Using low power transponders and tags for RFID applications.

by

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1. Abstract

A general description of transponder families is given aiming real RFID applications such as animal and objects identification, access control, car immobilization, electronic purse, laundry tagging, ticketing. High security identification and multi-tag identification applications are addressed. Some key parameters of the system are discussed such as antenna resonant frequencies adjustment, detuning effect, communication distance range of a system, transponder cost vs performances.

2. Introduction

Regarding the rapid increase of the RFID market, many companies not really specialized in RF system design, but having experience in real time processing software and hardware design tend to use such technology for their applications where the wireless communication greatly improve the user comfort.

As transponder prices went down, high volume applications arose such as car immobilizing system, animal identification, retailing ...

For simplicity, only Low Frequency band systems (typically 125kHz) will be addressed however all these guidelines can be applied to Medium Frequency band systems (typically 13.56MHz).

RFID systems are composed of three components - a reader (also called transceiver), a transponder (also called tag), and a computer or data processing system. It can be easily found such components as OEM products but antenna circuits are often not provided as they are application dependent. So the first problem engineers are faced is : which antenna geometry should I use to reach 50cm with this transponder integrated circuit ?

The third chapter gives some general rules and guidelines to calculate an initial set of parameters of an RFID system such as, reader antenna geometry, transponder antenna geometry, emitted power ...

The fourth chapter will address the so called « Read Only applications » such as access control, object tagging, car anti-theft system. The main principle of these transponders is that they have a factory programmed identification code stored in a read-only Memory.

The fifth chapter will addressed the so called « Read/Write applications » where the transponder can carry and store some software programmable data in a non volatile memory. Typically, retail, gas cylinder identification, ticketing, ski pass applications need such feature.

The sixth chapter will focus on the cost of an RFID system, and mainly how to target low cost system.

3. System parameters

The wireless communication achieved in LF (or MF) band is based on the magnetic coupling of two resonant circuits (also called inductive circuits) tuned at frequencies as close as possible. The reader emits a magnetic field and when a transponder passes through it powers up and begins to transmit its on-chip stored data. The signal generated by the reader usually provides timing information as well as enough energy to power the tag.

As communication range is much smaller than signals wavelength a simple model can be used forgetting what RF system designers are commonly using such as scattering parameters, reflection coefficient, impedance matching ...

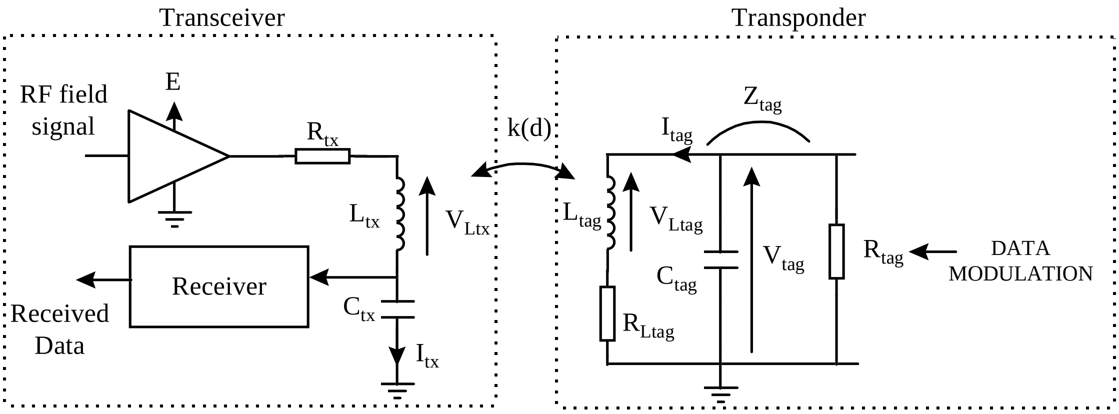

Figure 1 - RFID system front-end equivalent circuit

The lossy transformer theory will be used in conjunction with magnetic field theory to evaluate RFID systems performances.

Figure 1 gives a schematic and simplified image of an RFID system front-end including transceiver and transponder view. L_{tx} represents the reader antenna and L_{tag} the transponder antenna. Currently, C_{tag} and R_{tag} are given parameters by the transponder IC.

Generally air coil are used on both sides, except for car immobiliser, animal identification where the transponder antenna is based on windings running on a small ferrite. This increases the antenna Q factor and concentrates field force lines in order to compensate the coupling factor reduction due to the very small size of the transponder antenna.

In LF and MF band, today, 95% of the RFID market uses batteryless transponder, also called passive transponders, which means the transponder IC derives its power supply and its clock source from the induced sine wave voltage on the antenna. So a first communication range parameter is identified as the transponder powering distance mainly dependent of reader antenna current and circuit (I_{tx}, L_{tx}, C_{tx}, R_{tx}) and of the transponder parameters (L_{tag}, C_{tag}, R_{tag}).

Calculating the power received by the transponder can be done combining magnetic field formula (1), Lenz law (2) and lossy transformer system equations (3).

$$B(d) = \frac{\mu_0 . N_{tx} . I_{tx}}{2\pi} \frac{{r_{Ltx}}^2}{(\sqrt{d^2 + {r_{Ltx}}^2})^3} \tag{1}$$

$$V_{Ltag}(I_{tag} = 0) = N_{tag} . S_{tag} . \cos\theta . \frac{dB}{dt} \tag{2}$$

$$\begin{cases} V_{Ltx} = j\omega . L_{tx} . I_{tx} + j\omega . M . I_{tag} \\ V_{Ltag} = j\omega . M . I_{tx} + j\omega . L_{tag} . I_{tag} \end{cases} \tag{3}$$

$$M = k\sqrt{L_{tx} . L_{tag}} \tag{4}$$

parameters meaning :

N	⇔ antenna windings
V	⇔ voltage (V)
R	⇔ resistivity (Ω)
I	⇔ antenna current (A)
r	⇔ antenna radius (m)
d	⇔ distance between antennas (m)
S	⇔ antenna surface (m^2)
M	⇔ mutual inductance (H)
L	⇔ antenna inductance (H)
θ	⇔ antennas angle (parallel ⇔ 0°)

To evaluate the main electrical parameters (received power, transponder modulation index induced on reader antenna) the antenna coupling factor k has to be known. This parameter depends only on antennas geometry, distance in between and orientation. Combining (1), (2), (3) and (4) leads to the coupling factor formula given by (5). A minimum coupling factor of 1% is commonly used, this can give a first solution for antennas geometry as these parameter are usually application constrained.

$$k(d) = \frac{{r_{Ltx}}^2 . {r_{Ltag}}^2 . \cos\theta}{. \sqrt{r_{Ltx} . r_{Ltag}} . \left(\sqrt{d^2 + {r_{Ltx}}^2}\right)^3} \tag{5}$$

As an example, figure 2 shows the coupling factor of a reader antenna of radius 10cm and of a transponder antenna of radius 2cm with an angle of 0°.

A transponder IC power consumption is normally specified through its minimum power supply voltage and the associated current consumption. Therefore, an interesting electrical parameter to look at is the voltage V_{tag} induced on the transponder. It is derived combining (3) and ohm law on transponder circuit (6) which gives (7) : (to be continued on page 4)

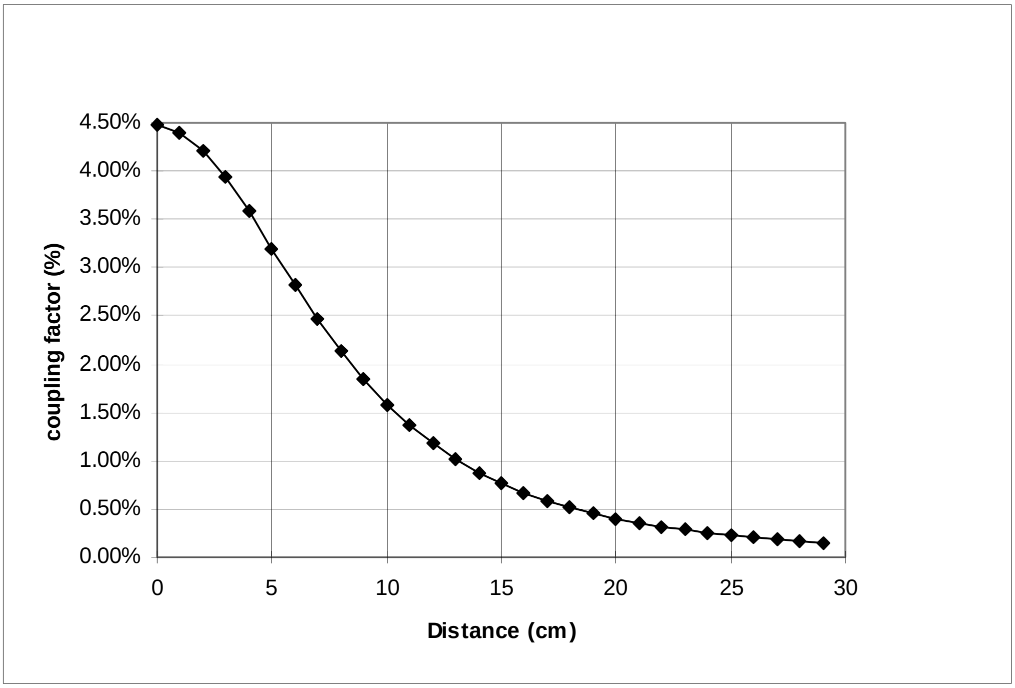

Figure 2 - Coupling factor vs antennas spacing

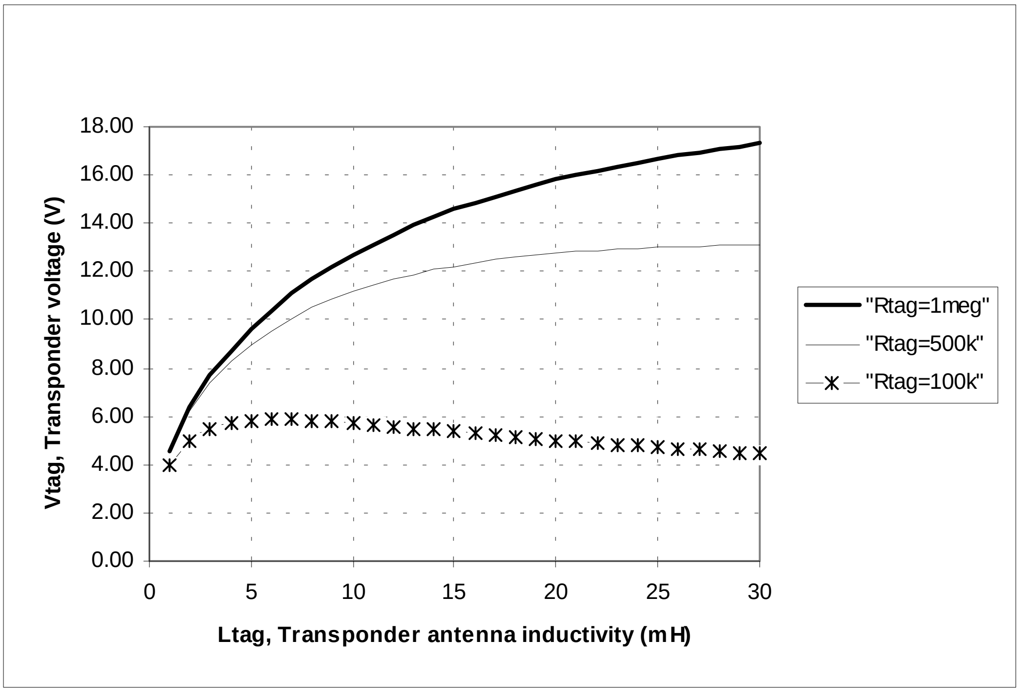

Figure 3 - Transponder voltage vs transponder antenna value

$$V_{Ltag} = -Z_{tag}.I_{tag} - R_{Ltag}.I_{tag} \quad (6)$$

$$V_{tag}(d) = \frac{k(d).\sqrt{L_{tx}.L_{tag}}.I_{tx}}{\frac{R_{Ltag}}{\omega_{0tag}{}^2.L_{tag}} + \frac{L_{tag}}{R_{tag}}} \quad (7)$$

assuming (8), a perfect tuning between transponder antenna circuit resonant frequency (ω_0) and magnetic field frequency (ω).

$$\omega = \omega_{0tag} = \frac{1}{\sqrt{L_{tag}.C_{tag}}} \quad (8)$$

A detuning between these frequencies induces a reduction in V_{tag} voltage.

Figure 3 shows the voltage induced on a transponder antenna depending on the distance between antennas and for different transponder load assuming the following set of parameters :
k=0.5%, L_{tx}=0.35mH, I_{tx}=100mA, constant transponder Q factor Q_{tag}=20, $\omega_0=2\pi$.125kHz.

In practice, the transponder antenna voltage will never reach values of 18V as it will be limited by on chip voltage clamping elements. Using these curves, the goal is to determined the optimum value for the transponder antenna. Importance of the transponder IC power consumption is clearly shown.

Some general rules can be extracted from this first calculation to maximize powering distance of a transponder :

- maximize coupling factor by increasing antenna geometry as much as the application permits.
- maximize reader antenna current by increasing reader power supply voltage
- maximize reader antenna Q_{tx} factor as much as transponder data rate permits, and as much as antenna drivers permit.
- maximize transponder antenna circuit Q_{tag} factor
- use low power and low voltage operated transponder.

The second RFID system parameter which influences the overall system performance is the reader sensitivity. This parameter can be divided in two factors :

1. the input sensitivity of the demodulation chain
2. the transponder modulation induced on the reader antenna

Factor 1 is given by the reader specific performances and will not be discussed as it is out of the purpose of this paper.

Factor 2 must be maximized and will be derived with the following calculation.

The main reader electrical parameter which contains the transponder modulation is the antenna current (I_{tx}). Its derivation using (3), (5) and (6) gives (9) :

$$I_{tx} = \frac{E}{R_{tx} + \frac{\omega^2.k^2(d).L_{tx}.L_{tag}}{Z_{tag} + R_{Ltag} + j.\omega.L_{tag}}} \quad (9)$$

assuming (10), a perfect tuning between field frequency (ω) and reader antenna circuit resonant frequency (ω_{0tx}).

$$\omega = \omega_{0tx} = \frac{1}{\sqrt{L_{tx}.C_{tx}}} \quad (10)$$

$$Z_{tag} = \frac{R_{tag}}{1 + j.R_{tag}.C_{tag}.\omega} \quad (11)$$

The transponder modulation is induced on I_{tx} through Z_{tag} variations. The higher the I_{tx} variations, the longer the communication range. Hence, right hand side term of I_{tx} denominator variations have to be maximized.

When the transponder is in the non modulating state, R_{tag} is maximum and only depends of transponder IC current consumption, hence Z_{tag} expression (11) can be approximated as follow :

$$Z_{tag} = \frac{1}{j.C_{tag}.\omega} \quad (12)$$

Replacing Z_{tag} in (9) with (12) gives I_{tx} minimum (13), assuming (8) a perfect tuning between transponder antenna circuit resonant frequency (ω_0) and magnetic field frequency (ω).:

$$I_{tx}(\min) = \frac{E}{R_{tx} + \frac{\omega^2.k^2(d).L_{tx}.L_{tag}}{R_{Ltag}}} \quad (13)$$

Regarding (13), it can be seen that I_{tx}(min) does not depend of L_{tag} value as the L_{tag} over R_{Ltag} is independent of the number of windings. The last assumption holds true for normal air coil using single conductor as wire when the skin effect and proximity effect are negligible.

When the transponder is in the modulating state, R_{tag} is minimum and depends on the transponder IC modulator impedance, few kilo-ohms is quite common. In this case, Z_{tag} should be as low as possible to be negligible compared to R_{Ltag} and $\omega.L_{tag}$. In this case, I_{tx} is maximum and given by (14) :

$$I_{tx}(\max) = \frac{E}{R_{tx} + \omega.k^2(d).L_{tx}} \quad (14)$$

In view of (13) and (14), the following general guidelines can be used to maximize the transponder modulation induced of the reader antenna :

- maximize transponder Q_{tag} factor (R_{Ltag} min)
- maximize antennas coupling factor
- maximize transponder antenna value L_{tag}
- maximize reader antenna Q_{tx} factor(R_{Ltx} min) as much as transponder data rate permits, and as much as antenna drivers permit.

When having determined L_{tx} and L_{tag}, the antenna design phase can start. To complete this study, we give in (15) an empirical formula for antenna design which gives good agreement between calculation and measurements.

$$L(\mu H) = \frac{0.08.d^2.n^2}{3d + 9l + 10e} \qquad (15)$$

where n = number of windings,
d = coil diameter (cm)
l = coil width (cm)
e = coil thickness (cm)

Finally, all this shows the importance to maximize antenna Q factor on both sides, reader and transponder but there are some limitations. The frequency bandwidth of the reader antenna should not be forgotten as it is a function of the Q factor, and transponder data rate must be included in this frequency bandwidth. Also, each antenna circuit has got frequency tuning tolerances due to component variations. It has to be reminded that to simplify the previous calculation, a perfect frequency tuning between field frequency and antennas resonant circuit has been assumed. Therefore, after a first set of system parameters has been calculated using above formulas, a second iteration process should be done including the effect of frequency detuning to check if the components tolerances meet the overall system performance requirements.

4. LF Read Only transponder applications

When in 1993, a major German insurance company put up pressure to either protect vehicles against massively increasing theft or else renounce to full insurance coverage, nobody believed that RFID as a then emerging technology would see one of it's first major successes, still unbeaten in numbers by any other application today. Objection was raised as to the reliability of potential systems, their suitability in an automotive environment and of course, the lack of standards in what then seemed to be a mystic collection of proprietary systems, was seen to be a major obstacle.

An extremely fast but substantial development effort was undertaken by a few powerful automotive industry suppliers, resulting in a miniaturized "Inkey" system and it's car lock transceiver counterpart to be fitted to new cars as early as 1994 already. This first generation system, still fitted to certain models of most major car makers, consisted of a 64 bit read-only, rod or brick type transponder, embedded in the ignition key of the vehicle and a transceiver antenna with it's electronics package on PCB, integrated around and behind the lock. The functionality consists of safely cutting power supply to the starter, the fuel pump, the system ignition and other system elements, required for the vehicle's operation during driving for the case, where the presented key does not match one of the pre-stored codes. Specifications for the miniaturized transponders were very stringent, requiring maximum read distance in a metal loaded environment over industry practice thermal ranges with only a few ppm failure rate admitted! Three mainstream systems were adopted by the majority of the automotive industry and have since been fitted to millions of new cars with great success. Immobilizers today in Europe are part of the normal equipment of cars and whilst still no standard rules neither the application nor the products, several systems have established a de facto standard and wide public acceptance: What is good for the automotive industry can be used in many applications elsewhere!

In parallel, a variety of retrofit systems were developed to protect vehicles already put into circulation. Most of these contactless systems rely on the same principle except that they use keyholders and that their transceivers are mounted inside a more convenient place in the dashboard. Their success in the market was not as expected and their need is no longer given, considering that almost all European vehicles are now equipped with OEM systems.

The possibility to emulate the code with an unsophisticated reader/transponder black-box and hence to circumvent the immobilizer was early 1995 at the origin of a new development, aiming at increased security features. It was widely felt, that the barrier level was not high enough and that the target of an 80% reduction of car thefts, mainly for high-end models, could be missed. Second generation products now interface with several more motor management functions and the read-write transponders feature encrypting in the communication with the lock, rendering fraudulent attempts to drive away with the vehicle almost impossible. As an example, a typical encrypted communication protocol so called « challenge/response » is described in figure 4. Statistics of stolen cars, fitted with first generation immobilizers, showed however, that the problem had been dramatically reduced and the objective had been met if not exceeded.

One of the first RFID applications was animal ID and whilst this most useful application never came to the importance that it should have done, it still is the first domain with an official standard. ISO 11784/11785, released in 1996/7 indeed lay down the rules, applying to a variety of ID products such as implants, ear marks, bolus etc. and are intended for establishing a traceability, predominantly for herd animals. The standard is contested by suppliers of proprietary systems, used for companionship animals, but at present is upheld and therefore still valid. The standard prescribes a frequency and a series of communication protocols on transponder level as well as a numbering system to be embedded in the 128 bits of the transponder IC memory.

Criticism relate to the potential flaws in uniqueness of the allocated numbers and the possibility of fraud and similar to the above described automotive fears, the industry considers sophisticating the application with additional security. It is however widely felt, that the barrier of a 128 bit read-only transponder is quite sufficient to reduce to near insignificance any attempt to circumvent the target and that additional features would only laden the cost of the products, rendering the application impossible for agriculture.

Current projects of the European Union clearly tend to the use of an ISO compliant system to be tested on a large scale and several European Governments appear to work on the setting-up of the necessary infrastructure. 1998 and 1999 will therefore see another major application emerge for read-only products, which will remain an important product group for years to come.

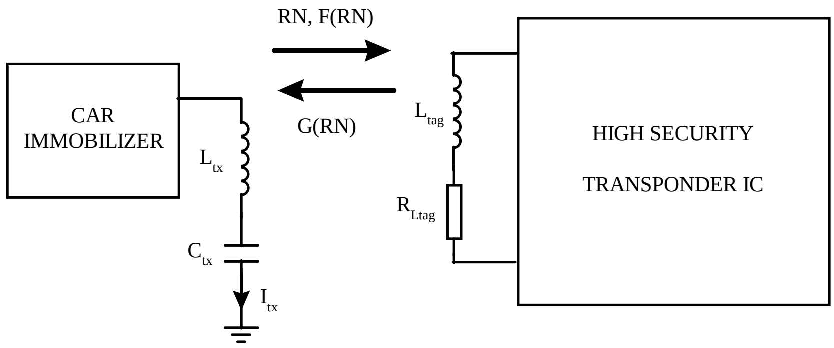

Figure 4 - « Challenge/Response » authentication protocol example

Phase 1: The Car Immobilizer sends the « challenge » message, formed by a Random number, followed by a date stream called f(RN) calculated with a secret key and the random number.
Phase 2: The transponder upon reception of the challenge message checks the f(RN).
Phase 3: If challenge message passes transponder check, the transponder calculates a g(RN) number with the random number and the same secret key but with another algorithm. This forms the « response » message.
Phase 4: The Car Immobilizer upon reception of the response message checks the g(RN) and if ok declares the authentication procedure successful.

5. LF Read Write transponder applications

In September 1995, the world's leading maker of fashion watches and the Austrian leader of electronic ski-ticketing systems agreed to a co-operation in the field of contactless ski-ticketing. The goal of the co-operation was to combine the strength of the Austrians with the innovative SWATCH® concept and the resulting advantages. Launched in December 1995 in Laax (Switzerland), the concept is today installed in more than 300 ski resorts worldwide.

Hardly any other application could underline better the term of hands-free operation and the readers who practice skiing, have stood in a queue with all the gear in their hands (and your very small children next to you) at minus 12°C will understand at once the advantages of passing through skilift access turnstiles without having to fumble for his or her skipass.

The SWATCH® access wrist watch for this application is equipped with a 1 kbit read write IC, connected to an antenna within the watch. The system is passive, does not draw power from the onboard battery, but still operates within a distance of min. 10 cm from under the skidress to the reader station. Said transceiver will communicate with the watch and safely alter the contents of the EEPROM memory to reflect a credit balance, access authority (for daily passes) etc. and since the watch remains with of the owner beyond the skiing, the application reduces waste as generated with plastified cards or the like. Benefits for the ski resort include a substantial increase in raw data, captured throughout the sites and used for statistical purposes, extension planning, punctual improvements etc. The RFID technology is accepted by the users to the same extent as are bar code and/or magnetic stripe tickets.

The watch application stands for a series of opportunities, where the digital interface between human beings and machines greatly facilitates desired transaction; both in time and accuracy. The fact that RFID watches are perceived to be a necessary, even fashionable accessory of people will add to the understanding and public acceptance of the technique.

Another important application field of R/W transponder is the multi-tag identification where sending information to the tag is an absolute requirement. For applications like laundry automation, textile rental, inventory control, it is necessary to identify and count several transponders present at the same time within a reader RF field. One of most known protocol is the so called Supertag™ anti-collision protocol developed in CSIR (South of Africa) and licensed by BTG (United Kingdom). The main principle of this protocol is that the transponders messages are very short and randomly repeated during the time. This supposes an excellent on chip random generator for the transponder IC. Some additional features like temporary inhibition and final inhibition commands allow the reader to mute the identified transponder thus reducing the number of message collisions allowing a higher number of tags in the field.

6. Low cost system design

Particular emphasis is to be given to system design cost since most RFID applications do become price sensitive shortly after the start of the deployment phase; as and when number of installed items and/or quantities become significant. System cost shall therefore mean ❶the application development cost, ❷the cost of hardware including tags, readers, network hardware and other peripherals as well as computing facilities, their installation and commissioning and finally ❸ the cost of system operation throughout it's planned lifecycle. Since the quantifiable elements of the expected gains are often difficult to demonstrate beyond doubt, such system cost have to be kept as low as possible, yet without attempting to unprudently save money during development.

Assuming the majority of development cost to lay within the proper translation of the performance requirements, i.e. the definition of the intended functioning, the creation of software, the setting-up of operational procedures for all elements and finally the testing of the system components, a big lump of the available funding is already gone. Unless the application is intended to be a turnkey package to be sold many times "without adjustments" or alternatively a truly high volume niche application with an useful lifetime of several years, the development price of a system represents by enlarge the major cost of the application project, relegating cost of transponders and readers well below the level of attention that these items are usually given.

The recent emergence of single chip reader ASSP has greatly improved the potential for low cost, handheld, medium range readers in the 120 to 150 kHz band. Several semiconductor producers now offer comparable solutions with auto-frequency adjust features (PLL loops) for the design of simple, rugged transceiver units. Some of these reader ASSP are truly low power ICs and simply interface with a microcontroller of the designers choice, hence leaving vast room for feature incorporation. Provided that designers do not want push communication performance beyond reason, customized readers can be developed in less than 3 months. An increasing number of products, ranging from OEM boards through to handheld computers with an RFID reading capability and an RFDC (or infrared) interface are now readily available on the market and their prices are still falling.

Often, the system low cost requirement is driven by the cross-subsidizing policy, applied by several system houses in overall product/system pricing. The art consists of squeezing the cost of "consumables" below the publicly perceived level of item value in order to maximize margins. The lure consists of overpricing mainly transponders or tags with a view to recover underpriced application development and costly adjustments of other, associated hardware items. This way of proceeding is increasingly dangerous with emerging new component producers, entering the market and selling their hardware as off-the-shelf commodity; mainly when the "consumables" are of mainstream technology and therefore system compatible.

The design of LF-transponders, i.e. tags in the 120 to 150 kHz range make use, at least, of an IC, actually the heart of the features, and connected to a copper antenna coil, sometimes even a capacitor. Miniaturized rod type transponders as used for animal implantable ID carriers furthermore use a ferrite but in essence, the single most costly item remains the IC and therefore, considerations of wire optimization, the use of bobbins etc. may be ignored for the purpose of this paper.

Designs nowadays incorporate single chip solutions, mounted on PCB, TAB, lead frame or even better, connected without further carrier structure directly to the antenna. The trade-off between an onboard capacitor (single chip) and a multicomponent subassembly, as for instance required in half duplex systems clearly favors in terms of cost and reliability products, that minimize the number of built-in components. Finally, consideration has to be given to the packaging of transponders in line with the intended use and lifetime, may be even with respect of ultimate disposal after the end of it's useful life. Widespread use of cheap plastic encapsulation, including PVC laminates may well reduce item cost but later become unacceptable.

Analyzing a straightforward Access Control Application with an add-on benefit of shopfloor data collection for a smaller company (50 to 100 employees) would show the use of some 10 transceiver stations for area protection and data collection and maybe 200 tags for the employees. The system would have to be wired to the company's IT facility and off-the-shelf software adjusted to the company's particular situation (Logo display etc.) At prices of $400.- per transceiver and $5.- of the badges and estimation the installation and wiring at $2000.-, one would invest $7000.- in such a system with a semiconductor content of less that $300.- Of course, the time it takes to issue the badges (with personal photo?), to re-engineer the operation and to explain (and re-explain) the new system to each employee would have to be added.

Not enough attention is given yet to the determination of saving potential and productivity increases, resulting out of an RFID application. It is widely felt that many current installations are the fruit of an "imperative" situation or some "gadget" of an influential group of people, insisting in their "solution". Overall system cost in all these cases is the minimum that one can get away with and it is needless to add that such systems operate with restrictions and that the reputation of auto ID solutions suffers.

7. Conclusions

A simple theory has been developed to allow non RF specialist to build up RFID systems using OEM products like transponder IC and RFID reader board. Some major applications have been described showing the large potential of the RFID market. Very high volume applications are about to emerge requiring optimized low cost solutions like the « Retail tag » and contactless smart card applications.

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