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BROWN UNIV PROVIDENCE RI DIV OF APPLIED MATHEMATICS F/6 12/1  
AVERAGING METHODS FOR THE ASYMPTOTIC ANALYSIS OF LEARNING AND A--ETC (11)  
JUN 80 H J KUSHNER, H HUANG N00014-76-C-0279

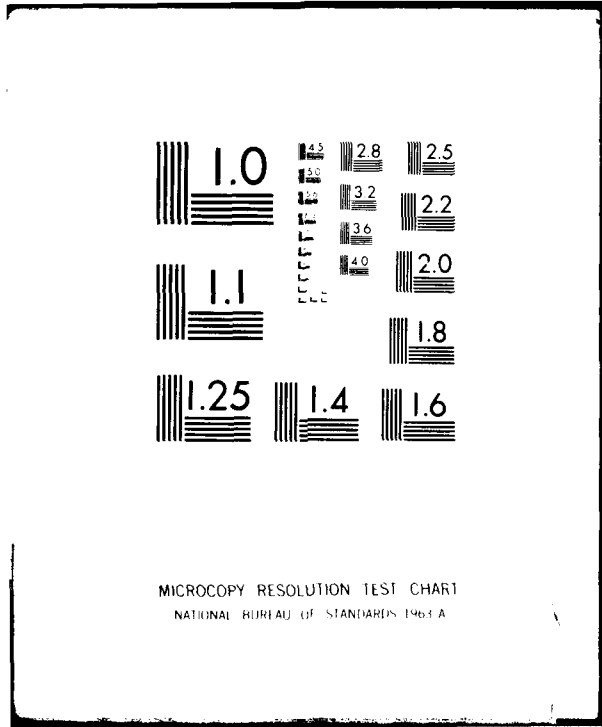
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1. REPORT NUMBER <b>AFOSR/TR-80-0574</b>		2. GOVT ACCESSION NO. <b>AD-A088110</b>	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) <b>AVERAGING METHODS FOR THE ASYMPTOTIC ANALYSIS OF LEARNING AND ADAPTIVE SYSTEMS, WITH SMALL ADJUSTMENT RATE</b>		5. TYPE OF REPORT & PERIOD COVERED <b>Interim</b>	
7. AUTHOR(s) <b>H. J./Kushner Hai/Huang</b>		8. CONTRACT OR GRANT NUMBER(s) <b>AFOSR-76-3092</b>	
9. PERFORMING ORGANIZATION NAME AND ADDRESS <b>Brown University Division of Applied Mathematics, Providence, RI 02912</b>		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS <b>61102F 2304/A4</b>	
11. CONTROLLING OFFICE NAME AND ADDRESS <b>Air Force Office of Scientific Research/NM Boiling AFB, Washington, DC 20332</b>		12. REPORT DATE <b>June 1980</b>	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) <b>12/39</b>		13. NUMBER OF PAGES <b>37</b>	
		15. SECURITY CLASS. (of this report) <b>UNCLASSIFIED</b>	
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	

16. DISTRIBUTION STATEMENT (of this Report)  
**Approved for public release; distribution unlimited.**

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)  
**DTIC ELECTED AUG 15 1980**

18. SUPPLEMENTARY NOTES  
**E**

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)  
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AVERAGING METHODS FOR THE ASYMPTOTIC ANALYSIS  
OF LEARNING AND ADAPTIVE SYSTEMS, WITH SMALL ADJUSTMENT RATE

H. J. Kushner\*

Hai Huang\*\*

Abstract

Recently proved theorems concerning weak convergence of non-Markovian processes to diffusions, together with an averaging and a stability method, are applied to two (learning or adaptive) processes of current interest: (1) an automata model for route selection in telephone traffic routing, (2) an adaptive quantizer for use in the transmission of random signals in communication theory. The models are chosen because they are prototypes of a large class to which the methods can be applied. The technique of application of the basic theorems to such processes is developed. Suitably interpolated and normalized "learning or adaptive" processes converge weakly to a diffusion, as the "learning or adaptation" rate goes to zero. For small learning rate, the qualitative properties (e.g., asymptotic (large-time) variances and parametric dependence) of the processes can be determined from the properties of the limit.

*AFOSR-76-3092*

\*Divisions of Applied Mathematics and Engineering, Brown University, Providence, R.I. 02912. This research was supported by the Air Force Office of Scientific Research ██████████, the National Science Foundation (Eng. 77-12946), and the Office of Naval Research (N00014-76-C-0279-P003).

\*\*Division of Applied Mathematics, Brown University, Providence, R.I. 02912. This research was supported by the National Science Foundation (Eng. 77-12946) and the Office of Naval Research (N00014-76-C-0279-P003).

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I. INTRODUCTION

References [7], [1] develop a useful method to study the asymptotic properties as  $\epsilon \rightarrow 0$  and  $n\epsilon \leq T < \infty$  for any real  $T$  of solutions to stochastic difference equations of the form

$$(1.1) \quad Y_{n+1}^{\epsilon} = Y_n^{\epsilon} + \epsilon h_{\epsilon}(Y_n^{\epsilon}, \xi_n^{\epsilon}) + \sqrt{\epsilon} g_{\epsilon}(Y_n^{\epsilon}, \xi_n^{\epsilon}) + o(\epsilon), \quad Y_n^{\epsilon} \in R^r,$$

where the distributions of the random sequence  $\{\xi_n^{\epsilon}\}$  might depend on the  $\{Y_n^{\epsilon}\}$ . Such equations occur frequently in applications. The methods in [1] also work when  $\epsilon$  is replaced by a sequence  $\epsilon_n \rightarrow 0$  as  $n \rightarrow \infty$  from which asymptotic properties (rates of convergence) of various forms of stochastic approximations can be obtained.

The emphasis in [1] (an application of [7]) concerned the case where the  $h_{\epsilon}$  and  $g_{\epsilon}$  are smooth, and no details for the non-smooth case or its applications were given, nor was the asymptotic case where  $n \rightarrow \infty$ , then  $\epsilon \rightarrow 0$  treated. This is a deficiency, since in many applications in communication, control and automata theory, the  $h_{\epsilon}$  and  $g_{\epsilon}$  might simply be indicator functions and the noise  $\{\xi_n^{\epsilon}\}$  depend on  $\{Y_n^{\epsilon}\}$ , and the asymptotic properties (as  $n \rightarrow \infty$ , then  $\epsilon \rightarrow 0$ ) desired. Here, we apply the basic results of [7] to two such problems. The two problems have current technological importance in their own right and each has been the subject of a great deal of work. Our method often yields a complete analysis of the asymptotic properties under realistic conditions. The two problems are typical of a wide class, and they illustrate the power and applicability of the general technique, as well as the method of applying it to concrete problems. In a sense the method is an extension with more complex memory structure of the sort of "slow learning" results obtained by Norman [9], and should have broad applications to the areas cited above.

The basic type of result is the following. Define  $Y^\epsilon(\cdot)$ ,  $t \in [0, \infty)$ , by  $Y^\epsilon(0) = Y_0^\epsilon$  and  $Y^\epsilon(t) = Y_i^\epsilon$  on  $[i\epsilon, (i+1)\epsilon)$ . Under appropriate conditions, Theorem 1 gives weak convergence of  $\{Y^\epsilon(\cdot)\}$  in  $D^X[0, \infty)$  to a particular diffusion process, as  $\epsilon \rightarrow 0$ . Now, let  $\{n_\epsilon\}$  denote a sequence of integers tending to  $\infty$  as  $\epsilon \rightarrow 0$ . For  $t \geq 0$ , define  $\tilde{Y}^\epsilon(t) = Y^\epsilon(t + n_\epsilon)$ . The tilde  $\tilde{\cdot}$  always denotes a shift by  $n_\epsilon$  (discrete parameter) or  $\epsilon n_\epsilon$  (continuous parameter). By using Theorem 1 but starting  $\{Y_n^\epsilon\}$  at time  $n_\epsilon$  instead of at time 0, we will get a great deal of information on the asymptotic properties (large  $n$ , small  $\epsilon$ ). The next section gives some background material from [7]. Sections III to VI treat a learning automata approach to certain problems in adaptive routing of telephone calls [2]-[3]. The second problem, in Sections VII-VIII, concerns the asymptotic theory of an adaptive quantizer from communications applications [4], [5].

II. SOME BACKGROUND MATERIAL

$D^{\mathbb{R}}[0, \infty)$  denotes the space of  $\mathbb{R}^{\mathbb{R}}$ -valued functions on  $[0, \infty)$  which are right-continuous and have left-hand limits, and is endowed with the Skorokhod topology [6].  $\mathcal{C}_0^{\hat{}}$  denotes the continuous functions on  $\mathbb{R}^{\mathbb{R}} \times [0, \infty)$  with compact support and  $\mathcal{C}_0^{\alpha, \beta}$  the subset whose mixed partial derivatives up to order  $\alpha$  in  $t$  and  $\beta$  in the components of  $x$  are continuous. Let  $b_i(\cdot, \cdot)$ ,  $a_{ij}(\cdot, \cdot)$ ,  $i, j \leq r$ , be continuous functions on  $\mathbb{R}^{\mathbb{R}} \times [0, \infty)$ . Let the operator

$$A = \sum_i b_i(x, t) \frac{\partial}{\partial x_i} + \frac{1}{2} \sum_{i, j} a_{ij}(x, t) \frac{\partial^2}{\partial x_i \partial x_j}$$

be the infinitesimal operator of a diffusion process  $X(\cdot)$ . Assume that the solution to the martingale problem (on  $D^{\mathbb{R}}[0, \infty)$ ) of Strook and Varadhan [8] corresponding to  $A$  has a unique non-explosive solution for each initial condition.

Let  $b_N(\cdot)$  denote a function with values in  $[0, 1]$ , equal to 1 on  $S_N = \{x: |x| \leq N\}$ , equal to zero in  $\mathbb{R}^{\mathbb{R}} - S_{N+1}$  and with second derivatives bounded uniformly in  $x$  and  $N$ . Define  $\{Y_n^{\epsilon, N}, n \geq 0\}$  by

$$(2.1) \quad Y_{n+1}^{\epsilon, N} = Y_n^{\epsilon, N} + [\text{ch}_{\epsilon}(Y_n^{\epsilon, N}, \xi_n^{\epsilon}) + \sqrt{\epsilon} g_{\epsilon}(Y_n^{\epsilon, N}, \xi_n^{\epsilon}) + o(\epsilon)] b_N(Y_n^{\epsilon, N}),$$

$$Y_0^{\epsilon, N} = Y_0^{\epsilon} \text{ if } |Y_0^{\epsilon}| \leq N \text{ and is zero otherwise,}$$

and define  $Y^{\epsilon, N}(\cdot)$  analogously to  $Y^{\epsilon}(\cdot)$ . For purely technical reasons, it is convenient to state the theorem in terms of  $\{Y_n^{\epsilon, N}\}$ . Let  $A^N$  be the infinitesimal operator of a (not necessarily unique) diffusion process, denoted by  $X^N(\cdot)$ , and suppose that its coefficients  $a_N(\cdot, \cdot)$ ,  $b_N(\cdot, \cdot)$  are continuous, bounded,



have compact support and equal  $a(\cdot, \cdot), b(\cdot, \cdot)$  in  $S_N$ . Suppose that  $\{Y^{\epsilon, N}(\cdot)\}$  converges weakly to some such  $X^N(\cdot)$  as  $\epsilon \rightarrow 0$ , for each  $N$ . Then [7]  $\{Y^{\epsilon, N}(\cdot)\}$  converges weakly to  $X(\cdot)$  as  $n \rightarrow \infty$ . The following theorem is a restatement of Theorem 3 of [7] with  $\tau_{\epsilon} = \epsilon$ . Theorem 2 of [7] provides a very convenient method of proving tightness, and we will use it in the sequel. Let  $E_n^{\epsilon, N}$  denote expectation conditioned on  $\{Y_j^{\epsilon, N}, j \leq n, \xi_j^{\epsilon}, j < n\}$ .

Theorem 1. Assume the conditions stated above on the solution to the martingale problem on  $D^X[0, \infty)$  corresponding to operator  $A$ , and on  $A^N$  and  $X^N(\cdot)$ . For each  $N$ , and  $f(\cdot, \cdot) \in \mathcal{D}$ , a dense set (sup norm) in  $\mathcal{C}_0^1$ , let there be a sequence  $\{f^{\epsilon, N}(\cdot)\}$  satisfying the following conditions: it is constant on each interval  $[n\epsilon, n\epsilon + \epsilon)$ , at  $n\epsilon$  it is measurable with respect to the  $\sigma$ -algebra induced by  $\{Y_j^{\epsilon, N}, j \leq n, \xi_j^{\epsilon}, j < n\}$  and

$$(2.2) \quad \sup_{n, \epsilon} E |f^{\epsilon, N}(n\epsilon)| + \sup_{n, \epsilon} \frac{1}{\epsilon} E |E_n^{\epsilon, N} f^{\epsilon, N}(n\epsilon + \epsilon) - f^{\epsilon, N}(n\epsilon)| < \infty,$$

and as  $\epsilon \rightarrow 0$  and for each  $t$  as  $n\epsilon \rightarrow t$ ,

$$(2.3) \quad E |f^{\epsilon, N}(n\epsilon) - f(Y_n^{\epsilon, N}, n\epsilon)| \rightarrow 0,$$

$$(2.4) \quad E \left| \frac{E_n^{\epsilon, N} f^{\epsilon, N}(n\epsilon + \epsilon) - f^{\epsilon, N}(n\epsilon)}{\epsilon} - \left( \frac{\partial}{\partial t} + A^N \right) f(Y_n^{\epsilon, N}, n\epsilon) \right| \rightarrow 0.$$

Then, if  $\{Y^{\epsilon, N}(\cdot), \epsilon_0 > \epsilon > 0\}$  is tight in  $D^X[0, \infty)$  for each  $N$ , where  $\epsilon_0$  does not depend on  $N$  and  $Y^{\epsilon}(0)$  converges weakly to  $X(0)$ ,  $\{Y^{\epsilon}(\cdot)\}$  converges weakly to  $X(\cdot)$ , the unique solution to the martingale problem with initial condition  $X(0)$ .

### III. AN AUTOMATA PROBLEM - INTRODUCTION

Narendra [2], [3] and others have studied the application of automata and learning theory to problems in the routing of telephone calls through a multi-node network and have suggested a variety of interesting automata models for this application. Under various assumptions (both explicit and implicit) they have stated convergence results in a number of cases. Generally, their results are applications of Norman's [9] results on slow learning. Here, we take one of their models and show how to apply Theorem 1 to get a much more complete asymptotic theory (large time) for small rate of change of the automata behavior ( $\epsilon$ ), and under more realistic conditions. The case dealt with here can readily be generalized - as will be commented on below. The example illustrates the power and usefulness of the approximation techniques used here. The algorithm should be considered as a prototype. It might not be the best, but it well serves to illustrate the method.

The problem formulation. Calls arrive at a transmitting or switching terminal at random at discrete time instants  $n = 0, 1, 2, \dots$ , with  $P\{\text{one call arrives at } n\text{th instant}\} = \mu$ ,  $\mu \in (0, 1)$ ,  $P\{>1 \text{ call arrives at } n\text{th instant}\} = 0$ . From the terminal, there are two possible routings to the destination, route 1 and route 2, the  $i$ th route having  $N_i$  independent lines - and can thus handle up to  $N_i$  calls simultaneously. Let  $[n, n+1)$  denote the  $n$ th interval of time. The duration of each call is a random variable with a geometric distribution:  $P\{\text{call completed in the } (n+1)\text{st interval} \mid \text{uncompleted at end of } n\text{th interval, route } i \text{ used}\} = \lambda_i$ ,  $\lambda_i \in (0, 1)$ . The members of the double sequence of the interarrival times and call durations are mutually independent. It is possible to work with more general Markovian arrival processes, but we retain a simple structure in order to emphasize the main points. In practice, a more complex

network would occur - and perhaps cycles might exist, and a vector routing parameter would be used, one component per node. But the main idea is similar. As in Theorem 4, the average dynamics are used for the stability analysis. From that point on, the proof of the appropriate generalization of Theorem 5 would be quite similar to the proof of Theorem 5.

The parameter  $\epsilon$  will be used for the rate of adjustment of the routing automaton - the device which selects the route. The adjustment mechanism will be defined later. The routing automaton operates as follows. For each fixed  $\epsilon$ , let  $\{y_n^\epsilon\}$  denote a sequence of random variables - with values in  $[0,1]$ . In order to have an unambiguous sequencing of events, suppose that the calls terminating in the  $n$ th interval actually terminate at time  $n + \frac{1}{2}$ , and arrivals and route assignments are at the instants  $0, 1, 2, \dots$  precisely. Thus the state at time  $(n+1)^-$  does not include the calls just terminated or calls arriving at  $(n+1)$ . Define the "route occupancy process"  $X_n^\epsilon = (X_n^{\epsilon,1}, X_n^{\epsilon,2})$ , where  $X_n^{\epsilon,i}$  is the number of lines of route  $i$  occupied at time  $n^+$ . Thus,  $X_n^{\epsilon,i} \leq N_i$ . If a call arrives at instant  $n+1$ , the automaton "flips a coin", and chooses route 1 with probability  $y_n^\epsilon$  and chooses route 2 with probability  $(1-y_n^\epsilon)$ . If all lines of the chosen route  $i$  are occupied at instant  $(n+1)^-$ , then the call is switched to route  $j$  ( $j \neq i$ ). If all lines of route  $j$  are also occupied at instant  $(n+1)^-$ , then the call is rejected, and disappears from the system.

In a more realistic situation, the network would have many nodes - not simply 2, and many possibilities of routing from node to node. The adjustment algorithm might be different, but the problem would be handled in exactly the same way. The object is to adjust the  $\{y_n^\epsilon\}$  sequentially (based on the system behavior) so that some desired behavior occurs. In order to be specific, we use the following "linear-reward" algorithm [3]. Let  $J_{in}^\epsilon$  denote the indicator

of the event {call arrives at  $n+1$ , is assigned first to route  $i$  and is accepted by route  $i$ }. For practical as well as theoretical purposes, it is important to bound  $y_n^\epsilon$  away from the points 0 and 1. Let  $0 < y_l < y_u < 1$ . We use the algorithm (3.1), where  $\left|_{y_l}^{y_u}$  denotes truncation at  $y_u$  or  $y_l$ , and  $\alpha(y) = 1-y$ ,  $\beta(y) = -y$ .

$$(3.1) \quad y_{n+1}^\epsilon = [y_n^\epsilon + \epsilon \alpha(y_n^\epsilon) J_{1n}^\epsilon + \epsilon \beta(y_n^\epsilon) J_{2n}^\epsilon] \left|_{y_l}^{y_u}.$$

Define  $\alpha_\epsilon(\cdot)$ ,  $\beta_\epsilon(\cdot)$  such that  $\alpha_\epsilon(\cdot) = \alpha_\epsilon(\cdot)$  in  $[y_l, y_u - \epsilon]$  and  $\beta_\epsilon(\cdot) = \beta_\epsilon(\cdot)$  in  $[y_l + \epsilon, y_u]$  and otherwise are such that (3.2) is equivalent to (3.1):

$$(3.2) \quad y_{n+1}^\epsilon = y_n^\epsilon + \epsilon [\alpha_\epsilon(y_n^\epsilon) J_{1n}^\epsilon + \beta_\epsilon(y_n^\epsilon) J_{2n}^\epsilon].$$

We will study the asymptotics of the behavior of a centered and normalized  $\{y_n^\epsilon\}$  for small  $\epsilon$ . Part of the difficulty, which our scheme is well able to handle, is due to the fact that  $\{y_n^\epsilon\}$  is not Markovian. In the theoretical parts of [2], [3], the problem is set up so that  $\{y_n^\epsilon\}$  is Markovian.

Some definitions. If the choice probabilities  $y_n^\epsilon$  are held fixed at some value  $y$  for all  $n$ , then the route choice automaton still makes sense, although there is no learning. For fixed route selection probability  $y \in (0,1)$ , let  $\{X_n(y)\} = \{X_n^1(y), X_n^2(y)\}$ ,  $0 \leq n < \infty$  denote the corresponding route occupancy process. For the process  $\{X_n(y)\}$ , the state space  $Z = \{(i,j) : i \leq N_1, j \leq N_2\}$  (whose points are supposed ordered in some fixed way) is a single ergodic class, and the

probability transition matrix, denoted by  $A'(y)$ , has infinitely differentiable components. With given initial condition  $\{P\{X_0(y)=\alpha\}, \alpha \in Z\}$  define  $P_n(\alpha|y) = P\{X_n(y)=\alpha\}$  and the vector  $P_n(y) = \{P_n(\alpha|y), \alpha \in Z\}$ . Then

$$(3.3) \quad P_{n+1}(y) = A(y)P_n(y).$$

The pair  $\{(X_n^E, y_n^E), n \geq 0\}$  is a Markov process on  $Z \times [y_v, y_u]$  and the marginal transition probability  $P\{X_{n+1}^E=(k, \ell) | X_n^E=(i, j), y_n^E\}$  is just the  $((i, j)$ -column,  $(k, \ell)$ -row) entry of  $A'(y_n^E)$ . Define the vector  $P_n^E = \{P_n^E(\alpha), \alpha \in Z\}$  where  $P_n^E(\alpha) = P\{X_n^E=\alpha | y_\ell^E, \ell < n, X_0^E\}$ . Then

$$(3.4) \quad P_{n+1}^E = A(y_n^E)P_n^E.$$

Also, let  $P(y) = \{P(\alpha|y), \alpha \in Z\}$  denote the unique invariant measure for  $\{X_n(y)\}$ , with marginal defined by  $P^1(j|y) = \sum_k P(j, k|y)$ ,  $P^1(y) = \{P^1(j|y), j \leq N_1\}$ , and similarly for route 2. Finally, define the transition probability  $P(\alpha, j, \alpha_1|y) = P\{X_j(y)=\alpha_1 | X_0(y)=\alpha\}$  and write the marginal as

$$P^i(\alpha, j, k|y) = P\{X_j^i(y)=k | X_0(y)=\alpha\}.$$

Define  $E_n^E$  to be the expectation conditioned on  $\{X_\ell^E, y_\ell^E, \ell \leq n\}$ .

A relationship of (3.1) to a differential equation. Define  $v_i = (1 - \lambda_i)^{N_i}$ .

Note that

$$(3.5a) \quad E_n^E J_{1n}^E = \mu y_n^E [1 - v_1 I\{X_n^E, 1 = N_1\}],$$

$$(3.5b) \quad E_n^\epsilon J_{2n}^\epsilon = \mu(1-y_n^\epsilon) [1 - v_2 I\{X_n^{\epsilon,2} = N_2\}].$$

For small  $\epsilon$ , it is reasonable to try to relate the behavior of  $\{y_n^\epsilon\}$  to the solution of (3.6), where  $\hat{F}(y)$  is just  $E[\alpha(y)J_{1n}^\epsilon + \beta(y)J_{2n}^\epsilon]$ , but with  $\{X_n^\epsilon, y_n^\epsilon\}$  replaced by  $\{X_n(y), y\}$  and using the stationary measure.

$$(3.6) \quad \begin{aligned} \dot{y} &= \mu\alpha(y)y[1-v_1P^1(N_1|y)] - \mu(1-y)\beta(y)[1-v_2P^2(N_2|y)] \\ &= \mu y(1-y)[v_2P^2(N_2|y) - v_1P^1(N_1|y)] \equiv \hat{F}(y). \end{aligned}$$

As  $y$  increases,  $P^1(N_1|y)$  increases (and  $P^2(N_2|y)$  decreases) monotonically. Thus, there is a unique point  $\bar{y} \in (0,1)$  such that  $\hat{F}(\bar{y}) = 0$ . Also,  $\hat{F}(y) > 0$  for  $y < \bar{y}$  and  $\hat{F}(y) < 0$  for  $y > \bar{y}$ . We assume that  $\bar{y} \in (y_l, y_u)$  and we also make the apparently unrestrictive assumption that  $\hat{F}'_y(\bar{y}) \neq 0$ . We actually will study the asymptotic properties of  $U_n^\epsilon \equiv (y_n^\epsilon - \bar{y})/\sqrt{\epsilon}$ , for large  $n$  and small  $\epsilon$ . In particular, let  $n_\epsilon$  be a sequence of integers tending to  $\infty$  as  $\epsilon \rightarrow 0$ , and define the processes  $\tilde{U}^\epsilon(\cdot)$  by  $\tilde{U}^\epsilon(0) = U_{n_\epsilon}^\epsilon$  and  $\tilde{U}^\epsilon(t) = U_{n_\epsilon+1}^\epsilon$  on  $[i\epsilon, i\epsilon+\epsilon)$ . When the  $\tilde{U}^\epsilon(\cdot)$  are dealt with, the  $\{n_\epsilon\}$  will either be explicitly defined or their values will be unimportant. We show weak convergence of  $\{\tilde{U}^\epsilon(\cdot)\}$  to the Gauss-Markov diffusion  $u(\cdot)$  defined by (6.3). If  $n_\epsilon \rightarrow \infty$  fast enough as  $\epsilon \rightarrow 0$ , then the limit  $u(\cdot)$  is stationary. The general method can be applied to many other problems in learning, automata and systems theory.

IV. SOME PRELIMINARY RESULTS

In this section, we prove some auxiliary results concerning uniform convergence of  $P_n(y)$  and its derivatives to  $P(y)$  and its derivatives.

Theorem 2. For each  $y \in [y_\ell, y_u]$ , let  $A'(y)$  denote a Markov transition matrix (continuous in  $y$ ) such that the corresponding Markov chain  $\{X_n(y)\}$  is ergodic with invariant measure  $P(y)$ . Then  $P(\cdot)$  is also continuous and there is a  $\delta > 0$  such that the eigenvalues of  $A(y)$ , except for the single eigenvalue unity, are bounded in absolute value by  $1-\delta$  for all  $y \in [y_\ell, y_u]$ .  $P_n(y)$  converges to  $P(y)$  uniformly (and at a geometric rate) in  $y \in [y_\ell, y_u]$  and in  $P_0(y)$ .

Proof. The last sentence follows from the penultimate sentence. The continuity of  $P(\cdot)$  is a consequence of the uniqueness for each  $y$ , of the eigenvector of  $A(y)$  corresponding to the eigenvalue unity (the invariant measure). Next, suppose that there is no such  $\delta$ . Let  $A(y)$  be a  $q \times q$  matrix and let  $\lambda_1(y), \dots, \lambda_q(y)$  denote the eigenvalues. Order them such that  $\lambda_1(y) \equiv 1$ . Then there is a  $\tilde{y}$  and a sequence  $\{y_n\} \subset [y_\ell, y_u]$  such that as  $y_n \rightarrow \tilde{y}$ , at least one eigenvalue (other than the one which is always unity) approaches the unit circle. In particular, suppose that the ordering is such that  $|\lambda_2(y_n)| \rightarrow 1$  and that (choosing a subsequence if necessary) the  $\lambda_i(y_n)$  converge to some  $\tilde{\lambda}_i$  as  $n \rightarrow \infty$ , for  $i = 1, \dots, q$ . The  $\{\tilde{\lambda}_i\}$  must be the eigenvalues of  $A(\tilde{y})$ . But then  $A'(y)$  is not the transition matrix of an ergodic process, a contradiction.

Q.E.D.

Definition. Let  $\Sigma(y)$  denote the span of the eigenvectors and generalized eigenvectors of  $A(y)$ , except for the eigenvector which corresponds to the eigenvalue unity.

Theorem 3. Assume the situation of Theorem 1, but let  $A(\cdot)$  be continuously differentiable on  $[y_l, y_u]$  (at the endpoints, take the left- or right-hand derivatives, as appropriate); then so is  $P(\cdot)$ , and  $P_y(y)$  is the unique solution in  $\Sigma(y)$  to the equation

$$(4.1) \quad P_y(y) = A(y)P_y(y) + A_y(y)P(y).$$

Furthermore, the derivative  $P_{n,y}(y)$  given by

$$(4.2) \quad P_{n+1,y}(y) = A(y)P_{n,y}(y) + A_y(y)P_n(y)$$

converges geometrically to  $P_y(y)$ , uniformly in  $y \in [y_l, y_u]$  and in the initial condition  $P_0(y)$ , if we set  $P_{0,y}(y) = 0$ .

If  $A(\cdot)$  has continuous second derivatives on  $[y_l, y_u]$ , then so do  $P(\cdot)$  and  $P_n(\cdot)$ , and  $P_{yy}(y)$  is the unique solution in  $\Sigma(y)$  to

$$(4.3) \quad P_{yy}(y) = A(y)P_{yy}(y) + 2A_y(y)P_y(y) + A_{yy}(y)P(y).$$

Also,  $P_{n,yy}(y)$  converges geometrically to  $P_{yy}(y)$ , uniformly in  $y \in [y_l, y_u]$  and in the initial conditions, if  $P_{0,y}(y) = P_{0,yy}(y) = 0$ .



Proof. Fix  $y$ . Since  $(I-A(y))V = 0$  for  $V \in \Sigma(y)$  implies that  $V = 0$ , in order for (4.1) to have a unique solution in  $\Sigma(y)$  it is necessary and sufficient that  $A_y(y)P(y) \perp \mathcal{N}(I-A'(y))$ , where  $\mathcal{N}$  denotes the null space of the matrix.  $\mathcal{N}(I-A'(y))$  is the set of vectors  $Q$  such that  $A'(y)Q = Q$ . Since there is a unique eigenvalue of value unity and since the row sums of  $A'(y)$  are all unity, the components of  $Q$  must all have the same value. Thus, the necessary and sufficient condition reduces to  $A_y(y)P(y) \perp$  constant vectors. For any constant vector  $C = (c, c, \dots)'$ ,  $C'A(y) = C'$ . Thus,  $C'A_y(y) = 0$  and hence  $A_y(y)D \perp$  constant vectors for any vector  $D$ . Consequently (4.1) has a unique solution  $\bar{P}_y(y)$  in  $\Sigma(y)$ .

Next, we show that  $\bar{P}_y(y)$  is the desired derivative. Write (for  $y \in (y_l, y_u)$ , otherwise  $\delta > 0$  or  $\delta < 0$ , as appropriate)

$$A(y+\delta)P(y+\delta) - A(y)P(y) = P(y+\delta) - P(y).$$

Thus,

$$(4.4) \quad \frac{[A(y+\delta)-A(y)]}{\delta} P(y+\delta) = (I-A(y)) \frac{[P(y+\delta)-P(y)]}{\delta}.$$

The left-hand side of (4.4) is uniformly bounded and is in  $\Sigma(y)$  for each  $\delta > 0$  (since  $(I-A(y))V \in \Sigma(y)$  for any  $V$ ) and it converges to  $A_y(y)P(y)$  as  $\delta \rightarrow 0$ . When considered as an operator from  $\Sigma(y)$  to  $\Sigma(y)$ ,  $[I-A(y)]$  has a bounded inverse. Thus, as  $\delta \rightarrow 0$ ,  $[P(y+\delta)-P(y)]/\delta$  converges to  $P_y(y)$ , which must equal  $\bar{P}_y(y)$ , by the uniqueness proved above.

We now turn to the convergence (4.2). By Theorem 1,  $P_n(y)$  converges geometrically to  $P(y)$ , uniformly in  $[y_l, y_u]$  and in  $P_0(y)$ . Also, since we use

$$P_{0,y}(y) = 0,$$

$$P_{n+1,y}(y) = \sum_{j=0}^n A_y^{n-i}(y) A_y(y) P_i(y).$$

But  $A_y(y)P_i(y)$  is a bounded sequence in  $\Sigma(y)$ , and as  $i \rightarrow \infty$  it converges geometrically and uniformly to  $A_y(y)P(y)$ . Also  $\Lambda(y)$  is a contraction when acting in  $\Sigma(y)$ , uniformly in  $y \in [y_\ell, y_u]$ . These facts imply the desired convergence of  $P_{n,y}(y)$ . The limit must be a solution to (4.1).

The assertions concerning  $P_{yy}$  are proved in the same way and we omit the details. Q.E.D.

V. TIGHTNESS OF  $\{U_n^\epsilon, \text{SMALL } \epsilon, \text{LARGE } n\}$

By " $\epsilon$  small" and " $n$  large" we mean that there are  $\epsilon_0 > 0, N_\epsilon < \infty$ , such that the assertion holds for  $\epsilon \leq \epsilon_0, n \geq N_\epsilon$ . The actual value of  $\epsilon_0$  will be unimportant. Basic to the proof of weak convergence of  $\{\tilde{U}^\epsilon(\cdot)\}$  is the tightness of  $\{U_n^\epsilon, \text{small } \epsilon, \text{large } n\}$ .

Theorem 4. For each small  $\epsilon > 0$ , there is an  $N_\epsilon < \infty$  such that the doubly indexed sequence  $\{U_n^\epsilon, \epsilon \text{ small}, n \geq N_\epsilon\}$  is tight, where  $U_n^\epsilon = (y_n^\epsilon - \bar{y})/\sqrt{\epsilon}$ .

Proof. Define  $V(y) = (y - \bar{y})^2$ . We have

$$(5.1a) \quad E_n^\epsilon (y_{n+1}^\epsilon - y_n^\epsilon) = \mu \epsilon [\alpha_\epsilon(y_n^\epsilon) y_n^\epsilon (1 - \nu_1 I\{X_n^{\epsilon,1} = N_1\}) + \beta_\epsilon(y_n^\epsilon) (1 - y_n^\epsilon) (1 - \nu_2 I\{X_n^{\epsilon,2} = N_2\})],$$

$$(5.1b) \quad E_n^\epsilon (y_{n+1}^\epsilon - y_n^\epsilon)^2 = \epsilon^2 \mu [\alpha_\epsilon^2(y_n^\epsilon) y_n^\epsilon (1 - \nu_1 I\{X_n^{\epsilon,1} = N_1\}) + \beta_\epsilon^2(y_n^\epsilon) (1 - y_n^\epsilon) (1 - \nu_2 I\{X_n^{\epsilon,2} = N_2\})].$$

For small  $\epsilon$ ,

$$E_n^\epsilon (y_n^\epsilon - \bar{y}) [\alpha_\epsilon(y_n^\epsilon) J_{1,n}^\epsilon + \beta_\epsilon(y_n^\epsilon) J_{2,n}^\epsilon] \leq E_n^\epsilon (y_n^\epsilon - \bar{y}) [\alpha(y_n^\epsilon) J_{1,n}^\epsilon + \beta(y_n^\epsilon) J_{2,n}^\epsilon],$$

since  $0 \leq \alpha_\epsilon(y) \leq \alpha(y)$  and  $\alpha_\epsilon(y) \neq \alpha(y)$  only if  $y_n^\epsilon - \bar{y} \geq 0$  (for small  $\epsilon$ ), and conversely for the  $\beta_\epsilon$  term. Using the above inequality, (5.1a) and  $|y_{n+1}^\epsilon - y_n^\epsilon| = O(\epsilon)$ ,

$$(5.2) \quad E_n^\epsilon V(y_{n+1}^\epsilon) - V(y_n^\epsilon) \leq 2\mu \epsilon (y_n^\epsilon - \bar{y}) [\alpha(y_n^\epsilon) y_n^\epsilon (1 - \nu_1 I\{X_n^{\epsilon,1} = N_1\}) + \beta(y_n^\epsilon) (1 - y_n^\epsilon) (1 - \nu_2 I\{X_n^{\epsilon,2} = N_2\})] + O(\epsilon^2).$$

Define  $V_1^\epsilon(n)$  by

$$(5.3) \quad V_1^\epsilon(n) = 2\mu\epsilon(y_n^\epsilon - \bar{y})\alpha(y_n^\epsilon)y_n^\epsilon v_1 \sum_{j=n}^{\infty} [P^1(N_1|y_n^\epsilon) - P^1(X_n^\epsilon, j-n, N_1|y_n^\epsilon)] \\ + 2\mu\epsilon(y_n^\epsilon - \bar{y})\beta(y_n^\epsilon)(1-y_n^\epsilon)v_2 \sum_{j=n}^{\infty} [P^2(N_2|y_n^\epsilon) - P^2(X_n^\epsilon, j-n, N_2|y_n^\epsilon)].$$

Note that  $P^i(X_n^\epsilon, 0, N_i|y_n^\epsilon) = I\{X_n^\epsilon, i=N_i\}$ . By Theorem 2, the sums converge absolutely (the summands go to zero at a geometric rate) uniformly in  $n, y_n^\epsilon, X_n^\epsilon$ . Thus  $|V_1^\epsilon(\cdot)| = O(\epsilon)$ , uniformly in all the variables.

Next, evaluate

$$E_n^\epsilon V_1^\epsilon(n+1) - V_1^\epsilon(n) = -2\mu\epsilon(y_n^\epsilon - \bar{y})\alpha(y_n^\epsilon)y_n^\epsilon v_1 [P^1(N_1|y_n^\epsilon) - I\{X_n^\epsilon, 1=N_1\}] \\ - 2\mu\epsilon(y_n^\epsilon - \bar{y})\beta(y_n^\epsilon)(1-y_n^\epsilon)v_2 [P^2(N_2|y_n^\epsilon) - I\{X_n^\epsilon, 2=N_2\}] \\ (5.4) \quad + \sum_{j=n+1}^{\infty} 2\mu\epsilon v_1 \{E_n^\epsilon(y_{n+1}^\epsilon - \bar{y})\alpha(y_{n+1}^\epsilon)y_{n+1}^\epsilon [P^1(N_1|y_{n+1}^\epsilon) - P^1(X_{n+1}^\epsilon, j-n-1, N_1|y_{n+1}^\epsilon)] \\ - (y_n^\epsilon - \bar{y})\alpha(y_n^\epsilon)y_n^\epsilon [P^1(N_1|y_n^\epsilon) - P^1(X_n^\epsilon, j-n, N_1|y_n^\epsilon)]\}$$

+ a similar sum for route 2.

We next show that the sums in (5.4) =  $O(\epsilon^2)$  uniformly in all the variables  $n, y_n^\epsilon, X_n^\epsilon$ . For simplicity we work only with the first sum (route 1). By  $|y_{n+1}^\epsilon - y_n^\epsilon| = O(\epsilon)$ , the smoothness of  $\alpha(\cdot)$  and  $\beta(\cdot)$  and Theorem 2, the sum changes by  $O(\epsilon^2)$  if  $(y_{n+1}^\epsilon - \bar{y})\alpha(y_{n+1}^\epsilon)y_{n+1}^\epsilon$  is replaced by  $(y_n^\epsilon - \bar{y})\alpha(y_n^\epsilon)y_n^\epsilon$ . Upon making the substitution and using the Markov property of  $\{X_j(y), j \geq n\}$  with the value  $y = y_n^\epsilon$  and "initial" condition

$$X_n(y_n^\epsilon) = X_n^\epsilon,$$

$$E_n^\epsilon P^1(X_{n+1}^\epsilon, j-n-1, N_1 | y_n^\epsilon) = P^1(X_n^\epsilon, j-n, N_1 | y_n^\epsilon),$$

we can rewrite the sum as

$$(5.5) \quad O(\epsilon) \sum_{j=n+1}^{\infty} E_n^\epsilon \{ [P^1(N_1 | y_{n+1}^\epsilon) - P^1(N_1 | y_n^\epsilon)] \\ - [P^1(X_{n+1}^\epsilon, j-n-1, N_1 | y_{n+1}^\epsilon) - P^1(X_{n+1}^\epsilon, j-n-1, N_1 | y_n^\epsilon)] \} + O(\epsilon^2).$$

Write  $\delta y_n^\epsilon = y_{n+1}^\epsilon - y_n^\epsilon$ , and use the differentiability (Theorem 3) of the  $P^i$  and the law of the mean to write (5.5) in the form

$$O(\epsilon) \delta y_n^\epsilon \sum_{j=n+1}^{\infty} E_n^\epsilon \int_0^1 [P_y^1(N_1 | y_n^\epsilon + s \delta y_n^\epsilon) - P_y^1(X_{n+1}^\epsilon, j-n-1, N_1 | y_n^\epsilon + s \delta y_n^\epsilon)] ds + O(\epsilon^2).$$

By Theorem 3, the sequence of absolute values of the integrands converges to zero geometrically as  $j \rightarrow \infty$ , uniformly in  $s$ ,  $n$ ,  $\delta y_n^\epsilon$ , and  $X_{n+1}^\epsilon$ . This, together with  $|\delta y_n^\epsilon| = O(\epsilon)$ , yield that (5.5) is  $O(\epsilon^2)$ . The same result holds for the sum in (5.4) corresponding to route 2.

Define  $V^\epsilon(n) = V(y_n^\epsilon) + V_1^\epsilon(n)$ . By (5.2) and (5.4) and the fact that the sums in (5.4) are  $O(\epsilon^2)$ ,

$$E_n^\epsilon V^\epsilon(n+1) - V^\epsilon(n) \leq O(\epsilon^2) + 2\mu\epsilon(y_n^\epsilon - \bar{y}) [\alpha(y_n^\epsilon) y_n^\epsilon (1 - v_1 P^1(N_1 | y_n^\epsilon)) \\ + \beta(y_n^\epsilon) (1 - y_n^\epsilon) (1 - v_2 P^2(N_2 | y_n^\epsilon))].$$

Owing to the definition of  $\alpha(\cdot)$  and  $\beta(\cdot)$  and the fact that  $y_n^\epsilon \in [y_\ell, y_u]$ , the

bracketed term has its unique zero at  $y_n^\epsilon = \bar{y}$  and it is positive (negative, resp.) for  $y_n^\epsilon < \bar{y}$  ( $y_n^\epsilon > \bar{y}$ , resp.). Thus, there is a  $\gamma > 0$  such that

$$(5.6) \quad E_n^\epsilon V^\epsilon(n+1) - V^\epsilon(n) \leq O(\epsilon^2) - \epsilon\gamma V(y_n^\epsilon).$$

By  $|V_1^\epsilon(n)| = O(\epsilon)$  uniformly in  $n$ ,  $E_n^\epsilon V^\epsilon(n+1) - V^\epsilon(n) \leq O(\epsilon^2) - \epsilon\gamma V^\epsilon(n)$ , and hence

$$(5.7) \quad EV^\epsilon(n) \leq (\exp - \epsilon\gamma n)EV^\epsilon(0) + O(\epsilon).$$

Again, since  $|V_1^\epsilon(n)| = O(\epsilon)$ , uniformly in  $n$ , (5.7) holds for  $V(y_n^\epsilon)$  replacing  $V^\epsilon(n)$ , from which the existence of the  $\{N_\epsilon\}$  and the asserted tightness follows.

In particular, let  $0 < K_0$  be arbitrary and let  $N_\epsilon$  be the smallest integer  $n$  such that  $(\exp - \epsilon n\gamma) \leq K_0\epsilon$ . Q.E.D.

VI. WEAK CONVERGENCE OF  $\{\tilde{U}^\epsilon(\cdot)\}$

Definition. Recall the definition of  $N_\epsilon$  given at the end of the proof of Theorem 4. For any sequence of integers  $n_\epsilon > N_\epsilon$ , define  $Q_\epsilon = n_\epsilon - N_\epsilon$ . Define  $\tilde{y}_n^\epsilon = y_{n_\epsilon}^\epsilon$  and similarly define the "shifted" sequences  $\tilde{U}_n^\epsilon$ ,  $\tilde{X}_n^\epsilon$  and  $\tilde{J}_{in}^\epsilon$ . Then

$$(6.1) \quad \tilde{U}_{n+1}^\epsilon = \tilde{U}_n^\epsilon + \sqrt{\epsilon} [\alpha_\epsilon (\tilde{y}_n^\epsilon) \tilde{J}_{1n}^\epsilon + \beta_\epsilon (\tilde{y}_n^\epsilon) \tilde{J}_{2n}^\epsilon].$$

By Theorem 4,  $\{\tilde{U}_n^\epsilon, \epsilon \text{ small}\}$  is tight. For each integer  $N$ , define  $\tilde{U}_n^{\epsilon, N}$ ,  $\tilde{y}_n^{\epsilon, N}$ ,  $\tilde{J}_{in}^{\epsilon, N}$  via

$$(6.2) \quad \tilde{U}_{n+1}^{\epsilon, N} = \tilde{U}_n^{\epsilon, N} + \sqrt{\epsilon} [\alpha (\tilde{y}_n^{\epsilon, N}) \tilde{J}_{1n}^{\epsilon, N} + \beta (\tilde{y}_n^{\epsilon, N}) \tilde{J}_{2n}^{\epsilon, N}] b_N(\tilde{U}_n^{\epsilon, N}),$$

where  $b_N(\cdot)$  is defined above (2.1) and we set  $\tilde{U}_0^{\epsilon, N} = \tilde{U}_0^\epsilon$  if  $|\tilde{U}_0^\epsilon| \leq N$  and equal to zero otherwise. Also  $\tilde{U}_n^{\epsilon, N} = (\tilde{y}_n^{\epsilon, N} - \bar{y}) / \sqrt{\epsilon}$  defines  $\tilde{y}_n^{\epsilon, N}$ .  $\tilde{J}_{in}^{\epsilon, N}$  is simply the indicator function of the set {route i is tried first and call accepted} for the system  $\{\tilde{X}_n^{\epsilon, N}, \tilde{y}_n^{\epsilon, N}\}$ , where the choice probabilities  $\{\tilde{y}_n^{\epsilon, N}\}$  are used to select the routes and  $\{\tilde{X}_n^{\epsilon, N}\}$  is the corresponding route occupancy process. We suppose that  $\tilde{X}_0^{\epsilon, N} = X_{n_\epsilon}^\epsilon$ . Let  $\tilde{E}_n^{\epsilon, N}$  denote expectation conditional on  $\tilde{y}_n^{\epsilon, N}$  and  $\tilde{X}_n^{\epsilon, N}$ . Since  $|\tilde{y}_n^{\epsilon, N} - \bar{y}| \leq \sqrt{\epsilon(N+1)}$ , for small  $\epsilon$  it is irrelevant whether we use  $\alpha_\epsilon$ ,  $\beta_\epsilon$  or  $\alpha$ ,  $\beta$  in (6.2), and we use  $\alpha$ ,  $\beta$  for simplicity. By Theorem 1, if we show that (for each  $N$ )  $\{\tilde{U}_n^{\epsilon, N}(\cdot)\}$  is tight and that all weak limits satisfy (6.3) until first escape from  $S_N$ , then  $\{\tilde{U}^\epsilon(\cdot)\}$  is tight and all weak limits satisfy (6.3).

We now define some auxiliary processes which are used in the averaging method employed in the proof. Let  $\bar{P}$  denote the measure defined by the stationary process  $\{X_j(\bar{y}), j \geq 0\}$ , with corresponding expectation operator  $\bar{E}$ . For each  $n$ , it is necessary to introduce the process  $\{X_j(\bar{y}), j \geq n\}$ , but with "initial" condition  $X_n(\bar{y}) = \tilde{X}_n^{\epsilon, N}$ . (I.e., after time  $n$ , the route choice probability is  $\bar{y}$ .) The opera-

tor  $\bar{E}_n^{\epsilon, N}$  denotes the expectation of functions of this process  $\{X_j(\bar{y}), j \geq n\}$  conditional on the "initial" condition  $X_n(\bar{y}) = \bar{X}_n^{\epsilon, N}$ . Let  $J_{ij}(\bar{y})$  denote the indicator function  $I\{\text{call arrives at } j+1, \text{ is assigned to and accepted by route } i\}$ , when the route choice variable is  $\bar{y}$  and the route occupancy process is  $\{X_j(\bar{y})\}$ . Whether we intend the ergodic process or the process  $\{X_j(\bar{y}), j \geq n\}$  starting at time  $n$  with  $X_n(\bar{y}) = \bar{X}_n^{\epsilon, N}$  will be made obvious by use of either  $\bar{E}$  or  $\bar{E}_n^{\epsilon, N}$ . Define

$$\delta u_j(\bar{y}) = [\alpha(\bar{y})J_{1j}(\bar{y}) + \beta(\bar{y})J_{2j}(\bar{y})].$$

Under  $\bar{P}$ , the right side has zero expectation.

Theorem 5. For any sequence  $n_\epsilon \geq N_\epsilon$ ,  $\{\bar{U}^\epsilon(\cdot)\}$  is tight in  $D[0, \infty)$ . All weakly convergent subsequences converge to a Gauss-Markov diffusion satisfying (6.3).  
If  $\epsilon Q_\epsilon \rightarrow \infty$  as  $\epsilon \rightarrow \infty$ , then the limiting diffusion  $u(\cdot)$  is stationary in that  $u(0)$  has the stationary distribution. (In all cases  $u(0)$  is independent of  $B(\cdot)$ .)

$$(6.3) \quad du = Gu dt + \sigma dB, \quad B(\cdot) = \text{standard Brownian motion,}$$

$$(6.4) \quad G = \hat{F}_y(\bar{y}) = \frac{\partial}{\partial y} \mu y(1-y) [v_2 P^2(N_2|y) - v_1 P^1(N_1|y)] \Big|_{y=\bar{y}},$$

$$(6.5) \quad \sigma^2 = \bar{E}(\delta u_0(\bar{y}))^2 + 2 \sum_{n=1}^{\infty} \bar{E} \delta u_0(\bar{y}) \delta u_n(\bar{y}).$$

Proof. Part 1. Until Part 4, all superscripts  $N$  will be omitted. Thus we write  $(\bar{E}_n^\epsilon, \bar{E}_n^\epsilon, \bar{X}_n^\epsilon, \bar{y}_n^\epsilon, \bar{X}_n^{\epsilon, 1}, \dots)$  for  $(\bar{E}_n^{\epsilon, N}, \bar{E}_n^{\epsilon, N}, \bar{X}_n^{\epsilon, N}, \bar{y}_n^{\epsilon, N}, \bar{X}_n^{\epsilon, N, 1}, \dots)$ . We actually work with the  $N$ -truncated process in Parts 1 to 3.



By (5.1),

$$(6.6) \quad \mathbb{E}_n^{\nu_\epsilon}(\bar{U}_{n+1}^{\nu_\epsilon} - \bar{U}_n^{\nu_\epsilon}) = \sqrt{\epsilon} \mu \bar{y}_n^{\nu_\epsilon} (1 - \bar{y}_n^{\nu_\epsilon}) [\nu_2 I\{X_n^{\nu_\epsilon, 2} = N_2\} - \nu_1 I\{X_n^{\nu_\epsilon, 1} = N_1\}] b_N(\bar{U}_n^{\nu_\epsilon}).$$

Let  $f(\cdot, \cdot) \in \mathcal{D} = \mathcal{C}_0^{2,3}$ , the space of bounded  $(x, t)$  functions with compact support whose mixed partial derivatives up to order 2 in  $t$  and 3 in  $x$  are continuous. To apply Theorem 1 to  $\{\bar{U}^{\nu_\epsilon}(\cdot)\}$ , we will get an  $f^{\nu_\epsilon}(\cdot)$  of the form

$$f^{\nu_\epsilon}(\nu_\epsilon) = f(\bar{U}_n^{\nu_\epsilon}, \nu_\epsilon) + f_0^{\nu_\epsilon}(\nu_\epsilon) + f_1^{\nu_\epsilon}(\nu_\epsilon) + f_2^{\nu_\epsilon}(\nu_\epsilon)$$

where the  $f_i^{\nu_\epsilon}(\nu_\epsilon)$  will be defined in the sequel. For each  $N$ , all  $o(\cdot)$  or  $O(\cdot)$  are uniform in all variables except their argument. We have

$$\begin{aligned} \mathbb{E}_n^{\nu_\epsilon} f(\bar{U}_{n+1}^{\nu_\epsilon}, \nu_\epsilon + \epsilon) - f(\bar{U}_n^{\nu_\epsilon}, \nu_\epsilon) &= \mathbb{E}_n^{\nu_\epsilon} [f(\bar{U}_{n+1}^{\nu_\epsilon}, \nu_\epsilon) - f(\bar{U}_n^{\nu_\epsilon}, \nu_\epsilon)] + f_t(\bar{U}_n^{\nu_\epsilon}, \nu_\epsilon) \epsilon + o(\epsilon), \\ \mathbb{E}_n^{\nu_\epsilon} [f(\bar{U}_{n+1}^{\nu_\epsilon}, \nu_\epsilon) - f(\bar{U}_n^{\nu_\epsilon}, \nu_\epsilon)] &= \mathbb{E}_n^{\nu_\epsilon} f_u(\bar{U}_n^{\nu_\epsilon}, \nu_\epsilon) (\bar{U}_{n+1}^{\nu_\epsilon} - \bar{U}_n^{\nu_\epsilon}) + \frac{1}{2} \mathbb{E}_n^{\nu_\epsilon} f_{uu}(\bar{U}_n^{\nu_\epsilon}, \nu_\epsilon) (\bar{U}_{n+1}^{\nu_\epsilon} - \bar{U}_n^{\nu_\epsilon})^2 + o(\epsilon) \\ (6.7) \quad &= \sqrt{\epsilon} \mu f_u(\bar{U}_n^{\nu_\epsilon}, \nu_\epsilon) \bar{y}_n^{\nu_\epsilon} (1 - \bar{y}_n^{\nu_\epsilon}) b_N(\bar{U}_n^{\nu_\epsilon}) [\nu_2 I\{X_n^{\nu_\epsilon, 2} = N_2\} - \nu_1 I\{X_n^{\nu_\epsilon, 1} = N_1\}] \\ &\quad + \frac{f_{uu}(\bar{U}_n^{\nu_\epsilon}, \nu_\epsilon)}{2} \mathbb{E}_n^{\nu_\epsilon} (\bar{U}_{n+1}^{\nu_\epsilon} - \bar{U}_n^{\nu_\epsilon})^2 + o(\epsilon). \end{aligned}$$

By the differentiability result of Theorem 3, we can rewrite the term before the  $o(\epsilon)$  as follows:\*

$$\begin{aligned} & \epsilon b_N^2(\bar{U}_n^{\nu_\epsilon}) \frac{f_{uu}(\bar{U}_n^{\nu_\epsilon}, \nu_\epsilon)}{2} \mathbb{E}_n^{\nu_\epsilon} [\alpha(\bar{y}_n^{\nu_\epsilon}) J_{1n}^{\nu_\epsilon} + \beta(\bar{y}_n^{\nu_\epsilon}) J_{2n}^{\nu_\epsilon}]^2 \\ &= \epsilon b_N^2(\bar{U}_n^{\nu_\epsilon}) \frac{f_{uu}(\bar{U}_n^{\nu_\epsilon}, \nu_\epsilon)}{2} \mathbb{E}_n^{\nu_\epsilon} [\alpha(\bar{y}) J_{1n}(\bar{y}) + \beta(\bar{y}) J_{2n}(\bar{y})]^2 + o(\epsilon). \end{aligned}$$

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\*The terms  $\mathbb{E}_n^{\nu_\epsilon} J_{1n}(\bar{y})$  and  $\mathbb{E}_n^{\nu_\epsilon} J_{1n}^{\nu_\epsilon}(\bar{y}_n^{\nu_\epsilon})$  differ only in that in the first case  $\bar{y}$  is used as the choice variable to get the successor state to  $X_n^{\nu_\epsilon}$ , and  $\bar{y}_n^{\nu_\epsilon}$  is used in the second case.

Part 2. We will "average out" the terms in (6.7) one by one. Define  $f_1^\epsilon(n\epsilon)$  (analogous to the definition of  $V_1(n)$  in the last section)

$$(6.8) \quad f_1^\epsilon(n\epsilon) = \sqrt{\epsilon} \mu b_N(\tilde{U}_n^\epsilon) \tilde{Y}_n^\epsilon (1 - \tilde{Y}_n^\epsilon) f_u(\tilde{U}_n^\epsilon, n\epsilon) \sum_{j=n}^{\infty} [v_2(P^2(\tilde{X}_n^\epsilon, j-n, N_2 | \tilde{Y}_n^\epsilon) - P^2(N_2 | \tilde{Y}_n^\epsilon)) - v_1(P^1(\tilde{X}_n^\epsilon, j-n, N_1 | \tilde{Y}_n^\epsilon) - P^1(N_1 | \tilde{Y}_n^\epsilon))] .$$

Proceeding analogously to the method of Theorem 4 for  $V_1^\epsilon(n)$ , we evaluate (writing  $P^i(\tilde{X}_n^\epsilon, j-n, N_i | \tilde{Y}_n^\epsilon)$  in the more convenient form  $E_n^{\tilde{Y}_n^\epsilon} P^i(\tilde{X}_{n+1}^\epsilon, j-n-1, N_i | \tilde{Y}_n^\epsilon)$  in  $T_3$  below, for  $j > n$ ; see above (5.5))

$$(6.9) \quad E_n^{\tilde{Y}_n^\epsilon} f_1^\epsilon(n\epsilon + \epsilon) - f_1^\epsilon(n\epsilon) = T_1 + T_2 + T_3,$$

$$T_1 = -\sqrt{\epsilon} \mu \tilde{Y}_n^\epsilon (1 - \tilde{Y}_n^\epsilon) b_N(\tilde{U}_n^\epsilon) f_u(\tilde{U}_n^\epsilon, n\epsilon) [(v_2 I\{\tilde{X}_n^\epsilon, 2 = N_2\} - v_1 I\{\tilde{X}_n^\epsilon, 1 = N_1\}) - (v_2 P^2(N_2 | \tilde{Y}_n^\epsilon) - v_1 P^1(N_1 | \tilde{Y}_n^\epsilon))] .$$

$$T_2 = \sqrt{\epsilon} \mu E_n^{\tilde{Y}_n^\epsilon} [f_u(\tilde{U}_{n+1}^\epsilon, n\epsilon + \epsilon) b_N(\tilde{U}_{n+1}^\epsilon) \tilde{Y}_{n+1}^\epsilon (1 - \tilde{Y}_{n+1}^\epsilon)] \cdot \sum_{j=n+1}^{\infty} [v_2 (P^2(\tilde{X}_{n+1}^\epsilon, j-n-1, N_2 | \tilde{Y}_{n+1}^\epsilon) - P^2(N_2 | \tilde{Y}_{n+1}^\epsilon)) - v_1 (P^1(\tilde{X}_{n+1}^\epsilon, j-n-1, N_1 | \tilde{Y}_{n+1}^\epsilon) - P^1(N_1 | \tilde{Y}_{n+1}^\epsilon))] ,$$

$$T_3 = -\sqrt{\epsilon} \mu [f_u(\tilde{U}_n^\epsilon, n\epsilon) \tilde{Y}_n^\epsilon (1 - \tilde{Y}_n^\epsilon) b_N(\tilde{U}_n^\epsilon)] \cdot \sum_{j=n+1}^{\infty} E_n^{\tilde{Y}_n^\epsilon} [v_2 (P^2(\tilde{X}_{n+1}^\epsilon, j-n-1, N_2 | \tilde{Y}_n^\epsilon) - P^2(N_2 | \tilde{Y}_n^\epsilon)) - v_1 (P^1(\tilde{X}_{n+1}^\epsilon, j-n-1, N_1 | \tilde{Y}_n^\epsilon) - P^1(N_1 | \tilde{Y}_n^\epsilon))] .$$

Using the differentiability result of Theorem 3 and the fact that  $v_2 P^2(N_2 | \bar{y}) = v_1 P^1(N_1 | \bar{y})$ , we get that  $T_1$  equals the negative of the first term on the right side of (6.7) plus

$$(6.10) \quad \epsilon \mu b_N(\tilde{U}_n^\epsilon) \frac{\partial}{\partial y} \{y(1-y) [v_2 P^2(N_2 | y) - v_1 P^1(N_1 | y)] \tilde{U}_n^\epsilon \Big|_{y=\bar{y}} + o(\epsilon).$$

In  $T_2$ , by replacing  $\tilde{y}_{n+1}^\epsilon$  by  $\tilde{y}_n^\epsilon$  and  $b_N(\tilde{U}_{n+1}^\epsilon) f_u(\tilde{U}_{n+1}^\epsilon, n\epsilon + \epsilon)$  by

$$b_N(\tilde{U}_n^\epsilon) f_u(\tilde{U}_n^\epsilon, n\epsilon) + (b_N(\tilde{U}_n^\epsilon) f_u(\tilde{U}_n^\epsilon, n\epsilon))_u (\tilde{U}_{n+1}^\epsilon - \tilde{U}_n^\epsilon),$$

we only alter the term by  $o(\epsilon)$ . Let us make these replacements in  $T_2$  and denote the resulting term by  $T_2^0$ . Now, split  $T_2^0$  into two parts  $(T_{21}^2, T_{22}^2)$ , the first (second, resp.) being  $T_2$  but with  $b_N(\tilde{U}_n^\epsilon) f_u(\tilde{U}_n^\epsilon, n\epsilon)$  ( $(b_N(\tilde{U}_n^\epsilon) f_u(\tilde{U}_n^\epsilon, n\epsilon))_u (\tilde{U}_{n+1}^\epsilon - \tilde{U}_n^\epsilon)$ , resp.) replacing  $b_N(\tilde{U}_{n+1}^\epsilon) f_u(\tilde{U}_{n+1}^\epsilon, n\epsilon + \epsilon)$ . By the differentiability results of Theorem 3 and the fact that  $|\tilde{y}_{n+1}^\epsilon - \tilde{y}_n^\epsilon| = O(\epsilon)$  and an argument like that below (5.5), it can be shown that  $T_{21}^0 + T_3 = o(\epsilon)$ . Thus

$$(6.11a) \quad T_2 + T_3 = o(\epsilon) + \sqrt{\epsilon} \mu \tilde{y}_n^\epsilon (1 - \tilde{y}_n^\epsilon) (b_N(\tilde{U}_n^\epsilon) f_u(\tilde{U}_n^\epsilon, n\epsilon))_u \\ \cdot E_n^{\tilde{y}_n^\epsilon} (\tilde{U}_{n+1}^\epsilon - \tilde{U}_n^\epsilon) \sum_{j=n+1}^{\infty} [v_2 (P^2(\tilde{X}_{n+1}^\epsilon, j-n-1, N_2 | \tilde{y}_n^\epsilon) - P^2(N_2 | \tilde{y}_n^\epsilon)) \\ - v_1 (P^1(\tilde{X}_{n+1}^\epsilon, j-n-1, N_1 | \tilde{y}_n^\epsilon) - P^1(N_1 | \tilde{y}_n^\epsilon))].$$

We now simplify (6.11a) by a series of replacements, each one altering the term by  $o(\epsilon)$ . First replace all the  $\tilde{y}_n^\epsilon$  by  $\bar{y}$ . By Theorem 3 and  $|\tilde{U}_{n+1}^\epsilon - \tilde{U}_n^\epsilon| = o(\sqrt{\epsilon})$  and a differentiability argument such as used below (5.5), this only alters the

term by  $o(\epsilon)$ . Since  $v_2 P^2(N_2 | \bar{y}) - v_1 P^1(N_1 | \bar{y}) = 0$ , we delete this part of the resulting summand. We now have

$$(6.11b) \quad T_2 + T_3 = o(\epsilon) + \sqrt{\epsilon} [b_N(\hat{U}_n^\epsilon) f_u(\hat{U}_n^\epsilon, n\epsilon)]_u \bar{E}_n^\epsilon(\hat{U}_{n+1}^\epsilon - \hat{U}_n^\epsilon) \sum_{j=n+1}^{\infty} q_j^\epsilon,$$

where for  $j \geq n+1$ ,

$$q_j^\epsilon = [v_2 P^2(\hat{X}_{n+1}^\epsilon, j-n-1, N_2 | \bar{y}) - v_1 P^1(\hat{X}_{n+1}^\epsilon, j-n-1, N_1 | \bar{y})] \mu \bar{y}(1-\bar{y}) = \bar{E}_{n+1}^\epsilon \delta u_j(\bar{y}).$$

Finally, by the differentiability result of Theorem 3, (6.11b) equals

$$(6.12) \quad T_2 + T_3 = o(\epsilon) + \epsilon b_N(\hat{U}_n^\epsilon) [b_N(\hat{U}_n^\epsilon) f_u(\hat{U}_n^\epsilon, n\epsilon)]_u \sum_{j=n+1}^{\infty} \bar{E}_n^\epsilon \delta u_n(\bar{y}) \delta u_j(\bar{y}).$$

The difference between (6.11b) and (6.12) is simply due to whether  $\hat{y}_n^\epsilon$  or  $\bar{y}$  is used to get  $\hat{X}_{n+1}^\epsilon$  and  $\hat{U}_{n+1}^\epsilon$  from  $\hat{X}_n^\epsilon$  and  $\hat{U}_n^\epsilon$ .

Part 3. Now, we "average out" the sum in (6.12). Define  $f_2^\epsilon(n\epsilon)$  by

$$f_2^\epsilon(n\epsilon) = \epsilon b_N(\hat{U}_n^\epsilon) [b_N(\hat{U}_n^\epsilon) f_u(\hat{U}_n^\epsilon, n\epsilon)]_u \sum_{j=n}^{\infty} \sum_{k=j+1}^{\infty} [\bar{E}_n^\epsilon \delta u_j(\bar{y}) \delta u_k(\bar{y}) - \bar{E} \delta u_j(\bar{y}) \delta u_k(\bar{y})].$$

By the (uniform) geometric convergence result of Theorem 2, the sum converges absolutely and  $|f_2^\epsilon(n\epsilon)| = O(\epsilon)$ . By a straightforward calculation using the stationarity of  $\{\delta u_n(\bar{y})\}$  under  $\bar{P}$ , we can show that

$$\begin{aligned} \bar{E}_n^\epsilon f_2^\epsilon(n\epsilon + \epsilon) - f_2^\epsilon(n\epsilon) &= - (6.12) + o(\epsilon) \\ &+ \epsilon b_N(\hat{U}_n^\epsilon) [b_N(\hat{U}_n^\epsilon) f_u(\hat{U}_n^\epsilon, n\epsilon)]_u \sum_{j=1}^{\infty} \bar{E}(\delta u_0(\bar{y}) \delta u_j(\bar{y})). \end{aligned}$$

Finally, we treat the term before the  $o(\epsilon)$  of (6.7) - in the form in which it is written below (6.7). Define  $f_0^\epsilon(n\epsilon)$  by

$$f_0^\epsilon(n\epsilon) = \epsilon \frac{f_{uu}(\tilde{U}_n^\epsilon, n\epsilon)}{2} b_N^2(\tilde{U}_n^\epsilon) \sum_{j=n}^{\infty} [\bar{E}_n^\epsilon(\delta u_j(\bar{y}))^2 - \bar{E}(\delta u_j(\bar{y}))^2].$$

By a procedure similar to that used for  $f_1^\epsilon(n\epsilon)$ , it can readily be shown that

$$\begin{aligned} \tilde{E}_n^\epsilon f_0^\epsilon(n\epsilon + \epsilon) - f_0^\epsilon(n\epsilon) &= o(\epsilon) + \epsilon \frac{f_{uu}(\tilde{U}_n^\epsilon, n\epsilon)}{2} b_N^2(\tilde{U}_n^\epsilon) \bar{E}(\delta u_0(\bar{y}))^2 \\ &\quad - \epsilon \frac{f_{uu}(\tilde{U}_n^\epsilon, n\epsilon)}{2} b_N^2(\tilde{U}_n^\epsilon) \bar{E}_n^\epsilon [\alpha(\bar{y})J_{1n}(\bar{y}) + \beta(\bar{y})J_{2n}(\bar{y})]^2. \end{aligned}$$

Summarizing the previous calculations

$$\begin{aligned} \tilde{E}_n^\epsilon f^\epsilon(n\epsilon + \epsilon) - f^\epsilon(n\epsilon) &= o(\epsilon) + \epsilon f_t(\tilde{U}_n^\epsilon, n\epsilon) + \epsilon f_u(\tilde{U}_n^\epsilon, n\epsilon) \tilde{G}_n^\epsilon b_N(\tilde{U}_n^\epsilon) \\ (6.14) \quad &+ \epsilon f_u(\tilde{U}_n^\epsilon, n\epsilon) b_{N,u}(\tilde{U}_n^\epsilon) b_N(\tilde{U}_n^\epsilon) \sum_{j=1}^{\infty} \bar{E} \delta u_0(\bar{y}) \delta u_j(\bar{y}) \\ &+ \epsilon \frac{f_{uu}(\tilde{U}_n^\epsilon, n\epsilon)}{2} b_N^2(\tilde{U}_n^\epsilon) [\bar{E}(\delta u_0(\bar{y}))^2 + 2 \sum_{j=1}^{\infty} \bar{E} \delta u_0(\bar{y}) \delta u_j(\bar{y})]. \end{aligned}$$

Part 4. Conclusion. Reintroduce the superscript  $N$ . Fix  $N$ . All the  $f_i^{\epsilon, N}$  are bounded and of order  $O(\sqrt{\epsilon})$  and  $\{\tilde{U}_0^{\epsilon, N}\} = \{\tilde{U}^{\epsilon, N}(0)\}$  is tight. Also  $\tilde{E}_n^{\epsilon, N} f^{\epsilon, N}(n\epsilon + \epsilon) - f^{\epsilon, N}(n\epsilon) = O(\epsilon)$ . Thus, by [7], Theorem 2, the bounded sequence  $\{\tilde{U}^{\epsilon, N}(\cdot)\}$  is tight in  $D[0, \infty)$ . Let  $\epsilon$  index a weakly convergent subsequence with limit  $U^N(\cdot)$ . Since  $A$  is defined to be the infinitesimal operator of (6.3), by (6.14) and Theorem 1, we see that  $U^N(\cdot)$  solves the martingale problem corresponding to an infinitesimal operator  $A^N$  whose coefficients equal those of  $A$  in  $S_N$ . Thus, by Theorem 1,  $\{\tilde{U}^{\epsilon, N}(\cdot)\}$  converges weakly to a solution  $u(\cdot)$  of (6.3). The independence of  $B(\cdot)$  and  $u(0)$  is a consequence of the fact that  $u(\cdot)$  is the unique solution to the martingale problem. The stationarity assertion is not hard to prove, but we omit the details. Q.E.D.

VII. ASYMPTOTIC THEORY OF AN ADAPTIVE QUANTIZER: INTRODUCTION

In recent years there has been a great deal of effort concerning the efficient quantization of signals in telecommunications systems, e.g. of voice signals in telephone transmission systems. Let  $z(\cdot)$  denote the actual signal process and  $\Delta$  a sampling interval. In the problem of interest, the signal is sampled at moments  $\{n\Delta, n=0,1,\dots\}$ , then the samples  $\{z(n\Delta)\}$  are quantized, and it is only the quantized samples which are transmitted. Let  $0 = \xi_0 < \xi_1 < \dots < \xi_{L-1} < \xi_L = \infty$ ,  $0 = \eta_1 < \eta_2 < \dots < \eta_L$  where  $\xi_i, \eta_{i+1}, i = 0, \dots, L-1$ , are real numbers. Let the quantization function  $Q(\cdot)$  be defined as follows: there is a  $\gamma > 0$  such that for  $z(n\Delta) > 0$ ,  $Q(z(n\Delta)) = \gamma\eta_i$  if  $z(n\Delta) \in [\gamma\xi_{i-1}, \gamma\xi_i)$ , and set  $Q(-z) = -Q(z)$ . The parameter  $\gamma$  is a scaling parameter. As the signal power increases (decreases),  $\gamma$  should increase (decrease) for efficient reconstruction of the signal from the sequence of quantizations.

The problem of choosing appropriate values of  $\gamma$  when the signal powers can vary by an order of magnitude or more has led to the study of adaptive quantizers. We give only a brief description in order to formulate the problem. For more detail and discussion of the engineering considerations, the reader is referred to the references [4], [5]. Let  $\epsilon$  denote a "rate of adjustment" parameter for the scale parameter  $\gamma$  and let  $\gamma_n^\epsilon$  denote the value of the adapted scale parameter at the  $n$ th sampling instant. Set  $\beta \in (0,1]$  and let  $0 < M_1^\epsilon < M_2^\epsilon < \dots < M_L^\epsilon < \infty$  with  $M_1^\epsilon < 1, M_L^\epsilon > 1$ . We study an adaptive quantizer which is a truncated form of the (typical in such an application) adaptive system

$$(7.1) \quad \gamma_{n+1}^\epsilon = (\gamma_n^\epsilon)^\beta B_n^\epsilon, \quad \text{where } B_n^\epsilon = M_1^\epsilon \text{ if } |z(n\Delta)| \in [\gamma_n^\epsilon \xi_{i-1}, \gamma_n^\epsilon \xi_i).$$

Goodman and Gersho [4] did a thorough analysis of (7.1) for the case  $\beta = 1$  and  $\{z(n\Delta)\}$  independent and identically distributed. With  $\beta < 1$ , the system

has some desirable robustness properties and this case, together with simulations, is discussed by Mitra [5] and others. The last reference is concerned more with reconstruction of the process  $z(\cdot)$  from  $\{Q(z(n\Delta))\}$  and does not give an asymptotic analysis.

Generally, with non-i.i.d.  $\{z(n\Delta)\}$ , it is hard to get concrete information on  $\{y_n^\epsilon\}$  for large  $n$ . If the signal power varies over time or if (as is realistic for moderate values of  $\Delta$ )  $\{z(n\Delta)\}$  is not i.i.d., then techniques such as used in [4] fail, but for small rates of adjustment ( $\epsilon$ ) an asymptotic analysis can still shed light on the process behavior. At the present time, it seems that little more can be done for the general case. Here, we scale the problem so that an asymptotic analysis is possible. For mathematical as well as practical purposes, it is useful to confine  $y_n^\epsilon$  to some finite positive interval  $[y_l, y_u]$ . Now, we define the truncated form of (7.1) which will be studied. Let  $\alpha > 0$ ,  $0 < \alpha\epsilon < 1$  and let  $\{\ell_i\}$  be real numbers such that  $\ell_1 < \ell_2 < \dots < \ell_L$  and  $\ell_1 < 0$ ,  $\ell_L > 0$ . Then we use

$$(7.2) \quad y_{n+1}^\epsilon = (y_n^\epsilon)^{1-\alpha\epsilon} B_n^\epsilon \Big|_{y_l}^{y_u},$$

where  $|$  denotes truncation and

$$B_n^\epsilon = (1+\epsilon\ell_1) \quad \text{if} \quad |z(n\Delta)| \in [y_n^\epsilon \ell_{i-1}, y_n^\epsilon \ell_i].$$

The asymptotic results can be used to get information on the effects of the  $\{\ell_i\}$ ,  $\Delta$ , structure of  $z(\cdot)$  and  $\alpha$  on the performance for small  $\epsilon$ . For notational convenience below, let  $y_l < 1$  and  $y_u > 1$ . Rewrite (7.2) in the form (7.3), where  $y^{1-\epsilon\alpha} = y[1-\epsilon\alpha \log y] + O(\epsilon^2)$  and  $(1+\epsilon b_n^\epsilon) \equiv B_n^\epsilon$  are used, and  $F$  and  $b_n^\epsilon$  have the obvious definitions.

$$(7.3) \quad y_{n+1}^\epsilon = \left[ y_n^\epsilon (1 + \epsilon b_n^\epsilon) - \epsilon \alpha y_n^\epsilon \log y_n^\epsilon + O(\epsilon^2) \right] \Big|_{y_\ell}^{y_u} - \left[ y_n^\epsilon + \epsilon F(y_n^\epsilon, z(n\Delta)) + O(\epsilon^2) \right] \Big|_{y_f}^{y_u}.$$

In [4], the process  $\{\log y_n^\epsilon\}$  rather than  $\{y_n^\epsilon\}$  is dealt with.

We proceed in very much the same way that we did for the automata problem. The main difference arises from the unboundedness of  $\{z(n\Delta)\}$ , under assumption (7.6). By definition,

$$b_n^\epsilon = \sum_{i=1}^L \ell_i I\{|z(n\Delta)| \in [y_n^\epsilon \xi_{i-1}, y_n^\epsilon \xi_i]\}.$$

There are continuous functions  $\ell_i^\epsilon(\cdot)$  such that (7.4) and the properties below it hold.

$$(7.4) \quad \begin{aligned} y_{n+1}^\epsilon &= y_n^\epsilon (1 + \epsilon \beta_n^\epsilon(y_n^\epsilon)) - \epsilon \alpha y_n^\epsilon \log y_n^\epsilon + O(\epsilon^2) \\ &\equiv y_n^\epsilon + \epsilon F_\epsilon(y_n^\epsilon, z(n\Delta)) + O(\epsilon^2), \end{aligned}$$

where

$$(7.5) \quad \beta_n^\epsilon(y) = \sum_{i=1}^L \ell_i^\epsilon(y) I\{|z(n\Delta)| \in [y \xi_{i-1}, y \xi_i]\}.$$

Also,  $\ell_i^\epsilon(\cdot)$  can be chosen such that  $\ell_i^\epsilon(\cdot) = \ell_i$  out of an  $O(\epsilon)$  neighborhood of  $y_\ell$  (resp.  $y_u$ ) if  $\ell_i < 0$  (resp.  $\ell_i > 0$ ), and  $0 \geq \ell_i^\epsilon(y) \geq \ell_i$  for  $\ell_i < 0$  and  $0 \leq \ell_i^\epsilon(y) \leq \ell_i$  for  $\ell_i > 0$ .



Some assumptions. For specificity,  $z(\cdot)$  is assumed to be a stationary Gaussian process with a rational spectral density. Thus there are an asymptotically stable matrix  $M$ , a matrix  $C$ , a row vector  $D$ , and a process  $v(\cdot)$  such that

$$(7.6) \quad dv = Mvdt + Cdw$$

$z = Dv$ ,  $w(\cdot)$  = vector-valued standard Brownian motion.

This assumption is not essential - only certain smoothness properties of the multivariate density are used, together with the exponential rate of decrease of the effects of the initial conditions.

Define  $\hat{F}_\epsilon(y) = EF_\epsilon(y, z(n\Delta))$  and  $\hat{F}(y) = EF(y, z(n\Delta))$ . Let  $\sigma_0^2 = \text{var } z(t)$ .

We have (the subscript  $y$  denotes the derivative)

$$(7.7) \quad \frac{d}{dy} \left( \frac{\hat{F}(y)}{y} \right) = \frac{2}{\sqrt{2\pi\sigma_0}} \sum_{i=1}^L \ell_i [\xi_i \exp - \frac{\xi_i^2 y^2}{2\sigma_0^2} - \xi_{i-1} \exp - \frac{\xi_{i-1}^2 y^2}{2\sigma_0^2}] - \alpha/y$$

$$= \frac{2}{\sqrt{2\pi\sigma_0}} \sum_{i=1}^{L-1} (\ell_i - \ell_{i+1}) \xi_i \exp - \xi_i^2 y^2 / 2\sigma_0^2 - \alpha/y.$$

We can see from the terms in (7.7) that  $\hat{F}(y)/y$  is the sum of two strictly convex functions, the first being bounded and having a negative slope, and the second going to  $\infty$  as  $y \rightarrow 0$  and to  $-\infty$  as  $y \rightarrow \infty$ . Thus there is a unique  $\bar{y} \in (0, \infty)$  such that  $\hat{F}_y(\bar{y}) = 0$ . Also  $\hat{F}(y) > 0$  for  $0 < y < \bar{y}$  and  $\hat{F}(y) < 0$  for  $y > \bar{y}$  and  $\hat{F}_y(\bar{y}) \neq 0$ . We assume that  $y \in (y_\ell, y_u)$ . For small  $\epsilon$ , the assertions in the last sentence hold with  $\hat{F}_\epsilon$  replacing  $\hat{F}$ . Define  $U_n^\epsilon = (y_n^\epsilon - \bar{y})/\sqrt{\epsilon}$  and let  $E_n$  denote expectation conditioned on  $\{v(j\Delta), j < n\}$ .

VIII. TIGHTNESS OF  $\{U_n^\epsilon, \text{SMALL } \epsilon, \text{LARGE } n\}$

The proof is similar to that of Theorem 4 in Section V and we only set it up and indicate how to deal with the fact that  $\{z(n\Delta)\}$  is unbounded.

Theorem 6. Under the conditions in Section VII, the conclusions of Theorem 4 hold.

Proof. Define  $V(y) = (y-\bar{y})^2$ . There is a  $\gamma > 0$  such that  $(y-\bar{y})\hat{F}(y) \leq -\gamma V(y)$ , all  $\epsilon > 0$  and  $y \in [y_\ell, y_u]$ . We have

$$(y_{n+1}^\epsilon - y_n^\epsilon)^2 = O(\epsilon^2), \quad y_{n+1}^\epsilon = y_n^\epsilon + \epsilon \hat{F}_\epsilon(y_n^\epsilon) + \epsilon [F_\epsilon(y_n^\epsilon, z(n\Delta)) - \hat{F}_\epsilon(y_n^\epsilon)] + O(\epsilon^2),$$

$$\hat{F}_\epsilon(y) = y \sum_{i=1}^L \ell_i^\epsilon(y) P\{y \xi_{i-1} \leq |z(n\Delta)| < y \xi_i\} - \alpha(y \log y),$$

(8.1)

$$E_n^\epsilon (y_{n+1}^\epsilon - y_n^\epsilon)^2 = \epsilon \hat{F}_\epsilon(y_n^\epsilon) + \epsilon y_n^\epsilon \sum_{i=1}^L \ell_i^\epsilon(y_n^\epsilon) [P\{y \xi_{i-1} \leq |z(n\Delta)| < y \xi_i | v(n\Delta - \Delta)\} - P\{y \xi_{i-1} \leq |z(n\Delta)| < y \xi_i\}] \Big|_{y=y_n^\epsilon} + O(\epsilon^2).$$

As done in connection with (5.2) (where  $\alpha_\epsilon, \beta_\epsilon$  were replaced by  $\alpha, \beta$ ), we get an upper bound for the second moment by replacing  $\ell_i(y_n^\epsilon)$  by  $\ell_i$  (hence  $\hat{F}_\epsilon$  by  $\hat{F}$ ). Thus

$$(8.2) \quad E_n^\epsilon V(y_{n+1}^\epsilon) - V(y_n^\epsilon) \leq O(\epsilon^2) + 2\epsilon (y_n^\epsilon - \bar{y}) \hat{F}(y_n^\epsilon) + 2(y_n^\epsilon - \bar{y}) [\text{sum in (8.1) with } \ell_i^\epsilon(\cdot) \text{ replaced by } \ell_i].$$

Next, define  $V_1^\varepsilon(n)$  by  $V_1^\varepsilon(n) = V_1^\varepsilon(n, y_n^\varepsilon)$ , where

$$(8.3) \quad V_1^\varepsilon(n, y) = 2\varepsilon (y - \bar{y}) \sum_{j=n}^{\infty} \prod_{i=1}^L y^{\ell_i} [P\{y\xi_{i-1} \leq |z(j\Delta)| < y\xi_i | v(n\Delta - \Delta)\} \\ - P\{y\xi_{i-1} \leq |z(n\Delta)| < y\xi_i\}].$$

$|V_1^\varepsilon(n)|$  can be estimated by use of the following fact. There are  $K_0 < \infty$  and  $a > 0$  such that  $|e^{Mt}| \leq K_0 e^{-at}$ . There is an  $a_1 > 0$  and a  $K_1 < \infty$  such that for  $\tau_2 > \tau_1 > 0$  and on the set  $\{v(t) : |v(t)| e^{-a\tau_1/2} \leq 1\}$ ,

$$(8.4) \quad |P\{v(t+\tau_i) \in B_i, i=1,2 | v(t)\} - P\{v(t+\tau_i) \in B_i, i=1,2\}| \leq K_1 e^{-a_1 \tau_1}.$$

for all  $B_1, B_2$ .

In order to use (8.4) (in this application we set  $B_2 =$  range space of  $v(t)$ ), write the sum in (8.3) as

$$(8.5) \quad \sum_{j=n}^H + \sum_{j=H+1}^{\infty},$$

where  $H = \min\{m: e^{-(m-n)\Delta a/2} |v(n\Delta - \Delta)| \leq 1\} = O(1 + \max(0, \log |v(n\Delta - \Delta)|))$ . Then the first sum in (8.5) is  $O(1 + \max(0, \log |v(n\Delta - \Delta)|))$ , and the second is  $O(1)$  by (8.4) and the summability of  $\sum_{j \geq 0} \exp -a_1 j\Delta$ . Thus  $|V_1^\varepsilon(n)| = O(\varepsilon) [1 + \max(0, \log |v(n\Delta - \Delta)|)] \leq O(\varepsilon) (1 + |v(n\Delta - \Delta)|)$ . From this point on, the proof is exactly the same as that for Theorem 4. Q.E.D.

IX. THE LIMIT THEOREM

We continue to use the tilde  $\tilde{\nu}$  terminology of Section VI, and define  $\tilde{U}_n^\epsilon, \tilde{Y}_n^\epsilon, \tilde{E}_n^\epsilon$ , etc., as there. Also, set  $\tilde{z}(n\Delta) = z(n_\epsilon \Delta + n\Delta)$  and  $\tilde{v}(n\Delta) = v(n_\epsilon \Delta + n\Delta)$ . The idea now is still to prove weak convergence of  $\tilde{U}^\epsilon(\cdot)$ . We use  $\tilde{E}_n^\epsilon$  for expectation conditional on  $\{v(j\Delta), j < n + n_\epsilon\}$ . We have ((9.1b) defines  $\tilde{Y}_n^{\epsilon, N}$  by  $\tilde{U}_n^{\epsilon, N} = (\tilde{Y}_n^{\epsilon, N} - \bar{y})/\sqrt{\epsilon}$ )

$$(9.1a) \quad \tilde{U}_{n+1}^\epsilon = \tilde{U}_n^\epsilon + \sqrt{\epsilon} \hat{F}_\epsilon(\tilde{Y}_n^\epsilon) + \sqrt{\epsilon} (F_\epsilon(\tilde{Y}_n^\epsilon, \tilde{z}(n\Delta)) - \hat{F}_\epsilon(\tilde{Y}_n^\epsilon)) + o(\epsilon^{3/2}),$$

$$(9.1b) \quad \tilde{U}_{n+1}^{\epsilon, N} = \tilde{U}_n^{\epsilon, N} + \sqrt{\epsilon} [\hat{F}_\epsilon(\tilde{Y}_n^{\epsilon, N}) + (F_\epsilon(\tilde{Y}_n^{\epsilon, N}, \tilde{z}(n\Delta)) - \hat{F}_\epsilon(\tilde{Y}_n^{\epsilon, N})) + o(\epsilon^{3/2})] b_N(\tilde{U}_n^{\epsilon, N}).$$

Theorem 7. Under the conditions of Section VII, the conclusions of Theorem 5 hold, but where  $G = \hat{F}_y(\bar{y})$  and (stationary process  $z(\cdot)$  used)

$$\sigma^2 = EF^2(\bar{y}, z(0)) + 2 \int_{n=1}^{\infty} EF(\bar{y}, z(n\Delta))F(\bar{y}, z(0)).$$

Remark. If  $M, C$  or  $D$  were time-varying, then an extension of the technique is possible, provided that the time variation per step is  $O(\epsilon)$ . The limit diffusion yields information on the dependence of the performance on the parameters  $\alpha, \{\lambda_i\}, \Delta, \{\xi_i\}$ , as well as an estimate of the asymptotic variance and correlation function for small  $\epsilon$ .

Proof. Except for the unboundedness of the noise  $\{z(n\Delta)\}$ , the proof would be essentially the same as that of Theorem 5, and only an outline will be given.

Owing to the truncation  $|\tilde{U}_n^{\epsilon, N}| \leq N+1$ , the  $F_\epsilon, \hat{F}_\epsilon$  in (9.1b) can be replaced by  $F$  and  $\hat{F}$ , respectively, without changing the values, for small  $\epsilon$ . Let us make the replacement. Fix  $f(\cdot, \cdot) \in \mathcal{C}_0^{2,3}$ . Drop the superscript  $N$  on all variables for notational convenience, as done in Theorem 5. Then, by a Taylor expansion,

$$\begin{aligned}
 (9.2) \quad \mathbb{E}_n^\epsilon f(\tilde{U}_{n+1}^\epsilon, n\epsilon + \epsilon) - f(\tilde{U}_n^\epsilon, n\epsilon) &= o(\epsilon) + \epsilon f_t(\tilde{U}_n^\epsilon, n\epsilon) + \epsilon f_u(\tilde{U}_n^\epsilon, n\epsilon) \hat{F}_y(\bar{y}) \tilde{U}_n^\epsilon b_N(\tilde{U}_n^\epsilon) \\
 &+ \sqrt{\epsilon} f_u(\tilde{U}_n^\epsilon, n\epsilon) \mathbb{E}_n^\epsilon [F(\bar{y} + \sqrt{\epsilon} \tilde{U}_n^\epsilon, \tilde{z}(n\Delta)) - \hat{F}(\bar{y} + \sqrt{\epsilon} \tilde{U}_n^\epsilon)] b_N(\tilde{U}_n^\epsilon) \\
 &+ \frac{\epsilon}{2} f_{uu}(\tilde{U}_n^\epsilon, n\epsilon) \mathbb{E}_n^\epsilon [F(\bar{y} + \sqrt{\epsilon} \tilde{U}_n^\epsilon, \tilde{z}(n\Delta)) - \hat{F}(\bar{y} + \sqrt{\epsilon} \tilde{U}_n^\epsilon)]^2 b_N^2(\tilde{U}_n^\epsilon).
 \end{aligned}$$

Since the second derivative of  $\mathbb{E}_n^\epsilon F(y, \tilde{z}(n\Delta))$  with respect to  $y$  is bounded by constant  $[1 + |\tilde{v}(n\Delta - \Delta)|]$ , the next-to-last term of (9.2) can be written as

$$\begin{aligned}
 (9.3) \quad \sqrt{\epsilon} f_u(\tilde{U}_n^\epsilon, n\epsilon) \mathbb{E}_n^\epsilon [F(\bar{y}, \tilde{z}(n\Delta)) - \hat{F}(\bar{y})] b_N(\tilde{U}_n^\epsilon) \\
 + \epsilon f_u(\tilde{U}_n^\epsilon, n\epsilon) \frac{\partial}{\partial y} \mathbb{E}_n^\epsilon [F(y, \tilde{z}(n\Delta)) - \hat{F}(y)] \Big|_{y=\bar{y}} \tilde{U}_n^\epsilon b_N(\tilde{U}_n^\epsilon) + o(\epsilon) [1 + |\tilde{v}(n\Delta - \Delta)|].
 \end{aligned}$$

The last term of (9.2) can be written as (recall that  $\hat{F}(\bar{y}) = 0$ )

$$(9.4) \quad \frac{\epsilon}{2} f_{uu}(\tilde{U}_n^\epsilon, n\epsilon) \mathbb{E}_n^\epsilon [F(\bar{y}, \tilde{z}(n\Delta)) - \hat{F}(\bar{y})]^2 b_N^2(\tilde{U}_n^\epsilon) + o(\epsilon).$$

Now, we use the method of Theorem 5 in order to average out the terms of (9.2). We use  $f^\epsilon(n\epsilon) = f(\tilde{U}_n^\epsilon, n\epsilon) + \sum_{i=3}^6 f_i^\epsilon(n\epsilon)$ . Define  $f_3^\epsilon(n\epsilon)$  by (to average out the second term of (9.3))

$$f_3^\epsilon(n\epsilon) = \epsilon f_u(\tilde{U}_n^\epsilon, n\epsilon) b_N(\tilde{U}_n^\epsilon) \tilde{U}_n^\epsilon \sum_{j=n}^{\infty} \frac{\partial}{\partial y} \mathbb{E}_n^\epsilon [F(y, \tilde{z}(j\Delta)) - \hat{F}(y)] \Big|_{y=\bar{y}}.$$

By an argument similar to that used below (8.5), together with the derivative bound stated above (9.3), it can be shown that  $\mathbb{E}_n^\epsilon f_3^\epsilon(n\epsilon + \epsilon) - f_3^\epsilon(n\epsilon) = -$  (second term of (9.3))  $+ o(\epsilon) [1 + |\tilde{v}(n\Delta - \Delta)|^2]$  and that  $|f_3^\epsilon(n\epsilon)| \leq O(\epsilon) [1 + |\tilde{v}(n\Delta - \Delta)|]$ . Next, introduce  $f_4^\epsilon(n\epsilon)$  (to average out (9.4)):

$$f_4^\epsilon(n\epsilon) = \frac{\epsilon}{2} f_{uu}(\tilde{U}_n^\epsilon, n\epsilon) b_N^2(\tilde{U}_n^\epsilon) \sum_{j=n}^{\infty} [E_n^{\tilde{v}^\epsilon} F^2(\bar{y}, \tilde{z}(j\Delta)) - EF^2(\bar{y}, \tilde{z}(j\Delta))].$$

Then, as for  $f_3^\epsilon$ , we have  $|f_4^\epsilon(n\epsilon)| \leq O(\epsilon) [1 + |\tilde{v}(n\Delta - \Delta)|]$ . Using this, it is not hard to show via a small amount of manipulation that

$$\begin{aligned} E_n^{\tilde{v}^\epsilon} f_4^\epsilon(n\epsilon + \epsilon) - f_4^\epsilon(n\epsilon) &= -\frac{\epsilon}{2} f_{uu}(\tilde{U}_n^\epsilon, n\epsilon) b_N(\tilde{U}_n^\epsilon) [E_n^{\tilde{v}^\epsilon} F^2(\bar{y}, \tilde{z}(n\Delta)) - EF^2(\bar{y}, \tilde{z}(n\Delta))] \\ &\quad + o(\epsilon) [1 + |\tilde{v}(n\Delta - \Delta)|]. \end{aligned}$$

Next, introduce  $f_5^\epsilon(n\epsilon)$  in order to average out the first term of (9.3):

$$f_5^\epsilon(n\epsilon) = \sqrt{\epsilon} f_u(\tilde{U}_n^\epsilon, n\epsilon) b_N(\tilde{U}_n^\epsilon) \sum_{j=n}^{\infty} E_n^{\tilde{v}^\epsilon} F(\bar{y}, \tilde{z}(j\Delta)).$$

Then, again,  $|f_5^\epsilon(n\epsilon)| = o(\sqrt{\epsilon}) (1 + |\tilde{v}(n\Delta - \Delta)|)$  and we can write

$$(9.5a) \quad E_n^{\tilde{v}^\epsilon} f_5^\epsilon(n\epsilon + \epsilon) - f_5^\epsilon(n\epsilon) = - (\text{first term of (9.3)})$$

$$+ \epsilon E_n^{\tilde{v}^\epsilon} [f_u(\tilde{U}_{n+1}^\epsilon, n\epsilon) b_N(\tilde{U}_{n+1}^\epsilon) - f_u(\tilde{U}_n^\epsilon, n\epsilon) b_N(\tilde{U}_n^\epsilon)] \sum_{j=n+1}^{\infty} E_{n+1}^{\tilde{v}^\epsilon} F(\bar{y}, \tilde{z}(j\Delta)).$$

With a small amount of manipulation, we can show that the last term of (9.5a) equals

$$(9.5b) \quad \epsilon b_N(\tilde{U}_n^\epsilon) [f_u(\tilde{U}_n^\epsilon, n\epsilon) b_N(\tilde{U}_n^\epsilon)]_u \sum_{j=n+1}^{\infty} E_n^{\tilde{v}^\epsilon} F(\bar{y}, \tilde{z}(j\Delta)) F(\bar{y}, \tilde{z}(n\Delta)) + o(\epsilon) [1 + |\tilde{v}(n\Delta - \Delta)|].$$

Finally,  $f_6^\epsilon(n\epsilon)$  is introduced in order to average out the sum term in (9.5b) in the same way that  $f_2^\epsilon(n\epsilon)$  was used to average out (6.12) in Theorem 5. Define

$$(9.6) \quad f_6^\epsilon(n\epsilon) = \epsilon [f_u(\tilde{U}_n^\epsilon, n\epsilon) b_N(\tilde{U}_n^\epsilon) |_{u_N} b_N(\tilde{U}_n^\epsilon) \cdot \\ \cdot \sum_{j=n}^{\infty} \sum_{k=j+1}^{\infty} \{ \tilde{E}_n^\epsilon F(\bar{y}, \tilde{z}(k\Delta)) F(\bar{y}, \tilde{z}(j\Delta)) - EF(\bar{y}, \tilde{z}(k\Delta)) F(\bar{y}, \tilde{z}(j\Delta)) \}].$$

By (8.4),  $f_6^\epsilon(n\epsilon)$  is well defined and is  $O(\epsilon) [1 + |\tilde{v}(n\Delta - \Delta)|^2]$ , as will now be proved.

Define  $H$  as below (8.5) and let  $\tilde{E}_n^{\epsilon} B_{jk}^{\epsilon}$  denote the  $(j, k)$ th summand in (9.6) and write the sum in (9.6) as

$$\sum_{j=n}^H \sum_{k=j+1}^{\infty} \tilde{E}_n^{\epsilon} B_{jk}^{\epsilon} + \sum_{j=H+1}^{\infty} \sum_{k=j+1}^{\infty} \tilde{E}_n^{\epsilon} B_{jk}^{\epsilon} \equiv I + II.$$

By the argument connected with (8.5), the inner sum in  $I$  is bounded by

$$(9.7) \quad \sum_{k=j+1}^{\infty} |\tilde{E}_n^{\epsilon} B_{jk}^{\epsilon}| \leq \sum_{k=j+1}^{\infty} \tilde{E}_n^{\epsilon} |\tilde{E}_j^{\epsilon} B_{jk}^{\epsilon}| = O(1 + |\tilde{v}(n\Delta - \Delta)|).$$

Thus, by the bound on  $(H-n)$ ,  $I \leq O(1 + |\tilde{v}(n\Delta - \Delta)|^2)$ . To treat  $II$ , we note the following: there is a  $K_2 < \infty$  such that for  $H < j < k$ ,  $|\tilde{E}_n^{\epsilon} B_{jk}^{\epsilon}| \leq K_2 \exp -a_1(j-n)\Delta$ .

Also, for  $k > j$ ,

$$\tilde{E}_j^{\epsilon} F(\bar{y}, \tilde{z}(k\Delta)) \leq K_2 [\exp -a_1(k-j)\Delta + I\{ |(\exp -a(k-j)\Delta) \tilde{v}(j\Delta - \Delta)| \geq 1 \}].$$

With a little more work, these estimates yield the existence of a  $K_3 < \infty$  such that  $|\tilde{E}_n^{\epsilon} B_{jk}^{\epsilon}| \leq (1 + O(|\tilde{v}(n\Delta - \Delta)|)) K_3 \exp -a_1 \Delta [(j-n) + (k-j)]/2$ , from which the fact that  $II = O(1)$  and the last sentence of the previous paragraph both follow.

It is straightforward to show that

$$\begin{aligned} \mathbb{E}_n^t f_6^t(n\epsilon + \epsilon) - f_6^t(n\epsilon) &= -(\text{sum term in (9.5)}) \\ &+ \epsilon b_N(\tilde{U}_n^t) [f_u(\tilde{U}_n^t, n\epsilon) b_N(\tilde{U}_n^t)]_u \sum_{n=1}^{\infty} \mathbb{E} F(\bar{y}, \tilde{z}(n\Delta)) F(\bar{y}, \tilde{z}(0)) + o(\epsilon) [1 + |\tilde{v}(n\Delta - \Delta)|^2]. \end{aligned}$$

Summarizing, with  $f^t(n\epsilon)$  defined by  $f^E(n\epsilon) = f(\tilde{U}_n^t, n\epsilon) + \sum_{i=3}^6 f_i^E(n\epsilon)$ , we have

$$\begin{aligned} (9.8) \quad \mathbb{E}_n^t f^E(n\epsilon + \epsilon) - f^t(n\epsilon) &= o(\epsilon) [1 + |\tilde{v}(n\Delta - \Delta)|^2] + \epsilon f_t(\tilde{U}_n^t, n\epsilon) + \epsilon f_u(\tilde{U}_n^t, n\epsilon) \hat{F}_y(\bar{y}) \tilde{U}_n^t b_N(\tilde{U}_n^t) \\ &+ \epsilon b_N(\tilde{U}_n^t) [f_u(\tilde{U}_n^t, n\epsilon) b_N(\tilde{U}_n^t)]_u \sum_{n=1}^{\infty} \mathbb{E} F(\bar{y}, z(n\Delta)) F(\bar{y}, z(0)) \\ &+ \epsilon b_N(\tilde{U}_n^t) \frac{f_{uu}(\tilde{U}_n^t, n\epsilon)}{2} \mathbb{E} F^2(\bar{y}, z(0)) + o(\epsilon) [1 + |\tilde{v}(n\Delta - \Delta)|^2]. \end{aligned}$$

Now, if the  $\{\tilde{U}^{\epsilon, N}(\cdot)\}$  (returning to the use of superscript N) were tight for each N, then (9.8) and Theorem 1 imply that any weakly convergent subsequence of  $\{\tilde{U}^{\epsilon, N}(\cdot)\}$  converges to a diffusion with operator  $A^N$ , whose coefficients equal those of A in  $S_N$  and, hence, that the original  $\{\tilde{U}^{\epsilon}(\cdot)\}$  converge weakly to the solution of (6.3) with the G and  $\sigma$  defined in Theorem 7.

But (dropping the superscript N again)  $|\sum_{i=3}^6 f_i^E(n\epsilon)| = O(\sqrt{\epsilon}) [1 + |\tilde{v}(n\Delta - \Delta)|^2]$  and  $|\mathbb{E}_n^t f^E(n\epsilon + \epsilon) - f^E(n\epsilon)| = O(\epsilon) + o(\epsilon) [1 + |\tilde{v}(n\Delta - \Delta)|^2]$  and for any  $T < \infty$ ,  $K > 0$ , the Gaussian property implies that

$$\lim_{\epsilon \rightarrow 0} P\{\sup_{n \leq T/\epsilon} \epsilon |\tilde{v}(n\epsilon)|^2 \leq K\} = 0.$$

Thus, tightness follows by Theorem 2 of [1] or [7], as it did for the case of Theorem 1. Q.E.D.



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