

# A miniature reader/active tag streamlines supply chain management

A miniature reader/active tag (mini-RAT) is proposed as a local interrogator of passive tags in a container employing radio frequency identification (RFID). The mini-RAT can retrieve inventory from passively tagged assets, store the inventory in memory for on-demand retrieval, or relay gathered inventory to a remote access interrogator. It can relay the information in real time to a master interrogator (a fixed network access box, a palm or mobile hand-held interrogator, a portable PC or a laptop). This article describes the design of the proposed mini-RAT's hardware to enable implementation of a nesting architecture.

By Fred Mohamadi

There is a need for reduced labor involvement to manually build a manifest for pallets and containers tracked using radio frequency identification (RFID). Additionally, reducing errors introduced by manual processes enhances the accuracy of manifests. Furthermore, making it more difficult to place unauthorized and unwanted material in pallets/containers, and reporting depletion of supplies as they are removed for use allows accurate identification and managing tracking of assets. Finally, real-time updates to the Global Transportation Network of consolidations and active device locations enables concurrent updates required during the consolidation/shipping process.

Current hand-held interrogators are not only expensive for mass deployment, some are not designed based on the open standards, and they can also be inefficient in collecting the information while in motion. The proposed miniature reader/active tag (mini-RAT) as a local interrogator of passive tags in a container is designed to retrieve inventory from passively tagged assets, store the inventory in memory for on-demand retrieval, or relay gathered inventory to a remote access interrogator. Furthermore, it can relay the information real time to a master interrogator (a fixed network access box, a palm or mobile hand-held interrogator, a portable PC or a laptop). It is constructed to be tamper proof, environmentally resilient and rechargeable. In essence, the proposed mini-RAT offers a minimum of 10x reduction in capital and operation expenses, with the potential of extending the range by an order of magnitude.

As shown in Figure 1, in this scheme a master interrogator (802.11 access box from various suppliers such as D-Link) initiates

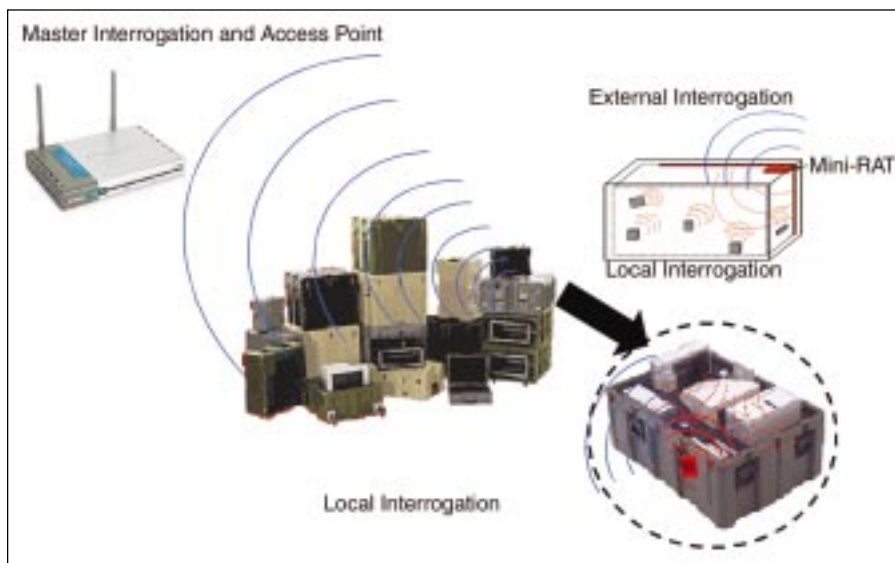


Figure. 1 Illustration of the mini-RAT-based radio frequency identification (RFID) system.

*This article describes the design of mini-RAT's hardware to enable implementation of a nesting architecture.*

function of the mini-RAT. The interrogator asset awakens the mini-RAT that is equipped with a special transponder receiver. It

receives the interrogation signal, recognizes the activity code and places the mini-RAT in the active mode. While mini-RAT settles to an active mode, it will transmit an RF signal equal to the resonating frequency of passive tags present in the container, hence gathers the reflected signal modulated with the codes that uniquely identify presence of the assets. The codes are previously stored (hard written) in the passive tags and are unique for identification of their inventory.

This article describes the design of mini-RAT's hardware to enable implementation of a nesting architecture. Plus, it should be able to address the following realistic scenarios:

- Analysis of supply chain management (SCM) from pack-up/move, transit, and transit to area of operation (AO).

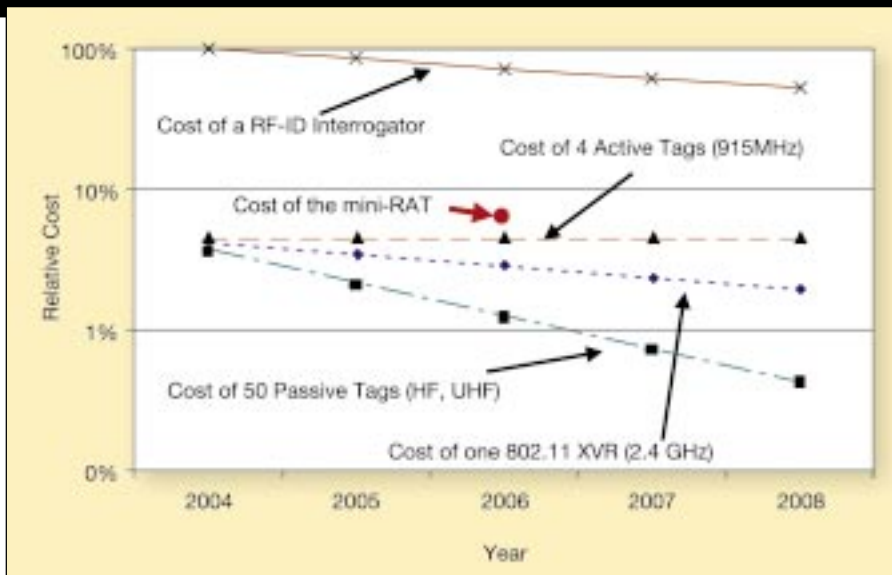


Figure 2. Projected costs of interrogator and tags and 802.11 fixed access WLAN.

■ Rapid replenishment that involves assemblage of materials into shipment units transfers, or transport, the “break down” of or trans-shipment of the aggregate units, receipt processing and the stowage of the materials by the receiving entities.

■ Seamless view of total asset visibility (TAV) and in-transit visibility (ITV) when service and joint stocks are constantly being removed/added to a container.

The human factor of designing the mini-RAT is crucial as well. It should be easy to operate, yet simple to maintain and repair because it uses available off-the-shelf components, including the replaceable integrated multichip-module (MCM). An integrated in-field test unit ensures that CAT is fully operational prior to deployment.

Acting as a relay to a master interrogator, the mini-RAT interrogates the passive tags at its proximity and reports the results to its onboard memory or to a remote interrogator. The COTS-based design includes:

- A low-cost 802.11 PCMCIA card.
- A UHF transmitter/receiver.
- Flash memory card.
- Other required COTS components (synthesizer, regulator, connectors, daughter board to connect PCMCIA to the UHF Tx/Rx unit, etc.).
- An FPGA will be used to address a sequencer for signal routing and management of automatic inventory collection from passive tags, beam scanning management, and passive tag reflected signal collision management, time stamping (with GPS upgrade module), routing of gathered data into and retrieval from the memory card. The memory card is not only used for gathering of tagged inventory, it can data log them if the GPS interface is also used.
- A unique antenna design and control unit for beam manager-based local interroga-

tion of passive tags to address enhanced scanning of obscure tags.

■ Packaging and assembly of the mini-RAT unit that fits properly with the existing containers and pallet sizes.

### Value proposition

Figure 2 presents the relative cost of various components of a generic RFID system<sup>1-5</sup>. Indicated in the chart is a relative cost of active and passive tags operating at UHF frequency range. Included is the cost of an RFID interrogator (available from many vendors). The mini-RAT has a sweet spot of at least an order of magnitude less cost than the existing interrogators. Mini-RAT is capable of local interrogation of surrounding passive tags and then relaying the collected data to a master interrogator to process them or locally storing the data for retrieval on-demand.

■ It is crucial to note that the severe cost reduction of passive tags and current volume demand for 802.11 at commodity prices are the main factors to address implementation of mini-RAT in this article. BOM for the 802.11 is below \$10 as opposed to a low-end and medium price RFID interrogator/reader costs that are around \$300 to \$2,500, respectively.

■ The proposed mini-RAT has the capability to transmit the collected data back to an

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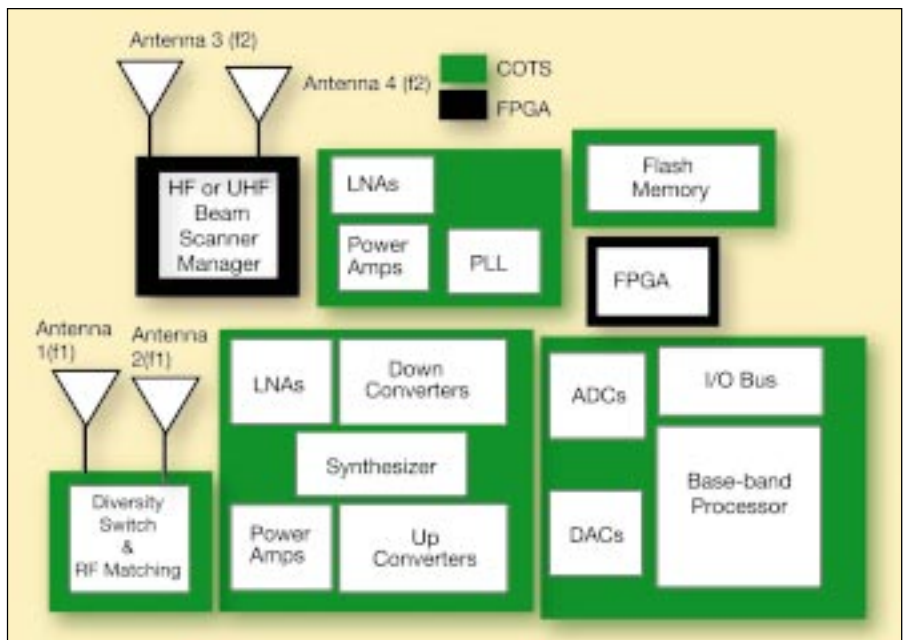


Figure 3. The mini-RAT interrogator system (COTS components are green colored).

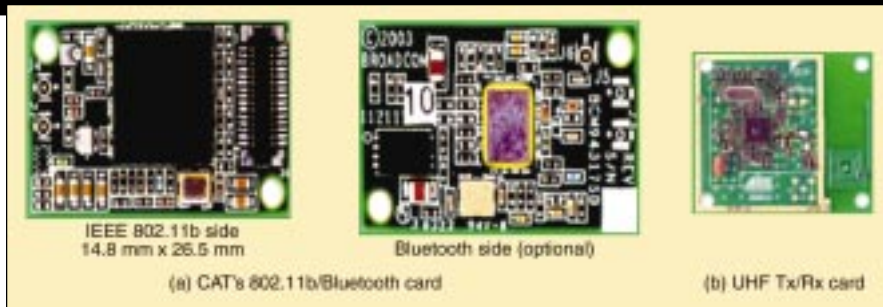


Figure 4. A mini-RAT interrogator with 802.11b/Bluetooth card (a) and UHF Tx/Rx card (b).

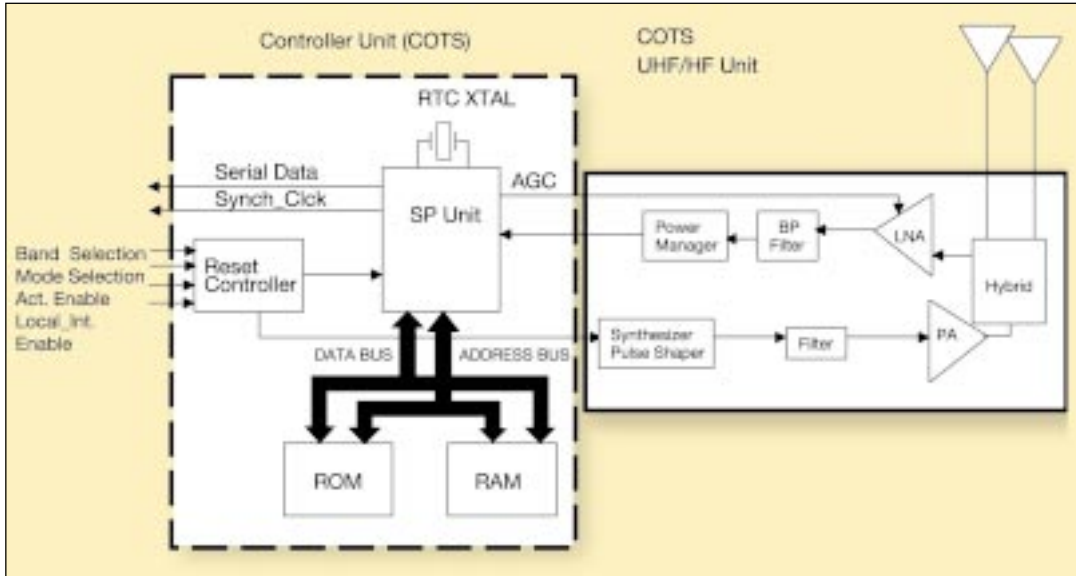


Figure 5. Mini-RAT's HF/UHF unit and the controller function.

access or master interrogator as far as 500 meters (1,500 feet). Current palm-based or hand-held low to medium range RFID interrogators cover ranges from 14 cm (13.56 MHz) to 10 meters (915 MHz).

### Proposed system overview

A diversity scheme (using multiple antennas as shown in Figure 3) is a method that is used to develop information from a master interrogator transmitted over independent fading paths. This means that the diversity method requires a number of transmission paths be available, all carrying the same message but having independent fading statistics. The mean signal strengths of the paths should also be approximately the same.

Figure 3 represents the proposed block diagram of the mini-RAT. Two diversity antennas (numbered one and two in the diagram) at frequency  $f_1$  (2.4 GHz, ISM band) address diversity of the local interrogator and enable wireless communication with a master interrogator. The antenna pair is printed on the same PCMCIA board. A pair of dedicated antennas addresses resonant frequency  $f_2$  (HF or UHF range) for extraction of data from passive tags. The  $f_2$  antennas are externally connected and are replaceable such that they can trigger resonance of the passive tags. The RSSI function or a

similar 802.11 RF chip feature is used to collect the impinging energy at  $f_1$  frequency as a source of triggering signal and to commence the mini-RAT wake up mode. Mini-RAT signals to the control unit upon recovering from wake-up mode to initialize the local interrogation function and commence radiation at  $f_2$  frequency.

A simple, yet innovative process, can address the information retrieval in real time vs. on-demand: Based on a broadcast from the master interrogator (802.11 Tx), the mini-RAT will be awakened and initiates radiating the surrounding passive tags. The collected reflection signals from radiated passive tags will be used to extract the tag (inventory) information and broadcast back to the master interrogator in a half-duplex mode complying with the CSMA/CA signaling requirement of 802.11. If the acknowledgement is not received back from the master interrogator, the mini-RAT will commence storing the data into the flash memory. The mini-RAT then may continue to read (if it has not read all tags), or stop reading if it is convinced that it has read them all. As soon as the Tx channel for 2.4 GHz becomes available, the memory content will be DMA'ed to the master interrogator.

Figure 4a depicts the 802.11b with Bluetooth option board (available from Broadcom) designed for portion of the

mini-RAT that is about 14.8 mm by 26.8 mm and will be connected to the UHF Tx/Rx (433, 868, and 915 MHz). These boards and a UHF antenna pair form the mini-RAT. Shown in Figure 5b is the design of the UHF transceiver from Atmel.

### Technical challenges

Technical challenges to be addressed in the design of the mini-RAT:

1. Collision of inventory data from reflected passive tags at the UHF receiver of mini-RAT should be resolved.

2. Impairment of the Tx/Rx channel between mini-RAT and the master interrogator is the technical challenge to overcome specially in the environment where multipath delays are prolonged due to the reflections around metal-based storage rooms. The issue is more serious for non-line of site (NLOS) wireless LAN (WLAN) communication.

3. Chip count reduction for cost optimization; Integration of the RF

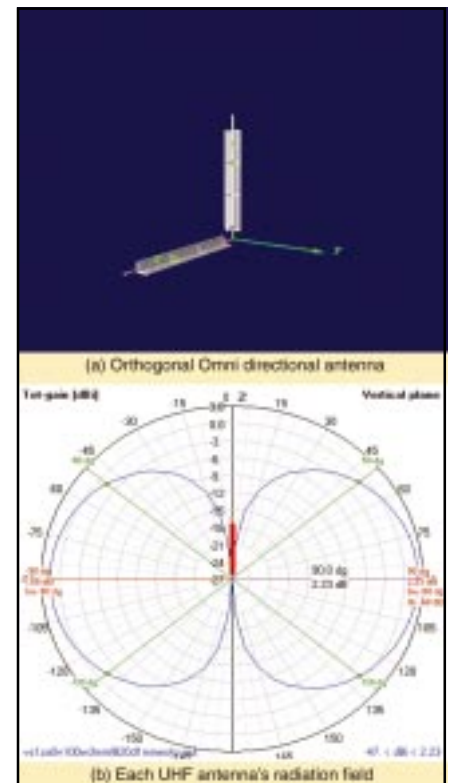
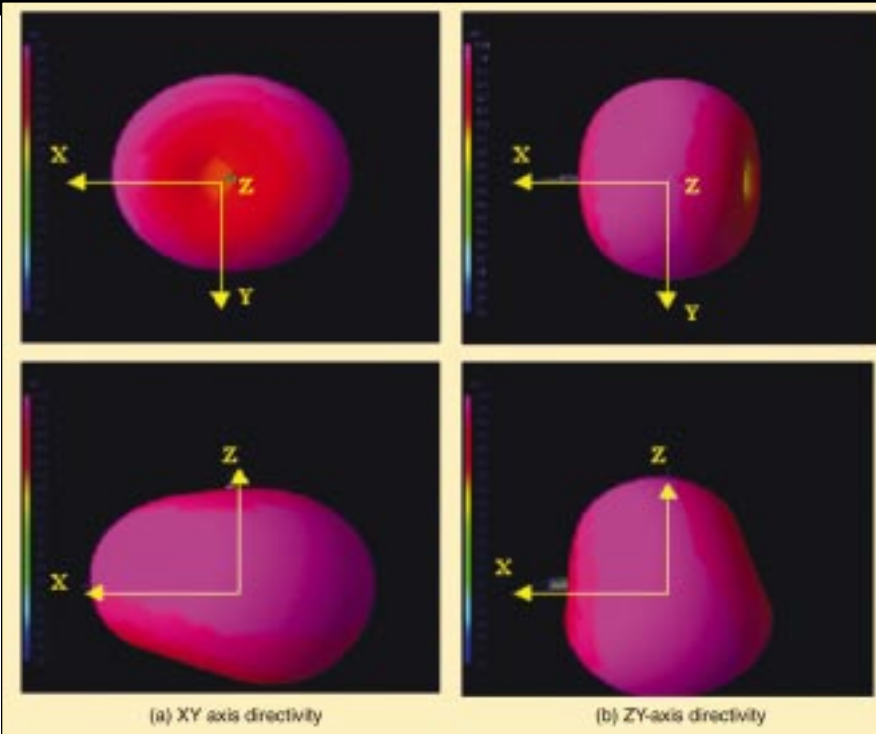


Figure 6. Orthogonal omni-antenna design (a) and its omnidirectional radiation pattern (b).



**Figure 7. Directivity management using a proposed two-antenna solution.**

(LAN, up and downconverters, and power amplifier for frequencies  $f_1$  and  $f_2$ ) and the Baseband processor (analog-to-digital, digital-to-analog, ARM processor, I/O bus,

memory bus and local ROM and SRAM) are key critical success factors to design of an optimum power-cost mini-RAT. Fortunately, using COTS available from various vendors

can address the 802.11 Tx/Rx communication portion of the design. COTS can also be used to address Tx/Rx of mini-RAT at UHF. However, addressing management of local interrogation function requires development of an FPGA.

4. Antenna design (ISM band): Typical 802.11-based systems use two antennas for diversity. The antenna selection is based on the RSSI and a decision (better S/N) from the baseband processor. As it will be addressed later in the article, a unique methodology of phase management can provide additional 6 dB gain to minimize effect of multipath fading.

5. Antenna design (UHF and HF frequencies): The sweet spot of the utilization are passive HF tags (13.5 MHz), passive and active tags at UHF (433 MHz, 868 MHz or 915 MHz). The mini-RAT has to address problems of reflected signal within container(s), multiple reflection from various tags (jamming) and effective radiation capture cross section of each tag depending on their loading and placement condition. These issues need to be addressed such that accurate information about all of the tags are reliability collected with 100% precision analysis in the master interrogator.

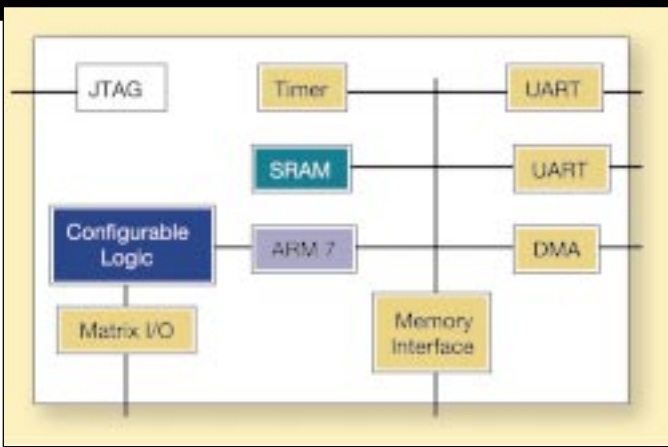


Figure 8. FPGA implementation of controller functions.

### System solution

Figure 5 presents the block diagram of the mini-RAT's HF/UHF unit (available from RF Micro Devices, Atmel, and Maxim Integrated Products)<sup>6-8</sup>. The FPGA interfaces with the unit to initiate the radiation of the HF or UHF frequency such that the resonant frequency of the passive tags trigger unique inventory code modulation and reflect back the modulated signal with the carrier frequency equal to the resonant frequency. The received code is then amplified and reshaped as digital data using a ARM-based signal-processing chip

data traffic flow as well as includes the interface to flash memory, HF/UHF I/O and the PCMCIA interface.

### Single and multi-antenna solution

A variety of embodiments for antenna element may be used within each integrated receiver/transmitter antenna design. Omnidirectional antenna is proposed for the design of the antenna. The length of each arm is proportional to the fraction of the wavelength for the desired operating frequency.

available from many vendors. The data is then collected to a flash memory card using an FPGA and direct memory access (DMA) function. FPGA also controls the stored data be sent to an access point via a slightly modified standard PCMCIA card. The FPGA hence address the

As shown in Figure 6, the proposed omnidirection antenna is implemented on a low-cost flexible material. The design shields will provide directionality, while the packaging of the antenna using a flexible substrate enables easy placement of the antenna in a container. Figure 6a shows a pair of omni antennas used for enhanced detection of the passive tags by providing a simple scanning scheme.

Figure 6b presents the electromagnetic field simulation results for an omnidirection antenna pair operating at UHF range<sup>9</sup>. Each antenna and its unique directionality and shielding strip occupy an area of 30 cm by 3 mm. The antenna is placed in a laminated plastic that can be easily attached to the interior of the container and hooked to the mini-RAT unit. A flexible substrate with  $\epsilon_r = 2$  results in array beamwidth  $\sim 60^\circ$  and 2 dBi of gain when launched with a 1 volt signal into a 50 Ohm load.

### Proposed scan filed by the twin antennas

- (a) X-Y axis directivity
- (b) Z-Y-axis directivity

Figure 7 directivity management using a

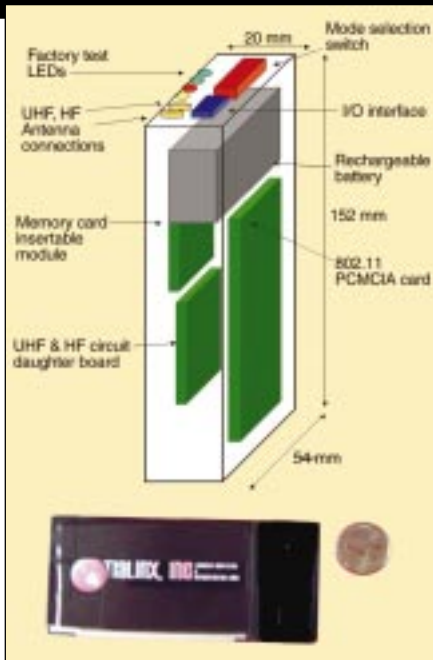


Figure 9. CAT implementation and dimensions.

proposed two-antenna solution. Radiation pattern for X-Y axis is shown in (a), and Z-Y axis in (b).

Figure 7 presents the spatial beamforming and scanning capability of the proposed two-antenna solution. The top pictures are the

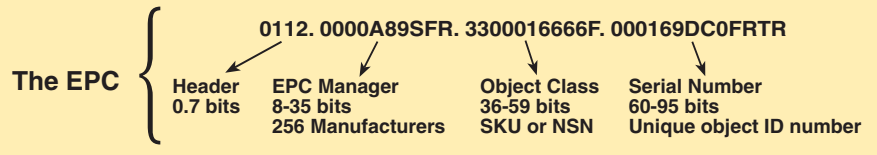


Table 1. EPC per passive tag.

**Anti-Collision Protocol:** An RFID reader is only able to communicate with a single RFID tag at a time. If more than one tag responds to a query, the reader detects a collision. In this case, it doesn't read accurately any of the information transmitted by the tags. The reader and tags then need to be engaged in protocol exchange so that the reader can communicate with the conflicting tags one at a time. Various methods are used to read multiple tags in within a range of a reader:

**Singulation Protocol:** A singulation protocol enables the reader to talk to each tag singly. While there are a number of available singulation protocols, one method can be a RFID-tag system that employs a singulation technique known as tree-walking. This singulation technique is (a) likely to be the most common one deployed in practice and (b) supportive of the more flexible modes of blocking proposed in the industry. RFID-tag systems typically operate at a frequency of either 13.56 MHz or 915 MHz. Tags operating at 915 MHz usually rely on tree-walking

as a singulation technique<sup>10</sup>, and are expected to be the most common type used in the United States. Tags operating at 13.56 MHz use the ALOHA protocol for singulation. The blocker-tag techniques do not work as cleanly with this protocol, since it is not possible to block certain subranges of IDs on a selective basis.

### Simultaneous identification (SID) mechanism

SID is a method of avoiding message collisions to enabling multiple transponders to communicate simultaneously with the reader. The SID mechanism offers the capability to inventory in a short time a large number of transponders by their unique address, provided they are within the reader operating range. The SID mechanism is based on an algorithm handled by the reader:

- Each transponder has a unique address.
- Transponders are interrogated by a sequence of SID requests, using a special addressing scheme.

	Mode	Tx	Rx	Sleep	Activity Time	Unit
<b>Mini-RAT Read/Write and Reporting Operation</b>						
Information per Tag (EPC)	196					Bits
Jumbo Field	128					Bytes
Passive Tags in the Container/Pallet	100					
Total Information to be Read					102.4	kBits
Read Cycle per Tag					200	mSec.
Total Read Time					20	Sec.
Flash Write Time per Byte					10	mSec.
Write Time to Mini-RAT's Memory					128	Sec.
Total Mini-RAT Interrogation and Storing Data Time					148	Sec.
Mini-RAT Tx Rate to the Master Interrogator (Access Unit)					1	Mbps
Mini-RAT to Master Interrogator Data Dump					102.4	mSec.
Mini-RAT On-demand Interrogation by Master Interrogator					48	Per Day
<b>Mini-RAT to Master Interrogator CommuniMini-RATion</b>						
802.11 Tx (RF+Baseband+Memory+I/O)	Awake	1155				mW
802.11 RX (RF+Baseband+Memory+I/O)	Awake		825			mW
802.11 (RF+Baseband+Memory+I/O) Peak Detector	Sleep Mode			50		mW
UHF Tx (RF+Baseband+Memory+I/O)	Awake	1000				mW
UHF Rx (RF+Baseband+Memory+I/O)			175			mW
UHF (RF+Baseband+Memory+I/O)	Deep Sleep			24		mW
FPGA/Sequencer (0.13 mic CMOS, 100k Gate, 40 MHz)	Awake				80	mW
FPGA Sleep Mode	Sleep Mode			0.1		mW
Sleep Mode Operation				74.1		mW
<b>Energy Consumption</b>						
Total Sleep Mode Energy per Day				1778.4		mW.Hour
Total Read/Write Energy per Day					2318.7	mW.Hour
Total DMA Energy to Master Interrogator					1.6	mW.Hour
Total Energy Consumption per Day					4098.6	Microsec.
Number of Batteries					2	
Battery Energy Available (6F22, 6AM6 or similar)					5200	mW.Hour
Recharge/Replacement Time					60.90	Hours
Recharge/Replacement Time					2.54	Days

**Table 2. Mini-RAT power consumption.**

■ If two or more transponders answer to the same interrogation, the collision is detected and stored into reader's memory.

■ If only one transponder answers, its address is registered into the reader's memory. It will not be interrogated again during the current SID cycle.

■ The reader then executes the collision-handling algorithm, which results in the interrogation of transponders not yet identified by a modified addressing scheme.

■ The cycle is continued until no collision is detected, i.e. all transponders have been identified and their addresses stored in the reader's memory. The inventory of transponders is then complete.

The SID polling mechanism is selective. The time slots during which transponders can answer are specified by the reader, by the mean of interruption (SID pause) in the emission of the carrier frequency. Within a given time slot, transponders answer only if there is a match between their unique factory-programmed SID address and the "SID\_Poll

Request," according to well-defined rules based on the mask parameter specified by the reader. As the time slots are "clocked" by the reader, the total duration of the SID\_Poll Command execution is optimized to the number of transponders in the field. The SID\_Poll Request is followed by a sequence of long power bursts, pauses and short power bursts. As described earlier, before transmitting the SID\_Poll Request, the reader performs a power-up pulse to supply all the tags within its interrogation field with enough initial power. The duration of this pulse is specified in common transponder IC data sheet<sup>11</sup>.

### FPGA implementation

A highly optimized FPGA is available from Triscend/Rochester (Figure 8) that has a 32-bit ARM7 processor core in the center of its reconfigurable controller chip. The chip has a dual UART and DMA support. If necessary, the memory interface provides access to flash memory and more RAM. The configurable system-logic (CSL) matrix

incorporates cells with flip-flops that can be set up as dual-port memory. The cells also comprise dedicated circuitry for adders, multiplexers and counters. High-speed DMA devices have access to on-chip RAM and off-chip memory. There are two UARTs on the chip, however, all other peripherals are implemented using the CSL matrix, which is also DMA accessible.

### Power management unit

Table 1 presents the tag information within a passive tag. A minimum of 196 bits of data should be stored and retrieved. Size of the tag ID has direct impact in writing to memory and relaying the information to the external interrogator.

Table 2 reflects the tabulation of various operating sections leading to the consumption of battery power by dynamic as well as the static circuits. The key element is function of the power management unit. The modified 802.11 PCMCIA card will operate asymmetrically (for Tx from Mini-RAT to the

access unit). Its RX function and sleep mode must be altered substantially to conserve power. This will be achieved by using a power peak detector at the Rx of 802.11 board. The batteries need to be recharged every 60 hours if mini-RAT operates in the interrogator and relay mode. The recharging can be delayed for every 120 hours if 802.11 feature is not activated, assuming updating schedule of every 30 minutes.

### Unit dimensions

The implementation concept of mini-RAT has been shown in Figure 9, as unit size has been compared to a quarter. The near PCMCIA size mini-RAT is highly versatile in compactness at no compromise to the performance due to the unique power manager unit, simple and yet innovative system/antenna/circuit design.

The aforementioned units: UHF/HF local interrogator, 802.11 a/b/g PCMCIA card, and power management unit are available in COTS for a breadboard design. The unique design and integration of the FPGA will enable communication between the units and allows interface to a memory module for on-demand or remote retrieval of the gathered data. Design of the antenna and phase management unit (in FPGA) addresses a robust mechanism for internal scan of tags in a container(s) or within the pallet. The transmitted inventory data to the main interrogator/access point will be used to track proper identification, authentication of the links. RFID

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