MACA–An Efficient Channel Allocation Scheme in Cellular Networks

Xiaoxin Wu[1], Biswanath Mukherjee, and S.-H. Gary Chan
[1]Department of Electrical and Computer Engineering
University of California, Davis, CA 95616, U.S.A.

Abstract— **In a cellular network, a fixed number of channels is normally assigned to each cell. However, under this scheme, the channel usage may not be efficient because of the variability in the offered traffic. Different approaches such as channel borrowing (CB) and dynamic channel allocation (DCA) have been proposed to accommodate variable traffic. In this paper, we expand on the CB scheme and propose a new channel allocation scheme – mobile-assisted connection-admission (MACA) algorithm – to achieve load balancing in a cellular network. In this scheme, some special channels are used to connect mobile units from different cells; thus, a mobile unit, which is unable to connect to its own base station because it is in a heavily-loaded "hot" cell, may be able to get connected to its neighboring cold cell's base station through a two-hop link. We find that MACA can greatly improve the performance of a cellular network.**

I. Introduction

Traditionally, a set of wireless channels is assigned to a cell in a fixed manner (i.e., the so-called fixed channel-allocation scheme) at system deployment [1], [2], [3]. In this way, the channel-reuse pattern can be optimized for a static traffic load, and the management of channel assignment to a mobile terminal is simplified. However, such a scheme may not be able to efficiently accommodate fluctuating traffic in a cell; i.e., when the traffic increases, the call-blocking probability may increase to an undesirable level.

To mitigate such a shortcoming, global channel-allocation schemes have been proposed, in which the pool of channels can be dynamically assigned to a cell depending on its current traffic demand [4], [5]. However, such schemes generally require complex and centralized control. To compromise between a completely fixed channel allocation and a completely dynamic channel allocation, we propose an approach in which some "dynamic" channels can be set aside from a fixed allocation network so that a cell with a high traffic (i.e., a "hot" cell) can borrow channels from its neighboring "cold" cell (i.e., a cell with low traffic). This scheme, just like dynamic schemes, assigns more channels to a hot cell so as to accommodate more traffic in the hot cell.

The scheme is similar to the channel borrowing (CB) scheme [6], [7], in which when a cell does not have enough channels, it will "borrow" one or more channel from its neighboring cells temporarily. Although simple, CB has some problems such as "channel locking" because it changes the pre-designed frequency-reuse pattern. Another similar scheme is proposed in [8], in which users in the overlapping zone of cells will pick the channels from the cell with the least traffic. This doesn't cause the channel-locking problem; however, the problem with this approach is that only a limited number of users in the overlapping zone can use the scheme. Our scheme overcomes all of these limitations.

We illustrate our new channel-allocation scheme in Fig. 1. Effectively, we are adding an ad-hoc overlay network on the fixed-infrastructure cellular network. Channels assigned to this ad-hoc network, which we call ad-hoc channels here, can be used to help the fixed-infrastructure to achieve load balancing; in contrast, the channels in the fixed-infrastructure cellular network are called RF channels. Because of the mobile features of the ad-hoc network, we call this scheme mobile-assisted connection-admission (MACA) algorithm.

Fig. 1 shows a system with MACA, in which the hot cells are shaded. The channels drawn in solid lines are the RF channels and the channels drawn in dashed lines are the ad-hoc channels. We refer to Users D, G, and B as agents, because they act as intermediate units to help connect a user from a hot cell to a cold cell's base station. MACA normally contains two hops, but it can also contains more than two hops (as from User E to User B to User G to User G's base station), which we call multihop MACA. An user out of the coverage of the fixed wireless network, but not that far away, such as User H, can also have itself connected by taking User G as the agent.

In MACA, if ad-hoc channels are the RF channels reserved for the ad-hoc operation, we call the scheme in-band MACA. If ad-hoc channels are some other wireless channels such as infrared channels, we call the scheme out-of-band MACA. To increase the channel reuse, ad-hoc channels have lower power and can only reach a short distance compared to the normal RF channels. When MACA is needed, if a new user to a hot cell is at the edge of this cell, it can use MACA directly through an agent in a neighboring cold cell. If the new user is at the center of the hot cell or cannot reach any agent, the base station may ask a current active user who is close to a

0-7803-6454-6/00/$10.00 (C) 2000

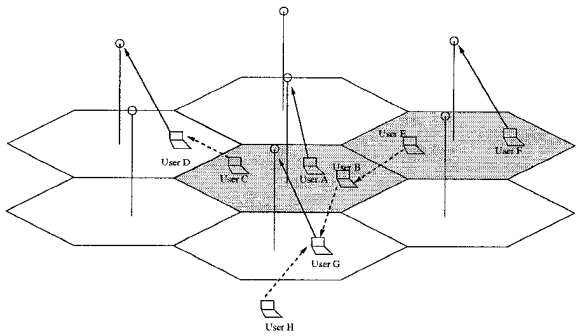

Fig. 1. A mobile network with MACA.

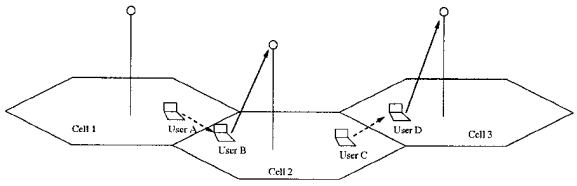

Fig. 2. Using channel switching to achieve MACA to cross cells.

neighboring cold cell to use MACA and release the local RF channel, which will be assigned to this new user. We call this operation "channel switching". "Channel switching" scheme can also help a user achieve a sort of multihop MACA (or "crossing-cell MACA"). As shown in Fig. 2, User A comes to the hot cell (Cell 1) and channels are available in Cell 3, which is separated by another hot cell, Cell 2, from Cell 1. Channel switching is used in Cell 2; thus, User C will use MACA and release the RF channel in Cell 2. This released channel can then be used by User A with MACA through User B as agent. If users and agents are uniformly distributed in cells, our analysis shows that there is a good probability to build a link between a user and an agent even if the ad-hoc channel has a very short coverage.

Because of the mobile feature of MACA, there is some complexity in MACA link set up and maintenance. However, in MACA the user only needs to find any suitable agent, not a specific one. The routing technique for MACA may be similar to that for ad-hoc networks [9], [10], but much simpler. Fixed repeaters can also be built at the edges of cells for MACA. In this case, the operation is simplified by trading off the increased cost of the fixed infrastructure.

To increase the ad-hoc channel reuse, when a local RF channel is released in a cell and some users in this cell are using MACA, the newly released RF channel will be assigned to a MACA user and the ad-hoc channel and the RF channel in the neighboring cell used in MACA are released. We call this "ad-hoc channel release" (ACR). If several users in a cell are using MACA when an RF channel in this cell is released, the MACA user with the worst quality (measured by signal power) in the ad-hoc channel or with the highest neighboring cell traffic (measured by the number of occupied channels), or the MACA user who joins the cell latest will take this RF channel and stop using MACA. Our simulation results show that, with ACR in MACA, fewer ad-hoc channels are needed.

This paper is organized as follows. In Section II, we present the operation and analysis of the system, and we use a simple two-cell model to build an analytical model to analyze the system performance with MACA. In Section III, we show some illustrative numerical results and comparisons. We conclude the study in Section IV.

II. System Operation and Analysis

A. System Operation

Like the spectrum in a normal cellular network, the spectrum for the ad-hoc channels is also divided into two parts: the traffic channels and the signaling channels. The major operational procedures are as follows:

- In a wireless network with MACA, a mobile unit which would like to be an agent will broadcast a "free" signal through the signaling channel, in which the information such as signal power, agent's ID and traffic in the cell of this agent is included. This "free" signal can only be received by the mobile units within the coverage of the ad-hoc channel. Normally, only the mobile units in cold cells (cells which have free RF channels) can act as agents, but in special cases, such as the case where crossing-cell MACA is needed, the mobile units in the hot cells can also act as agents.
- A user (an idle user or an active user) will collect these "free" signals to build an agent table. The agents are picked by the connection stability with this mobile user, which is similar to the associativity-based routing (ABR) [11] scheme in an ad-hoc network. When this user needs to use MACA, it will pick up one agent from the agent table, find a proper ad-hoc channel (the ad-hoc channel without co-channel interference), and build the connection with this agent. Once the agent gets the MACA request, it will send back an ACK to the user. Simultaneously, the agent will send a request to its base station. Once an RF channel is assigned to the agent, it will inform the user to start using MACA. The user can finally communicate with the fixed infrastructure.
- A user keeps an agent table in which it caches all the reachable agents' information. When the agent used in MACA is not suitable any more, normally because the quality of service (QoS) measured by the received bit-error rate (BER) in the ad-hoc channel degrades to a certain value caused by the motion of both the agent and the user, the mobile user will send MACA request to another agent picked from

its agent table. The new MACA link is built and the old one is released.

- The base station has to keep the information about all its users and agents. When a user who is using MACA moves out of all the agents' coverage or a newcomer to the hot cell cannot reach any agent in any cold cell, the base station will use the "channel switching" scheme, i.e., it will ask one of its active users at the edge of the cell to use MACA and release the local RF channel. This user is picked by its handoff approach; thus, it can use the channel in the foreign cell directly when it crosses the boundary.
- When the call is finished, or there is a local RF channel released and ACR is used, the MACA user will release both the ad-hoc channel and the RF channel in the agent's cell.

B. System Analysis

In this section, we use a two-dimensional Makov-chain model to analyze the system performance (i.e., new-call blocking probability) with MACA in a simple network model which has only two cells. This two-cell model can be used to approximate a linear cellular network such as a highway cellular network.

Assume two cells, Cell 1 and Cell 2, next to each other with c_R channels in each cell and c_a ad-hoc channels between the two cells. The call arrival in each cell obeys a Poisson process and the call duration time is negative exponentially distributed. Here we don't consider handoff. A call is blocked in one cell when 1) there is no free channel in both cells or 2) there is no free channel in the call's arrival cell and there is no free ad-hoc channel. Assume the arrival rates in Cell 1 and Cell 2 are λ_1 and λ_2 and the average call holding time in Cell 1 and Cell 2 are $1/\mu_1$ and $1/\mu_2$. Fig. 3 shows the state transition diagram with $c_R = 3$ RF channels in each cell and $c_a = 2$ ad-hoc channels. State (i, j) is the state that there are i active users in Cell 2 and j active users in Cell 1. From the state-transition diagram, we can find the state probabilities ($p(i, j)$), from which we can find the blocking probability in each cell. The blocking probability in Cell 1 (P_{b1}) and the blocking probability in Cell 2 (P_{b2}) are as follows:

$$p_{b1} = \sum_{i=0}^{c_R - c_a} p(i, c_R + c_a) + \sum_{i=c_R - c_a + 1}^{c_R + c_a} p(i, c_R + c_a + 1 - i) \tag{1}$$

$$p_{b2} = \sum_{j=0}^{c_R - c_a} p(c_R + c_a, j) + \sum_{j=c_R - c_r + 1}^{c_R + c_a} p(c_R + c_a + 1 - j, j). \tag{2}$$

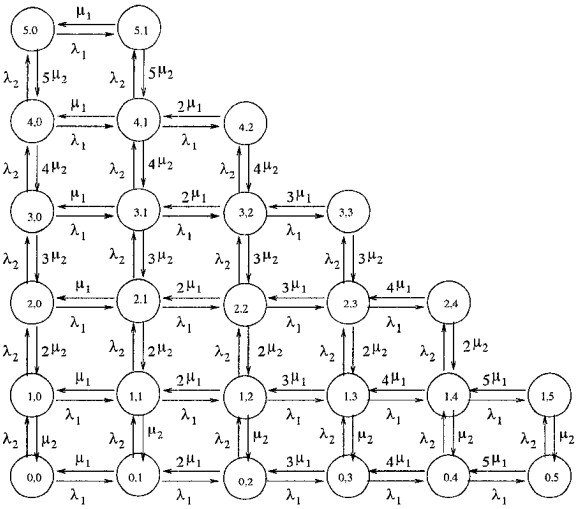

Fig. 3. State-transition diagram for MACA in a 2-cell model with $C_R = 3$ RF channels and $c_a = 2$ ad-hoc channels.

III. Numerical Results

In this section, we compare the MACA system performance with our analysis model and a simulation model. We refer to ρ as the load in each cell, and $\rho = \lambda/c\mu$, where c is the total number of RF channels in each cell, while λ and μ are the arrival rate and departure rate in each cell, respectively.

A. Numerical Results for the Two-Cell Model

Fig. 4 shows the performance of MACA compared with those of the DCA and the FCA schemes in a two-cell model. We assign 30 channels in each cell. Two channels from each cell are used for ad-hoc channels for the inband MACA; thus, there are 4 ad-hoc channels. The out-of-band MACA also has 4 ad-hoc channels. In DCA, 60 channels are used by the users from both of the cells. We find that the performance of out-of-band MACA is always better than that of FCA while the performance of inband MACA is better than that of FCA only at light load. We also find that the performance of DCA is better than that of MACA with a small number of ad-hoc channels.

Fig. 5 shows that, when the number of ad-hoc channels is large enough, the performance of out-of-band MACA will eventually match that of DCA in the two-cell model.

B. Simulation Results in a 7×7 Cell Network Model

A two-dimensional model is more realistic for a cellular network in an urban area. However, developing an analytical model for a two-dimensional cellular network with MACA is difficult, so we resort to simulation results. In the two-dimensional model, since each cell has more neighboring cells to use MACA with, the performance is better than that in the one-dimensional model.

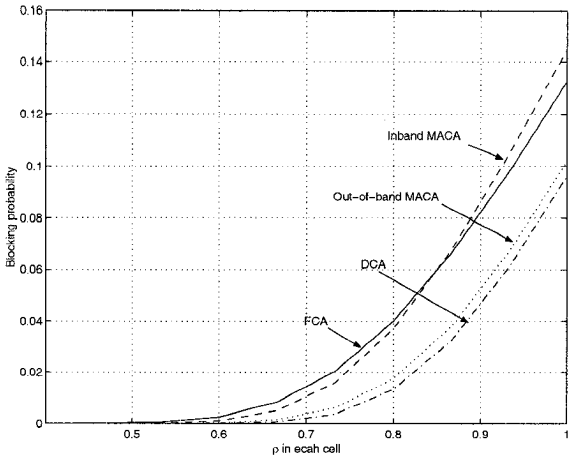

Fig. 4. Blocking probability comparison in a two-cell model.

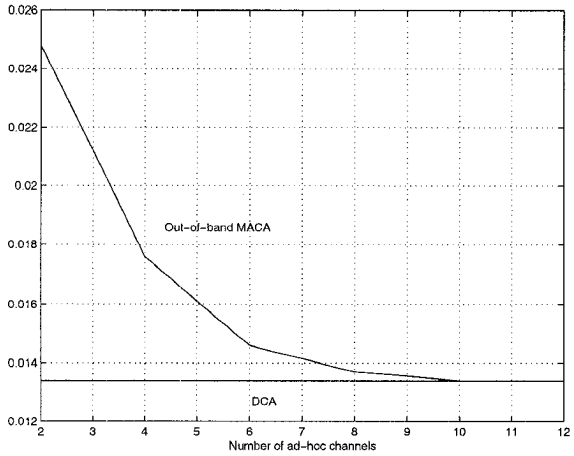

Fig. 5. Blocking probability for DCA and out-of-band MACA with different numbers of ad-hoc channels for $\rho = 0.8$.

Here, we examine a simple 7×7 two-dimensional cellular system, in which there are 7 rows of cells, and each row has 7 cells. Each cell has Poisson call arrivals with the same arrival rate λ. The call holding time is negative exponentially distributed with mean $1/\mu$. We assume that there are 120 different channels in the entire network and we set the cluster size for frequency reuse to be 4, i.e., the channel with the same frequency cannot be reused in two neighboring cells. For FCA, there are 30 channels in each cell. For the inband MACA scheme, if from one cell n channels are used for ad-hoc channels, then there are $4 \times n$ ad-hoc channels in the system. The constraint for the ad-hoc channel reuse is that the same ad-hoc channel cannot be reused in the same cell. We simulate approximately 5 million arrivals to the 7×7 cellular network. The blocking probability we use for the system performance is the total number of blocked calls divided by the total number of call arrivals in the entire system during the simulation run.

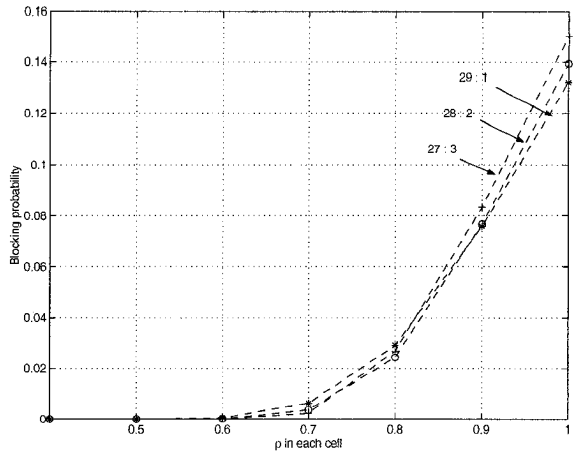

Fig. 6. Blocking probabilities for inband MACA with different number of ad-hoc channels (1, 2, 3).

Fig 6 shows the performance of three inband MACA schemes with different numbers of ad-hoc channels (1, 2, and 3 per cell). It shows that more ad-hoc channels will lead to a little better performance at low load and worse performance at high load, although the differences are not very significant. It appears that the inband MACA with 28 fixed channels in each cell and 8 ad-hoc channels in the system is a good compromise.

Fig. 7 shows the overall blocking probability comparison among different schemes. For the inband MACA, we set aside 8 ad-hoc channels in the system and use 28 RF channels in each cell. For out-of-band MACA, we use 8 ad-hoc channels. The number of RF channels in each cell is 30. We also show the blocking probability in a hybrid channel-allocation scheme, in which each cell has 28 fixed channels and 8 channels are used as global dynamic channels. We find that, at light load, inband MACA has better performance than FCA, but at heavy load, the performance of inband MACA is worse. Out-of-band MACA has much better performance than FCA, inband MACA, and the hybrid scheme. DCA still has the best performance. Although not shown here, we found from our simulations of the 7×7 network model, with MACA, that the cells at the corners or at the edges of the network layout have larger blocking probabilities since they have fewer neighboring cells to use MACA with, while in DCA, these cells have smaller blocking probabilities since they have less co-channel interference.

Fig. 8 shows the improvement when using ACR for both inband MACA and out-of-band MACA. In our simulation, we try to ask the user who will use MACA for the longest time to release the channel. Since it is difficult to predict how long a call holding time will be, we pick the user joining the cell the latest to stop using MACA such that there is a relatively larger chance that this user may have longer holding time left. The results demon-

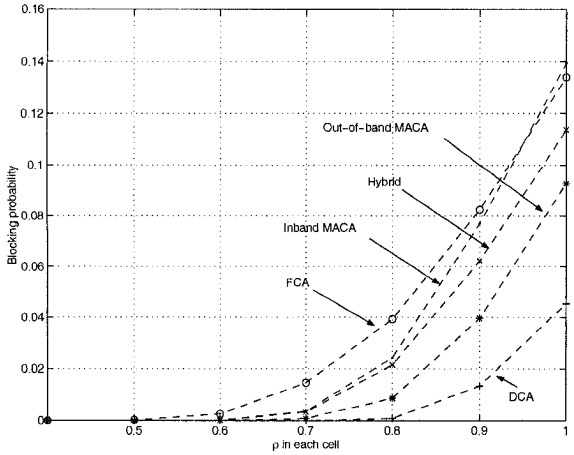

Fig. 7. Blocking probabilities for different schemes.

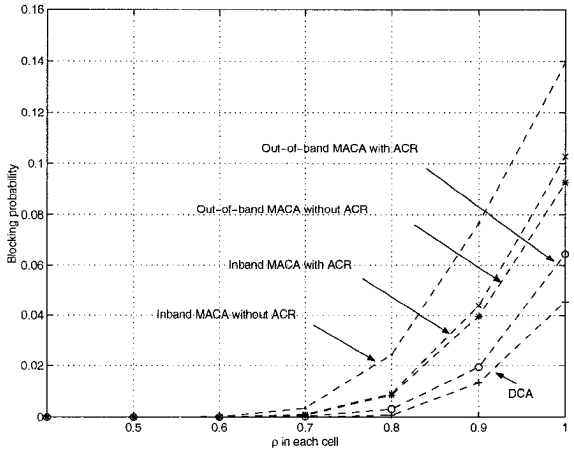

Fig. 8. Performance improvement with ACR.

strate that ACR can greatly improve the performance of MACA.

Fig. 9 shows the performance of out-of-band MACA when the number of ad-hoc channels changes. We find that, to achieve the same performance, MACA scheme with ACR needs fewer ad-hoc channels than the MACA scheme without ACR. This figure shows that, when the number of ad-hoc channels becomes large, the performance of MACA approaches the performance of DCA. If the number of ad-hoc channels is large enough, the performance of both the MACA with and without ACR is better than DCA.

IV. Conclusion

In this paper, we proposed a new channel-allocation scheme, called MACA, in which special channels are deployed between cells to achieve load balancing. We examined the performance of MACA with a 2-cell analytical model and a 7×7-cell simulation model. We find that MACA can greatly improve the performance over FCA.

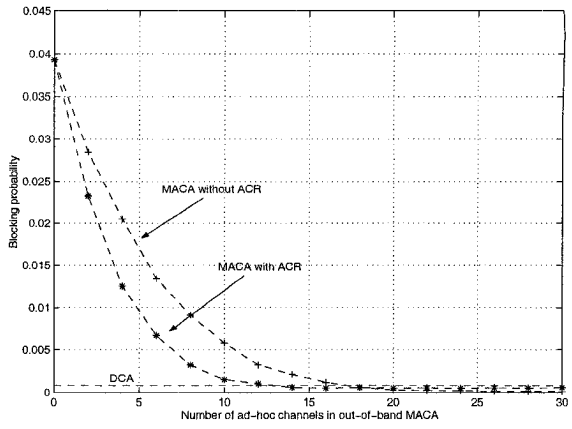

Fig. 9. Blocking probability for out-of-band MACA with different numbers of ad-hoc channels for $\rho = 0.8$

In some case, the performance of MACA is comparable to DCA.

References

[1] A. A. Ahinoda and M. D. Yacoub, "Combined Techniques for Channel Allocation Algorithms in mobile radio systems," *IEEE Proceedings online*, vol. 144, no. 3, pp. 205-210, June 1997.

[2] I. Katzela and M. Naghshineh, "Channel Assignment Schemes for Cellular Mobile Telecommunication Systems: A Comprehensive Survey," *IEEE Personal Communications*, vol. 3, pp. 10-31, June 1996.

[3] P. C. Tai and S. S. Rappaport, "Generalized Fixed Channel Assignment in Microcellular Communication Systems," *IEEE Transactions on Vehicular Technology*, vol. 43, pp. 713-721, Aug. 1994.

[4] L. J. Cimini, G. J. Foschini, C. -L. I, and Z. Miljanic, "Call Blocking Performance of Distributed Algorithms for Dynamic Channel Allocation," *IEEE Transactions on Communications*, vol. 42, pp. 2600-2607, Aug. 1994.

[5] R. Saunders and L. Lopes, "Performance Comparison of Global and Distributed Dynamic Channel Allocation Algorithms," *Proc., IEEE Vehicular Technology Conference (VTC)*, Stockholm, Sweden, vol. 2, pp. 799-803, June 1994.

[6] S. K. Das, S. K. Sen, and R. Jayaram, "A Structured Channel Borrowing Scheme for Dynamic Load Balancing in Cellular Networks," *Proc., 17th International Conference on Distributed Computing Systems*, pp. 1216-1228, May 1997.

[7] J. C. Chung, C. H. Po, and T. S. Tian, "A Channel Borrowing Scheme in a Cellular Radio System with Guard Channels and Finite Queues," *Proc., IEEE ICC*, vol. 2, pp. 1168-1172, June 1996.

[8] B. Eklundh, "Channel Utilization and Blocking Probability in a Cellular Mobile Telephone System with Directed Retry," *IEEE Transactions on Communications*, vol. COM-34, pp. 329-337, Mar. 1986.

[9] E. M. Royer and K. T. Chai, "A Review of Current Routing Protocols for ad hoc Mobile Wireless Networks," *IEEE Personal Communications*, vol. 6, pp. 46-55, Apr. 1999.

[10] S. R. Das, R. Castaneda, J. Yan, and R. Sengupta, "Comparative Performance Evaluation of Routing Protocols for Mobile, ad hoc Networks," *Proc., 7th International Conference on Computer Communications and Networks*, pp. 153-161, Oct. 1998.

[11] C.-K. Toh, "Associativity-Based Routing for Ad-Hoc Mobile Networks," *Wireless Pers. Commun. J., Special Issue on Mobile Networking and Computing System*, vol. 4, no. 2, pp. 103-139, Mar. 1997.