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Smart RFID Tags

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1. Introduction

RFID has been identified as one of the cornerstones of the upcoming Internet of Things (IoT) and the focus is moving from conventional RFID towards next generation pervasive networked and interconnected systems. In the future IoT billions of objects are envisioned to report their identity, location, environmental conditions and history over wireless connections.

An on-going effort that will support this gradual change is the development of "smart RFID tags", tags that are able to sense, monitor, and adapt to their changing environment. RFID systems alone provide item and product visibility within the supply chain. This visibility can further be translated into actionable data and predictive changes with additional information attained through sensing capabilities. Intelligent RFID tags can combine sensing, computation and communication into a single, small device. The need for new sensing solutions is highlighted further by the fact that legislation, regulatory and quality demands are setting requirements for certain branches (pharmaceuticals, explosives, transportation of dangerous goods, foods, etc). Cold chain compliance is a key requirement for pharmaceuticals, hospital transfusions, clinical trials, foods and perishable items. RFID can be used to fight counterfeiting and RFID can provide the electrical pedigree of a product.

Most efforts on RFID tag design so far have been concentrated on the ultra low price tag segment. This has led to compromised performance when label tags have been applied in “unsuitable” environments and has been evidenced as low reading accuracy in many RFID pilots. In order to reach a high reading accuracy and reliable long distance operation, RFID tags ought to be immune or adapt to their environment (e.g. presence of metals, liquids, gas...) to avoid detuning and other impairing effect caused by their surroundings. New solutions to implement platform insensitive/platform tolerant and platform adaptive RFID tags are emerging.

2. Platform tolerant and platform adaptive tags

2.1 Introduction

Although antenna theory as such is independent of the field of applications, the central role played by the antenna in the tag design makes the designing of RFID tag antennas different from any other antennas. The antenna design must comply with many competing tag design

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criteria such as: the overall cost including manufacturing issues, compact size and shape of the tag, frequency bandwidth, antenna gain, robustness and reliable operation over long distances. For example in a mobile phone there is always the handset structure into which the antenna is to be integrated. It means that one can take advantage of the already existing parts and use them as a part of the antenna. In many other electronic applications there is a printed circuit board that provides at least the ground plane for the antenna and consequently, the additional cost of the antenna is often negligible when compared to the rest of the device.

In an RFID tag, the antenna basically defines the tag itself, the only other parts being the tag substrate or matrix and the microchip that costs a few eurocents and is less than one cubic millimetre in size. The reading distance of a passive RFID system depends on the realized gain of the antenna and the antenna gain is a more critical parameter than for an active short range device such as a Bluetooth accessory. RFID tags are to be attached directly onto several different kinds of articles, which set some special requirements for the platform tolerance of the tag antennas. In the following, platform tolerant antenna solutions mainly for UHF will be examined. In terms of platform tolerance, the problems with HF (13.56 MHz) RFID are somewhat different. This is due to the fact that at HF frequencies the coupling between the reader and the tag is based on magnetic near field and the mutual inductance between the respective antenna coils. With some limitations, platform tolerance can be implemented for HF as well, but with different types of solutions. These will be shortly described in section 2.4.

2.2 Platform tolerance

The inexpensive labels utilizing an electric dipole type antenna are by far the most common type of UHF tags. Owing to their simple structure and suitability for cost-effective large-scale manufacturing, they have set the minimum price for passive RFID tags and rendered the use of RFID possible for many new applications. On the other hand, their application area is still quite limited. These tags cannot be put on metal surfaces or e.g. on surfaces of a liquid container. Also certain materials that do not necessarily prevent the operation of the tag, may limit the read range so severely that the reliability of the whole system is harshly reduced.

The inapplicability of label tags on certain surfaces is a fact that is purely based on physics – a two-dimensional antenna cannot work when placed on a conducting surface. A platform tolerant operation always requires some thickness. As many important applications require tags to be put on this kind of challenging surfaces, there has been a growing need for new types of tags. The fact that the current label tags are indiscriminately used in very different type of environments has lead to a situation where the tag typically is the weakest link of an RFID system and causes the whole system fail. For a reliable and robust RFID system, a certain read range of the tag should be guaranteed independently of the physical environment.

To overcome this, the ideal tag should be small in size, inexpensive, mechanically durable, should provide long operation range and should be possible to be attached into various objects, without any significant effects on its performance. [Foster et al., 1999] The so-called platform tolerant or metal surface tags can provide at least the last three of these properties of an ideal tag. This type of a tag is not a new concept. The need for such tags was already encountered in the very beginning of the development of UHF RFID systems. The simplest possible and commonly used solution to obtain a somewhat platform tolerant operation was to raise a conventional label dipole a few millimetres above the problematic surface, using e.g. a plastic spacer. This allows the tag to work, but the reading distance becomes typically only a fraction of what was originally intended for the same tag in free space.

There are some tag solutions in which this kind of raised dipole type tag antennas have been optimized to operate on a metal surface. This optimization can only be made in terms of antenna impedance in order to provide the conjugate matching between the microchip and the antenna. This so-called detuning effect can then be compensated, but the operation principle of such an antenna is still inappropriate to operate as a platform tolerant structure. It results in the so-called on-metal tag. On-metal tags and platform tolerant or platform insensitive tags are not necessarily the same thing. In many cases, an on-metal tag is only tuned for a metal surface, which means that for any other surfaces, their performance is compromised. Another approach has been to optimize tags for specific environments and mounting platforms. This approach results in many tag models i.e. one for each possible platform. Technically, this can already give good results. But there are two main problems. Firstly: the application environment needs to be very well known in order to select the right tag. For example, when tagging a cardboard box in a warehouse, one would have to know what the content is and how far from the surface of the box this content is. Secondly: a large variety of tag models is needed and thus it will be more difficult to reduce the tag price by production volumes.

The conclusion is that uncompromised operation can be best guaranteed by implementing a tag design that is really platform tolerant. Importantly, platform tolerance should be based on the physical operation principle of the antenna. Because of its general-purpose nature, such a tag could then be fabricated in large quantities, reducing the unit price. It is already possible to implement such tags and some models are already available on the market.

The main effects of the near environment on the antenna performance are the near field losses and the so-called detuning effect. [Rao et al., 1999] Losses in the near field reduce the radiation efficiency of the antenna. The detuning effect is due to the change of the antenna feed impedance visible to the microchip. The detuning of the antenna ruins the power matching between the antenna and the chip. These two effects affect the measured effective aperture of the antenna. The effective aperture also contains the directivity of the antenna. [Pursula et al., 2007] The realized gain, determined by the effective aperture of the antenna, in the direction of the reader is, together with a certain sensitivity of the microchip, what basically determines the read range of the tag.

By thinking how the world around us looks at the UHF frequencies, i.e. around 900 MHz, we see that it is magnetically quite neutral but very heterogeneous in terms of electric field. This means that the environmental disturbances of the antenna operation, reducing the realized gain, take place mainly via the electric near field of the antenna. Consequently, in a platform tolerant antenna, the magnetic near field of the antenna can be allowed to burst out of the outer dimensions of the tag antenna, whereas the electric field should be kept within the antenna structure. It also means that in all of the platform tolerant structures, the magnetic dipole is always of special significance as a radiator. By concentrating the near electric field inside the antenna itself and taking advantage of radiators based on magnetic dipole, both effects of the antenna near environment can be minimized, thus implementing a platform tolerant structure.

As HF RFID is based on utilizing magnetic coupling, the system is less sensitive to electrical disturbances and changing permittivities in the near environment of the tag. Metal platforms, however, are problematic also for HF. In fact, magnetically coupled near field tags are also available for UHF. These tags are typically simple one-round metal loops of 10 mm in diameter and they are used for item-level tagging. With those, some tens of centimetres of reading distance can be achieved. Metal platforms, however, are problematic also for these near field tags. One solution for HF platform tolerance is described in chapter 2.4.

As the feed impedance of a platform tolerant antenna is very stable from a mounting platform to another, the antenna is allowed to be narrowbanded, whereas with other types of antennas the sensitivity to external disturbances is typically reduced by broadbanded impedance matching. This difference is illustrated in Fig.1. The goal impedance, which is the complex conjugate of the chip impedance, is marked with a red spot. As broadbanded tuning is based on a compromised match (Fig.1 left), using platform tolerant antennas, we can implement a better match and gain in the read range.

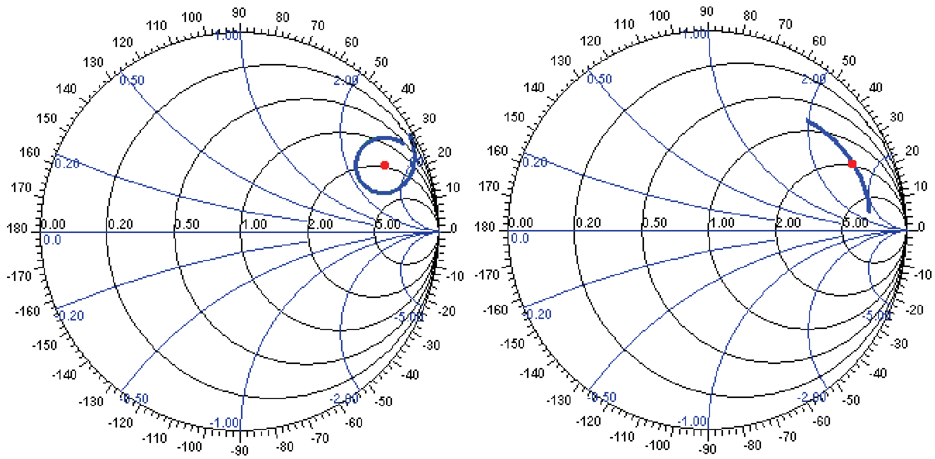

Fig. 1. Broadbanded (left) and narrowbanded impedance match between the antenna and the microchip.

2.3 PIFAs and PAFFAs

Most of the platform tolerant UHF tags are based on the antenna structure known as PIFA, which stands for ‘Planar Inverted F Antenna’. [Hirvonen et al., 2004] PIFA is a very popular antenna type in general. In addition to the platform tolerant RFID tags, PIFA-type antennas are commonly used in mobile phones and e.g. for wireless networking in laptop computers. PIFA type RFID tags are shown in Fig. 2. There is a ground plane placed at the bottom and a radiating patch on top of the antenna. The length of the patch is about a quarter of the wavelength. The metal layers are short-circuited in one end and the chip is connected between them at the second point. By selecting the feed point, different feed impedances can be realized. This is important, because the RF front end of the microchip has to be optimized in terms of the efficiency of the RF rectifier; the resulting input impedance is then a secondary parameter. [Facen et al., 2006] Consequently, the RFID transponder chips and antennas are practically never 50 Ohm or even self-resonant structures. Instead, a very typical feed impedance of the transponder antenna is about (20 + j150) Ohms at 900 MHz.

Technically, PIFA is a very good solution: platform tolerant operation can easily be achieved and the main direction of radiation is exactly where we would like to have it – outward from the mounting surface. As the electric field of the PIFA is enclosed between the metal layers, the detuning effect of a well-designed PIFA is almost negligible. The directivity of the antenna, instead, increases as the tag is put onto a conducting surface. This is due to concentration of all the radiation in to the open hemisphere, whereas in free space the PIFA has a back lobe in its radiation pattern. The problematic issues about PIFA are the high price and the large size. The price is mostly due to a complicated structure and thus a complicated fabrication process. Especially the number of steps in the fabrication process is an important parameter here. PIFA tags have typically a separate plastic casing and a separate antenna inlay.

A typical fabrication process consists of injection moulding of the casing, etching of the antenna inlay and finally combining the two parts. And this last phase is typically the most challenging one, because of two things: firstly, the tuning of this antenna type is quite sensitive to the dimensional tolerances. Secondly, handling this flexible inlay requires special tools in the assembly line. In some cases, an additional ground plane, which is a metal plate, is also used beneath the antenna. The longest outer dimension of the antenna is a little over a quarter of a wavelength that is typically from 6 to 12 centimetres depending whether there is air or some plastic between the layers. The property of platform tolerance requires that the ground plane and thus the whole antenna to be somewhat bigger than the radiating top patch of the antenna.

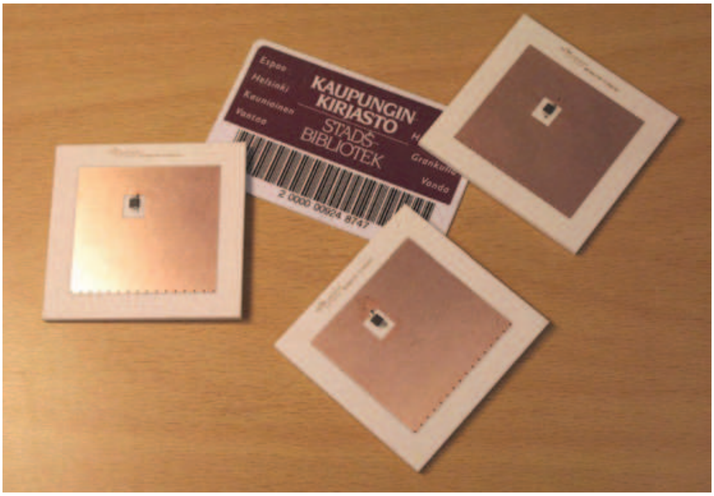

Fig. 2. PIFA tags, 2005. Courtesy of VTT, Technical Centre of Finland.

Because of the constant pressure on the cost of an RFID tag, concepts such as PAFFA ('Planar Asymmetrically Fed Folded Antenna') have been developed. [6] The idea has been motivated by overcoming some of the structural complexity of PIFA - making a platform tolerant hard tag economically more competitive with label tags. The difference between PIFA and PAFFA structures is that in a PAFFA structure only one connection between the two metal layers of the antenna is needed. Because this required connection is in the end of the antenna, the antenna can be implemented e.g. by bending a flexible inlay around a piece of plastic. As vias and thus PCB processes are not needed, the metallization can also be

made using new techniques, e.g. by printing directly on a plastic substrate. [Allen et al., 2007] Technically, the idea is based on replacing the feed point connection between the metal layers by a quarter-wave open-ended microstrip line. The other possibility is to use a half-wave line that is short-circuited from one end. To reduce the size of the tag, these lines can also be meandered. As the microstrip lines also take part in the radiation of the antenna, their dimensioning can be optimized in terms of the desired radiation pattern. They also provide a degree of freedom when finding the right feed impedance for the microchip. A PAFFA type tag is shown in Fig. 3.
The PAFFA structure can be defined to consist of two quarter-wave microstrip lines between which the microchip has been connected. One of theses lines is short-circuited and the other is open-ended. The short circuited end of the first forms the magnetic dipole needed for platform tolerant operation. The resonant behaviour of the microstrip lines can also be utilized for some new features. By implementing multiple resonances in one tag antenna, a so-called global tag can be made. [Hirvonen et al., 2006] [Hirvonen et al., 2006] This global or triple frequency tag provides optimal operation at all of the frequency bands allocated for UHF RFID around the world: 867 MHz in Europe, 915 MHz in North America and 953 MHz in Japan. Compared to some global tag solutions that are based on utilizing one broadbanded resonance, the three separate resonances provide remarkably better performance, combined with platform tolerance.

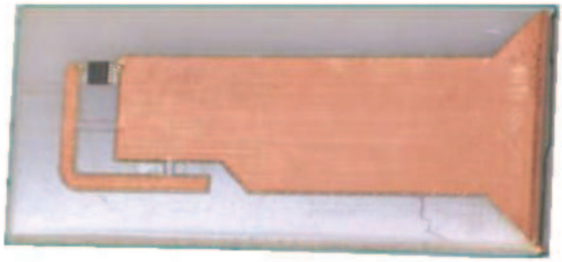

Fig. 3. PAFFA tag. Courtesy of VTT, Technical Centre of Finland, 2006.

2.4 Tag miniaturization
Physical size is one of the key parameters for RFID tags. In theory, microstrip antennas can be miniaturized by meandered lines. As long read range and thus good radiation efficiency is also required, meandered microstrip structures are not the best solution. Instead, some special materials can provide at least partial solutions. The basic idea with these is to reduce the effective wavelength λ inside the antenna structure. This is because the antenna should have a particular electrical length to operate efficiently. For PIFA and PAFFA type structures, the required electrical size is about a quarter of a wavelength. Compared to the physical size, the electrical size can be increased by raising either permittivity or permeability of the tag substrate material, according to the equation:

$$\lambda = \frac{c_0}{f\sqrt{\varepsilon_r \mu_r}}, \tag{1}$$

where c_0 is the speed of light in free space, f is the operation frequency, ε_r is the relative permittivity and μ_r is the relative permeability of the material. There are some materials with high permittivity available on the market. Typical plastics and materials for printed circuit boards have relative permittivity values of 2…5. Materials with relative permittivity over 5 can be often considered as "high permittivity" materials. But additionally to the material permittivity and permeability, the material losses are important parameters concerning their applicability for tag antennas. PIFA and PAFFA structures are especially sensitive to electrical losses and hence the material for antenna substrate should be carefully selected. If the inter-metal space in the antenna is to be filled with this material, the electric loss tangent ($tan\delta$) or loss factor of the material should in practice be below 0.005.

The main problems in utilizing high-permittivity materials are that the loss factor typically increases together with the relative permittivity and, even in the case of low loss factor; the high permittivity also increases the current densities and thus the conductive losses in the antenna metallization. A further problem with high permittivity materials is the resulting narrow frequency bandwidth. In terms of bandwidth, a better way would be to use high permeability instead of high permittivity. This can be understood in terms of physical equivalents: as increasing permittivity increases the effective area of the antenna, high permeability increases the effective height, making the magnetic dipole more efficient. Consequently, the high-permeability material could then be used for making the tag thinner. Comparing these two ways of miniaturizing the antenna, high permeability would be at least theoretically a more beneficial way. Utilizing a PIFA type basic structure, the ultimate solution would be to combine both: high permeability for the magnetic dipole part of the antenna and high permittivity for the end in which the electric field of the antenna is concentrated. Unfortunately, all the high permeability materials for UHF that are currently available are quite lossy i.e. their magnetic loss tangent is relatively high. [Martin et al., 2007] Therefore, practically all of the small tags utilizing special materials are so far based on the use of high permittivity substrates. [Hwang et al., 1997] However, the development for UHF applicable high-permeability materials is in progress. So far some applicable high frequency ferrites have been used in low-profile UHF near field tags.

For HF frequencies high permeability ferrites with a relative low loss factor are available and can be used between the tag coil and the surface. Here the idea is, instead of miniaturizing the tags, to direct the magnetic flux between the coil and the mounting platform, resulting in an on-metal HF tag. [Bovelli et al., 2006]

2.5 Platform adaptive tags

In addition to the platform tolerant tag antennas, another possible approach for implementing platform tolerance of the tag is the use of an adaptive RF front end of the tag IC. In this case, as the environment changes, the microchip automatically changes its input impedance for conjugate matching between the IC and the antenna. With this method, more simple tag antennas can be used. Technically, this solution can be based on a varactor diode or a pattern of switchable capacitors on the microchip. [Rostbakken et al., 1995] Theoretically, also more complex adjustable impedance matching networks can be used, but in most cases an adequate impedance match can be achieved by just tuning the parallel capacitance. Typically, some tens of picofarads can be implemented on a CMOS chip within an area that is still realizable.

Compared to platform tolerant antennas, the approach of adaptive RF front end has its limitations. The most critical thing is that the system cannot cope with the reduced radiation efficiency of the antenna in the proximity of lossy substances. One challenge about this type of a system is that the matching network requires some electrical power already in a phase when the impedance matching between the antenna and the chip may be poor. Therefore this type of a solution is more suitable for semi-passive than passive tags. The simple parallel-type tuning also suits best with simple reactive antennas such as near field UHF or HF loop antennas.

3. RFID sensor tags

3.1 Introduction

Along with the RFID technology, a new focus area placed on RFID sensor tags is emerging. RFID sensor tags are associated with a product, person or a location through a simple ID and are capable of measuring and acquiring data from the users' behaviour and the environment such as temperature, pressure, tampering, shock, humidity, etc. RFID sensor tags also allow the connection of data loggers and remote controls as well as the connection of displays, printed sensors, and biosensors via the traditional RFID tags.

Various user cases related to RFID-based smart sensing have emerged: in March 2006, the Japanese Ministry of Internal Affairs and Communications (MIC) started developing a system that allows for detailed information gathering about a disaster area by sprinkling RFID sensor tags from the sky. In June 2006, British Petroleum began a trial of an RFID-based sensor network to help it better manage chemical inventory, increase stock visibility and reinforce safe-handling business rules. In January 2007, the global shipping company DHL announced the deployment of RFID sensor tags to its pharmaceutical customers to track the temperature and shelf life of products being shipped from warehouse to store. And lately, in December 2007 Motorola and Intelleflex announced a strategic relationship in extended capability RFID; Motorola Ventures co-leads $15 million series C investment in Intelleflex. Specializing in battery-assisted RFID, the Silicon Valley-based company targets the aviation, yard management, logistics, hospitality sectors, and asset-tracking applications.

The HF range is currently the most widely used operation frequency for RFID and the unlicensed ISM band around 13.56 MHz is globally available for RFID devices. Its use is expected to grow further in the near future driven by the newly established NFC (Near Field Communication) technology that allows users to read small amounts of data from tags, as well as to communicate in a peer to peer fashion with other devices, by a simple touch with a handheld remote control such as a cellular phone. In January 2007 Nokia launched the world's first fully integrated NFC phone. With devices such as the Nokia 6131 NFC phone, users can make contactless payments and access mobile services with ease. In the future, users will be able to pick up information from their environment using NFC technology and sensor tags.

On the other hand, ultra high frequency (UHF 860-960 MHz) systems are gaining acceptance in many application areas. For example, the retailer Marks & Spencer has launched the largest UHF item level tagging in its department stores deploying more than 100 million UHF RFID tags with embedded EM Microelectronics passive 869 MHz RFID chips. The technology has helped Marks & Spencer increase both efficiency and customer service. Compared to lower-frequency systems the major difference and advantage of a UHF system is that it is able to operate in the radiating (propagating) far field of the reader. Lower-frequency systems utilize inductive coupling between reader and transponder, i.e. non-propagating magnetic field decreasing rapidly with distance from the reader device. In practice, operational ranges of several meters together with moderate reader sizes, such as handheld readers, can only be obtained by operating in the far field region. At HF the reading distance is comparable to the size of the reader. The establishment and acceptance of a world wide standard in the form of EPC Global has paved the way for faster implementations. Lately, the transponder price has undercut the critical 10 cent barrier, which makes them attractive for high volume applications.

3.2 RFID sensor tags types

Among the two dominating frequencies of RFID operation, i.e. HF and UHF, three categories of RFID sensor tags can be distinguished: active, semi-passive, and passive solutions. The available commercial passive and semi-passive solutions for wireless sensors and data acquisition systems mainly work at low operation frequencies and are based on short range inductive coupling. The active solutions based on UHF can provide much longer operation ranges and enhanced features at a higher cost.

Active RFID sensor tag transponders are constantly powered by a battery and contain an active radio transceiver. For example, Telepathx ITS [14] has developed an active system that integrates RFID tags, crash sensors, and wireless mesh networks to automatically detect crashes, assess the severity, and report the incident to public safety forces. The RFID sensor tags can transmit 100-125 meters in any direction. The sensor has a small battery installed for transmission purposes that has a life span of 10 years. Different RFID sensor tags can operate at the 433 MHz, 900 MHZ, or 2.4 GHz frequencies.

Semi-passive RFID sensor tags are hybrid implementations of active and passive transponders. A semi-passive tag contains a battery for powering the IC circuitry operations and backscatters the incoming reader field for tag to reader communication. Such semi-passive tags have three main advantages 1) Better sensitivity than passive tags (up to 30 meters) 2) Longer battery life than active tags 3) Can perform active functions under their own power, even when no reader is present. For example, Alvin Systems [15], located in Turkey, has launched a cold chain solution with credit card size smart labels that combine RFID operation compliant with the ISO 15693 standard, temperature sensors, and mobile Pocket PCs. The RFID sensor tags monitor the condition of temperature-sensitive objects during transportation or storage - for quality assurance and enhanced cold chain operations. Lately, Montalbano [16], an Italian-based company has started commercializing MT RFID sensor tags that have a credit card size and shape, are ISO 15693 compliant and can be applied to pallets and boxes of goods as well as on rounded surfaces. MTshock tags detect and store every single collision or shock that art-works, explosives, vintage wine, or any kind of fragile goods can suffer. MT humidity tags store relative humidity changes while MTSense tags monitor the thermal history of the monitored product.

Passive RFID sensor tags do not contain a power source and consequently, can only perform active measurements when powered by a nearby RFID reader. The existing passive RFID sensor tags are mainly based on proprietary solutions. For example, Bioett [17], a Swedish company has developed a system based on a biosensor for temperature monitoring. A chemical Time Temperature Biosensor is activated when the label is placed on the product to be traced and the Bioett System monitors the accumulated effect of temperature on products over time. Since this solution is based on bar code reading, the amount of information that can be coded is limited and reading distances are in the cm-range. Efforts to develop passive RFID based sensor transponders working at UHF frequencies in order to

achieve longer reading ranges and smaller transponder sizes are growing but so far the results are at demonstration level.
Different solutions have been envisioned in the past. (i) Changing the polarization of the tag antenna as a function of the sensor response but this method requires two different antennas at the interrogator side and the sensor response can only contain 1-bit information. (ii) Using two tags with one tag being activated when the sensor response has reached a threshold (iii) Redesigning the RFID chip to include the sensor interface. For this last solution, papers have been published presenting working passive sensor tags [Pursula et al., 2007], [Cho et al., 2005] but these demonstrators only support their own proprietary protocol, which impedes their penetration to the market. A prototype of a passive UHF chip compatible with the ISO 18000-6c standard and capable of accessing four different external sensors was developed by VTT. The operational range of the first generation temperature measuring device was 80 cm.

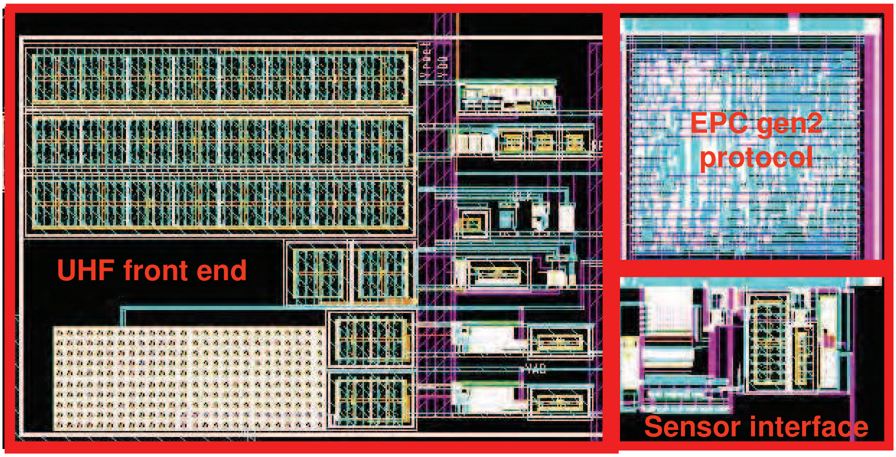

Fig. 4. Passive UHF RFID sensor able to monitor external capacitive and resistive sensors. Courtesy of VTT, Technical Research Centre of Finland, 2008.

3.3 RFID sensor tag architecture
3.3.1 Introduction
The current development of RFID and other wireless communication based sensor solutions have so far been mostly concentrating on active, rather high cost and high power solutions. Consequently, the sensors used in these solutions have not been optimised for low power consumption and the concept does not adopt well for low cost solutions. Semi-passive RFID sensor solutions based on an extension of the EPC Global protocol and equipped with proper power management, a low power sensor interface and tailored low power sensors offer a unique opportunity to develop commercially viable, low cost and low power solutions. Using cheap integrating platforms makes even disposable sensor tags viable. New solutions will be introduced into the market within a few years and the compliance with EPC Global can pave the way for a fast acceptance. Passive RFID sensor tags complement the solution and provide long lifetime, maintenance free solutions for appropriate applications, e.g. moisture monitoring in construction materials.

For such applications, efforts are needed on sensor development. Indeed, passive RFID sensor tags require low power sensors as well as low power interface electronics. Typically, about 100 μW (microwatts) of RF power is available for a passive UHF tag at a distance of 5 meters (assuming an antenna gain of about 0 dB and a 2 W equivalent radiated power). Product sheets indicate that typical tag integrated circuits currently require around 30 μW of RF power to operate. With a good RF rectifier efficiency of 20 % [Facen et. al, 2006], around 20 μW of the 100 μW is available for the DC electronics. This 70 μW marginal in RF power then equals 14 μW for the sensor electronics, if the reading distance of 5 m is to be maintained. Existing sensor interfaces, such as sigma-delta converters, pipelined or folded converters are usually high power architectures (up to 10 mA) as they are targeting high precision and fast implementations (greater than 10 bits and 30 MHz sampling rates), and thus are not suited for low power applications.

Consequently, new solutions are needed to develop mixed signal sensor interface architectures that would combine high resolution and low power operation with target DC power consumption of less than 20 μW in active mode, and less than 1 μW in power down mode. A tag IC could contain a generic mixed signal sensor interface that would allow multiple external sensors to be connected.

3.3.2 RFID sensor tag architecture

The RFID sensor tag is composed of:

a. An antenna directly matched to the tag's front end impedance to communicate with the reader
b. An analogue RF front end that typically contains rectifier circuitry to convert RF power into DC, a clock, a modulator and a demodulator
c. A logic part that is the translator between the front end and the sensor interface by coding, decoding, commanding, processing, and storing information. The logic implementation usually follows a defined standard and a certain associated protocol.
d. The signal interface that adapts the external signals (sensor reading, data logging, microcontrollers, display, keyboard...) to the standardized RFID tag. The signal interface can be of several nature:
   - A bus interface such as SPI, I2C to connect directly the logical part of the RFID tag to an additional block such as a data logger, microcontroller, display, etc. In this case, the RFID sensor tag can be either semi-passive or active.
   - A sensor interface that converts the change of value of a sensor into something that can be properly treated. The sensor interface is composed of a sensor readout circuitry (charge amplifier, resistive bridge...) and an analogue to digital converter (ADC). The sensor interface can either be passive (the readout electronics and the analogue to digital converter are fully powered by the reader's field) or semi-passive: an additional battery powers up the interface as well as the logic.

Different solutions exist for antennas, the RF front end and the logical part which are treated in the literature, whereas a low power signal interface is a relatively new concept in the RFID context. In the case of sensor reading, the mixed signal interface should implement low power architecture for passive, semi-passive, and even for active solutions for life span purposes. Solutions for low power architectures are detailed in the following paragraphs.

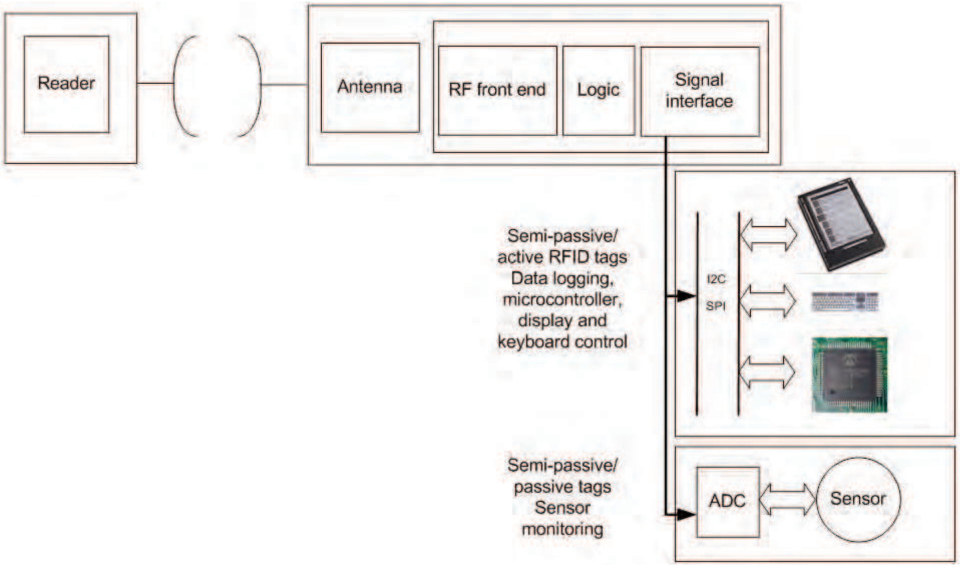

Fig. 5. A possible RFID sensor tag architecture

3.3 Analogue to digital converters architecture review

In this chapter different analog to digital converter architectures will be reviewed and their suitability for low power RFID based sensor solutions will be discussed.

Successive Approximations A-to-D Converter

The successive-approximation-register (SAR) analogue-to-digital converters [20], [Black], [Sauerbrey, 2003] are frequently the architecture of choice for medium-to-high-resolution applications, typically with sample rates below 5 Mega samples per second (MS/s). SAR ADCs most commonly range in resolution from 8 to 16 bits and provide low power consumption as well as a small form factor. This combination makes them ideal for a wide variety of applications, such as portable/battery-powered instruments, pen digitizers, industrial controls, and data/signal acquisition. The input signal does not need to be continuous, because the ADC takes a "snapshot" of the signal. The common blocks included in a SAR ADC are a sample and hold stage, a comparator, a successive approximation register, and a digital to analogue converter (DAC), see Fig. 6. At first, the SAR sets the most significant bit (MSB) of the DAC to be a logical one. If the output of the comparator indicates that the generated voltage is smaller than the actual analogue voltage, the MSB bit remains in the logical 'one' state. On the other hand, if the result of the comparison is the opposite, the MSB is set to zero. This "program" goes through all the bits until the least significant bit (LSB) is set.

Redundant Signed Digit (RSD) converter

RSD converters [Heubi, 1996] are rather similar to successive approximation converters but use an x2 amplifier instead of a DAC, hence doubling the voltage at each step and comparing to a same reference level. Such converters are less prone to the amplifiers' settling time and can be driven faster as the comparisons are made on scaled up voltages via the amplifier. Since the precision elements of the RSD architecture is only based on the x2 amplifier and the adder, less accurately matched components are required. As the same components are used at each step of the comparison, the design offers great linearity.

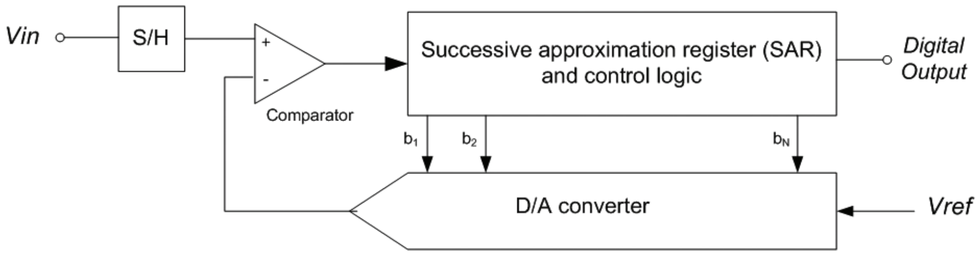

Fig. 6. Block level schematics of the SAR ADC

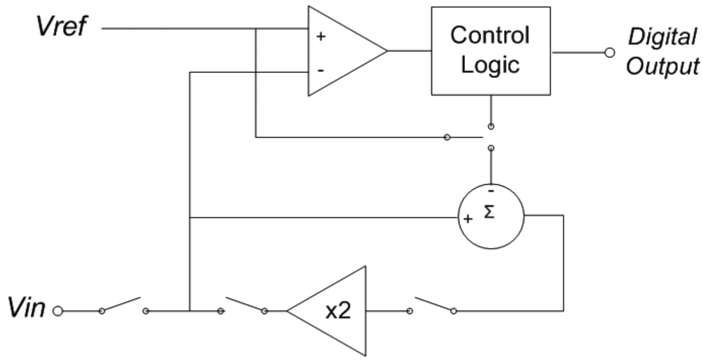

Fig. 7. Example of a Redundant Signed Digit ADC

Parallel or flash ADCs

Parallel or flash ADCs are very high-speed ADCs that are suitable for applications requiring very large bandwidths. They use parallel techniques to achieve short conversion times. Some only use one clock cycle as the conversion speed. Flash types ADC are fast but require a large number of comparators. Indeed, with an *N* bit resolution the flash ADC requires 2^N-1 comparators, which typically is area consuming. In addition, flash converters are power hungry and have a relatively low resolution.

Folding interpolating analogue to digital converter

A smart replacement of the flash architecture is the folding interpolating ADC [Kim et al., 2003]. The number of input amplifiers can be reduced compared to the flash architecture through the use of an interpolating architecture while the number of latch comparators can also be reduced by using a folding architecture. Together, the converter forms a folding interpolating converter that is similar to a two-step converter where a group of LSBs are determined separately from a group of MSBs. These converters belong to the class of medium-high fast converters and do not require a sample and hold circuit. They have smaller area and power dissipation than flash converters, but have a large input capacitance similar to flash converters. The main disadvantages of the folding interpolating converter are its high distortion at high frequencies due to the high frequency components generated internally, as well as a more complex architecture than that of flash converters.

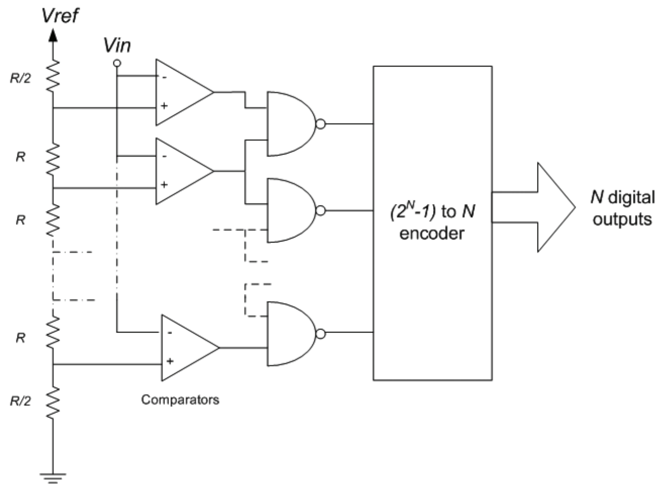

Fig. 8. Parallel or flash ADC architecture

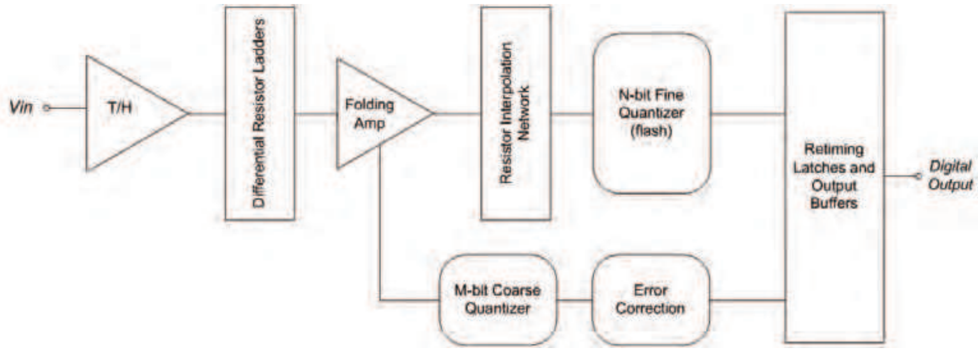

Fig. 9. A 6-bit conventional one-stage (direct) folding structure

Pipelined algorithmic analogue to digital converter

The pipelined algorithmic analogue-to-digital converter (ADC) [Vazl, 2003], [Miyazaki et al., 2001] has become the most popular ADC architecture for sampling rates from a few mega samples per second (MS/s) up to 100MS/s+, with resolutions ranging from 8 to 16 bits. The algorithmic ADC is based on *N* identical stages and *N* comparators that determine the sign of *N* outputs. Each i^{th} stage multiplies its input by 2, and adds it to or subtracts it from the voltage reference depending on the sign of the $(i-1)^{th}$ output stage giving the i^{th} bit at the output of the comparator.

Delta Sigma analogue to digital converter

Delta sigma converters are part of a different class of converters as they are based on oversampling and noise shaping rather than direct quantization of signal amplitudes. Delta Sigma analogue to digital converters are nowadays the most widely used oversampling ADCs found predominately in applications such as instrumentation, digital voice, and audio applications. Typically, their bandwidths are less than 1MHz with a range of 12 to 18 true bits [Dessouky et al.]. Because delta-sigma converters over sample their inputs, they can perform most anti-aliasing filtering in the digital domain. The sigma delta converter measures the input signal for a certain period of time and outputs a digital code corresponding to the signal's average over that time, thus the input signal of interest should be continuous.

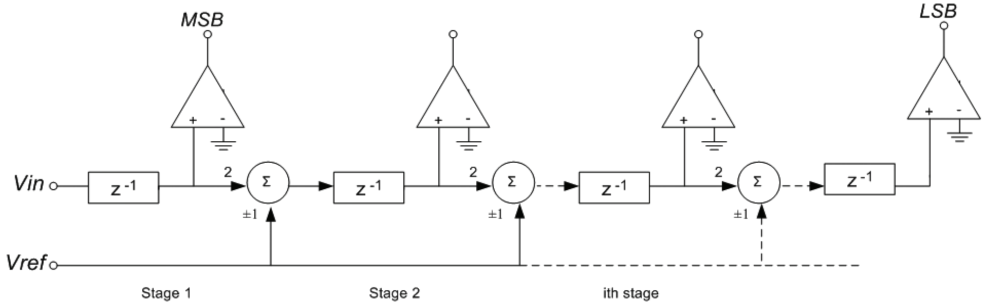

Fig. 10. Block diagram of a general pipelined analogue to digital converter

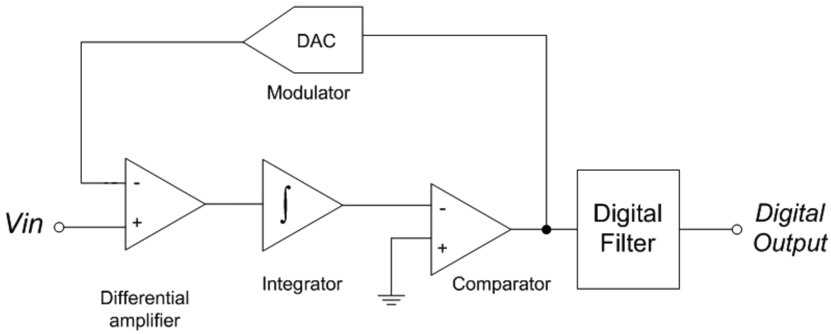

Fig. 11. General delta sigma analogue to digital converter

<u>Capacitance to frequency converter</u>

The capacitance to frequency converter [Chatzandroulis et al.], [Krummenacher, 1985] generates a modulated signal varying with capacitance changes. The capacitance to frequency converter is based on a relaxation oscillator that converts the capacitance into a period-modulated output signal. The converter includes an amplifier, a comparator, the capacitances C_1 and C_2, and a controlled current source I_{curr}. The bias source V_{ch} is used to discharge the capacitive sensor.

<u>Conclusion</u>

In contrast to wireless communication for mobile terminal (GSM/WCDMA) where high-speed ADC are required and where sigma delta converters prove to be robust and offer good analogue performance, ADC with medium resolution (8-12 bits) at samples rates up to a few mega samples have emerged to provide low power consumption, size reduction in applications such as RFID sensor tags.

The following table gives a comparison of all the above ADC structures applicable to RFID sensor applications. Both the delta sigma and the pipeline ADC have a longer latency than the SAR. It can be seen from the following table [Zheng, 1999], [33] that the pipelined analogue to digital converters, folding interpolating analogue to digital converters and flash converters are not suitable for the low power architectures required for RFID sensor tags.

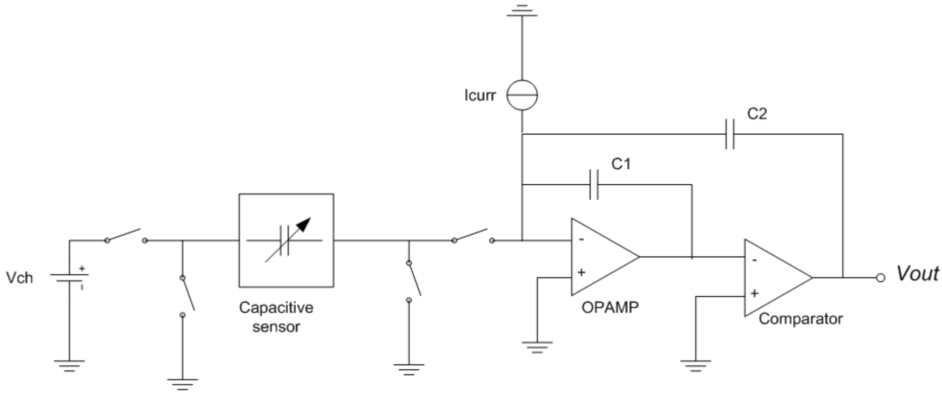

Fig. 12. Example of a capacitance to frequency converter

ADC Type	Resolution	Sampling rate	Silicon area	Power consumption
Successive approximation analogue to digital converter [20], [21], [22], [23]	9 bit; SNR=51.2dB	4.1kS/s (to 150kS/s)	0.18µm CMOS	0.85µW@4.1kS/s (to 30µW@150kS/s) @ 1V
	~8 bit (DC) , 7 bit (4.6kHz)	100kHz	0.053mm² in 0.25µm CMOS 2P5M	3.1µW (41pW stand by) @1V
Redundant Signed Digit (RSD) converter [24]	60 dB SNR for large input levels. 13.5 bits at 1 V and 14.5 bits at 2.5 V	16 kHz	0.8mm² in 2µm CMOS technology	125µW total power dissipation (@2.4V)
Folding analogue to digital converter [25]	10 bits	40 MHz	0.25µm CMOS 1P5M	62mW (@2.5V)
Pipelined analogue to digital converter [27], [28]	SNR=87dB; DR= 88dB	5MHz	0.63mm² in 0.35µm CMOS	950µW (@1V)
	10bit	30MHz	3.12mm² in 0.3µm CMOS 2P3M	16mW (@2V)
Delta Sigma analogue to digital converter [26], [29]	SINAD 64dB and Dynamic Range 82dB	1.28MHz with 8kHz bandwidth (OSR 64)	0.23mm² in 0.35um CMOS, (2 poly, 3 metal)	~ 60µW (from 0.8V to 1.5V)
Capacitance to Frequency converter [30], [31]	35Hz/mmHg (160kHz @ 0 mmHg)	49Hz data bandwidth?	1.44mm² in 0.8µm CMOS	4mW (@ 4V)
	10 bit	40kHz clk with 20Hz bandwidth	1.1mm² in 4µm CMOS 2P	80µW (@3 V)

Table 1. Comparison of different types of ADC structures.

The integration of sensors to tags requires the following:

- Proper sensor interface to offer good analogue performance while meeting the stringent power requirements
- Power down techniques to activate the sensor interface only when a measurement is to be taken which increases the reading range and battery life time of RFID sensor tags.
- Calibration method via the use of EEPROM to store calibration values to obtain a better measurement resolution.
- Need of a standard to address the integration of sensors/actuators to a tag

3.4 RFID sensor tags and standardization

3.4.1 Discussion on standardization

One challenge in implementing RFID sensor tags is the compliance with the RFID standards in use. Indeed, none of the main actual protocols (ISO/IEC 14443 and ISO/IEC 15693 at the 13.56 MHz HF frequency and ISO/IEC 18000-6c incorporating the EPCglobal Class-1 Generation-2 UHF standard) define the access to additional functions such as sensor interface of more generally microcontrollers and buses.

The IEEE Instrumentation and Measurement Society's Technical Committee on Sensor Technology TC-9 has developed the IEEE 1451 suite of standards for the design and implementation of "smart transducers". The standard defines a network capable application processor (NCAP) and a transducer interface module (TIM) that can have a maximum of 255 transducers (sensors/actuators) [34 - 38]. This suite of standards defines the interface between the TIM and the NCAP as either wireless (WiFi, BlueTooth, Zigbee, Future technologies) or wired (Point-to-point, SPI, serial interfaces, multi-drop interfaces, mixed-mode interfaces, CAN bus and CANopen interface, sensor to RFID communication) all under a specific separate standard (IEEE 1451.X). RFID "smart transducers" fall under the standards IEEE 1451.5 for wireless transducer interface and IEEE 1451.7 that is a proposed sensor-integrated RFID tag standard for battery-assisted tags.

An important issue is whether the IEEE 1451.5 concept is compatible with the ISO RFID standards. If not, a new series IEEE 1451.X could be developed to be compliant with the ISO/IEC standard. In the meanwhile, a working group on the IEEE 1451.7 for interfacing sensors to a battery-assisted RFID tag and using the existing ISO 18000 interfaces for data communication was formed in April 2007 to come up with a finalized version of the IEEE 1451.7 in 2008. Merges have already taken place with the ISO 18000-6(E) that now incorporates the IEEE 1451 as a transport-independent set of common sensor commands based on IEEE 1451.0. The ISO/IEC is also working on defining the sensor integration with corresponding sets of commands for sensors that would be part of an amendment for the ISO/IEC 18000-6c. Results are still is under discussion. [39].

A common effort between the standardization bodies, as well as leading manufacturers is therefore needed to encourage and facilitate the development of sensor-based RFID solutions and hence enable wireless networked solutions where RFID sensor tags would share and transfer information between each other.

3.4.2 Use of existing standards

An RFID sensor tag should operate and read the sensor without interfering with the standard protocol. Whereas the current ISO/IEC protocols do no yet specify explicitly the sensor interface, they however include the possibility to define proprietary commands.

These commands can include parameters, for example to select the sensor to be measured in a multi sensor smart tag. Different commands can be specified to control a sensor interface, an external interface, etc. To avoid breaking the protocol specification, in particular turn-around time, it is possible to split a command in to two successive commands. In the case of a sensor measurement, the reader can send a sensor measurement request, then wait a determined time and send a measurement value read command. In this way the sensor selection and acquisition are not time-constrained by the protocol timings. Table 2 shows the proprietary commands defined for a HF sensor tag developed at the Technical Research Centre of Finland.

description	*Byte 0*	*Byte 1*	*Byte 2*	*Byte 3*
Measurement request	0xF0	Sensor number	CRC	CRC
Read value	0xF1	CRC	CRC	

Table 2. Proprietary commands of an ISO 14443 smart tag

Using proprietary commands is an easy method to add functionalities to a tag, but requires designing new types of tags for every new implemented function, as well as using readers with custom software.

Another approach consists of using the standard *READ* and *WRITE* commands to control the tag interfaces. It is therefore possible to use standard tags and readers. To operate, glue logic is placed on the tag memory bus. This simple logic listens to all the requests from the tag core, and triggers some actions when some activity is detected on a special address. For a sensor interface, a simple protocol can be designed as:

- the reader issues a WRITE command at the specific address 1
- the glue logic intercepts the write action in the memory, and triggers the sensor measurement. The written word can carry information, such as the sensor number.
- when the measurement is done, the glue logic writes the result in the memory at specific address 2.
- the reader then issue a READ command at specific address 2 to gather the result

The same protocol can be used to control a serial interface master peripheral (I2C, SPI, 1-wire…). With such interface, the smart tag can be used with a variety of external sensors, displays, or integrated in a more complex system including a micro controller. Fig. 13 shows a schematic view of the UHF smart tag developed at the Technical Research Centre of Finland, including the glue logic and interfaces.

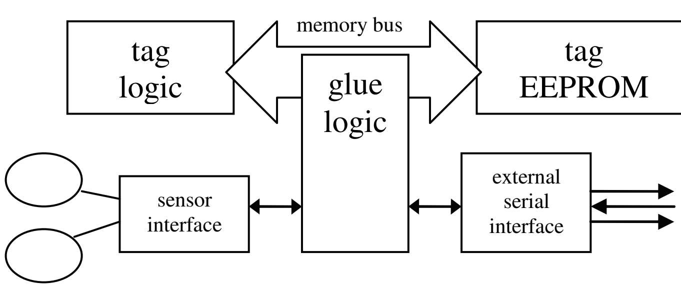

Fig. 13. UHF smart tag with external interfaces

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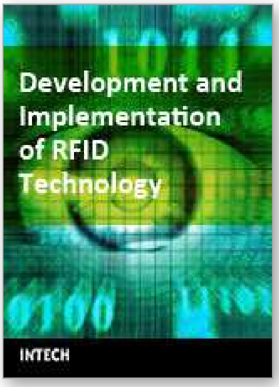
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