

## Fundamental Limitations on Reading Range of Passive IC-Based RFID and SAW-Based RFID

Clinton S. Hartmann and Lewis T. Claiborne, RF SAW, Inc., Richardson, Texas 75081

**Abstract:** For the first time, fundamental read-range limitations are calculated for two major types of “passive” (i.e. battery-less) RFID systems. Many applications require large read range. But, in shorter range applications excess read range provides read-path signal margin which enhances reading reliability, signal penetration, and/or flexibility in RFID system design, layout, and installation. Analysis was restricted to passive technologies because passive tags are required for the majority of future RFID applications. The analysis shows 2.44 GHz Surface Acoustic Wave (SAW) based RFID potentially has a 30X read range superiority compared to passive semiconductor IC-based RFID operating near 900 MHz.

### I. Introduction:

Over the last three decades Radio Frequency Identification (RFID) has led to a number of important applications in traffic control, high-value-asset tracking, manufacturing, and most recently supply-chain management. Two technologies have been prominent in addressing the applications that require a substantial (>3 meter) read range or a large enough dynamic range to be able to read ID tags in difficult circumstances, Surface-Acoustic-Wave (SAW) tags [1..4] and silicon IC-based tags [5..7]. These two technologies turn out to be fairly complimentary to each other in different applications.

Silicon based RFID tags must receive dc power to be read. The power either comes from a battery or from the reader signal itself which is rectified to overcome a threshold voltage. The non-battery powered silicon tags are referred to as “passive”. These have a limited dynamic range determined by the regulatory limits of broadcast power and by the forward loss of signal that falls below that required for the threshold. Battery power can be supplied to overcome the forward loss, “Semi-passive” tags, or can supply power to the return signal as well, “Active” tags. Readers for the silicon IC based tags typically have output power requirements of 1 to 4 Watts.

Surface-Acoustic-Wave (SAW) RFID is the other technology that can meet or, in many cases, exceed the

signal requirements for the same class of applications. However,

SAW RFID uses much lower reader power to meet reading requirements for better signal penetration under more difficult conditions. SAW tags have been used in automobile manufacturing, traffic control, and livestock ID applications. Early versions of the SAW tag were limited in data capacity but showed good reading range, good tolerance to gamma radiation and to high and low temperatures. These tags also can be used to measure temperature and distance in real time. The more recent development of a totally new modulation scheme for the SAW tags has made it possible to increase the data capacity to meet the EPCglobal standards up to 128 bits or higher. These devices operate with a spread-spectrum signal at 2.44 GHz instead of UHF and offer a low power reader alternative to the silicon tags by -40 dB. Since the spectrum of operation is available world wide, this new type of SAW tag is referred to a Global SAW Tag (GST).

Silicon IC, UHF RFID tags have found considerable acceptance in Supply Chain Management for bar-code augmentation or possible replacement. The often-referred-to WAL-MART and DOD supplier mandates has accelerated the development of this technology. It works well for reading case tags on conveyer belts, pallet and case tags for non-attenuating materials. SAW tags can be read with much lower signal levels and, therefore, can be used to read tags on metal objects and containers of liquids with much less reader power output when compared to the “passive” silicon RFID tags. The power generated by the RF SAW, Inc. Model 501 reader is < 0.5 mW. The dynamic range is sufficient for reading a 64bit tag at 60 feet with a 15 dB gain antenna. This read-range signal has sufficient margin for the reader to decode the highly attenuated signal in the center of a pallet. Thus, it can to read all the case tags of a pallet of shampoo bottles or a pallet of automobile air-conditioning compressors. The SAW tag reader power is low enough to be used in applications normally restricted and unavailable to the silicon tag readers. In fact, the Model 501 reader meets the HERO standards for being used around explosives with no reader stand-off distance requirement.

It has been demonstrated [1] that the GST RFID system consistently demonstrates significantly longer range and more reliable reading than passive IC-based RFID operating

Authors are with the RF SAW, Inc.,  
Richardson, Texas 75081,  
(corresponding author phone: 469-916-5964;  
e-mail: lclaiborne@rfsaw.com).

at UHF in spite of using 400X lower reader power in typical implementations. The physical principles for the GST operation are quite different from those of the powered silicon based RFID tags. The SAW tags have passive transducers that convert microwave EM signals into elastic Rayleigh waves via the piezoelectric effect. These waves are scattered by the electrodes on the surface of the crystal and reconverted by the transducer to electrical signal at the antenna. The process requires no DC power. By contrast, silicon RFID tags need a very strong reading signal from which they generate the DC power to operate the IC chip.

This paper shows that the ultimate performance limitation for SAW-based RFID is related to thermal noise power threshold given by  $kTB$ , where  $k$  is Boltzmann's constant ( $1.38e-23$  J/K),  $T$  is the device temperature in Kelvin degrees ( $\sim 290^\circ$  at room temperature), and  $B$  is the reader's noise bandwidth in Hertz ( $\sim 200,000$  for a typical SAW RFID reader). Similarly, it will be shown that the ultimate performance limitation for passive IC-based RFID is related to the equivalent thermal excitation voltage of an electron given by  $kT/q$ , where  $k$  and  $T$  are as before, and  $q$  is the charge of a single electron ( $1.6e-19$  coulombs).

It will be shown that this difference in fundamental performance limitations between these two technologies results in a practical reading range advantage for SAW-based RFID that approaches a factor of 30X. Also, this fundamental advantage is independent of type of semiconductor being used (silicon, germanium, gallium arsenide, hetero-junctions etc.) or the technology node (0.15 micron, 0.090 micron, 0.035 micron etc.).

## II. IC-Based RFID Technology:

Figure 1 shows a simplified diagram of an IC-based passive RFID system. Such tags are referred to as being "passive", but, a more accurate term would be "remotely-powered". While many factors can limit the performance of such a system, the fundamental limitation, that is one focus of this paper, will be shown to be given by answering the question "What is the smallest remote powering signal that can be converted into usable DC power for operating the IC-based RFID tag?" Obviously, that signal strength is determined at the tag's antenna.

Major points for IC-based RFID are: (1) The tag reader provides a powering signal to the tag. This signal must be continuous since any momentarily interruption of power causes the chip to stop operating and to loses its place in the read cycle. (2) The remote powering operation has an abrupt threshold such that if the powering signal as received by the tag drops below this threshold value, the tag ceases to operate. (3) Outbound data to the tag chip is provided by shallow AM (amplitude modulation) on the powering signal. Strong modulation must be avoided because the tag would lose power at the modulation minima. Such shallow modulation impacts data transmission accuracy. (4) A majority of the tag IC chip is typically devoted to circuitry for obtaining adequate DC powering voltage including rectifiers, charge pump, voltage regulation etc. The chip's digital circuitry is limited to a simple finite state machine because of insufficient DC current for powering a microcomputer. (5) The tag reply signal is created by amplitude modulating the naturally occurring backscatter

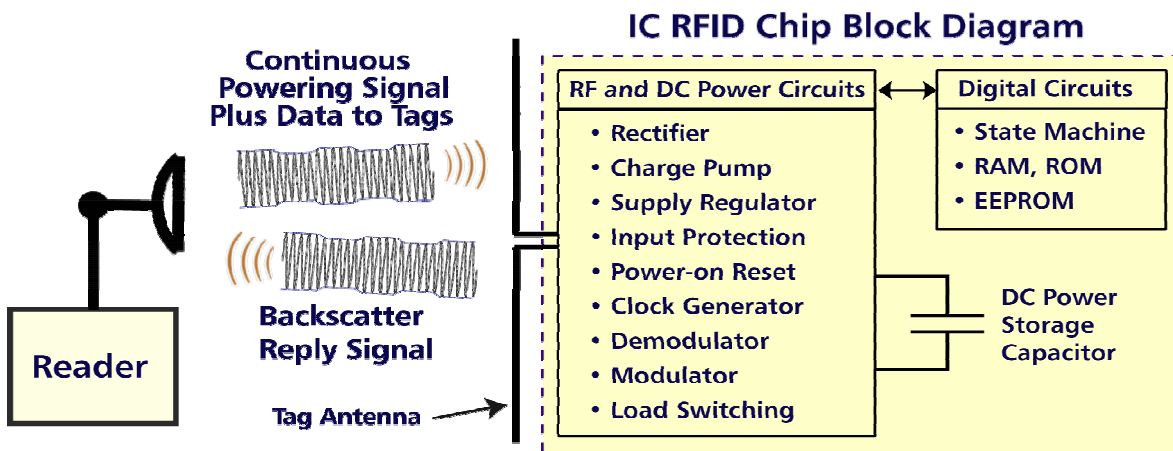


Figure 1. IC Based Passive RFID System

amplitude signal created by the tag’s antenna. The depth of modulation (and hence strength & reliability of the reply signal) is limited by the tradeoff between strongly modulating (i.e. shorting) the tag’s antenna and the disruption to the tag powering signal that would result from such shorting.

However, the major performance limitation for IC-based passive RFID tags is the abrupt signal threshold for the powering signal arriving at the tag’s antenna. If the signal drops below this level, the chip abruptly dies and reading is lost. Thus the fundamental question for performance limitation on IC-based tags is “What is the smallest signal that can be successfully rectified and turned into usable DC power for operating the IC-based RFID tag?”

Since the SAW chip operates using the piezoelectric effect, it does not require DC power. The SAW tag is a true linear passive device which means if a strong signal is received by the tag, the reply signal is also strong. If a weak signal is received by the tag, the reply signal is correspondingly weak. There is no abrupt threshold effect below which the tag no longer operates (as there is in a remotely powered IC tag). Thus the lower limit for SAW tag operation occurs when the reply signal received at the reader becomes too small for reliable detection.

SAW devices are a well established technology (just like IC’s) and are widely used in wireless equipment including

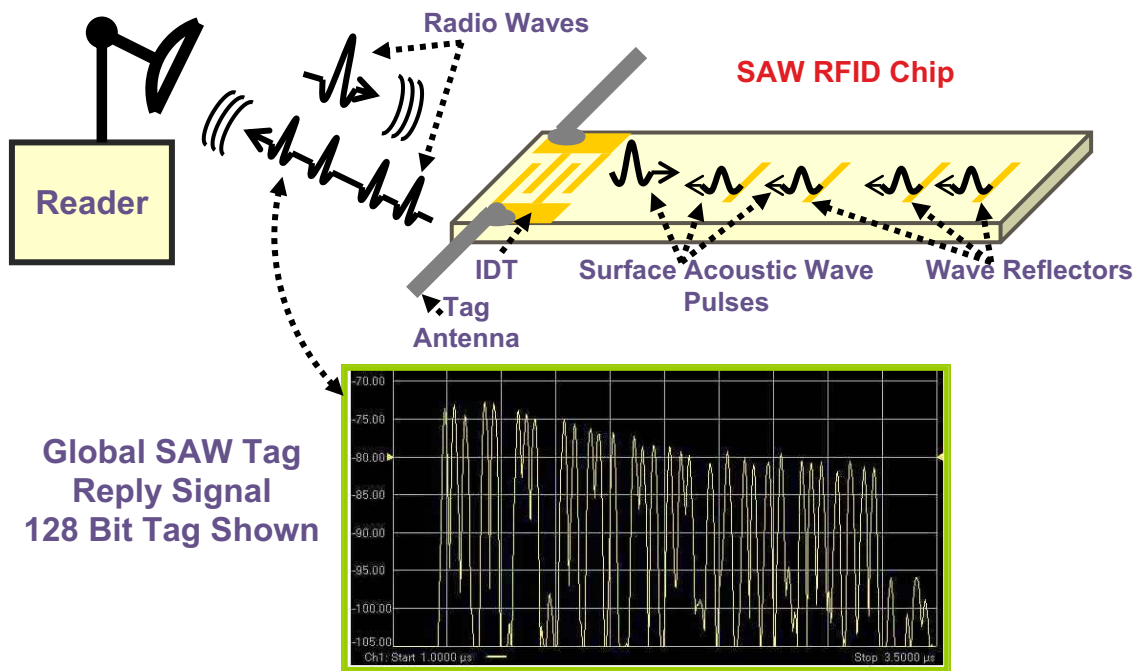


Figure 2.SAW-Based Passive RFID System

**III. SAW-Based RFID Technology:**

Figure 2 shows a simplified diagram of a SAW-based passive RFID system. In this case, the tag uses a truly “passive” Surface Acoustic Wave (SAW) device that requires no DC power. The SAW tag reader emits a radio frequency pulse excitation signal directed to the tag. After it is received by the tag, it is converted into a nano-scale Surface Acoustic Wave replica of that excitation signal on the SAW chip surface by action of the “IDT” (interdigital transducer) combined with piezoelectric effect of the SAW chip material. After a short distance, that acoustic wave travels past a set of wave reflectors to produce uniquely encoded acoustic wave pulses, which travel back to the IDT. The IDT, combined with the reverse piezoelectric effect, converts those pulses into an encoded radio wave reply signal that is radiated back to the reader by the tag antenna.

cellular phones, TVs, keyless auto entry systems, satellite communications, and many others. Billions of SAW devices are produced annually by many manufacturers around the world. SAW-based RFID has its origins in the early 1970’s. However, it never achieved wide-spread usage because the number of unique codes was severely limited. That changed dramatically with the invention of the Global SAW Tag in 2001 which provides a practically unlimited number of unique codes. The waveform of a 128 bit Global SAW Tag is shown at the bottom of Figure 2.

The communications link between the reader and SAW tag has very high reliability for several reasons. First, the Global SAW Tags use interference resistant PM/PPM modulation (passive IC-based tags use shallow AM with sub carrier modulation which is more interference prone). Second, the SAW tag does not start emitting its reply signal

until approximately 1 microsecond after receiving the excitation signal. This allows the “environmental echoes” to substantially die down before the SAW tag radiates its reply signal. In contrast, the backscatter reply signal from IC-based tags is generated simultaneously with environmental echoes and thus can be lost in the environmental background interference. Finally, the basic read cycle for SAW tags is very fast (typically ~ 1 millisecond). Therefore, during the dwell time when the SAW tags are in range of the reader, it is not unusual for several hundred interrogation cycles to occur. By using standard statistical methods, this large number of independent read results can be combined into a highly reliable single read result for each separate tag.

Overall, if the reply signals as received at the reader are sufficiently strong, very reliable SAW tag reading is generally achieved. Consequently, the fundamental limitation for the SAW-based RFID system occurs when the received signal level at the reader becomes too weak for reliable detection.

The major purpose of this paper is to discuss the fundamental differences between these two RFID technologies insofar as they affect reading range and reading reliability. This is justified because if adequate reading range and reading reliability are not achieved, all other considerations are not relevant.

#### IV. Fundamental Limitation of IC-based RFID Systems:

As discussed above, the fundamental limitation of IC-based systems is tied to answering the following question: “*What is the smallest signal that can be successfully rectified and turned into usable DC power for operating the IC-based RFID tag?*” To answer this question, one must define the optimum rectifying device that can be implemented. If, for example, a P-N junction diode [8,9] is used as the basis for answering the question, an unnecessarily pessimistic result is obtained because of the rather large forward break-over voltage of these devices. This forward break-over voltage penalty can be reduced by considering other diodes such as Schottky diodes and hot carrier diodes. To the author’s knowledge, the forward break-over threshold can be reduced to nearly zero by using a diode-connected p-channel MOSFET with the proper doping control and backside bias.

The equation for the diode current  $J$  as a function of applied voltage  $V$  has an exponential form similar to the following:

$$1) \quad J \approx A(V) [\exp((V - V_0) / V_T) - 1]$$

In Equation 1,  $A(V)$  is a slowly varying function of the applied voltage  $V$  that can be assumed to be a constant for the small voltages considered in this analysis,  $V_0$  is an break-over threshold voltage, which is set to zero to correspond to an optimal diode configuration, and  $V_T$  is the thermal excitation voltage of an electron given by  $kT/q$  where  $k$  is Boltzmann’s constant ( $1.38e-23$  J/K),  $T$  is the device

temperature in degrees Kelvin ( $\sim 290^\circ$ ), and  $q$  is the charge of a single electron ( $1.6e-19$  coulombs). Using these constants, it can be shown that

$$2) \quad V_T = kT / q = 0.025 \text{ volts.}$$

Using the above conditions, the characteristics of an optimum diode operating under small voltage conditions is described by the following equation.

$$3) \quad J \approx A * \exp( V / V_T )$$

Equation 3 implies that under small voltage conditions, an optimum physically realizable diode does not act like an ideal diode that allows current flow in only one direction. Rather it must be modeled as a voltage variable resistor as characterized by Equation 3 (or more generally by Equation 1). If one recognizes that this non-ideal diode also needs to be utilized as a key element in a charge pump circuit to build up the rectified voltage to the approximately 1 volt minimum needed to operate an IC, it can be shown that the resistance needs to vary by approximately a factor of 100 over the RMS voltage swing of tag input voltage.

The conductance (inverse of resistance) can be calculated by differentiating Equation 3 with respect to  $V$ . By noting that  $\exp(4.6) = 100$ , one obtains that optimum minimum voltage that can be successfully rectified by even the best semiconductor diode is given as follows:

$$4) \quad V_{MIN-OPT} \cong 4.6 V_T \cong 0.12 \text{ volts rms.}$$

All practical passive IC-based tags designs must have rectifiers with minimum rectified voltage values that are larger than given by  $V_{MIN-OPT}$  in Equation 4. The significance is that if the powering signal as received by the tag falls below its particular minimum threshold voltage, the tag ceases to operate.

The minimum voltage shown in Equation 4 is independent of both the type of semiconductor material which is being used and of the device geometry. This is true because this equation represents the best that can ever be achieved. Use of either a poor semiconductor material or poor device design can serve to greatly increase the actual  $V_{MIN}$  that is achieved in a particular design. Examples of “poor” semiconductor materials are polymer semiconductors (sometimes referred to as “printable electronics”). To the author’s knowledge, the lowest voltage rectification that have been achieved with these materials is 50 to 100 times larger than that given by Equation 3 and thus it seems unlikely that “remotely-powered” semiconductor tags will be feasible with these low cost materials anytime soon. Overall, one can certainly make a remotely powered IC-based tag that has a worse threshold voltage but not better than Equation 3.

But why is it that this minimum is independent of material type? Basically, this can be understood by examining the physical meaning of  $V_T$ .  $V_T$  is the thermal excitation voltage of an electron. As is well known, if any object is at a temperature above absolute zero, the atomic particles inside are vibrating and undergo fluctuations in energy whose an average value is given by  $kT$  (Boltzmann's constant multiplied by the object's temperature  $T$ ). In a semiconductor (or metal etc.), electrons are continually jumping between quantized energy levels with an average spread of  $kT$ . Since the charge of an electron is fixed (independent of the material in which it is located), these energy level fluctuations can be expressed by the voltage  $V_T$  defined in Equation 2. Since  $k$ ,  $T$ , and  $q$  are all independent of material type and device design, the voltage  $V_T$  is also independent of these items.

Viewed another way, a diode represents a type of barrier that should be easier to cross in the forward direction than in the reverse direction. However, when considering voltages that are getting close to  $V_T$ , the thermal excitation of the charge carriers is sufficient such that there is a high probability that a large number of carriers will simply jump over the barrier backwards thus defeating the diode's function.

So, what is the state of these IC-based tag technologies today? The best of current UHF RFID tags are already within a factor of 2 to 4 of  $V_{MIN-OPT}$  as given by Equation 4. This means that expected future advances in IC technology will not significantly improve the minimum signal level needed for a remotely-powered IC-based RFID tag. Thus any future improvements in reading range (and probably overall reading reliability) can only be achieved by either using higher gain antennas on the RFID tags (which increases tag size and thus is limited), or by obtaining permission to operate readers at higher power levels (which appears very unlikely in most situations due to radiation safety concerns).

## V. Fundamental Limitations on SAW-based RFID Systems:

As discussed above, the fundamental limitation for the SAW-based RFID system occurs when the received signal level at the reader becomes too weak for reliable detection. As is well known in communications theory, the background noise level from an antenna is given by  $kTB$  where  $k$  is Boltzmann's constant,  $T$  is the antenna temperature in degrees Kelvin, and  $B$  is the effective noise bandwidth at the output of the signal processing section of the receiver.

The signal to noise ratio at the SAW tag reader output can be calculated from the following equation.

$$5) \quad \frac{S}{N} = \frac{P_{XMIT} G_{XMIT} P_{G_{TagAnt}} G_{SAW} G_{TagAnt} P_{G_{RCVR}}}{NF * kTB}$$

In Equation 5,  $P_{XMIT}$  is the transmit power,  $G_{XMIT}$  is transmit antenna gain,  $P$  is the path gain (typically less than unity) between the reader antenna and the tag antenna,  $G_{TagAnt}$  is the gain of the tag antenna,  $G_{SAW}$  is the gain of the SAW RFID chip (also less than unity),  $G_{RCVR}$  is the gain of the reader receiving antenna (often the same as the transmit antenna),  $NF$  is the noise factor of the receiver, and  $kTB$  is the background noise level mentioned above.

While Equation 5 can be used in many ways, it will used here to calculate the minimum allowable path gain (actually a loss)  $P$  that one obtains for typical values of other variables in the above equation. Table 1 below shows assumed typical values for best currently available SAW-based RFID. Appendix A justifies the use of  $G_{SAW} = 0.0001$  and also discusses the possibilities for future improvements.

$\frac{S}{N}$ minimum	= 10
$P_{XMIT} G_{XMIT}$	= 4 watts (set by regulatory authorities)
$G_{TagAnt}$	= 4 (6 dB gain tag antenna)
$G_{SAW}$	= 0.0001 (40 dB loss to weakest reflector)
$G_{RCVR}$	= 100 (20 dB gain antenna)
$NF$	= 4 (6 dB noise figure)
$B$	= 200,000 (200 kHz noise bandwidth)
$kTB$	= $8.00 \times 10^{-16}$ watts

**Table 1: Typical Best Values for Modern SAW-Based RFID Systems**

By using the values in Table 1, the worst case allowable path loss,  $P$ , can be calculated.

$$6) \quad P_{WorstCaseSAW} \cong 4.47 \times 10^{-7}$$

## VI. Comparison of Worst Case Allowable Path Losses:

The analysis for the IC tag gave a minimum voltage at the tag input, not a power level as derived for the case of the SAW tag. However, that rms voltage can be converted to a power level by making a reasonable assumption for the best case tag output impedance (and corresponding IC input impedance). For the comparison done here, the impedance level for the IC tag is assumed to be 50 ohms. This is a typical value for current UHF RFID tags that are designed to cover a frequency range from ~860 MHz (Europe) to ~960 MHz (Japan). The equation for minimum power received at the IC-tag is as follows:

$$7) \quad MinICTagRFpower \cong \frac{V_{MIN}^2}{Z_{IN}} = \frac{(0.12)^2}{50} = 2.88 \times 10^{-4}$$

The one-way signal equation for the IC tag is given as follows:

$$8) \quad PowerAtTag = P_{XMIT} G_{XMIT} P_{G_{TagAnt}}$$

## REFERENCES

In the case of IC-based tags at UHF, the product of  $P_{XMIT}G_{XMIT} = 4$  as in the SAW case. However, the tag antenna gain,  $G_{TagAnt}$ , is more likely to be 1 or less because of tag size restrictions. Finally one should not simply substitute Equation 7 into Equation 8 to calculate a worst case allowable path loss for IC-tags. That would be unreasonably optimistic because the resulting value would have the tag operating at the edge of the totally losing power. To achieve reasonable read reliability, some extra margin is needed to cover the effects of outbound modulation, of backscatter modulation, and something for environmentally caused variations in power levels and sensitivities. (These extra margins are somewhat analogous to the modest 6 dB noise figure and the 10 dB minimum signal-to-noise ratio that were assumed to be needed for reasonably reliable operation in the case of the SAW tag.) If a similar 16 dB factor (or 40X) is used here, then the worst case allowable path loss for IC-based tags is given as follows:

$$9) P_{WorstCaseIC} = 2.88 e - 3$$

If one compares the worst case allowable path loss for SAW tags (Equation 6) to the worst case allowable path loss for IC tags (Equation 9), it is seen that the ratio of allowable one-way path losses for the two technologies is a factor of ~6,400. However, at the present time, SAW-based RFID is generally operates in the 2.45 GHz band whereas next generation IC-based tags operate at UHF (~0.92 GHz). If this difference in frequencies is considered, the ratio of allowable path losses is reduced to a factor of ~900. A factor of 900 in one-way path loss corresponds to a 30X larger reading range for SAW-based RFID if free-space signal propagation is assumed.

It should be noted that significant room for future improvement exists in the SAW technology case while IC technology is already providing performance that is nearing the fundamental theoretical limits for IC-based RFID. Thus the fundamental technology advantage of SAW-based RFID is expected to increase in the future.

### VII. Conclusion:

It has been shown that fundamental comparisons of the ability to withstand signal path attenuation (or equivalently, the ultimate tag reading range), indicates that SAW-based RFID has superior reading range compared to remotely powered IC-based RFID by factor of ~30X. This superiority results from fundamental physics differences between the two technologies and is unlikely to change.

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## Appendix A: Wave Reflector Design for Minimum Loss

As is evident from examination of the SAW tag device shown in Figure 2, the pulses that convey the tag ID information arise from wave reflectors that are placed on the SAW device substrate. The later pulses in the impulse response arise from the right-most wave reflectors in Figure 2 and thus these pulses must pass under other wave reflectors. When passing these earlier reflectors, a portion of the energy is reflected which subtracts energy from these passing pulses. The energy balance relationship between transmitted and reflected pulse energy for the  $i^{\text{th}}$  reflector is given as follows.

$$R_i^2 + T_i^2 = E \leq 1 \quad (\text{A1})$$

The amount by which the energy loss factor  $E$  differs from unity is a measure of other loss mechanisms exhibited by practical implementation of wave reflectors including a) scattering of SAW energy into bulk acoustic waves, b) acoustic damping losses caused by the wave reflector material (usually a metal film in current designs), and c)  $I^2R$  resistive losses (a second order loss mechanism that can occur when piezoelectric SAW substrates are used).

In SAW RFID tag designs, early reflectors are weaker than later reflectors so that a nominally uniform impulse response is achieved. However, in this paper, the amplitude of each pulse will be allowed to differ from the subsequent pulse amplitude by a slope factor  $S$ . If  $L$  is the round trip free surface propagation loss between two wave reflectors, the reflectivities of adjacent reflectors must obey the following relationship.

$$R_{i+1}T_i^2L = SR_i \quad (\text{A2})$$

Equations A1 and A2 are solved to obtain:

$$R_i = 0.5 \left[ \frac{-S}{R_{i+1}L} + \sqrt{\left( \frac{S}{R_{i+1}L} \right)^2 + 4E} \right] \quad (\text{A3})$$

Reflector strengths can be designed by setting the reflectivity of the final reflector to a value that is determined by the maximum allowed multi-bounce spurious level. Then the reflectivity of all preceding reflectors is determined by Equation A3.

Equation A3 coupled with the fact that neither  $E$  nor  $L$  can ever exceed unity are limiting factors in determining the minimum loss that can ever be achieved by a set of SAW tag wave reflectors. Also, if ultimate performance is based on the strength of the weakest pulse, setting the slope  $S$  equal to unity will correspond to having the optimum strength for the

weakest possible tag pulse. Thus one calculation set below will consist of setting  $E$ ,  $L$ , and  $S$  equal to unity to emulate the best that can ever be achieved.

One other set of values for these three parameters will also be considered, namely the values associated with a currently popular SAW substrate material,  $128^\circ$  rotated Y-cut lithium niobate ( $\text{LiNbO}_3$ ) with wave propagation along the X axis and when using aluminum metallization with a thickness of 5% of one SAW wavelength ( $\lambda$ ) and operating at a center frequency of 2.44 GHz. For this situation,  $E \approx 0.985$  (corresponding to fundamental mode open-circuit aluminum reflectors),  $L \approx 0.952$  (corresponding to  $-6.5$  dB/ $\mu\text{sec}$  free surface propagation loss and a nominal reflector spacing of 65.6 nsec), and the slope factor  $S$  equal to unity.

Figure A1 shows SAW tag device insertion loss as a function of data content measured in bits. All the curves shown assume a data modulation efficiency of 4 bits per pulse (which is exactly the efficiency achieved in the current versions of the Global SAW tag). The top most curve give an upper limit that could ever be achieved based on energy conservation (i.e. in the case of uniform reply pulse amplitudes, the power in each reply pulse can never exceed the energy in the incident reading pulse divided by the number of pulses). This upper curve is an absolute physical limit but it does not correspond to a design which obeys Equation A3.

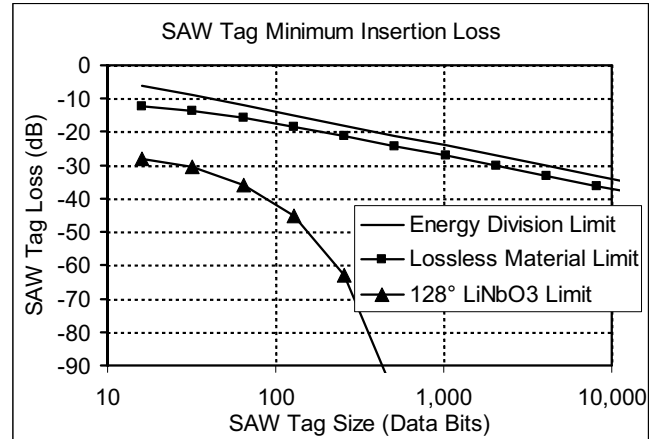


Figure A1: Minimum Insertion Loss of SAW Tags

The center curve in Figure A1 represents the minimum tag loss that can be achieved with a design that obeys Equation A3 and using idealized lossless SAW substrate and lossless wave reflectors (i.e. with  $E$ ,  $L$ , and  $S$  equal to unity). In addition it is assumed that the SAW IDT transducer loss and the propagation loss associated with the pedestal delay are negligible. However, the maximum reflector strength has been limited to be 0.3317 which corresponds to a multi-bounce spurious reflection suppression of at least  $-20$  dB.

Note that for small tag sizes (16 bits is the minimum considered in this analysis because that is the smallest data load possible with current GST design parameters), the lowest achievable loss is  $\sim -12$  dB which is 6 dB worse than dictated by energy division. However, for ideal lossless substrate materials, as the tag size increases, the minimum tag loss asymptotes to only 3 dB worse than dictated by energy division. Thus, if the near perfect SAW substrate materials are ever achieved, acceptable SAW tag losses would be achievable for tag sizes up to 10's of kilobits.

The bottom curve in Figure A1 corresponds to current state of the art in SAW tags. This curve gives the minimum SAW tag loss of current Global SAW Tags that are manufactured using  $128^\circ$  rotated Y-cut lithium niobate. These curves not only use the earlier stated values for  $E$  and  $L$ , they also assume a propagation loss associated with the pedestal delay of  $-6.5$  dB and a SAW IDT transducer loss of  $-7.5$  dB. Note that a 96 bit tag has a loss of  $-40$  dB.

All of these practical loss parameters can be improved. It is known that sapphire SAW substrates have roughly  $\frac{1}{4}$  the loss of lithium niobate. Also, low loss unidirectional transducers have already been experimentally demonstrated at this frequency.