Transmission control scheme for fast RFID object identification

Christian Floerkemeier
Institute for Pervasive Computing
ETH Zurich
8092 Zurich, Switzerland
floerkem@inf.ethz.ch

Abstract

There are a variety of approaches to improve the speed at which large RFID tag populations are being identified. In this paper, we present a transmission control strategy for a common class of RFID multiple access schemes. It builds on earlier work on Bayesian broadcast strategies, but has been adapted to address characteristics of the RFID domain. It has been designed for framed ALOHA and it makes no restrictive assumptions about the distribution of the number of tags in the range of the interrogator. Experimental evidence and simulation results are presented showing that the proposed transmission control scheme performs well in practise when compared to existing approaches.

1 Introduction

One of the main challenges for any RFID-based application is to maximize the speed with which tagged items can be identified. While traditional RFID applications, such as car immobilizers or animal tagging, usually feature no more than a single tag in the read range of an RFID reader, this will be different once cases and individual items in supply chain and logistics applications are being equipped with passive RFID tags. A gate reader at a dock door in a warehouse will typically have hundreds, if not thousands of tags, in its read range. Since artificially slowing down the loading process or conveyor belt speeds is not desirable from a business perspective, the fast and reliable identification of RFID tags is an important issue.

Approaches to improve the speed at which RFID tags are identified target the physical and medium access control layer of RFID communication protocols. Examples include increased data transfer rates due to more efficient spectrum usage on the physical layer and various different so-called anti-collision algorithms that aim to minimize the time it takes to identify all tags in the range. These RFID anti-collision protocols are usually variants of ALOHA or contention-resolving tree algorithms [2]. In framed ALOHA, which is used in a number of RFID communication protocols [1, 4, 8], the reader begins its interrogation round by announcing the frame size to the tags. Each tag selects one of the available slots at random and transmits a (temporary) identifier. According to [11], the expected throughput U of framed ALOHA with N tags and L slots in a frame is given by:

$$E(U) = \frac{N}{L}\left(1 - \frac{1}{L}\right)^{N-1} \tag{1}$$

The optimum throughput occurs at $L = N$ and is given by e^{-1} for large N. Since the number of tags present is usually not known, the performance of framed ALOHA depends on a transmission scheme that estimates the (unknown) number of tags based on feedback from the reader and chooses a corresponding frame size. This feedback from the reader comprises the number of slots, in which no, a single, and more than one tag replied. The latter is referred to as a collision because the data received by the reader are garbled. The multiplicity of conflict is usually not known.

The main contribution of this paper is such a transmission control strategy for RFID communication protocols based on framed ALOHA. The proposed transmission control scheme builds on earlier work by [9] on Bayesian broadcast strategies, but has been adapted to suit the characteristics of RFID. It has been in particular designed for framed ALOHA. It also makes no assumption about the statistical distribution of the number of tags in the read range. This is important because the number of tags in RFID applications tends to be variable and the traffic is highly correlated rather than caused by many independent point-to-point transmissions - imagine a dock door with the occasional pallet

0-7695-2520-2/06 $20.00 © 2006 IEEE

of more than thousand tagged items moving through. In RFID applications, the arrival and departure rates are influenced by application parameters, e.g., conveyor belt speeds, and RFID system design choices, e.g., in UHF RFID systems tags "disappear" for short periods as they enter a field null and lose power.

The paper is organized as follows: Section 2 presents related work. Our own design for a transmission control scheme is outlined in Section 3, followed by the results from our performance evaluation in Section 4.

2 Related Work

The idea of controlling the ALOHA channel is not new [6]. Work focussing in particular on controlling an ALOHA channel with an additional frame structure has been carried out by Schoute [11] and Wieselthier [15]. Schoute developed a backlog estimation technique for framed ALOHA which is exact under the assumption that the frame size is chosen in such a way that the number of stations which transmit in each time slot is Poisson distributed with mean 1. The backlog after the current frame B_t is then simply given by:

$$B_t = 2.39c \tag{2}$$

where c is the number of collisions in the current frame. Due the unknown distribution of the number of tags, the assumption made by Schoute leads to deviations between the estimate and the true number of tags present, whenever the above assumption is not valid. The comparison with the transmission scheme proposed in this paper, which does not make this simplifying assumption at the expense of additional computations, shows how this restriction affects the performance. Schoute also proposes a method to estimate the conditional probability distribution of collisions and single occupied slots in a frame, given the number of stations and the frame size. While we are using a combinatorial method to estimate the above probability distribution, the scheme in [11] uses a scheme recursive in the number of tags.

In [15], Wieselthier et al. present a performance evaluation of framed ALOHA with capture. Their work is based on the assumption that the number of slots per frame L is fixed and access to the channel can be controlled by adapting the probability with which backlogged stations respond in subsequent frames. In our analysis, the frame size is variable – though limited to powers of two – but all backlogged tags respond in subsequent frames.

More recently, Vogt [14] and Zhen et al. [16] also studied framed ALOHA in the context of RFID. Zhen et al. use the approach proposed by Schoute to estimate the number of tags. Vogt proposes a backlog estimation scheme that selects the tag number estimate that minimizes the error between the observed number of empty, singly-occupied, and collision slots and the expected values. While this approach does not assume a fixed multiplicity of conflict as the scheme proposed by Schoute does, it only considers the observations from the current frame and neglects past evidence. Vogt compares the above estimation algorithm to a estimation strategy that represents a lower bound:

$$B_t = 2c \tag{3}$$

The Q Algorithm defined in [1] represents another transmission control strategy. It keeps a representation of the current frame size which is multiplied by a constant β whenever a collision occurs and which is divided by β whenever an empty slot is detected. While the Q algorithm requires only modest computational resources, it does not specify a method to compute the crucial control parameter β. It only provides a range of suitable values ($1.07 \leq \beta \leq 1.41$).

The work by Rivest [9] is closely related to our work on transmission control strategies for slotted ALOHA. Rivest introduces an elegant pseudo-Bayesian transmission strategy by approximating the probability distribution of the number of tags N with a Poisson distribution. While our transmission scheme builds on the Bayesian approach outlined in [9], our mathematical model has been adapted to suit framed ALOHA and does not assume that the random variable N denoting the number of tags is Poisson distributed. Due to the large number of arriving and departing tags in RFID applications, the Poisson assumption leads to a slow response to changes in the number of tags present. In [3], Frigon et al. present a pseudo-Bayesian algorithm which extends to framed ALOHA and mixed priorities. It also assumes that the number of tags present follow a Poisson distribution.

Krohn et al. [5] recently presented an approach which presents a fast technique to estimate approximately the number of tags present in the read range. Their work is based on the assumption that there are empty slots and occupied slots only.

3 Transmission control strategies for framed ALOHA based RFID protocols

In this section we present a transmission strategy which addresses the shortcomings of the existing approaches mentioned in the previous section. The scheme explicitly models medium access in framed ALOHA and computes the probability that a certain number of tags are present based on the feedback from the reader. It makes no restrictive assumption about the probability distribution of the random variable which represents the number of tags transmitting. It also considers all past observations instead of the observations from the last frame only.

3.1 Bayesian transmission scheme

The individual steps of the broadcast scheme have been adapted from [9] to suit the nature of framed Aloha and RFID:

1. Compute the frame length L based on the current probability distribution of the random variable N that represents the number of tags transmitting.
2. Start frame with L slots and wait for tag replies.
3. Update probability distribution of N based on evidence from the reader at the end of the frame. The evidence comprises the number of empty, singly-occupied, and collision slots in the last frame.
4. Adjust probability distribution N by considering newly arriving tags and departing tags including the ones which successfully replied and do not transmit in subsequent slots.

3.1.1 Computing the optimum frame size

In step 1 of our procedure the optimum frame length is computed, given the probability distribution of N. We choose the frame length L which maximizes the expected throughput U (cf. Eqn. 1). This is computationally feasible because the available frame sizes are limited to powers of 2 in RFID protocols using framed ALOHA [1, 4, 8].

3.1.2 Bayesian Updating of the Probability Distribution

Let H, S, and C denote random variables indicating the number of empty, success (singly-occupied), and collision slots in a single frame with L slots and N tags. After the frame is completed and the feedback in terms of H, S, and C is available, the number of tags that replied is estimated. According to Bayes' rule, the probability that N tags have been transmitting in the frame at time t, given all evidence $z_{1:t}$ including the one from the past frame is then given by

$$\begin{aligned} Pr(N|z_{1:t}) &= \alpha Pr(N|z_{1:t-1}) \cdot Pr(z_t|N) \qquad (4) \\ &= \alpha Pr(N|z_{1:t-1}) \cdot Pr(H,S,C|N) \end{aligned}$$

where α is a normalizing constant. The likelihood $Pr(H,S,C|N)$ is given by

$$\begin{aligned} Pr(H,S,C|N) &= Pr(S,C|N) \qquad (5) \\ &= Pr(S|C,N) \cdot Pr(C|N) \qquad (6) \end{aligned}$$

3.1.3 Computing the conditional probability distributions $Pr(C|N)$ and $Pr(S|C,N)$

Let A_i denote the event that no or a single tag replied in slot i. The probability that no or only a single tag replied in slots $1, 2, ..k$ is then given by

$$Pr(\bigcap_{i=1}^{k} A_i) = L^{-N} \sum_{j=0}^{k} \binom{k}{j} \binom{N}{j} j!(L-k)^{N-j} \qquad (7)$$

Using the inclusion-exclusion principle [13] to find the probability $Pr(M = m|N)$ that the tags select a slot with exactly m slots being empty or singly-occupied we have that

$$Pr(M = m|N) = \sum_{k=m}^{L} \binom{k}{m} (-1)^{m+k} \binom{L}{k} Pr(\bigcap_{i=1}^{k} A_i) \qquad (8)$$

The probability that c collisions occurred in a frame with L slots and N tags, $Pr(C = c|N)$, is then simply given by

$$\begin{aligned} Pr(C = c|N) &= Pr(M = \overline{c}|N) \qquad (9) \\ &= L^{-N} \sum_{k=\overline{c}}^{L} \binom{k}{\overline{c}} (-1)^{\overline{c}+k} \binom{L}{k} \qquad (10) \\ &\quad \cdot \sum_{j=0}^{k} \binom{k}{j} \binom{N}{j} j!(L-k)^{N-j} \end{aligned}$$

where $\overline{c} = L - c$. It remains to determine $Pr(S|C,N)$. The number of ways that $2c + i$ tags are involved in c collisions is given by

$$D(C = c, I = i) = \binom{N-2c}{i} c^{i} \frac{(L-c)!}{(L-c-(N-2c-i))!} \qquad (11)$$

where I denotes a random variable which represents the number of tags involved in c collisions in addition to the "mandatory" $2c$ tags. It follows that

$$Pr(S = s|C = c, N) = \frac{D(C = c, I = N-2c-s)}{\sum_{k=0}^{N-2c} D(C = c, I = k)} \qquad (12)$$

3.1.4 Modelling newly arriving and departing tags

Once the posterior tag number distribution $Pr(N_t|z_{1:t})$ is calculated, we still need to incorporate the successful transmissions of the last frame. This only applies to RFID protocols where tags transition to a quiet state after successful identification. Under these circumstances, successful transmissions result in a reduction in tags which reply in the next frame. This means that we simply need to drop the first s entries of the posterior tag distribution in order to compute $Pr(N_{t+1} = n|z_{1:t})$:

$$Pr(N_{t+1} = n|z_{1:t}) = Pr(N_t = (n+s)|z_{1:t}) \quad (13)$$

The number of tags that transmit their ID in the next frame can also change because new tags arrived and others disappeared during the last frame. The exact probability distribution of newly arriving and departing tags, $P_A(n)$ and $P_D(n)$, depends on the application characteristics and technology parameters as mentioned earlier. We will consider two extreme cases. If a number of tags are placed within the range of an reader and no tags are removed or added, until all tags are identified, there is no need to update the probability distribution at all. On the other hand, there are scenarios where tags continuously move through the range of the reader. Here, new tags arrive because they leave a deep fade or are powered for the first time; some tags depart because they lose power as they enter a deep fade or disappear from the vicinity of the reader all together. We can compute the probabilities for N'_{t+1} then as:

$$\begin{aligned} Pr(N'_{t+1} = n) \;&=\; \sum_{j=0}^{n} Pr(N_{t+1} = j) P_A(n-j) \quad (14) \\ &+ \sum_{j=n+1}^{n_{max}} Pr(N_{t+1} = j) P_D(j-n) \end{aligned}$$

where the conditioning evidence $z_{1:t}$ is omitted.

4 Evaluation

In this section we evaluate the transmission control scheme outlined in the previous section. Figure 1 shows the results of an experimental evaluation. 64 HF Philips I-Code1 [8] tags are placed in the read range of an RFID reader made by Softronica [12]. The figure shows the variation of the estimate as a function of traffic. It compares the algorithm proposed by Schoute (cf. Eqn. 2), by Vogt, the lower bound estimate (cf. Eqn. 3), and our Bayesian scheme. To evaluate the transmission strategies in different traffic scenarios, we used five different frame sizes $(16, 32, 64, 128, 256)$. The different traffic rates shown in Figure 1 correspond to the ratio of the fixed number of tags to the frame size. The results illustrate how the Bayesian transmission scheme exhibits superior performance under the various traffic rates evaluated. It dynamically adjusts the multiplicity of conflict, whereas the multiplicity of conflict in the schemes proposed by Schoute and the lower bound estimate is fixed at 2.39 and 2, respectively. The more accurate estimate translates into a higher throughput in the subsequent frame. Based on the estimated number of tags, the Bayesian algorithm chooses a frame with 64 slots, while the other two schemes choose a frame with 32 slots assuming a traffic rate of 4. This corresponds to an expected throughput increase of 37% for the Bayesian scheme over the other two in this particular case (cf. Eqn. 1). The algorithm proposed by Vogt also provides a reasonable estimate, but shows greater variance. The variance of the Bayesian scheme is further decreased by including the information from past frames, which is not possible with the scheme proposed by Vogt. However, the throughput improvement mentioned is unlikely to occur over a complete identification cycle (cf. Figure 2(a) and 2(b)). The figures show the simulation results of the identification of a tag population of 500 tags with no arriving and departing tags except for the ones that are successfully identified. Three different scenarios are considered: the lower bound scheme (cf. Figure 2(a)) and the Bayesian scheme – with capture feedback (cf. Figure 2(b)) and without (cf. Figure 2(c)). Each of the subfigures shows the evolution of the true number of tags, the estimated number of tags, the chosen frame size, and the throughput. Note that the x-axis does not correspond to the time it takes to identify the tag population, but to the number of frames, which can vary in size. The Bayesian scheme can achieve a high throughput already after the

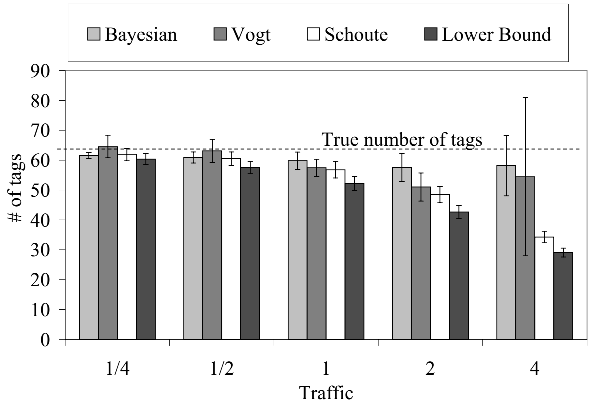
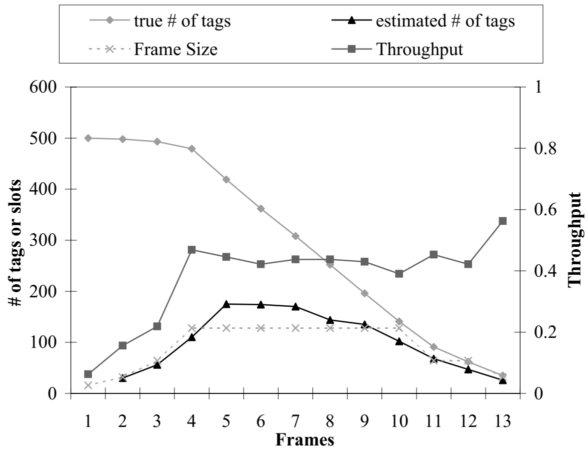
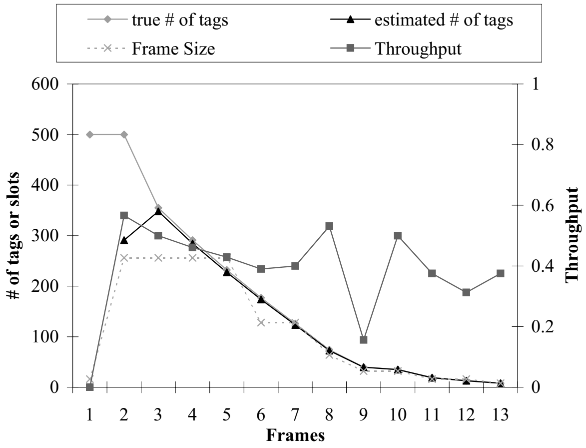


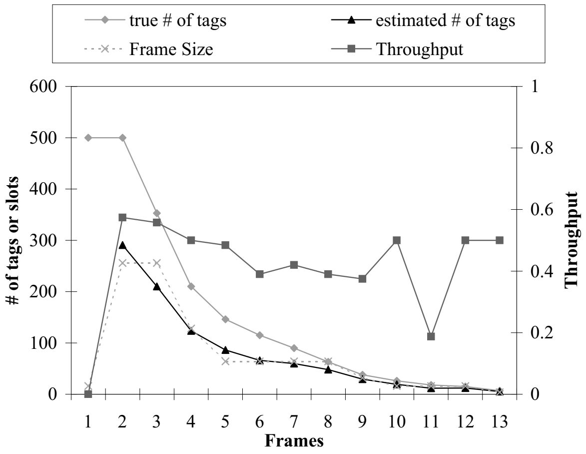
Figure 1. Experimental evaluation using 64 HF Philips I-Code1 Tags. The Bayesian approach is compared to scheme of Schoute, Vogt and the lower bound estimate.



(a) Algorithm based on lower bound estimate



(b) Bayesian algorithm with capture feedback



(c) Bayesian algorithm without capture feedback

Figure 2. Evolution of tag estimates, frame sizes, and throughput as the identification of 500 tags is simulated.

second frame because it provides a good estimate also at high traffic rates. The throughput of the Bayesian scheme is only superior in the early frames, however. Once there is an accurate estimate and the corresponding average traffic is close to 1, there is little difference in performance between the Bayesian transmission control strategy and the lower bound estimate.

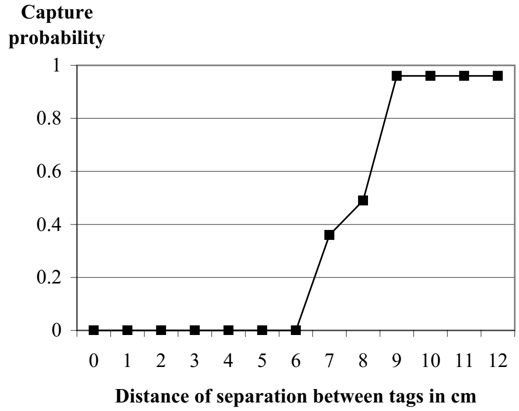


Figure 3. Experimental evidence of the capture effect: Two HF tags are forced to reply in the same slot. As the difference in received signal strength increases, the reader can capture the reply from the tag in close proximity.

The throughput in the simulations exceeds the theoretical maximum of e^{-1}. This is a result of the capture effect. The capture effect refers to the ability to receive a tag reply correctly, despite the presence of other tag replies transmitted simultaneously [10]. The experimental results shown in Figure 3 indicate that there will also be captured tag replies in inductively coupled RFID systems, if the difference in received signal strength is large enough. Although some RFID systems can distinguish a captured reply from a single reply under some conditions as shown in [7], we have to assume that the reader provides feedback without capture in most cases. The comparison of the simulation of feedback with capture and without capture (cf. Figure 2(b) and 2(c)) illustrates that our Bayesian algorithm will underestimate the true number of tags, if there is capture, but the reader cannot detect the presence of weak tag replies. The influence on the throughput is small because the underestimate is compensated by not including the capture effect in the computation of the expected throughput. It is straightforward to include feedback with capture in our transmission scheme. In Eqn. 10 and 12 captured replies are considered collisions; in Eqn. 13 captured replies are considered successful transmissions. Eqn. 1 also needs to be updated to include the estimated capture probability. In the experiment shown in Figure 1 we tried to eliminate the capture effect by minimizing the distance of separation between the different labels.

5 Conclusion

Fast identification of large tag populations represents a challenge for RFID systems. While physical layer parameters, such as data transfer rate, have a strong influence on the overall identification speed, the identification rate also depends on an appropriate transmission control strategy that controls access to the broadcast channel. In this paper, we present such a transmission control strategy for a common class of RFID anti-collision protocols based on a variant of ALOHA, called framed ALOHA. The proposed transmission control scheme builds on earlier work on Bayesian broadcast strategies, but has been adapted to suit the characteristics of RFID. It has been in particular designed for framed ALOHA. It also makes no assumption about the statistical distribution of the number of tags that replied and considers all past observations. Experimental evidence and simulation results show that the Bayesian broadcast scheme provides high throughput values even in the presence of capture and under high traffic rates, at which other approaches fail to estimate the true number of tags present accurately or show greater variance. The superior performance comes at the expense of significantly increased computational load. While some of the probability distributions can be computed a priori and stored in memory, the computational effort and/or memory space required remains an issue as the number of tags and frame sizes increases. The scheme proposed by Vogt represents thus the better trade-off between performance and computational resources required. In our experiments we also benefited from high signal-to-noise ratios. In other environments, the identification speed is also increasingly affected by transmission errors on the communication channel. Our approach requires at least one complete frame to estimate the number of tags present. Future work should focus on the development of a transmission scheme which estimates the number of tags present on a slot-by-slot basis and interrupts the running frame, when the current frame size is found to be suboptimal.

Acknowledgements

The author would like to thank Patrick Leuthold and Matthias Wille for their help with the implementation of the computational models and the simulation engine.

References

[1] EPCglobal. Class 1 Generation 2 UHF Air Interface Protocol Standard Version 1.0.9, 2005.

[2] K. Finkenzeller. *RFID Handbook: Radio-Frequency Identification Fundamentals and Applications.* John Wiley & Sons, 2000.

[3] J.-F. Frigon and V. C. M. Leung. A Pseudo-Bayesian ALOHA algorithm with mixed priorities. *Wireless Networks*, 7(1):55–63, 2001.

[4] International Organization for Standardization. ISO/IEC 18000 Part 6: Information technology automatic identification and data capture techniques - Radio frequency identification for item management air interface, 2003.

[5] A. Krohn, T. Zimmer, M. Beigl, and C. Decker. Collaborative Sensing in a Retail Store Using Synchronous Distributed Jam Signalling. In H. W. Gellersen, R. Want, and A. Schmidt, editors, *Third International Conference, PERVASIVE 2005*, volume 3468 of *Lecture Notes in Computer Science*, pages 237–254, Munich, May 2005. Springer-Verlag.

[6] S. Lam and L. Kleinrock. Packet switching in a multi-access broadcast channel: Dynamic control procedures. *IEEE Trans. Commun.*, COM-23, 1975.

[7] Philips Semiconductor. I-CODE1 System Design Guide, May 2002.

[8] Philips Semiconductor. I-CODE1 Label ICs Protocol Air Interface Datasheet, January 2005.

[9] R. L. Rivest. Network Control by Bayesian Broadcast. *IEEE Transactions on Information Theory*, IT-33(3):323–328, May 1987.

[10] L. Roberts. ALOHA packet system with and without slots and capture. *Computer Communication Revue*, 5(2):28–42, 1975.

[11] F. C. Schoute. Dynamic Frame Length ALOHA. *IEEE Transactions on Communications*, COM-31(4):565–568, Apr 1983.

[12] Softronica. RIDEL5000 Long Range ICODE Reader/Encoder, July 2000.

[13] W. Szpankowski. *Average Case Analysis of Algorithms on Sequences.* Wiley, 2001.

[14] H. Vogt. Efficient Object Identification with Passive RFID Tags. In F. Mattern and M. Naghshineh, editors, *First International Conference, PERVASIVE 2002*, volume 2414 of *Lecture Notes in Computer Science*, pages 98–113, Zurich, August 2002. Springer-Verlag.

[15] J. E. Wieselthier, A. Ephremides, and L. A. Michaels. An Exact Analysis and Performance Evaluation of Framed ALOHA with Capture. *IEEE Transactions on Communications*, COM-37(2):125–137, 1989.

[16] B. Zhen, M. Kobayashi, and M. Shimizu. Framed ALOHA for Multiple RFID Objects Identification. *IEICE Transaction on Communications*, E88-B(3):991–999, March 2005.