A Paradigm Shift in Passive RFID Tag Development and Manufacturing Flexibility to Provide Active Tag Functionality

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Abstract— Passive RFID is rapidly expanding for asset tracking while simultaneously opening broader fronts in passive communications and sensing as a platform technology. As technology improves and power requirements are lowered, the possibilities for increased flexibility bring about new "RFID" opportunities with active functionality (e.g., a Passive Camera). In addition, new manufacturing technologies can now provide flexibility and cost advantages for early stage developers when compared to ASIC ICs. This paper addresses a potential security application and other applications including passive camera technologies, inter-chip systems communications on an RFID tag, and new core prototyping and manufacturing technologies to accelerate development in the total RFID space.

Keywords — Passive Powering; Energy Harvesting; RFID; Prototype Development; Internet of Things

1 INTRODUCTION

1.1 Background

Passive Radio Frequency Identification (RFID) is rapidly expanding in many areas with new applications while simultaneously opening broader fronts in passive communications and sensing as a platform technology. As technology improves and power requirements are lowered, the possibilities for increased flexibility bring about new "RFID" opportunities. In addition, new manufacturing technologies can now provide flexibility and cost advantages when compared to Application Specific Integrated Circuits (ASIC) for both prototyping and production. This paper describes innovative methods of combining technologies for passive application while simultaneously looking at the new processing technologies for rapid prototype development with manufacturing potential.

1.2 A Passive Microprocessors

Microprocessors (µP) revolutionized our world, but they still require a power supply such as a battery. ASICs such as those in RFID tags can be powered over the air with ambient Radio Frequency (RF) energy, but they lack the programming flexibility of a user or product (Original

Equipment Manufacturer) OEM compared to a microprocessor. One new technology presented in this paper is a change in the computer paradigm where the flexibility of a programmable microprocessor is provided within a chip while being powered by over the air (ambient) RF energy. The µP technology can also be viewed as a standalone technology.

1.3 The Passive Camera

A second technology discussed in this paper couples a low power imaging (camera) chip to a microprocessor providing a passively powered camera. The combined technology will be noted as the Imager Microprocessor (IµP) technology which can be a stand-alone device.

In order to develop and evaluate this passive technology opportunity, a Texas Instruments CC2510 development system was selected for software and system development in conjunction with an Electronic Microchip, EM7760 [27], imaging chip with the typical power consumption of the of 3 mW. This combination is shown in Figure 1.

Figure 1. TI CC2510 Development System

A second system was initially built for testing the EM7760 chip which used an Arduino as shown in Figure 2. The Arduino was an alternative to demonstrate versatility, but the main elements of this paper rely on the TI CC2510 development system to illustrate the concepts and develop the software based on the 8051 Instruction Set Architecture (ISA).

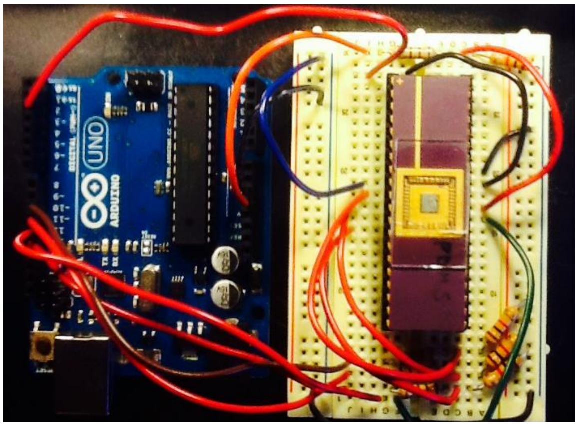

Figure 2. The Arduino Development System

1.4 The Over the Air Communications Link

While the above technologies are interesting, there needs to be an over the air communications link to retrieve the data from the passive devices. In our research, three alternatives have been considered and are all possible with different performance possibilities. In order to keep the technology totally passive, power is critical, and the most obvious means would be to perform backscatter on the signal from the reader or base station. In this paper, the term ***reader*** will be used in association with RFID protocol standards such as ISO 18000 – 63, and ***base station*** will be used with custom devices that are connected to a battery or other fixed power supply. It is also possible to perform passive communication with an active transmitter in contrast to backscatter which will also be discussed.

1.5 Parallel Communications and Protocols

Communications with a passive device such as an RFID tag is typically looked at as one on one communications which is true after some phase of the protocol has singulated (identified a specific single device) the group of potential communications. This aspect will be discussed in Section 4.

1.6 Prototyping

One of the important aspects of the rapidly developing field of RFID and the associated Internet of Things (IoT) is the ability for many people to be able to prototype their ideas in a rapid and relatively inexpensive fashion such as the Lego® concepts which have developed in recent years.

2 THE μP REMOTE EXECUTION UNIT (REU) TECHNOLOGY

Figurer 3, illustrates the three (3) fundamental technologies discussed in the Introduction Section which make up the passive system or systems and are indicated by the circled numbers 1, 2 and

3. These will be discussed as individual and combined products or technologies. RFID is a major portion of the IoT making development an important aspect.

2.1 The µP REU Architecture

It is possible to implement a passive RFID tag simply using a microprocessor [1, 2] as oppose to a typical ASIC although the power requirements are such that it is not useful in a typical competitive passive RFID environment. A disruptive microprocessor architecture has been developed where the main power consuming elements of the µP have been integrated into the reader with only a passive Remote Execution Unit (REU) being required on the RFID tag [3, 4, 5, 6, 7]. Therefore, the power consumption of a passive REU is equivalent to a conventional passive RFID tag with the functionality of a microprocessor. In addition to the reduced architecture, the REU power can be further reduced by running the REU in an asynchronous mode where the dynamic power consumption can be minimized by reducing the external clock rate to 1 KHz if necessary and appropriate. For some RFID applications, this is certainly not appropriate for communications as in ISO 18000 – 63, and an alternative mode of operation is possible as shown in Figure 3.

The market entry product, (1) in Figure 3, is currently envisioned as a very low power novel microprocessor combined with the necessary RF energy harvesting circuitry with an appropriate air interface. This µP and its passive implementation have been described in numerous publications [8-14]. The µP uses a reduced instruction set architecture (RISA) of an 8051 Instruction Set Architecture (ISA) to execute on a passively powered RFID tag. This was the reason for choosing the TI CC2510 because as mentioned, it is based on the 8051 ISA. The chip has been designed with the associated floor plan of the REU in Figure 3, in a 45nm technology with the floor plan as shown in Figure 4.

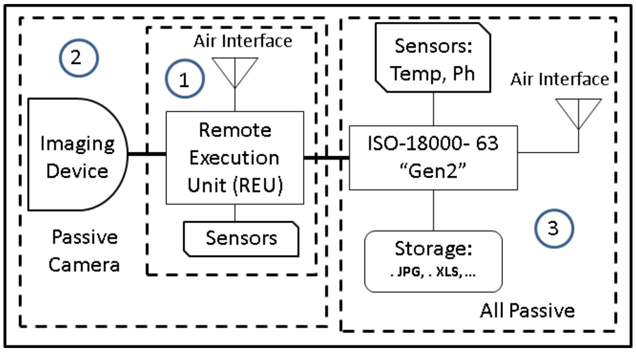

Figure 3. The Three Fundamental Technologies

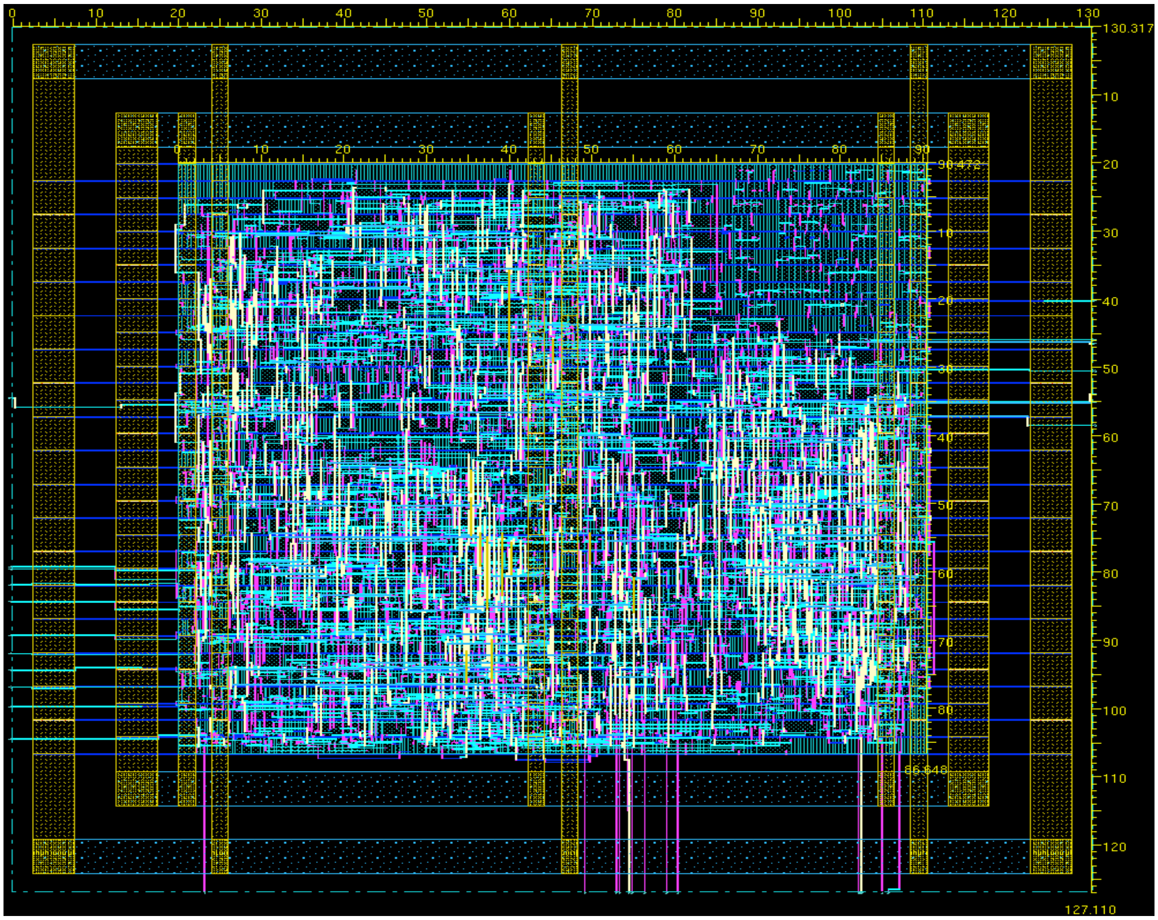

Figure 4. REU Flatten Layout for 45 nm Technology.

The programmable core of this architecture is the REU [14] as illustrated above which controls the imaging chip. The benefit here is the reduction in the power requirement for a programmable microprocessor-type device to the point where the chip can be passively powered (microwatts). This is done by (1) reducing the instructions to be executed on the chip, (2) removing clock requirements by using asynchronous logic, and (3) storing the program on a powered device, the Control Cortex, which may also provide the RF energy to power the complete system. The initial development has used an Intel 8051 Instruction Set Architecture (ISA). It has been shown [14] that the power reductions allow the chip to be remotely powered and programmed giving a programmable passive chip as opposed to a classic RFID ASIC. The core layout area occupied by the REU in Figure 4 is about 7,917 μm^2 (91 µm x 87 µm).

The REU is thus a remote passive device that executes a program from a base station or control computer unit (CCU) where both power and commands in the form of machine language instructions (8051 ISA) are transmitted to the REU. This can be done in the form of an RFID protocol or simply as a set of remote units with a simple, power efficient protocol [15]. One example of such a system is shown in Figure 5. For example, in a fixed system, as opposed to asset tracking/management, a power efficient protocol uses identification numbers such as 1 to 10 [16].

The classical RFID reader and tag combination provides a platform which can be viewed as a typical von Neumann computer architecture with the functions shared between the reader and the tag. The division of functionality will be based on power and functionality. The reader has a primary power source and thus can handle the functions not relevant to the tasks of identification and/or sensing. The tag needs to be flexible and responsive to the environment around it. When one looks at the frames transmitted to an RFID tag, these are analogous to machine language instructions of the classical computer. Thus, it is natural to place the classical Instruction Register (IR) on the tag and transmit the computer machine language instruction from the reader. It naturally follows that the decoding can be conveniently located on the passive tag. The part of the architecture placed on the tag is thus termed a Remote Execution Unit (REU).

At this point, two options are available, synchronous (high speed) or asynchronous (low power). For the purpose of discussion and example, the asynchronous option is chosen. This option permits two options for implementation as can be seen in Figure 1. If sensors are the primary application, speed is not as critical as with the traditional supply chain applications, and the air interface of the REU is used for communication. This is also the scenario for very low power applications due to the asynchronous logic which allows the reader to clock the logic thus providing an on-demand power profile. The REU is programmable and thus can serve as an interface between a tag and the passive camera thus providing a high speed communication interface.

2.2 An Air Interface and RF Energy Garvesting

The air interface as indicated in (1) of Figure 3 is similar to a conventional passive RFID chip. It provides half-duplex communication between an interrogator (i.e. reader) and a tag. In the forward link (reader to tag), a reader sends data along with the power to a tag. In the reverse link (tag to reader) a tag reflects (i.e. backscatters) RF signal to the reader by mismatching input impedance of a chip. The focus of the REU is to minimizing power as much as possible.

The University of Pittsburgh has a history and portfolio in dynamic energy harvesting for the air interface using continuing operation [17-20], battery charging for "pulsed" (intermittent) operation [21-24] multiple antennas/devices [16, 25], and including total systems on a single chip [26].

In order to passively power up the REU, a Powercast^{TM} RF energy harvester [36] was used to store energy prior to turning on the CC2510 and imaging sensor. The Powercast energy receiver can harvest a direct RF energy and convert it to DC power. The operating frequency range is 850MHz to 950MHz, which works with the standard 50-ohm antennas. The Powercats modules are designed to provide up to 5V with the conversion efficiency of about 70%. The RF energy harvesters are typically based on the voltage multiplier circuitry, which converts RF waves (AC signal) into DC signal. The typical RF multiplier is using diodes with a very low turn on voltage in order to facilitate the lowest level of RF energy harvesting sensitivity.

2.3 PASSIVE CAMERA

The above µP has been combined with an imaging chip, an EM7760 [27] for demonstration purposes, to form a passive camera indicated by (2) in Figure 3. This particular implementation is 64 rows by 48 columns and is used s a part of a simple prototype demonstration. The initial prototype for software development is battery powered and is shown in Figure 3. Together, the REU of (1) and the imaging device of (2) in Figure 1, form a passive camera.

Both the µP technology and the combined imager/µP technology are in play. The two technologies will both be considered in this paper, i.e., stand alone or in combination. All of the technology implementations are ultimately to be powered by ambient RF energy (passive) and are considered to be platform technologies for many applications. The initial commercial application will be focused on the imager/µP combination as a passive camera. The low power µP has been designed, simulated and tested using the Cadence software package, and the initial chip layout is shown in Figure 3. The Instruction Set Architecture (ISA) is that of the Intel 8051, making it possible for the industry to be able to generate specific software code (apps). This novel 8051 ISA µP shares the full instruction set with the RF powering device (base station) and the REU with the REU executing the reduced instruction set (RIS).

The imaging device is currently an EM7760 low power imaging chip which we have obtained directly from EM Microelectronic-Marin (EM). This device has been combined with a Texas Instruments 8051 µP development system to provide an imager/µP prototype. Related to our work with the imaging device, we have supplied Intel, at the request of EM, with some of these chips in development packages assembled at the RFID Center (40 pin dual in-line package) along with other information. The prototyping imaging system is shown in Figure 3.

As indicated in Section II, the REU is based on the 8051 ISA which allows use of the TI 2510 development system for software development. One demonstrated function is as a controller for the EM7760, and storage of the resulting image(s). The system of Figure 1, is battery powered for development convenience. Another CC2510 has be modified to disconnect the CC2500 Radio in order to demonstrate the passive camera and µP as a standalone device as in (1) and (2) of Figure 5. To show a picture has been taken and is in memory, an LED has been added as a visual indicator. This system is functional as a passive device with the prototype shown in Figure 6.

At this point, there are three alternatives for communicating the image to the base station: (1) backscatter via the REU, (2) backscatter via ISO 18000 – 63 Air Interface, or direct transmission via the CC2500 Radio or a transmitter as implemented in Section 4.

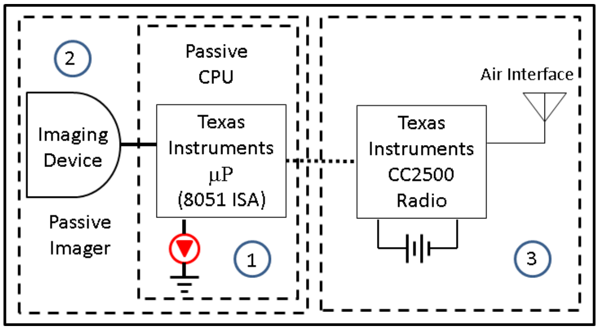

Figure 5. A Passive RFID Camera

To enable faster transfer and reduce the need for retransmissions, the CC2510 implements double buffering allowing two packets to be buffered in the FIFO in each direction. MISO and MOSI were transferring through a buffer called U1DBUF. Thus, the CC2510 and the sensor are actually communicating through the buffer. U1DBUF had a capacity of one byte.

From the CC2510 system point of view, the EM7760 device appears as a set of registers used to configure device modes and parameters. These register values can be both written and read. Some registers can be only read and provide the device status such as the frame mean value to the host system.

The memory mapped registers make it also easy to implement a parallel interface which may be real or virtual. In the prototype of Figure 5, the (1) to (3) interface is implemented with 8051 code which directly replicates the REU environment with a register transfer of the register containing the stored data from the SPI interface linking the imaging chip (2) to the virtual REU (1). The following paragraph describes the parallel interface between the REU and an RF interface such as the TI CC2510, (3) in Figure 3, or the memory of a passive chip. The serial to parallel SPI interface between the EM7760, (2) of Figure 3, and the virtual REU, (1) of Figure 3, has a simple corollary in terms of an I2C interface to couple the REU, (1) of Figure 3, to a passive chip, (3) of Figure 3, where the passive chip may be a Tego chip which has 24 Kbytes of memory for storing images that are then transmitted over the air to an RFID reader.

First the address of the register wanted to be written or read would be written into a specific BUFFER, transferring to EM7760 through a serial interface, subsequently, the value needed to be written into the register or read from the register would be written into BUFFER depending on the conditions for direction, i.e., transferring data to the EM7760 through MOSI or transferring data to the CC2510 through MOSI respectively. The data collected from the EM7760 is pushed in to the buffer. Because BUFFER is a FIFO array, when reading the data stored on the buffer, at the same time, a dummy byte is written to the buffer to pop out the data. Also the first bit that was read from or written into EM7760 is always most significant byte of the data or address, so the order of the byte transfer was set to be MSB first. The data can be saved on arrays or user defined variables on the CC2510 memory. This method of buffering has proven to be most efficient from a software and power standpoint. The registers of the REU are memory mapped making the transfer of the software from the CC2510 to the REU base station a simple process.

Experimentally, the image sensor is quite capable of responding to different shapes and which were produced directly on the top of pixel area on black and white mode. In customer discovery for passive camera applications, it was learned that verifying alignments is extremely important for applications ranging from orthopedic implants to door/platform positioning for automatically controlled transportation such as seen at many airports. In such applications where the human eye does not integrate out faults, the ability to identify sharply defined figures is required. For image display, the pixels are simply processed at the base station using MATLAB. One of the pictures from MATLAB is given in Figure 6. Note that this is a development system to analyze the system interactions and power consumption of the combination of the EM7760 and the µP. Thus, the use of a lens has been omitted, and various opening and blocking of the pixels has been achieved as shown on the right of Figure 6. In particular, edges and missing pixels can be seen on the right of the figure.

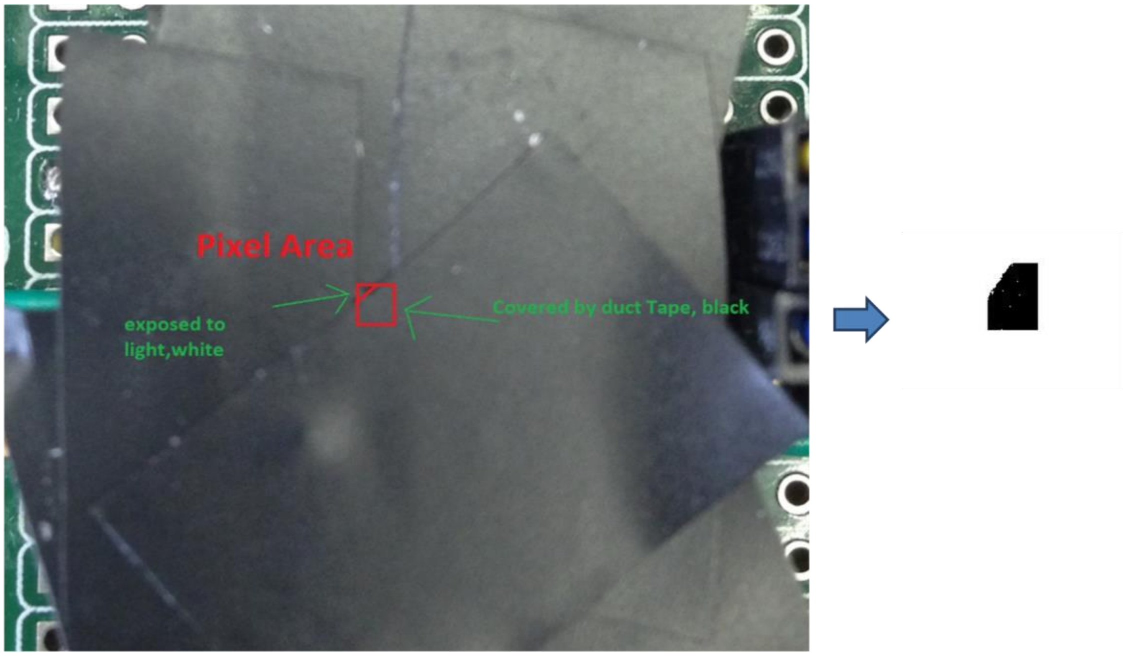

Figure 6. Picture Generated from MATLAB

3 COMMUNICATIONS INTERFACES

The RF powering of passive remotes is most demanding when an active transmitter is used on the remote device as compared to the least demanding which is backscatter. One form of an active transmitter is using the CC2500 radio of the TI CC2510 development board as shown in Figure 3. Other possibilities include custom devices and methods, one example of which will be discussed next.

3.1 Fully Passive Devices without Backscatter Transmission

The wireless device of Figure 7, is passive and powered by a continuous 915 MHz RF source. It has an active on-board RF transmitter. The transmitter operates at 2.45 GHz to avoid any interference with the power source and it requires much smaller transmitting antenna. This device was funded by NASA [25]. The passive functionality of the device can be represented as an electrical equivalent circuit shown in Figure 7. This device is instrumented with an on-board passively powered analog to digital (A/D) conversion of system power with the digital value transmitted via an infrared (IR) link and displayed in Figure 8. The top scope trace of Figure 8 illustrates a charging curve as is equivalence in the circuit of Figure 7, which allowed to determine the component values of the circuit. The circuit model captures the power consumption of the device, which operates in the passive mode along with its charging profile.

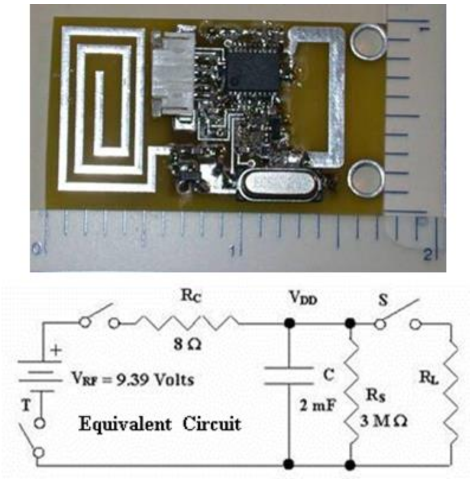

Figure 7. Passive Device and Equivalent Circuit

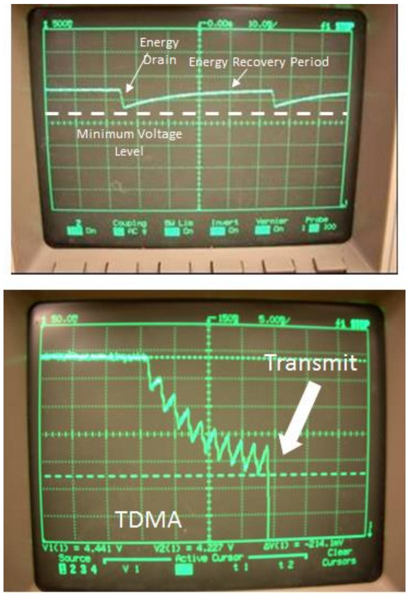

Figure 8. Passive Power VDD Profiles and Transmission

The field of ten (10) devices was known *a priori* making it possible to implement a simple protocol using serial numbers 1 to 10 [15, 15]. Signaling from the base station for devices to transmit is implemented by dropping the powering RF for a brief period to trigger the low voltage interrupt where a counter is incremented and compared to the serial number. This is similar to Time Division Multiple Access (TDMA) method of sharing the same communication channel. If there is a match, the device transmits a measured temperature value to the base station. The power, with system voltage (V_{DD}) as a surrogate, scenario is seen in Figure 8, for device number 10. The sharp drop in V_{DD} following the ten (10) prior drops is the result of a successful device to base station transmission of the measured temperature value.

3.2 Fully Passive Devices with Backscatter

The third technology to be added to the passive camera is indicated as (3) in Figure 1. The technology of (3) in Figure 9 has been developed, tested and licensed for use with total orthopedic knee and hip replacements as well as for trauma surgery [29]. This particular technology is being readied to undergo animal trials for Federal and Drug Administration (FDA) clearance. The inclusion here is as an adjunct to either (1) or (2) or both combined as shown in Figure 9. This technology and its perceived combinational use will be discussed further in Section 4.

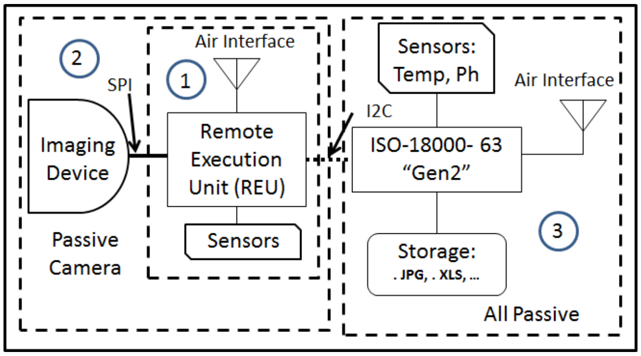

Figure 9. Backscatter Camera Air Interface

4 PARALLEL IMPLEMENTATIONS

In sensing environments as opposed to singulation of asset tags, it is possible to simultaneously execute processes such as Single Instruction Multiple Data (SIMD) architecture [33]. Figure 10, illustrates a typical distributed sensor array similar to the one that produced the V_{DD} illustrated in Figure 8. In the SIMD format, all devices sample simultaneously. In an environment such as illustrated in the proposed arrangement in Figure 11, it is possible to obtain a passive 3D image from multiple pictures of an object in an SIMD environment.

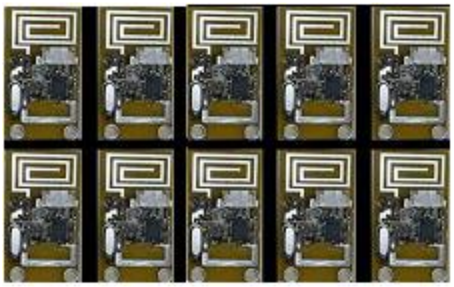

Figure 10. Typical 2D Sensor Array

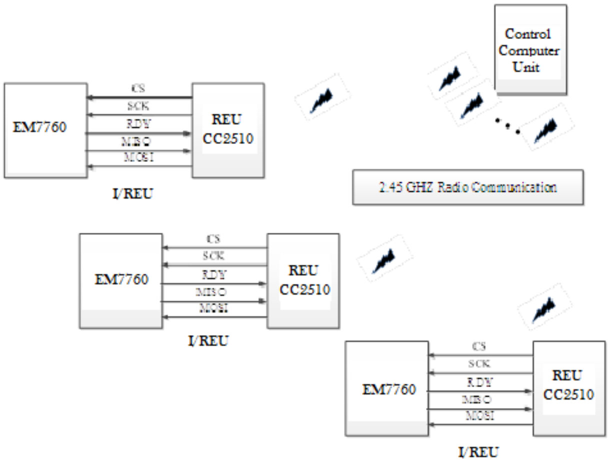

Figure 11. SIMD Array of IμP Devices

The operation mode of image sensors is based on 3D picture-taking commands from the Control Cortex are transmitted at 2.45 GHz and received by the REU-CC2510. Commands are processed by the REU-CC2510, feeding into the EM7760 to instruct it to take pictures. Image data is synchronized by the ~~SCK~~ clock input provided by REU-CC2510, feeding into REU-CC2510, eventually being sent back to the Control Cortex again at 2.45GHz. The Control Cortex is responsible for uploading all the images to the internet, including cloud database. The ~~RDY~~ EM7760's ready pin is used to provide status information to the REU-CC2510, indicating that image data is ready to be collected. The collected images can be presented as a "Passive Retina," where a composite image is formed from pictures from multiple passive cameras.

5 DEVELOPMENT CONSIDERATIONS AND PROTOTYPING

One of the advantages of advancing RFID technologies is access to simple prototyping devices. This section is focused on both development and prototyping.

In the context of this paper, development is the ability to put together hardware devices and software with associated interfaces and tools. Figures 1 and 2 are examples of development platforms where multiple alternative processors can be evaluated. While not quite "plug-and play" at a customer level, it is a plug-and-play for a staff of engineers. The illustrations of Figures 3, 5 and 6, also represent forms of development examples.

Again, in the above context, fabricating the chip of Figure 4, is a much different situation as shown in Table 1. PCB fabrication is a key to many RFID development scenarios but is not satisfactory for evaluating manufacturing concerns in a tag product. The IC cost and delay precludes manufacturing prototype development for individuals or small companies. This section looks at an alternative to PCB and IC fabrication for both development and prototyping.

5.1 Development

Prototyping RFID devices with commercial off-the-shelf (COTS) ASICs, is primarily limited to attachment, antenna, packaging and manufacturing. There is some flexibility using serial interfaces, e.g., I2C, with a number of the Gen2 chips, but relatively few variations are possible. The REU provides two (2) different types of flexibility in development and prototyping. The REU clocking for power reduction is such that it cannot satisfy some of the timing requirements of the Gen2 protocol. However, for those applications with less stringent timing requirements, the REU can function as a stand-alone RFID chip with a Gen2 command set as in (1) of Figure 9, or a custom set of commands. At this point, the REU provides for a wide range of development opportunities.

For those applications needing a camera or other sensors requiring an interface more complicated than an I2C or SPI serial interface, the REU functions as an on tag/on site flexible controller which can communicate with any Gen2 chip having a serial (or other) interface as in Figure 9. With this configuration, the Gen2 protocol provides the communication to the Gen2 RFID chip with the RF energy also powering the controlling REU and the imaging chip. Powering multiple devices/antennas in the same space has been previously shown to be effective [25]. Data are then read from the imaging chip through the REU to the Gen2 chip which is read by the standard Gen2 reader.

5.2 Prototyping

For purposes of example, the spectrum of electronic circuit prototyping will be view as a printed circuit board (PCB) at one end and an integrated circuit chip (IC) at the other end. For prototyping (and some development cases) purposes by hobbyists and non-industrial environments the metrics considered are; (1) cost, (2) time, (3) ease of integration with other elements and (4) ease of connecting a packaged part as oppose to connecting directly to IC pads. Considering these metrics and the ends of the spectrum, we have:

Table 1. PCB/IC Comparison

	PCB	IC
(1) Cost	< $100	> $10,000
(2) Time	2 Days	3 Months
(3) Integration	Soldering	Wire Bonding

(4) Connectivity	Easy	Issues

The difficulty with the PCB implementation is typically size. Another alternative for prototyping is additive manufacturing where feature sizes of 5 microns are obtainable at a relatively low cost. While 45 nm is obviously a much smaller feature size, the issue with many RFID applications is not size to the extent offered by an IC implementation.

A quick look at many of the existing passive RFID tags, it can be noted that the IC (chip) could be somewhat larger in area indicating size could easily be compromised for things such as development and prototyping and possibly manufacturing. In addition, it is quite possible that for many applications, the per unit cost may be less considering nonrecurring costs involved with IC development.

Current IC technology is on the order of 10 nm feature sizes with processes being investigated to further reduce the feature size. The question posed here is, "Is this the best or the only direction for RFID or can some applications/products use older *or other* technologies?" That question is the focus of this section.

As indicated above, many RFID tags have area that can be used, including a use that is beneficial to antenna performance [34]. In addition, if the logic/intelligence of the tag is flexible with no mechanical issues with bending, there are additional benefits compared to silicon IC chips.

While there are many variations of flexible electronics, the specific focus here is Evaporative Printing$^{\text{TM}}$, which is an additive manufacturing process with a feature size of 5 μm to produce transistors, capacitors, resistors, etc.

The particular additive manufacturing process to be considered here is amax$^{\text{TM}}$ which applies thin deposits onto a variety of substrates providing numerous alternatives to affix electronics circuitry to a device or *thing* without the need to manufacture and attach a separate tag such as in typical RFID applications. The circuitry can thus be made a part of the device or *thing*.

The process itself is a form of sputtering where the circuitry is "built" through various steps without the need for removal of material as is the case with IC fabrication. The amax$^{\text{TM}}$ process also requires precision alignment as would be the case using mask aligners in an IC process. However, these masking steps are straightforward in fabrication requiring less stringent environmental constraints resulting in reduced cost with a much faster turnaround time. The primary limitation at this point in time is the lack of automation in the design phase.

6 SUMMARY AND CONCLUSIONS

There is an increase interest in the Internet of Things. As the result, passive RFID is evolving into a much wider spectrum than illustrated in asset tracking and management fields. This spectrum will continue to expand with new developments in low power technologies and opportunities within the Internet of Things, where computing devices and sensors will be integrated within everyday products. As technology advances, it is possible to power more complex circuitry along with customized logic, utilizing remote execution platform. The main issues at present time are delivery of power and data communication with multiple passive devices. In this paper the possible architectures have been presented and the demonstration of the passive device with the image sensor has been discussed. In conclusion the industry will need to adjust to the possibility of passive devices and sensors required to be compact in order to be integrated within various products (i.e. orthopedic implants). These requirements are the main drivers for innovative ways of prototyping and manufacturing of discussed devices.

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FIGURES AND TABLES

Figure 1. TI CC2510 Development System

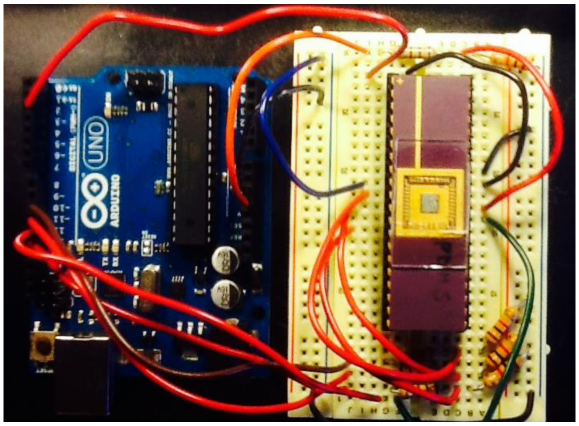

Figure 2. The Arduino Development System

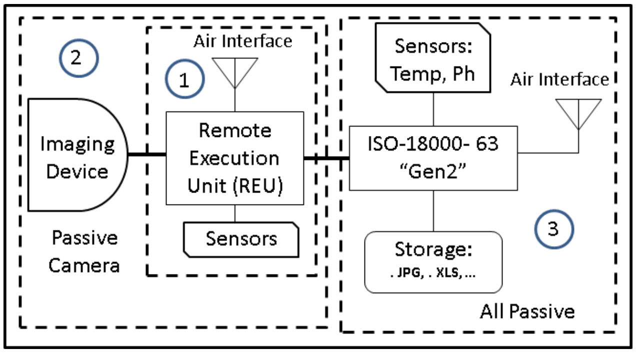

Figure 3. The Three Fundamental Technologies

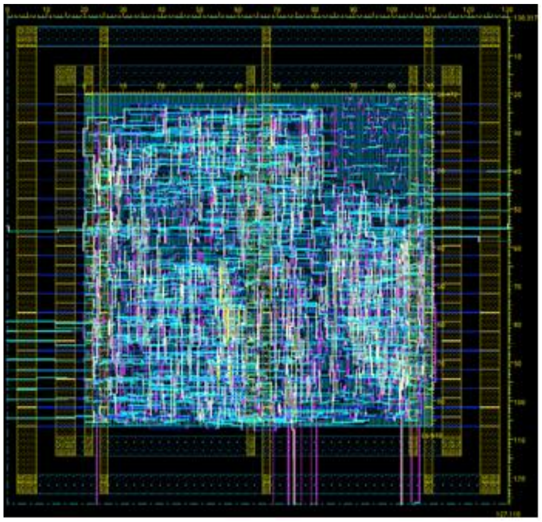

Figure 4. REU Flatten Layout for 45 nM Technology

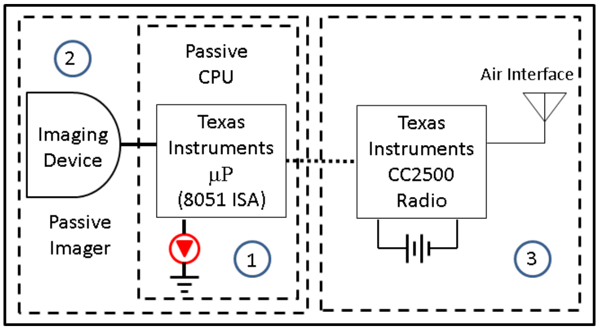

Figure 5. A Passive RFID Camera

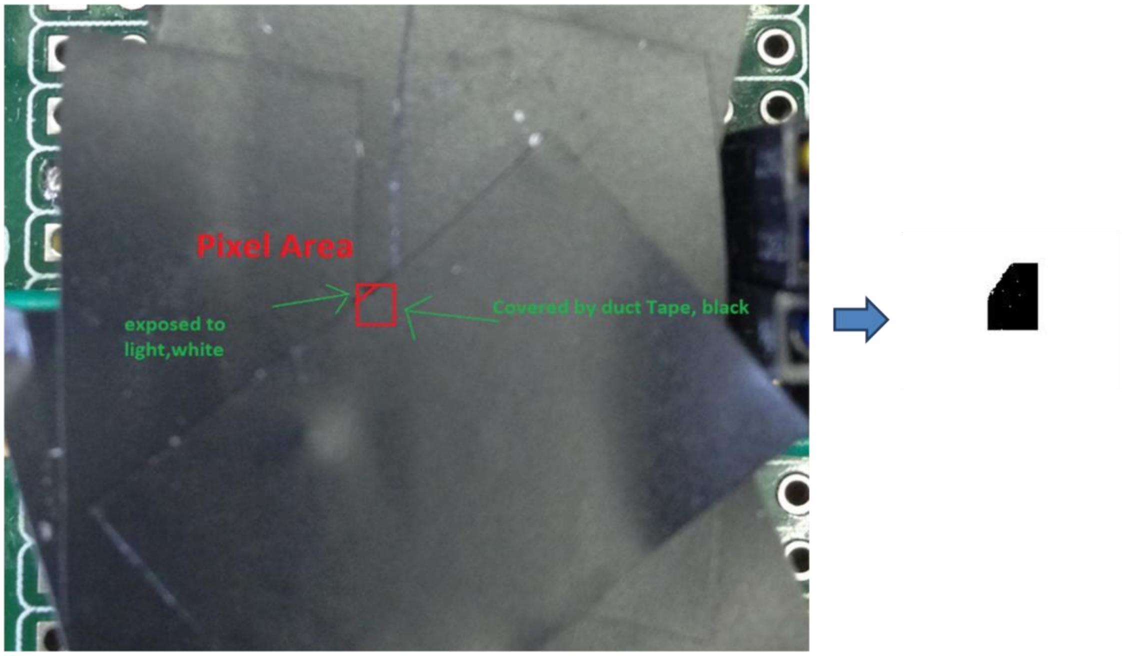

Figure 6. Picture Generated from MATLAB

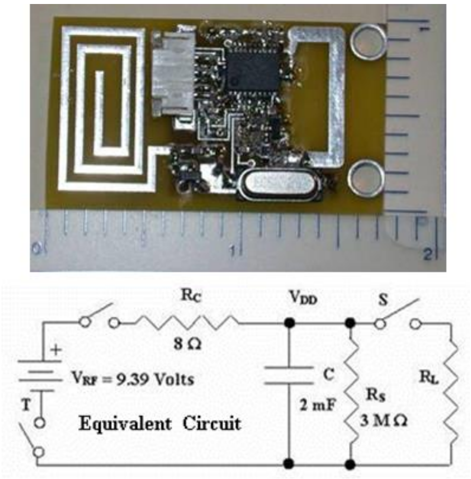

Figure 7. Passive Device and Equivalent Circuit

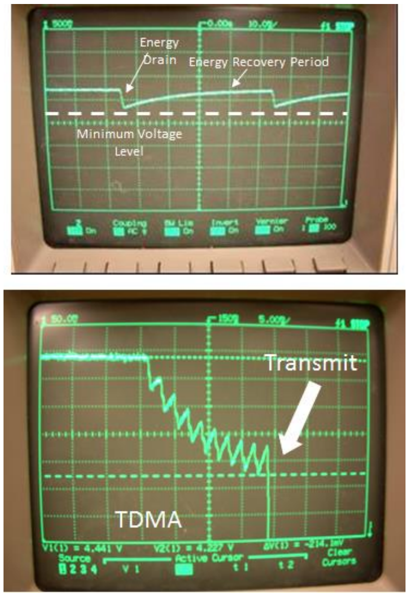

Figure 8. Passive Power VDD Profiles and Transmission

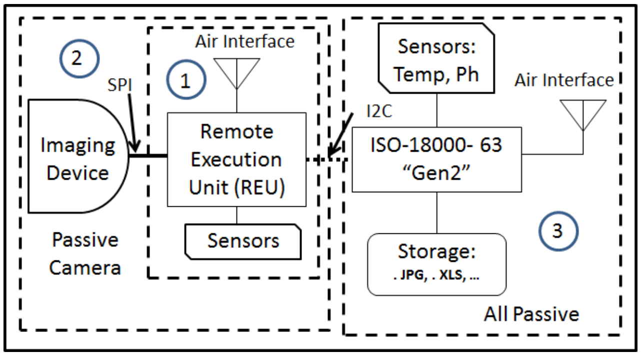

Figure 9. Backscatter Camera Air Interface

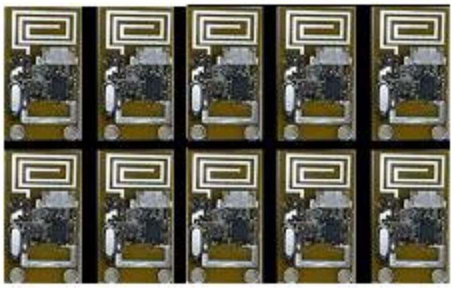

Figure 10. Typical 2D Sensor Array

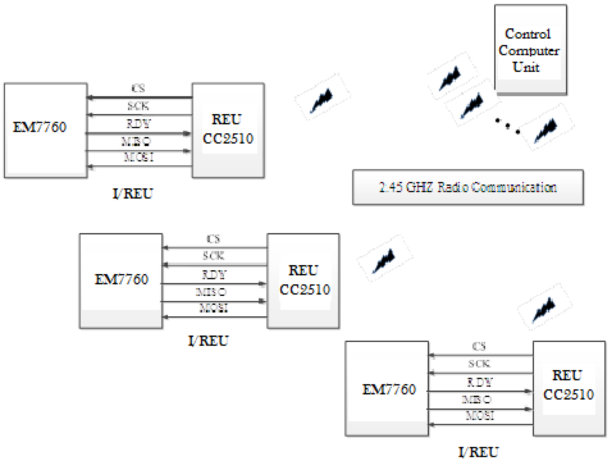

Figure 11. SIMD Array of IμP Devices

Table 1. PCB/IC Comparison

	PCB	IC
(1) Cost	< $100	> $10,000
(2) Time	2 Days	3 Months
(3) Integration	Soldering	Wire Bonding
(4) Connectivity	Easy	Issues