

# EXTENSIONS TO THE PSEUDO-RANDOM CLASS OF ENERGY-CONSERVING ACCESS PROTOCOLS

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**Abstract** - *A myriad of applications such as radio frequency identification (RFID) and smart card networks are emerging in which nodes are designed for extremely low-cost, large scale applications such that the replacement of batteries is not feasible. Energy conservation therefore becomes a major constraint. Classical access protocols are either not energy conserving or lead to unacceptable delays. In a previous work we proposed three new classes of energy-conserving access protocols designed to minimize delay while drastically reducing the energy required at the mobile node. In this paper, we propose an extension to one of those protocols which greatly reduces the worst case delay experienced by the packets.*

## 1. INTRODUCTION

Radio frequency identification (RFID) tags such as those used in warehouse and manufacturing systems represent a new type of mobile communication device where energy-conservation and low communication delay are critical system parameters. These devices are currently being used in a wide range of applications such as warehouse location tracking, automatic inventory, automatic purchasing and mobile remote sensing. The potential applications will increase as the RFID market expands 20 fold to over \$5 billion within the next 5 years [3].

The term RFID is used to describe a wide range of radio frequency identification devices. These range from purely passive devices which only can send back a few tens of bits over distances of a few centimeters to devices the size of bricks which may have extensive communications with orbiting satellites. Two major characteristics define the size, cost and capabilities of RFID devices: either active or passive power, and either active transmit or modulated backscatter (either passive or reflective) transmission [8]. Active tags typically contain a microprocessor, battery, support logic, and a spread spectrum communication device. The use of modulated backscatter spread spectrum in these devices allows the tags to utilize energy radiated on the shared channel from the base station as power for their uplink communication. There are a wide variety of passive tag designs though due to a lack of power source,

they all have very limited communication and computing ability. Due to this, in the following paper we are especially interested in active tags as they show a reasonable compromise between a processing power, communication distance and cost which makes them extremely flexible in the types of applications they can be used for.

Although RFID does not dominate the popular literature the way “high profile” mobile computing applications such as cellular data and compression for video do, it nevertheless has an enormous potential for profit and impact through factory automation, and automatic information retrieval. This potential has been seen by the number of major companies which have been investing substantial amounts of resources towards the development of RFID products. Motorola, Hughes (a subsidiary of GM Corporation), Micron and Texas Instruments boast the largest market shares of this industry with many other companies appearing regularly. The future of RFID devices can be seen from the applications already in use. The following examples are only a small section of RFID applications, but the size and complexity of tasks show the future potential:

- the US Postal system has begun utilizing tags to track letters throughout their offices to mail as it flows through their offices and warehouses [4].
- the United States Department of Defense recently purchased \$70 million of RFID equipment from Sav-

iTag for tracking cargo containers, shipping pallets, etc [12].

- the Federal Aviation Administration (FAA) has recently entered into research and development agreement with Micron Communications to develop a system for efficient tracking of baggage and passengers [9].
- Pierrel-Ospedali, one of Italy's major pharmaceutical companies has been using RFID tags in production processes to maintain high standards in quality and sterilization control [2].
- General Motors has been utilizing RFID tags for maintaining accurate and timely data on work-in-progress on their fully automated assembly lines [5].

There are four observations of these systems which substantially affects the appropriate choice of a channel access protocol:

1. *Scale*: There may be a very large number of wireless nodes within a small area. Even in a system utilizing microcells, a single base station may have to communicate with a thousand tags.
2. *Cost*: Due to the large number of extremely inexpensive items to "tag" as well as the cost-ineffectiveness of reuse or recycling, nodes must be extremely inexpensive, often on the order of only a few dollars.
3. *Size*: Nodes must be very small. The size of a pack of cards will be the maximum size for many applications.
4. *Traffic*: Communication is typically based on short, simple messages over a shared channel. Transmission speeds are usually low, on the order of tens of kilobits per second in order to minimize cost and power of transmission.

From these points it can be seen that two important issues must be addressed when designing an access protocol for a tag network: low energy utilization and low access delay. As in all mobile computing applications, the battery's energy is a limited and scarce resource, which is not expected to increase in potential more than 30% in the near future [11]. The large number of nodes makes it economically impossible to replace or recharge the batteries. Therefore tags must be designed so as to require a minimum of energy for operation. In order to conserve battery life, the tag can enter a "sleep" state where the CPU is in a low power mode and radio reception is disabled. In contrast with this, the "awake" state, in which the CPU operates at full energy and the radio frequency circuitry is active, can typically use 100 times as much energy.

Uplink transmission can typically use twice as much energy as reception [6]. As mentioned above, it is possible to use spread spectrum modulation such that the base

station indirectly provides the energy for limited uplink communication, but this requires that any uplink traffic be base station initiated. Therefore the "awake" state needs to be synchronized with the transmission of packets. It should be understood that for this type of transmission capability the circuitry is extremely simple and any power cycling of the communications circuits is merely the presence or lack of power to digital logic, a diode and antenna. There is no major power loss from switching between sleep and awake states.

The allowable delay in an RFID access protocol is an application dependent constraint. For example, tracking the movement of tags across the cells within a system requires updates to be performed within a short, bounded, amount of time. The system is already constrained by the speed of the shared channel and has to manage a potentially large number of tags. Therefore, it is extremely important for the access protocol to not add significantly to the transmission delay.

In [1], we addressed the problem of designing *communications protocols which operate under an energy constraint*, in which the fraction of time slots in which tags need to be in the active (awake) state is minimized and the access delay meets the applications constraints. Among the protocols proposed, the *pseudo-random* protocol showed very good behavior under both uniform and heterogeneous traffic destination distributions. Also, its flexibility and scalability suggested it would be the most suitable protocol for a general multicell tag system.

Unfortunately, no explicit bound on the length of the interval between two awake slots is included in the protocol. In this paper we describe and consider simulation results of a modification of the pseudo-random protocol which includes such a guarantee. Simulation results show that the new feature results in a limitation of the minimum energy that can be achieved. However, for a fixed energy, the average delay of the extended protocol is less than that of the original pseudo-random, with a consequent improvement of the performance for small delay constraints. As expected, the difference in performance decreases as the value of the guarantee increases. The introduction of a guarantee also results in a great improvement of the worst case delay. In the remainder of the paper we first describe the tag network model, followed by a description of both the pseudo-random and modified pseudo-random protocols. Using simulation results, we next describe the system behavior through comparison with the original pseudo-random protocol and finally conclude with a summary.

## 2. NETWORK MODEL AND PROTOCOLS DESCRIPTION

We consider a single cell system where a base station communicates with  $N$  tags through a wireless channel. The communication is packet-oriented. We assume the time to be slotted and the base station's transmissions to

be synchronized to the beginnings of slots. The packet length is constant and equal to one slot. In this model we do not explicitly treat transmission errors.

We define an *access protocol* as consisting of two components: a *transmission scheduling strategy* at the base station which in each slot selects a packet for transmission from the arrival queue, and a *wake-up schedule* at each tag which determines the slots in which the tag is awake. In general, the transmission scheduling strategy can take into account different parameters: the number of packets in the queue, the packets' ages, as well as the wake-up schedules of their destinations. In the protocols discussed here the "oldest packet" criterion is adopted to help meet the application delay requirements. We next present the pseudo-random protocol and the modified pseudo-random protocol.

### 2.1 Pseudo-Random Protocol

The pseudo-random protocols are a class of protocols based on deterministic (pseudo-random) schedules which preserves the power of randomization for fairness, while providing the advantages of determinism, i.e., the base station's ability to predict tags' state in each slot. In this class of protocols all tags run the same pseudo-random number generator and determine their state (awake or asleep) at each slot based on a probability  $p$  and the stored state of the random number generator. In order to avoid a complete overlap of the wake-up schedules, the pseudo-random generator of each tag is initialized using a unique seed, which is known at the base station. Therefore, by using the same pseudo-random number generator it is possible for the base station to determine the schedules of the tags it wants to transmit to. The base station can initiate changes in the value of  $p$  as a function of the load, the number of tags, etc. It is expected that with relatively low data rates (and therefore longer slot times) and the lower cost importance of the base stations compared to the tags, it is computationally possible to generate the large amount of random numbers within the amount of time necessary to make an adequate selection of which packet is to be sent. Additionally, at the tag level, reasonable random number generators are not difficult to program on a microcontroller. For example, as described in [7] the commonly used linear congruential random number generator can be implemented in only four float point assembly instructions. Alternatively a simple look-up table in non-volatile memory could be implemented if costs justify a CPU without floating-point capabilities.

### 2.2 Extensions to the Pseudo-Random Protocol

In this protocol we introduce a guarantee  $s_{max}$  on the maximum length of the asleep intervals. Each tag not only uses a pseudo-random generator to generate its wakeup schedule, but also forces a bound on the length of a sleeping interval by comparing a counter of consecutive sleep-

ing slots with the  $s_{max}$  threshold. In other words, at each slot the tag will be awake if the random number it generates is less than or equal to  $p$  or it has been asleep in all of the past  $s_{max}$  slots. This modification to the protocol does not introduce much additional complexity as it merely adds a counter to the sleep schedule calculation. As in the original pseudo-random protocol, the base station transmits in each slot the oldest among the packets whose destination is currently awake.

## 3. SIMULATION PERFORMANCE

We simulated the reception of 30,000 packets for both the pseudo-random protocol and its extension with  $s_{max}$  parameters of 5, 10, 15 and 20 slots. There were  $N = 1000$  tags in the system, and the packet destinations were chosen from a uniform distribution. We simulated two systems, one with packets arriving with interarrival rate values distributed according to a Poisson process rate of 0.05 and one with an arrival rate of 0.2.

The simulation results are plotted in Figs.1 through 4. Fig.1 and Fig.2 depict the average energy per tag vs. average delay per packet behavior of both the pseudo-random and its extension with varying values of  $s_{max}$ . It can be seen that for a particular value of  $s_{max}$  the minimum energy achieved by the extended pseudo-random is lower bounded by  $\frac{1}{s_{max}+1}$ . However, the average delay corresponding to a certain energy in the extended protocol is less than or equal to that of the original pseudo-random protocol, due to the fact that the probability of a tag being awake in the current slot is greater than the inverse of the average asleep interval. As  $s_{max}$  increases, the difference in performance between the two types of protocols decreases, matching the intuition that when  $s_{max}$  exceeds a certain value, the extended protocol should perfectly approximate the original pseudo-random. Different values of the packet arrival process's interarrival parameters do not affect the wake-up schedules, but only the effectiveness with which it can be used, resulting in a higher average delay when the probability of conflicts increase (i.e. for higher  $\lambda$ 's). The appropriate wakeup probability  $p$  should be chosen in a real system as a function of the acceptable delay, required energy savings, and the estimated arrival rate.

Although these two figures show an improvement in the average packet delay, the improvement in the overall distribution of packet delay more substantially shows the effect of the modification to the original protocol. In Figures 4 and 3 we have plotted histograms of the delay experienced by the packets for each of the simulated protocols. Each line of the plot shows the percentage of packets which experienced the delay for the original protocol, and the extended protocol with  $s_{max}$  values of 5, 10, 15 and 20 respectively. Each line for both figures shows the performance of the protocol with an average energy consumption per tag, of 0.17. Since we are adding awake slots when including the  $s_{max}$  threshold, it should

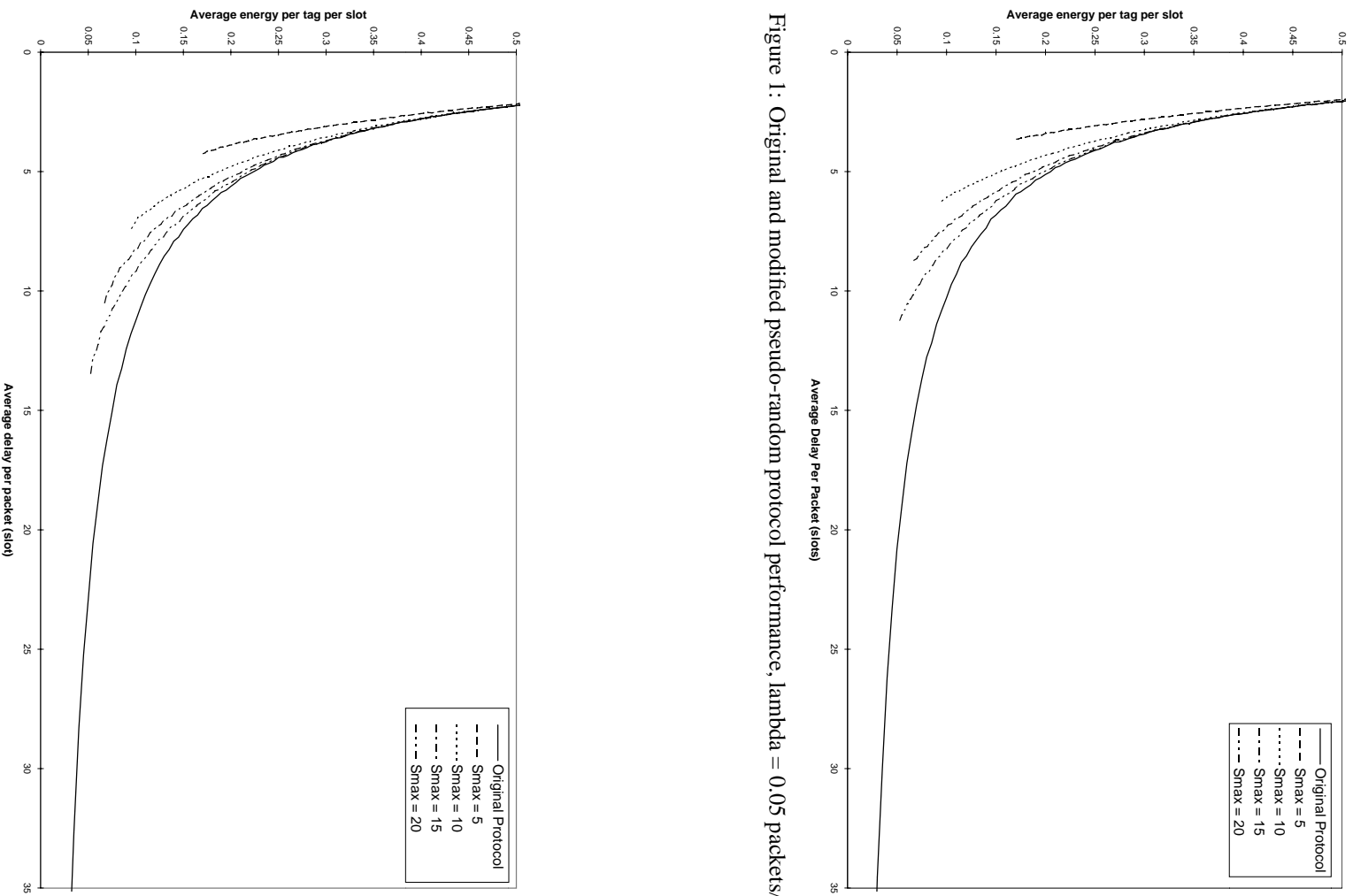


Figure 1 : Original and modified pseudo-random protocol performance,  $\lambda = 0.05$  packets/slot

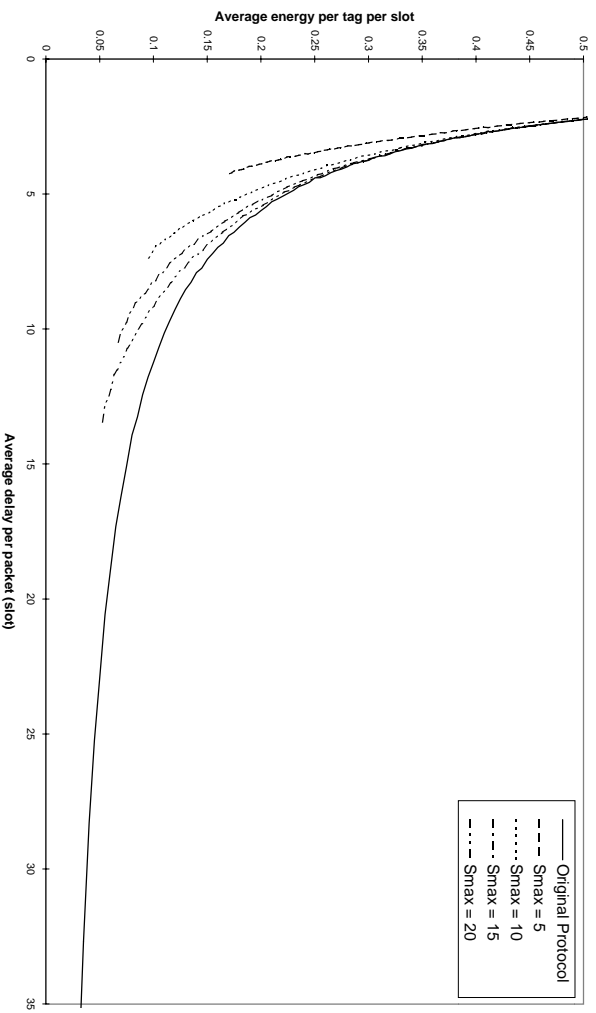


Figure 2: Original and modified pseudo-random protocol performance,  $\lambda = 0.2$  packets/slot

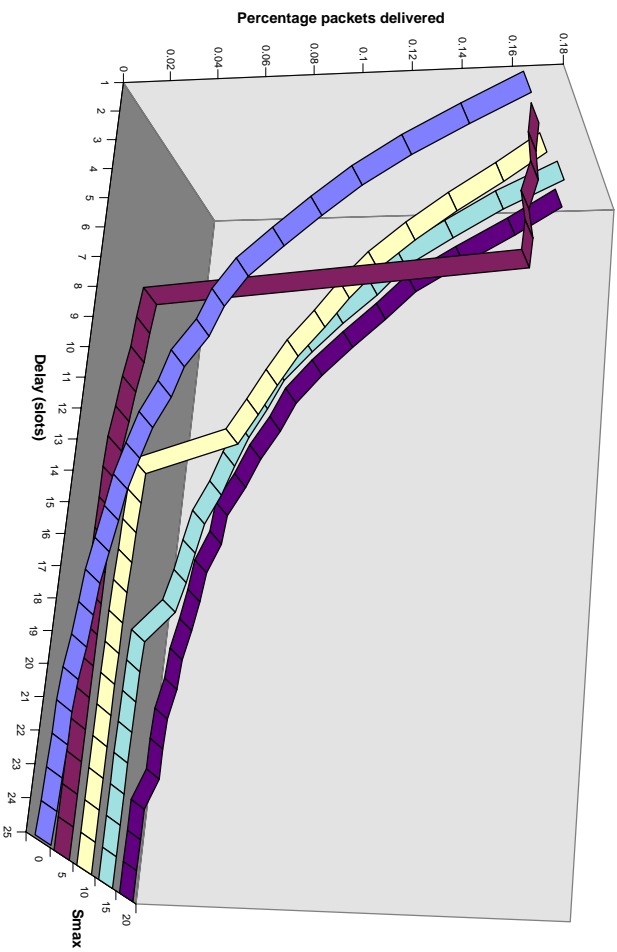


Figure 3: Histogram of delay distributions of the original and modified pseudo-random protocols for energy of 0.17 percent per tag per slot,  $\lambda = 0.05$  packets/slot

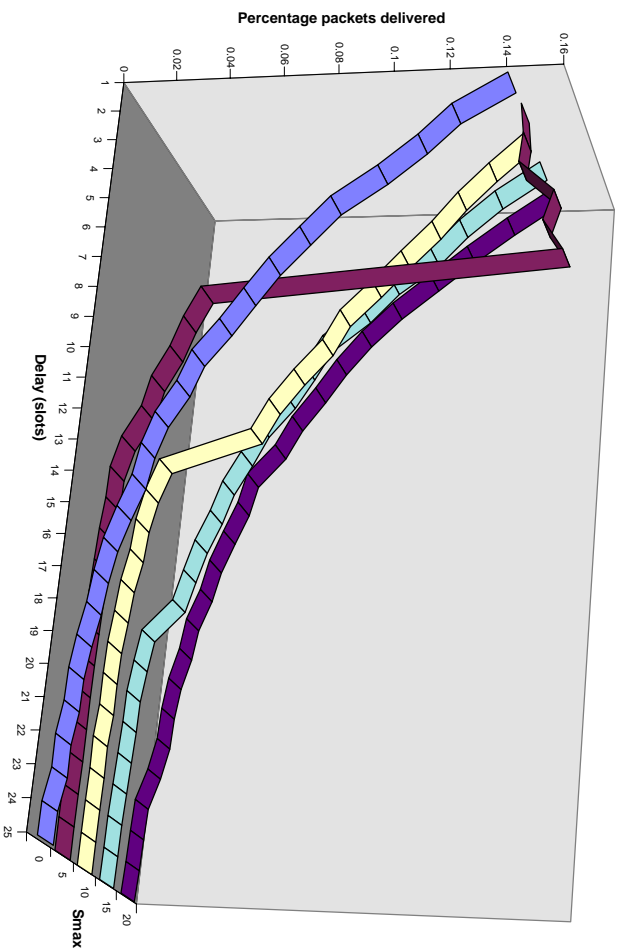


Figure 4: Histogram of delay distributions of the original and modified pseudo-random protocols for energy of 0.17 percent per tag per slot,  $\lambda = 0.2$  packets/slot

be noted that we are using different values for  $p$  for each protocol though all result in the same average energy. It can be seen that the original pseudo-random protocol has a delay distribution which falls off as a slowly decaying exponential curve starting with approximately 14 to 16% of the packets experiencing a 1 slot delay and nearly zero packets experiencing a delay of more than 25 slots. Note that a delay of 1 slot is minimum for our simulation system as we are utilizing slotted packet arrivals such that new packets are added to the queue of available packets at the very end of each slot. The protocol with a value of  $s_{max} = 5$  shows a dramatic improvement over the original protocol. Nearly none of the packets experience more than a 13 slot delay and approximately 90% of the packets experience a less than a 6 slot delay. The other lines of the histogram show how an increase in  $s_{max}$  increases the width of the delay distribution, eventually approximating the original protocol for  $s_{max} = 20$ .

Intuitively, these performance increases can be understood by considering the probability of an individual tag being asleep for a certain number of slots for either protocol. In the original protocol, each tag is asleep for  $j$  consecutive slots with a probability of  $p(1-p)^j$ . This means that, although for  $p = 0.17$  it is expected that on average a tag is only asleep for only 6 slots, there is a 30% probability that a tag will be asleep for greater than 6 slots. On the other hand, in a system with  $s_{max} = 6$ , the probability is zero of a tag being asleep for more than 6 slots for a similar amount of energy expended. Therefore, in the modified pseudo-random protocol we can see a substantial improvement in the delay distribution and any traffic delayed more than  $s_{max}$  slots is due to multiple packets at the base station having tags awake at the same time. Additionally, when using a non-zero value for  $p$ , the modified protocol's wakeup schedules should be uncorrelated to each other enough such that it is a rare case that traffic to one tag regularly conflicts with traffic with another tag. This can also be seen through the histograms.

#### 4. CONCLUSIONS

For many RFID applications, meeting the access delay constraints will be an important part of justifying a business' investment into this new technology. In this paper, we proposed an extension of the pseudo-random energy-conserving access protocol, which maintains the features of flexibility and efficiency of this protocol, while strongly reducing the worst-case delay. In particular, the minimum energy achievable by the extended pseudo-random is lower bounded by a function of the threshold parameter, but the average delay we obtain for a fixed energy-consumption is better than that of the original pseudo-random protocol. The new protocol provides a guarantee on the length of the interval before a tag can be reached, and it was shown that given a moderate packet arrival rate, we are able to substantially reduce the delay experienced by the vast majority of packets, while only adding an ex-

tremely small increase in tag complexity.

#### REFERENCES

- [1] Chlamtac, I. and Petrioli, C. and Redi, J. Energy-Conserving Access Protocols for IDNETs Technical Report 96-006, Boston University.
- [2] Pharmaceuticals picks-up on radio tags. *Control Systems*, 10(7):15–16, July-August 1993.
- [3] Dunn, D. RFID Engine Chugs Onto Scene. *Electronic Buyer's News*, February 5, 1996, pp 14.
- [4] Flynn, L. High-technology dog tags for more than just dogs: Wide uses are seen for radio-id devices. *New York Times*, August 1996.
- [5] Hakanson, W.P. Radio frequency id aids wip data collection. *Robotics World*, 7(3):23–6, May-June 1989.
- [6] Harris, E.P., Depp, S.W., Pence, E., Kirkpatrick, S., Sri-Jayantha, M., and Troutman, R.R. Technology directions for portable computers. *Proceedings of the IEEE*, 83(4):636–58, April 1995.
- [7] Knuth, D. *The Art of Computer Programming: Volume 2 / Seminumerical Algorithms*. Addison-Wesley Publishing Company, 2nd edition, 1981.
- [8] Koelle, A.R., Depp, S.W., and Freyman, R.W. Short-range radio-telemetry for electronic identification, using modulated re backscatter. *Proceedings of the IEEE*, 63(8):1260–1, August 1975.
- [9] Nash, J. Micron communications, inc., announces agreement with the federal aviation administration. *Press release from Micron Technology, also available at <http://www.microncommunications.com/pr/FAA.html>*, August 2 1996.
- [10] Ollivier, M. Rfid-a practical solution for problems you didn't even know you had! In *IEE Colloquium on Wireless Technology (Digest No.1996/199)*, pages 42–3. IEE, November 1996.
- [11] Powers, R.A. Batteries for low power electronics. *Proceedings of the IEEE*, 83(4):687–93, April 1995.
- [12] Townsend, V. Savi's tags track us equipment. *Jane's Defence Weekly*, 23(15):25, April 22 1995.