provide a means for automatic identification of appliances. The tag does not require a battery due to the backscatter technique used, and the method has potential applications in both online and offline situations.

References

[1] E.C. Snelling, "Soft Ferrites: Properties and Applications" (1969) Iliffe Books Ltd.

[2] M.H.L. Chan and R.W. Donaldson, "Attenuation of Communication Signals on Residential and Commercial Intrabuilding Power-Distribution Circuits", IEEE Trans. Electromagn. Compat., vol. EMC-28, No. 4, Nov. 1986, pp. 220-230.

[3] J.A. Malack and J.R. Engstrom, "RF Impedance of United States and European Power Lines", IEEE Trans. Electromagn. Compat., vol. EMC-18, Feb. 1976, pp. 36-38.

[4] EN50065-1, Signalling on Low Voltage Electrical Installations in the Frequency 3 kHz to 148.5 kHz, Brussels: CENELEC, 1991.

[5] E. Buracchini, "The Software Radio Concept", IEEE Communications Magazine, 38(9), Sept. 2000, pp.138-143.

Richard McWilliam, Alan Purvis
Durham University, School of Engineering
Durham, DH1 3LE, UK
Tel. +44 191 3743828, email r.p.mcwilliam@dur.ac.uk