Performance of a Multi-Channel Packet CDMA Protocol in a Fading Environment*

A. Chockalingam†, Weiping Xu, and Laurence B. Milstein
Department of Electrical and Computer Engineering
University of California, San Diego
9500 Gilman Drive, La Jolla, CA 92093-0407, USA

***Abstract*—In this paper, we analyze the throughput performance of a multi-channel wireless packet communication scheme using CDMA in the presence of Rayleigh fading. There are N mobile users which share M traffic channels ($N \geq M$), each of which is assigned a unique spreading sequence. Transmission attempts on the uplinks are made based on the busy/idle status of the M receivers, which is broadcast by the base station, every slot, on the downlink. A fading i.i.d channel model is used to describe the packet successes and failures. An analytical expression for the per channel throughput is derived, and simulation results are shown to verify the analysis. The proposed scheme provides an efficient, yet flexible, architecture for the next generation wireless systems.**

I. INTRODUCTION

Next generation wireless networks are designed to support high data rates, packet oriented transport, and multimedia traffic handling. To achieve this goal, among a multitude of other issues (e.g., physical layer issues like modulation techniques and RF concerns at high data rates), the design and investigation of efficient media access protocols need to be addressed. In this context, several new access protocols are being investigated [1], [2], [3]. In this paper, we propose and analyze a flexible, yet efficient, wireless access protocol based on *multi-channel packet CDMA*. In [4], we presented a media access protocol which makes use of the uplink (mobile-to-base station link) channel status information, which is conveyed to the mobiles through a *busy/idle flag* on the downlink (base station-to-mobile link) broadcast. The throughput performance of the system that uses a single traffic channel was analyzed in a fading environment. Here, we extend the protocol to utilize multiple traffic channels, each channel using a unique spreading sequence. Such an approach results in a system configuration that is scalable in a flexible manner to meet the high bandwidth requirement of the multimedia traffic. As we know, mobile radio channels are severely affected by time-varying losses due to distance, shadowing (blockage due to buildings, trees, etc.) and multipath fading. While the variation in the losses due to distance and shadowing is relatively slow, the variation due to multipath fading is quite rapid. The fading envelope due to multipath often follows a *Rayleigh* distribution, and the envelope squared (i.e., the power) has an *exponential* distribution [5]. In this paper, we assume that the slowly varing signal losses caused by distance and shadow are perfectly compensated through power control, whereas the rapid signal variations due to multipath fading remain uncompensated. We employ an i.i.d channel model to analyze the throughput characteristics of the proposed multi-channel packet CDMA protocol in a Rayleigh fading environment.

The paper is organized as follows. We present the multi-channel packet CDMA protocol description in Section 2, analyze its throughput performance as well as the slotted ALOHA CDMA protocol throughput in the presence of Rayleigh fading in Section 3, and show the numerical results in Section 4. Section 5 gives the conclusions

II. MULTI-CHANNEL PACKET CDMA PROTOCOL

The system is configured such that N mobile users share M traffic channels ($N \geq M$) on the uplink. All the uplink channels are slotted to one packet duration. Each uplink is assigned a unique spreading sequence such that the packets transmitted on a given channel are spread using its assigned spreading sequence. In other words, all the users in the network can use one of M different spreading sequences. The base station is provided with M receivers to demodulate all the uplink channels' traffic. Based on the busy/idle status of the M receivers, the base station broadcasts an M-bit *busy/idle word*, every slot, on the downlink. The busy/idle flag corresponding to each channel is set or reset depending on whether or not packets are being transmitted on that channel.

We consider each message originating at the mobiles to consist of two segments, namely a header segment and a data segment. The header segment, which carries a preamble for spreading code acquisition, and control information like the destination address, the number of packets in the data segment etc., is of one packet duration. The data segment, which represents the actual traffic, consists of a random number of packets. Transmission attempts are made by sending the header packet at the slot boundaries.

Each mobile, once it receives a message to be sent to the base station, first checks the status of the busy/idle word which it periodically receives from the base station on the downlink. If all the M busy/idle flags indicate busy status, the mobile refrains from making a transmission attempt, and reschedules the attempt to a later time. If one or more flags indicate an idle status, then the mobile *randomly* picks one of these idle uplink channels, and makes a transmission attempt by sending a header packet in the immediately following slot on the chosen uplink. The mobile expects the base station to respond to this header packet by setting the corresponding busy/idle flag to busy, in the event of successful header

---

*This work was partially supported by TRW Systems Integration Group, Airtouch Communications, and the MICRO program of the State of California.

†The first author is presently with Qualcomm, Inc., 6455 Lusk Boulevard, San Diego, CA 92121-2779. E-mail: achockal@qualcomm.com.

0-7803-3659-3/97 $10.00 ©1997 IEEE

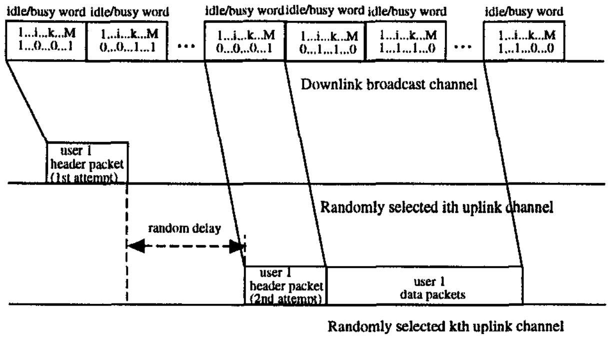

Fig. 1. Multi-channel packet CDMA protocol operation

packet reception. If this happens, the mobile transmits the data packets continuously on the uplink until all the packets in the message are sent. The base station resets the flag back to idle once the entire message transmission is complete. In the event of the header packet being lost (either due to collision among simultaneous transmissions from many users or due to channel introduced errors), the base station makes no response. Thus, the continued idle status of the flag prompts the mobiles to reschedule their transmission attempts to a later time. Figure 1 illustrates the operation of the proposed protocol for a given user. The above scheme is both flexible and efficient for the following reasons: First, the system can be scaled up or down simply by adding new or removing existing channels (i.e., increasing or decreasing M) based on the bandwidth needs of the network. Second, the concept of transmitting a header packet prior to the transmission of data packets allows collisions to be resolved within one packet interval so that packet losses due to collision are minimized. More importantly, the loss of throughput due to the overhead time involved in the code acquisition process in a packet CDMA system can be substantially reduced in the proposed scheme by providing the acquisition overhead bits only in the header packets and not in the data packets.

III. PERFORMANCE ANALYSIS

A. The proposed protocol

To analyze the system, we assume that the busy/idle word on the downlink is received both instantaneously and error-free at all the mobiles. In practice, the the busy/idle word could be corrupted by the channel (a busy status being flipped to idle status and vice versa), and thus error control techniques could be adopted to improve the reliability of the busy/idle word reception. The instantaneous feedback assumption can be valid where the delays due to propagation and processing are negligibly small compared to the slot duration. Further, we assume perfect power control and neglect the effect of capture. The length of each message (measured in integer numbers of data packets), x, is assumed to have a geometric distribution with a parameter g_m, i.e.,

$$\text{prob(message length} = x) = g_m(1-g_m)^{x-1}, x = 1, 2, 3, \ldots \quad (1)$$

Following the above description, we model the system using three different states, as shown in Figure 2. The *thinking* state is defined as the state in which a mobile generates a new message

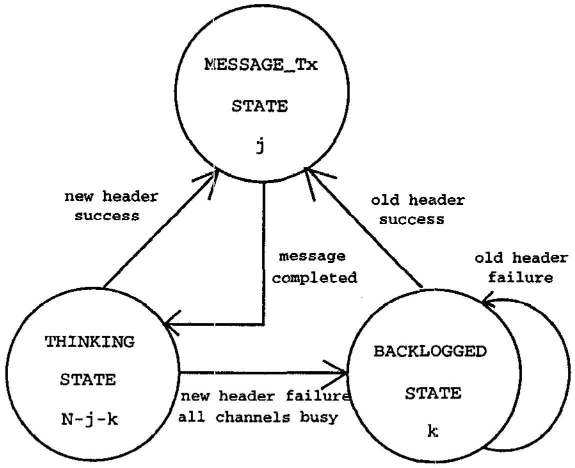

Fig. 2. Three state system model

with a probability λ, randomly chooses an idle uplink channel (if available), and transmits the header packet in the immediately following slot. If the header packet transmission is successful, the mobile moves from the *thinking* state to a *message_tx* state, in which it transmits the data packets continuously until all the packets in the message are sent, and then moves back to the *thinking* state. The mobile moves from the *thinking* state to a *backlogged* state if all the uplink channels are found busy upon arrival of a message. Similarly, if the header packet is lost due to collision or bad channel conditions, the mobile moves from the *thinking* state to the *backlogged* state. In the *backlogged* state, the mobile rechecks the status of the uplink channels after a random number of slots. This retransmission attempt delay is assumed to be geometrically distributed with parameter g_r. If a mobile in the *backlogged* state fails to retransmit its header packet successfully, it stays in this state until its header packet transmission is successful, after which it moves to the *message_tx* state.

Let x_t be the number of mobiles in the *message_tx* state and y_t be the number of mobiles in the *backlogged* state. The one step transition probability that the system moves from $(x_t = j, y_t = k)$ at time t to $(x_{t+1} = l, y_{t+1} = m)$ at time $t+1$ is given by

$$\begin{aligned} P_{jk,lm} &= \sum_{n=0}^{N-j} \sum_{c_s=0}^{min(M-j,n)} \binom{N-j-k}{a} \lambda^a (1-\lambda)^{N-j-k-a} \\ &\quad \cdot \binom{k}{n-a} g_r^{n-a}(1-g_r)^{k-n+a} \binom{j}{l-c_s} g_m^{c_s+j-l} \\ &\quad \cdot (1-g_m)^{l-c_s} f(c_s|n,j,k), \end{aligned} \quad (2)$$

where M is the total number of the spreading codes (i.e., the number of uplink channels), N is the total number of mobiles, $N \geq M$, $0 \leq j \leq M$, $0 \leq k \leq N-j$, $0 \leq l \leq M$, $0 \leq m \leq N-l$, $a = m - k + c_s$ is the number of users which generate a new packet in a slot time, g_m is the average probability of leaving the *message_tx* state, and $f(c_s|n,j,k)$ is a conditional probability that there are c_s header packets successfully transmitted if n users (from both the *thinking* state and the *backlogged* state) transmit simultaneously. The probability $f(c_s|n,j,k) \equiv f(c_s|n, M-j)$ is evaluated by a recursive expression,

$$\begin{aligned} f(c_s|n, M-j) &= \sum_{\substack{i=0\\ i\neq 1}}^{n} p_n^i f(c_s|n-i, M-j-1) \\ &\quad + p_n^1 f(c_s-1|n-1, M-j-1)(1-P_E) \\ &\quad + p_n^1 f(c_s|n-1, M-j-1)P_E, \end{aligned} \tag{3}$$

where $p_n^i \triangleq \binom{n}{i}(1-\frac{1}{M-j})^{n-i}(\frac{1}{M-j})^i$ is the probability that i out of n users transmit over an arbitrary channel, such as the first channel, with the initial conditions

$$f(c_s|n,0) = \begin{cases} 1 & \text{if } c_s = 0 \text{ and any } n \\ 0 & \text{if } c_s > 0 \text{ and any } n \end{cases}, \tag{4}$$

$$f(c_s|0,m) = \begin{cases} 1 & \text{if } c_s = 0 \text{ and any } m \\ 0 & \text{if } c_s > 0 \text{ and any } m \end{cases}, \tag{5}$$

$$f(c_s|1,m) = \begin{cases} P_E & \text{if } c_s = 0 \text{ and } m \geq 1 \\ 1-P_E & \text{if } c_s = 1 \text{ and } m \geq 1 \\ 0 & \text{if } c_s > 1 \text{ and } m \geq 1 \end{cases}, \tag{6}$$

$$f(c_s|n,1) = \begin{cases} 1 & \text{if } c_s = 0 \text{ and } n > 1 \\ 0 & \text{if } c_s > 0 \text{ and } n > 1 \end{cases}, \tag{7}$$

and

$$f(c_s|n,m) = 0 \text{ if } c_s < 0, \tag{8}$$

where P_E is the average probability of a packet error. By modeling the packet success/failure as the outcome of a comparison of the instantaneous signal-to-noise ratio to a threshold (i.e., if the received power is above the threshold, the packet is successfully decoded with probability 1; otherwise, it is lost with probability 1), the expression for P_E, for a multiplicative Rayleigh fading channel, can be derived as [4]

$$P_E = 1 - e^{-1/F}, \tag{9}$$

where $1/F$ is the comparison threshold, F being the fading margin of the system.

Let $\boldsymbol{P} = (P_{jk,lm})$ be the probability transition matrix and $\boldsymbol{\Pi} = \{\pi_{jk}\}$ denote the steady-state probability vector, which is obtained by

$$\boldsymbol{\Pi} = \boldsymbol{\Pi P}, \tag{10}$$

and

$$\sum_{j=0}^{M}\sum_{k=0}^{N-j} \pi_{jk} = 1. \tag{11}$$

The network throughput, θ, which is defined as the average number of packets successfully transmitted per time slot, is obtained from the average number of successful message packets, $E\{S_d\}$, and the average number of successful header packets, $E\{S_h\}$, in the steady state as

$$\theta = E\{S_d\} + E\{S_h\}, \tag{12}$$

where

$$E\{S_d\} = \sum_{j=1}^{M}\sum_{k=0}^{N-j} j\pi_{jk}(1-P_E) \equiv E\{S_n\}(1-P_E). \tag{13}$$

$E\{S_n\}$ is the average number of users in the *message_tx* state. The average number of successful header packets, $E\{S_h\}$, is obtained as

$$\begin{aligned} E\{S_h\} &= \sum_{j=0}^{M}\sum_{k=0}^{N-j}\sum_{l=0}^{M}\sum_{m=0}^{N-l} \pi_{jk} \sum_{n=1}^{N-j}\sum_{c_s=0}^{min(M-j,n)} c_s \binom{N-j-k}{a} \\ &\quad \cdot\lambda^a(1-\lambda)^{N-j-a}\binom{k}{n-a} g_r^{n-a}(1-g_r)^{k-n+a} \\ &\quad \cdot\binom{j}{l-c_s} g_m^{c_s+j-l}(1-g_m)^{l-c_s} f(c_s|n,j,k). \end{aligned} \tag{14}$$

Finally, we obtain the average channel throughput, i.e., the average number of packets successful transmitted per slot per channel, as

$$\theta_c = \frac{\theta}{M}. \tag{15}$$

Note that if $M = 1$ and $\lambda = g_r$, the numerical result obtained by Eqn.(15) is the same as that obtained by

$$\theta = \frac{N\lambda(1-\lambda)^{N-1}(1-P_E)(g_m+1-P_E)}{g_m + N\lambda(1-\lambda)^{N-1}(1-P_E)}, \tag{16}$$

which is the expression obtained in [4] for a single channel analytical model using a Bernoulli arrival process and an i.i.d. fading process.

B. Slotted ALOHA CDMA

The throughput expression for a multi-channel slotted ALOHA type CDMA scheme [6] is obtained below in order to draw a performance comparison with the proposed protocol. In a slotted ALOHA CDMA protocol, the mobiles can be in either of the two states, namely, the *thinking* state and the *backlogged* state. In the *thinking* state, the mobiles generate new data packets with probability λ in each slot. Since there is no busy/ide flag mechanism to sense the channel, the mobile would randomly select any one of the spreading codes and transmit the packet in the following slot. If packet transmission fails, then the mobile enters the *backlogged* state, in which a retransmission attempt is made after a geometrically distributed number of slots.

Let x_t represent the number of mobiles in the *backlogged* state at the end of slot t. The one step transition probability, from $x_t = j$ to $x_{t+1} = k$, is given by

$$\begin{aligned} P_{jk} &= \sum_{n=0}^{N}\sum_{c_s=0}^{min(M,n)} \binom{N-j}{b}\lambda^b(1-\lambda)^{N-j-b} \\ &\quad \cdot\binom{j}{n-b} g_r^{n-b}(1-g_r)^{j-n+b} f(c_s|n,j), \end{aligned} \tag{17}$$

where $0 \leq j \leq N$, $0 \leq k \leq N$, $b = k - j + c_s$ is the number of new packets, and $f(c_s|n,j)$ is the conditional probability that there are c_s packets successfully transmitted if n users transmit simultaneously. The probability $f(c_s|n,j)$ is obtained from (3) by setting $j = 0$. As before, the steady-state probability vector, $\boldsymbol{\Pi}^{(s)} = \{\pi_j\}$, and the transition probability matrix, $\boldsymbol{P}^{(s)} = (P_{jk})$, have the relation

$$\boldsymbol{\Pi}^{(s)} = \boldsymbol{\Pi}^{(s)}\boldsymbol{P}^{(s)}, \tag{18}$$

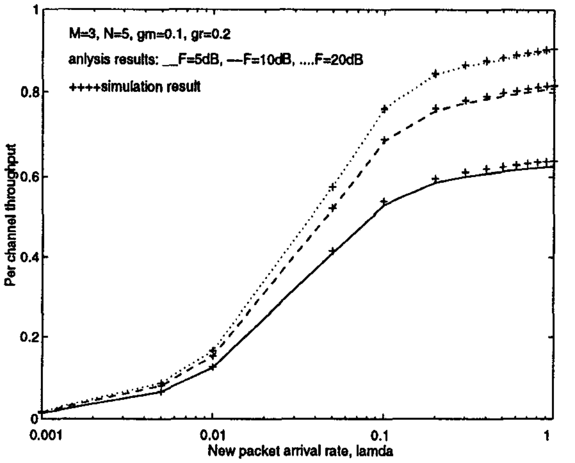

Fig. 3. Comparison of simulation and analysis on the per channel throughput

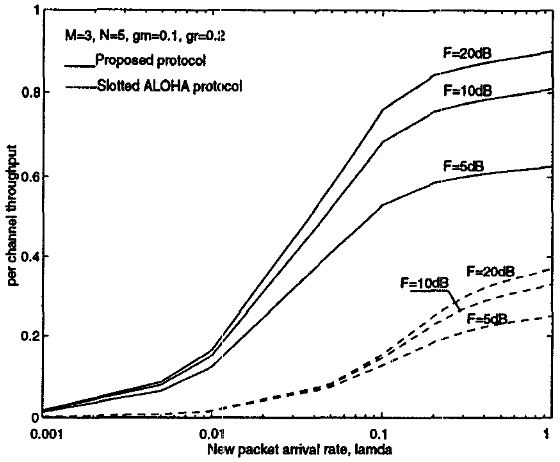

Fig. 4. Effect of the marginal fading on the per channel throughput

and

$$\sum_{j=0}^{N} \pi_j = 1. \tag{19}$$

The network throughput can be derived as

$$\begin{aligned}\theta^{(s)} &= \sum_{k=0}^{N}\sum_{j=0}^{N}\pi_j \sum_{n=1}^{N}\sum_{c_s=1}^{min(M,n)} c_s \binom{N-j}{b}\lambda^b(1-\lambda)^{N-j-b}\\ &\binom{j}{n-b} g_r^{n-b}(1-g_r)^{j-n+b} f(c_s|n,j). \end{aligned}\tag{20}$$

IV. NUMERICAL RESULTS

Numerical results for the per channel throughput are generated for $M = 3$, $N = 5$, $g_m = 0.1$, and $g_r = 0.2$, and plotted in Figure 3. The various values of fading margins considered are 5, 10, and 20 dB. Note that a g_m value of 0.1 corresponds to an average message length of 10 data packets (since $1/g_m$ is the mean of a geometric distribution with parameter g_m). Similarly, the retransmission delay parameter $g_r = 0.2$ means that the average time between retransmission attempts is 5 slots. To verify the analytical results, simulations are carried out, and the simulation results are also plotted. It can be seen that the proposed multi-channel packet CDMA scheme, in addition to being flexible, offers high values of per channel throughput as well. For example, when the fading margin is 20 dB (a value that is high enough to render the channel almost noiseless), the maximum throughput achieved is around 0.9. Even with practical values of fading margin, say 10 dB, the resulting maximum throughput is in excess of 0.8. When the fading margin decreases to 5 dB, the maximum throughput degrades to 0.63. It is also noted that both the analytical and simulation results closely match one-another.

Figure 4 compares the performance of the proposed packet CDMA scheme with that of the slotted ALOHA CDMA scheme for which the throughput expression is given in Eqn. (20). As expected, the proposed scheme easily outperforms the slotted ALOHA scheme because the proposed scheme makes use of both the feedback from the base station and the multiple data packets per message.

The effect of the number of channels, M, on the throughput characteristics of the proposed protocol is shown in Figure 5 for $N = 5$, $F = 10$ dB, $g_m = 0.1$, and $g_r = 0.4$. We find that at low arrival rates, a single channel system ($M = 1$) offers higher throughput than does a multi-channel system ($M = 2, 3$). This is because in the absence of enough traffic at the mobiles, all the channels go underutilized. But the behavior reverses (i.e., the single channel system offers less throughput than the mutli-channel system) at high arrival rates, where a single channel system looses more capacity through higher collision rates than does a mutli-channel system.

Finally, the throughput performance as a function of the retransmission delay parameter, g_r, and the new packet arriving rate, λ, is shown in the 3-D surface graphic, Fig. 6, and the 2-D contour, Fig. 7, for $N = 5$, and 10, $M = 3, N = 5$, $F = 10dB$, and $g_m = 0.1$. We see that it is possible to dynamically choose the retransmission delay parameter along the contour lines to achieve the maximum throughput according to the traffic quantities in the network. For example, to reach the maximum throughput, we choose $g_r = 0.1$ for N=5 at the new packet arrival rate $\lambda = 0.2$, and increase g_r to 0.18 at $\lambda = 0.1$.

V. CONCLUSIONS

We analyzed the throughput performance of a multi-channel wireless packet CDMA scheme in the presence of Rayleigh fading. The proposed scheme made use of multiple slotted channels, each of which employed a unique spreading sequence. The efficiency of the protocol is high because the transmisssion attempts on the uplink channels are made based on the busy/idle status of the receivers, which is broadcast by the base station, every slot, on the downlink. The resulting architecture is highly flexible in the sense

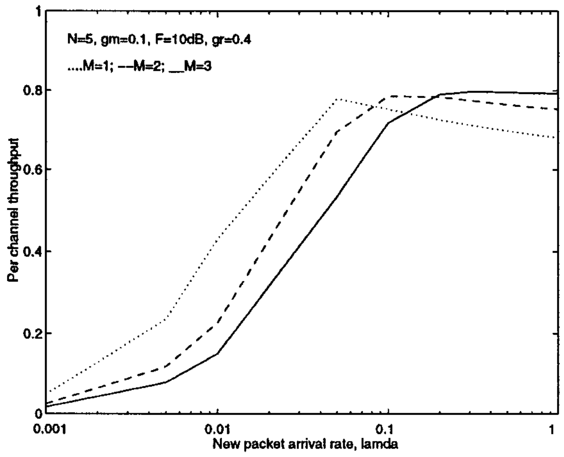

Fig. 5. Effect of the number of channels (M) on the per channel throughput

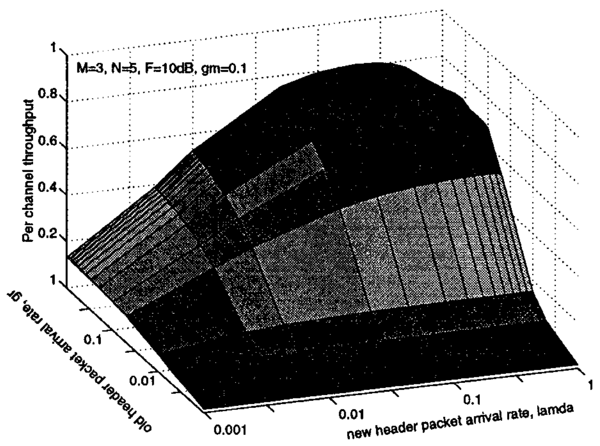

Fig. 6. Effect of g_r and λ on the per channel throughput 3-D surface graphic

that the system can be scaled up or down simply by adding or removing channels based on the bandwidth needs of the network. In addition, the concept of a header packet for each message resulted in significantly low overhead time employed for the code acquisition. Both analytical and simulation results show that the proposed scheme easily outperforms the slotted ALOHA CDMA scheme, and is suitable for next generation wireless networks. Another important aspect of the performance study is the protocol *delay performance*. Other possible extensions to the current work are analyses to investigate the effect of capture and non-zero error rate on the busy/idle flags transmission.

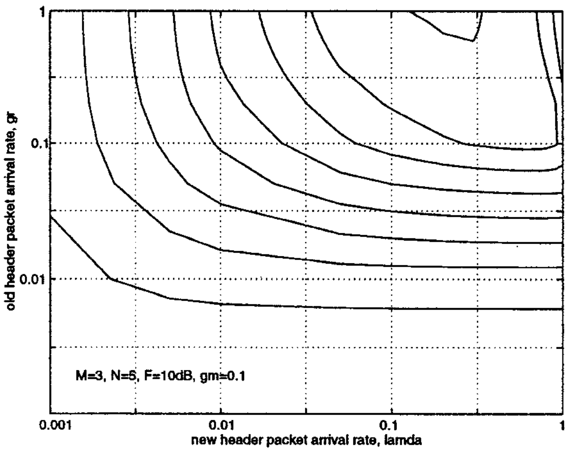

Fig. 7. Effect of g_r and λ on the per channel throughput 2-D contour graphic

REFERENCES

[1] D. Raychaudhuri, and N. D. Wilson, "ATM-based transport architecture for multiservices wireless personal communication networks," *IEEE Jl. Sel. Areas Commun.*, vol 12, No. 8, pp. 1401-1414, October 1992.

[2] G. M. Stamatelos, and D. D. Falconer, "Packet diversity techniques for a broadband ATM-oriented radio indoor environment", *Conf. Rec., IEEE ICC'94*, 1994.

[3] M. J. Mctiffin, A. P. Hulbert, T. J. Ketseoglou, W. Heimsch, and G. Crisp, "Mobile access to an ATM network using a CDMA air interface", *IEEE Jl. Sel. Areas Commun.*, Vol. 12, No. 5, June 1994.

[4] A.Chockalingam, L. B. Milstein, and M. Zorzi, "Performance of a wireless media access protocol on a Markovian fading channel," *Conf. Rec. IEEE GLOBECOM'96*, pp. 1769-1773, London, November 1996.

[5] W.C. Jakes, Jr., *Microwave mobile communications*, New York: John Wiley & Sons, 1974.

[6] Z. Zhang, and Y. J. Liu, "Performance analysis and simulation of code division multiple access cellular digital networks," *Conf. Rec., IEEE VTC'93*, 1993.