Performance Analysis of RLC/MAC Protocol in General Packet Radio Service

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Abstract—**We analyze the throughput and delay performance of the radio link control/media access control (RLC/MAC) protocol layers in General Packet Radio Service (GPRS) networks. Several time-slotted uplink radio frequency channels are shared by the mobiles on a $request-reservation$ based multiple access scheme. Using the theory of Markov chains, we derive expressions for the uplink throughput and delay performance of the GPRS-MAC protocol. Further, we evaluate the performance of the RLC (Acknowledged mode) layer using block level retransmission (as defined in the current GPRS) and compare it with that of using slot level retransmission (which is in the proposal stage). We show that slot level retransmission at the RLC layer performs better than block level retransmission, particularly when the channel error rate is high.**

I. Introduction

General Packet Radio Service (GPRS) is a packet mode wireless system that has been standardized to operate on GSM infrastructure, by introducing new packet support nodes and associated protocol stacks [1]. A portion of the radio resources (channel frequencies) in an existing GSM system may be dedidated for packet data services using GPRS. Alternatively, GPRS and GSM services may dynamically share the same radio resources. Thus, GSM voice services and GPRS data services can co-exist on the same GSM infrastructure. GPRS provides IP connectivity to mobile users by adding new packet nodes, namely, Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN), to the existing GSM infrastructure [1]. The protocol stacks at the Mobile Station (MS), Base Station Subsystem (BSS), SGSN, and GGSN are shown in Figure 1. In this paper, we are concerned with the *Radio Link Control/Media Access Control* (RLC/MAC) layers, whose peers are at the MS and the BSS [2].

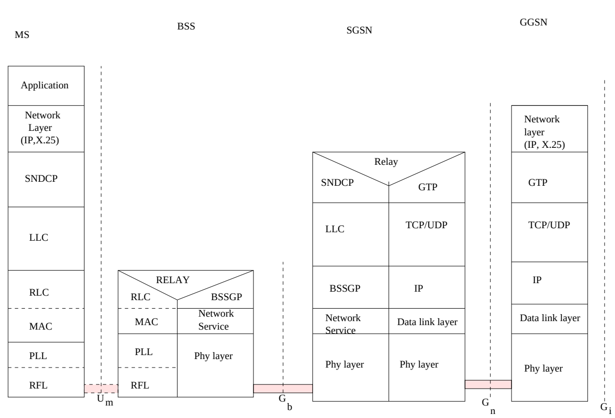

Fig. 1. GPRS architecture

The RLC/MAC layers in the GPRS protocol stack essentially are responsible for the way in which the GSM/GPRS radio resources (frequency-time slot pairs) are shared by various mobile users. The uplink (mobile-to-base station link) channel resources are shared based on a *request-reservation* mechanism.

Performance of the GPRS RLC/MAC layers under various radio channel and traffic load conditions influence the overall GPRS network performance. Several studies have investigated the performance of the GPRS RLC/MAC layers, but mainly through simulations [3],[4]. The performance of automatic repeat request (ARQ) mechanisms at the Logical Link Control (LLC) and RLC layers in GPRS has been analysed in [5], but without considering the uplink request-reservation dynamics of the MAC layer. Our new contribution in this paper is the modeling and *analytical* evaluation of the performance of the RLC/MAC protocols in GPRS, considering the *uplink request-reservation mechanism*. Using theory of Markov chains, we derive expressions for the uplink throughput and delay performance of the GPRS MAC protocol. We also evaluate the performance of the RLC (Acknowledged mode) layer using block level retransmission as defined in the current GPRS standard. We compare this performance with that of using *slot level retransmission* at RLC, which is being proposed as an alternate ARQ scheme [6]. We show that slot level retransmission performs better than block level retransmission, particularly when the channel error rate is high.

The rest of the paper is organised as follows. In Section II, we describe the GPRS LLC/RLC/MAC protocol layers and the system model. Section III provides the analysis of the throughput-delay performance of the GPRS-MAC protocol as well as the RLC performance analysis for slot level retransmission. Performance results and topics of future research are presented in Section IV.

II. LLC/RLC/MAC Layers in GPRS

The over-the-air communication between a mobile station (MS) and the GPRS network is defined by the physical layer and the data link layer functionalities. The physical layer functions involve modulation, demodulation, channel encoding/decoding, etc. The data link layer consists of two sublayers, namely, Logical Link Control (LLC) layer, and the Radio Link Control/Media Access Control (RLC/MAC) layer. The LLC layer operates between the MS and the SGSN, and provides a logical link between them. Packet data units (PDUs) from higher layers are segmented into variable size LLC frames. A stop-and-wait ARQ mechanism is provided at the LLC layer to re-transmit erroneous LLC frames.

The RLC/MAC layers, on the other hand, are primarily responsible for the efficient sharing of common radio resources by several MSs. The RLC/MAC peers are at the MS and the BSS. Each LLC frame is segmented into several RLC data blocks of fixed size. Each RLC data block occupies fixed number of slots, depending on the type of channel coding scheme used. The RLC function in Acknowledged mode provides for the selective retransmission of erroneous RLC data blocks.

The MAC operates on a slotted-ALOHA based reservation protocol. The MAC layer requests/reserves resources in number of data slots. The MAC function provides arbitration between multiple mobiles attempting to transmit simultaneously, and provides collision detection and recovery procedures.

Thus, in terms of error recovery at different layers, $a)$ MAC attempts to resolve collision of request packets, $b)$ RLC attempts to recover RLC data block errors through a selective repeat ARQ mechanism, and $c)$ LLC attempts recovery of LLC frames through a stop-and-wait ARQ mechanism. Link errors unresolved at LLC layer are passed on to higher layers (e.g., transport layer) to resolve.

A. GPRS MAC Protocol

The GPRS MAC protocol is responsible for the way in which the GSM/GPRS radio frequency-time slot pairs are shared by the mobile users. The uplink channel resources are shared on a request-reservation basis. Two types of uplink channels are defined in GPRS. They are Packet Random Access CHannel (PRACH) and Packet Data Traffic CHannel (PDTCH). PRACH is used by all the mobiles, on a contention basis, for the purpose of sending resource request packets. Typically, TS0 slot in a GSM frame of 8 slots is used as PRACH. All mobiles are allowed to transmit on PRACH slots, following slotted-ALOHA protocol [7]. Depending on the system load, the number of PRACHs can be increased. PDTCHs, on the other hand, are used for the transfer of data packets. Resource requests are made by the mobiles in terms of number of uplink PDTCH slots required. Based on these requests, PDTCH slots are dynamically assigned to the mobiles by the base station. Allocation can be done on a one time slot per GSM TDMA frame basis (called *single slot operation*) or multiple time slots per GSM TDMA frame basis (called *multi-slot operation*).

When MAC at the mobile side receives RLC data blocks to be transferred to the base station, it sends a request packet on the immediately following PRACH slot. The request packet indicates K, the number of PDTCH slots required. If the base station receives the request packet without collision or channel errors, and if PDTCH slots are available to honor the request, the base station informs the reservation information to the mobile on the downlink paging channel. The reservation information include the PDTCH frequency-time slots that can be used by the mobile for data transfer. The mobile then sends data in those K reserved slots. On the other hand, if the request packet is lost (due to collision or channel errors) or if PDTCH slots are not available, then the mobile will not get the reservation. The mobile will then reschedule its request packet retransmission attempt to a later time (typically, after a random backoff time).

B. System Model

Consider a single cell GPRS system with M, $M \geq 2$ uplink channels and N mobile users. Each channel corresponds to a frequency-time slot pair in the mobile-to-base station direction. Out of M channels, L, $1 \leq L < M$, channels are used as packet random access channels (PRACH), and the remaining $M - L$ channels are used as packet data traffic channels (PDTCH). Typically, slot TS0 in all GSM TDMA frames on a given frequency can form a PRACH. Likewise, on a given frequency, slot TS1 in all GSM TDMA frames can form PDTCH-1, slot TS2 can form PDTCH-2, and so on.

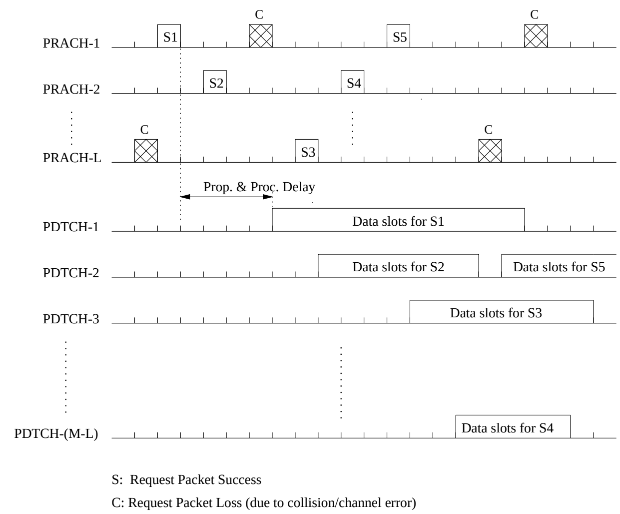

Fig. 2. GPRS-MAC Protocol Operation

We consider the *single slot operation*, where only one slot per GSM TDMA frame is assigned to a user on PDTCH. For example, TS1 slots in consecutive frames n, $n+1$,...,$n+K$ being assigned to a mobile for data transfer is a typical illustration of single slot operation.

Considering single slot operation, all M uplink channels can be modelled as synchronized slotted channels as shown in Figure 2. One request packet is one slot in size. One network layer packet data unit (PDU), including LLC/RLC headers and checksums, occupies several slots. Between the successful transmission of a request packet on a PRACH slot and the corresponding data transmission on the assigned PDTCH slots, some finite time gets elapsed because of the propagation and processing delays involved. This delay is typically of the order of a few slots.

III. Throughput-Delay Analysis

In order to carry out the performance analysis, we assume the following:
1. The network layer PDU arrival process (hence the new request packet generation process) is Bernoulli with arrival probability λ in each slot. A new network layer PDU is accepted only after the completion of the transfer of the previously accepted PDU.

2. The length of the PDU (including LLC/RLC headers and checksums), measured in number of slots, is geometric with paramater g_d, $0 < g_d < 1$.
3. Loss of request packets on PRACH is only due to collision
4. Retransmission attempts of request packets following a collision on PRACH (or non-availability of PDTCH) is geometrically delayed with parameter g_r, $0 < g_r < 1$.
5. Propagation and processing delays are assumed to be negligible.

As per the GPRS MAC model described above, the mobile can be in any one of the following states, namely *idle* state, *backlogged* state, *data-tx success* state, and *data-tx failure* state. See Figure 3. In *idle* state, a mobile remains idle with probability (1-λ) and generates a PDU with probability λ. If n requests come in a slot, then at most one request is received correctly (capture) with probability $cap(n, 1)$. The remaining $n-1$ mobiles go to *backlogged* state. If a mobile's request succeeds, but there are no available PDTCHs to serve the request, then also the mobile goes to the *backlogged* state. On the other hand, if there are available PDTCHs to serve a request, then the mobile goes to the *data-tx success* state or *data-tx failure* state, where it sends data on the assigned PDTCH slots.

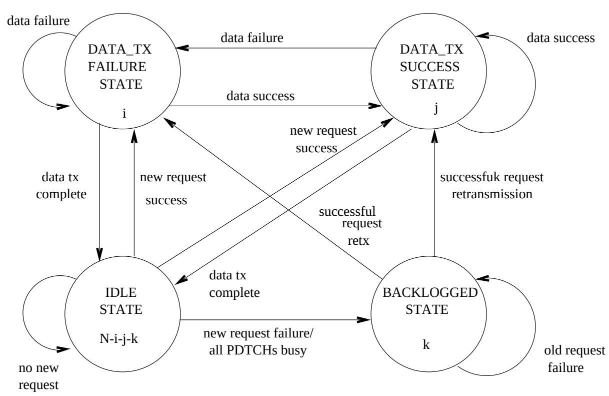

Fig. 3. Mobile Station State Transition Diagram

Let $\{\mathbf{D_{ft}}; \mathbf{t} \in \{\mathbf{1}, \mathbf{2}, \mathbf{3}, ...\}\}$ represent the number of mobiles in *data-tx failure* state at the beginning of slot t, $\{\mathbf{D_{st}}; \mathbf{t} \in \{\mathbf{1}, \mathbf{2}, \mathbf{3}, ...\}\}$ be the number of mobiles in the *data-tx success* state, and $\{\mathbf{B_t}; \mathbf{t} \in \{\mathbf{1}, \mathbf{2}, \mathbf{3}, ...\}\}$ be the number of mobiles in *backlogged* state. The three dimensional process $\{\mathbf{Z_t} = (\mathbf{D_{ft}}, \mathbf{D_{st}}, \mathbf{B_t}); \mathbf{t} \in \{\mathbf{1}, \mathbf{2}, \mathbf{3}, ...\}\}$ is a Markov chain because of the assumptions made above. The one-step state transition probability, $\tilde{P}_{z_1,z_2}$, that the system moves from state $\mathbf{Z_t} = \mathbf{z_1} = (\mathbf{i_1}, \mathbf{j_1}, \mathbf{k_1})$ at time t, to state $\mathbf{Z_{t+1}} = \mathbf{z_2} = (\mathbf{i_2}, \mathbf{j_2}, \mathbf{k_2})$, $0 \le i_1 \le M-L, 0 \le j_1 \le M-L-i_1, 0 \le k_1 \le N-i_1-j_1$, $0 \le i_2 \le M-L, 0 \le j_2 \le M-L-i_2, 0 \le k_2 \le N-i_2-j_2$, at time $t+1$ is given by

$$\begin{aligned}\tilde{P}_{z_1,z_2} \quad = \quad & \sum_{n=0}^{N-i_1-j_1} \sum_{c_s=0}^{L} \sum_{s_j=0}^{c_s} \sum_{s_f=0}^{i_2-c_s+s_j} \sum_{f_s=0}^{j_2-s_j} \qquad (1) \\ & \cdot \binom{N-i_1-j_1-k_1}{a} \lambda^a (1-\lambda)^{N-i_1-j_1-k_1-a} \\ & \cdot \binom{k_1}{n-a} {g_r}^{n-a} (1-g_r)^{k_1-n+a} \\ & \cdot \binom{j_1}{b_j} {g_d}^{j_1-b_j} (1-g_d)^{b_j} \\ & \cdot \binom{b_j}{s_f} {P_s}^{s_f} (1-P_s)^{b_j-s_f} \\ & \cdot \binom{i_1}{b_i} {g_d}^{i_1-b_i} (1-g_d)^{b_i} \\ & \cdot \binom{b_i}{f_s} (1-P_s)^{f_s} P_s^{b_i-f_s} \\ & \cdot \binom{c_s}{s_j} (1-P_s)^{s_j} P_s^{c_s-s_j} . f(c_s, n, L),\end{aligned}$$

where $a = m - k + c_s$, n is the number of requests sent, c_s is the number of successful requests in the t^{th} slot, $b_j = j_2 - s_j - f_s + s_f$, $b_i = i_2 - c_s + s_j - s_f + f_s$, $f_s \le b_i$, $s_f \le b_j$, P_s is the average probabilty of slot error, and

$f(c_s, n, x)$ = Prob(c_s successes given that n requests are sent and x PRACHs are available). Then,

$$\begin{aligned}f(c_s, n, x) \quad = \quad & \sum_{l=0}^{n} \sum_{c=0}^{1} \binom{n}{l} \left(\frac{1}{x}\right)^l \left(1 - \frac{1}{x}\right)^{n-l} \qquad (2) \\ & \cdot cap(l, c) . f(c_s - c, n - l, x - 1),\end{aligned}$$

where $cap(l, c)$ is the probability of capturing c out of l colliding request packets.

Eqn. (2) is terminated by fixing $f(c, n, 1) = cap(n, c)$. We set $cap(0, 1) = 0$, $cap(1, 1) = 1$, $cap(2, 1) = 0.7$, $cap(3, 1) = 0.5$, $cap(4, 1) = 0.2$, $cap(5, 1) = 0.1$, $cap(n, 1) = 0$ for $n > 5$, and $cap(n, 0) = 1 - cap(n, 1)$.

The above analysis assumes a large number of PDTCHs, so that a successful request always gets an assignment. If the number of PDTCHs is small compared to the number of users N, (i.e., $M - L < N$), then a successful request may not get an assignment as all the PDTCHs may be busy. This event occurs if $M - L - (L - 1) \le (i_1 + j_1) \le M - L$ and $M - L - (L - 1) \le (i_2 + j_2) \le (i_1 + j_1)$. For those z_1 and z_2 satisfying the above condition, compute the probability $\hat{P}_{z_1,z_2}$ and add it to the corresponding $\tilde{P}_{z_1,z_2}$ term calculated using Eqn. (1).

Let $x = M - L - (i_1 + j_1)$, $y = (i_1 + j_1) - (i_2 + j_2)$ and $\mu = k_2 - k_1$. Therefore, the probability $\hat{P}_{z_1,z_2}$ for the transition $z_1 = (i_1, j_1, k_1)$ to $z_2 = (i_2, j_2, k_2)$ transition is given by,

$$\begin{aligned}\hat{P}_{z_1,z_2} \quad = \quad & \sum_{\theta=0}^{k_1} \sum_{c_s=y+x+1}^{L} \sum_{s_f=0}^{i_2} \sum_{f_s=0}^{j_2} \qquad (3) \\ & \cdot \binom{N-i_1-j_1-k_1}{\mu} \lambda^\mu (1-\lambda)^{N-i_1-j_1-k_1-\mu} \\ & \cdot \binom{k_1}{\theta} {g_r}^{\theta} (1-g_r)^{k_1-\theta} \\ & \cdot \binom{j_1}{b_j} {g_d}^{j_1-b_j} (1-g_d)^{b_j} \\ & \cdot \binom{b_j}{s_f} {P_s}^{s_f} (1-P_s)^{b_j-s_f} \\ & \cdot \binom{i_1}{b_i} {g_d}^{i_1-b_i} (1-g_d)^{b_i}\end{aligned}$$

$$\cdot \binom{b_i}{f_s}(1-P_s)^{f_s} P_s^{b_i-f_s}.f(c_s,\mu+\theta,L),$$

where $b_j = j_2 - f_s + s_f$, $b_i = i_2 - s_f + f_s$, $f_s \le b_i$, $s_f \le b_j$. Thus,

$$P_{z_1,z_2} = \tilde{P}_{z_1,z_2} + \hat{P}_{z_1,z_2}. \quad (4)$$

The Markov chain $\{\mathbf{Z_t}; \mathbf{t} \in \{\mathbf{1},\mathbf{2},\mathbf{3},...\}\}$ has a finite number of states and is positive recurrent [8]. Hence, it has a stationary steady state distribution and is found by solving

$$\Pi = \Pi \mathbf{P}, \quad (5)$$

where $\Pi = [\pi_{ijk}], 0 \le i \le M-L, 0 \le j \le M-L-i, 0 \le k \le N-i-j$, is the steady state probability vector. The total system throughput, η, is defined as

$$\eta = \sum_{i=0}^{M-L} \sum_{j=0}^{M-L-i} \sum_{k=0}^{N-i-j} j\pi_{ijk}. \quad (6)$$

The per channel throughput, η_c, is then given by

$$\eta_c = \eta / M. \quad (7)$$

Next, we derive the mean PDU transfer delay performance. The mean PDU transfer delay, D, is defined as the the average number of slots elapsed from the slot where a PDU arrived to the slot where the PDU transmission is complete. The number of users in the non $idle$ state (i.e., *data-tx failure*, *data-tx success*, and $backlogged$) contribute to the mean delay. There are $\nu = (i+j+k)$ non $idle$ users in the system and averaging it over steady state distribution gives

$$\mathrm{E}(\nu) = \sum_{i=0}^{M-L} \sum_{j=0}^{M-L-i} \sum_{k=0}^{N-i-j} (i+j+k)\pi_{ijk}. \quad (8)$$

There are $N-i-j-k$ $idle$ users each will generate requests with probability λ in each slot. The average arrival rate to the system is given by

$$\Lambda = \lambda(N - E(\nu)). \quad (9)$$

From Little's theorem, the average time an user spends in the system is given by the ratio between the number of users in the system to the average arrival rate. Hence,

$$\mathrm{D} = 1 + \frac{E(\nu)}{\Lambda}. \quad (10)$$

Note that one is added to ensure that there is one slot delay for the mobiles to enter into the *non-idle* state.

A. RLC Acknowledged Mode

Note that the above analysis corresponds to the MAC protocol operation with RLC in the Un-Acknowledged mode (i.e., there is no ARQ at the RLC). In Acknowledged mode, however, RLC retransmits erroneous blocks using a selective repeat ARQ mechanism. Each RLC block consists of four slots. It is noted that slot level retransmission in RLC is proposed as an alternative to block level retransmission [6]. Here, we consider a slot level retransmission mechanism by which a slot in error is repeatedly retransmitted until it succeeds. In this subsection, we derive the throughput-delay performance when the slot level retransmission is used at the RLC.

Let the random variable T represent the number of slots per PDU and the random variable Y_i represent the number of transmission attempts of i^{th} slot until success. Thus, the total number of slots required for successfully transmitting T slots is given by,

$$\mathrm{X} = \sum_{i=1}^{T} Y_i. \quad (11)$$

The distribution of X is given by,

$$\Pr(\mathrm{X}{=}x) = g_d(1-P_s)[1-g_d(1-P_s)]^{x-1}, x = 1,2,3... \quad (12)$$

Now, in order to obtain the throughput and delay for the RLC (Acknowledged mode) with slot level retransmission, we need to just change the parameter g_d to $g_d(1-P_s)$ in Eqn. (1) and Eqn. (3).

IV. Results and Discussions

In Figure 4, numerical results for the average per channel throughput of the GPRS MAC protocol, obtained from Eqn. (7), for N=10, M=10, L=1, g_r = 0.1, and g_d = 0.1 are plotted as a function of request arrival probability, λ. The effect of slot errors with/without RLC slot level retransmission is also plotted. These results are compared with the corresponding RLC block level retransmission obtained through simulation. As the arrival rate increases the fraction of time the system spends in $idle$ state decreases, and this results in increased throughput. When there are no slot errors (i.e., P_s = 0%), all the slots carrying data traffic are successful, which represents the best possible performance. As the slot error rate increases (say, to 10%), the fraction of successful slots decreases, and hence the throughput decreases. On the other hand, for the same slot error

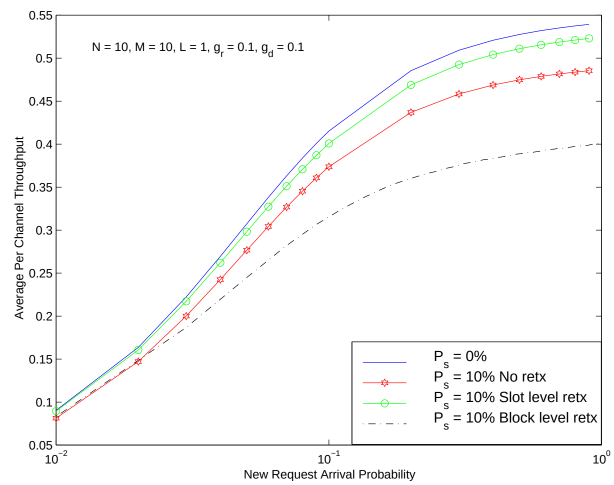

Fig. 4. Average per channel throughput, η_c versus new request arrival probability, λ. $N = 10$, $M = 10$, $L = 1$, $g_r = 0.1$, $g_d = 0.1$.

rate (of 10%), slot level retransmission improves the throughput performance. This is because, the fraction of time the channel is left *idle* is reduced due to the retransmission attempts, and as long as the channel error rate (P_s) is reasonably good, this would result in increased throughput. Another observation in Figure 4 is that the throughput achieved with block level retransmission is much lower than the slot level retransmission. This is because, in block level retransmission, even if one slot in a block is in error, the entire block (of 4 slots) will be retransmitted, and this considerably reduces the throughput. The degradation is more severe as the slot error rate gets larger (see Figure 7).

The mean PDU transfer delay performance of the GPRS MAC protocol is evaluated using Eqn. (10) for the same set of parameters and plotted in Figure 5. In the case of no retransmission

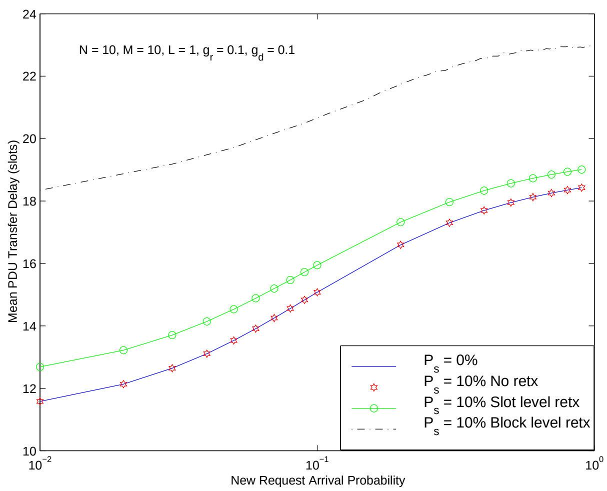

Fig. 5. Mean PDU transfer delay (in number of slots), versus new request arrival probability, λ. $N = 10$, $M = 10$, $L = 1$, $g_r = 0.1$, $g_d = 0.1$.

(i.e., RLC Un-Acknowledged mode), it takes the same number of slots to carry the traffic as in the no error case. Hence the delay is the same for both no error case as well as error case with no retransmission. The delay for slot level retransmission increases as it takes more slots to successfully deliever the data slots. In block level transmission, since the entire block gets retransmitted, even if one slot in a block is in error, the delay performance is worse than slot level retransmission.

The effect of the number of channels, M, on the throughput characteristics of the GPRS MAC protocol is shown in the Figure 6, for N=10, L = 1, g_r = 0.1, g_d = 0.1, and for λ = 1. From Figure 6, we observe the following. The per channel throughput increases as M increases, upto a certain a value of M, beyond which the throughput decreases. This is because, at low M, requests are *backlogged* due to unavailability of PDTCHs, and at high M, PDTCHs are *idle* most of the time.

The effect of slot error rate on the throughput performance is shown in Fig. 7. As expected, throughput decreases as slot error rate increases. We observe that, as we move from P_s = 10% to P_s = 30%, there is a steep fall in throughput in the case of block level retransmission (0.461 to 0.204), whereas the fall is less for slot level retransmission (0.5265 to 0.468).

Further investigations are going on to release the assumptions

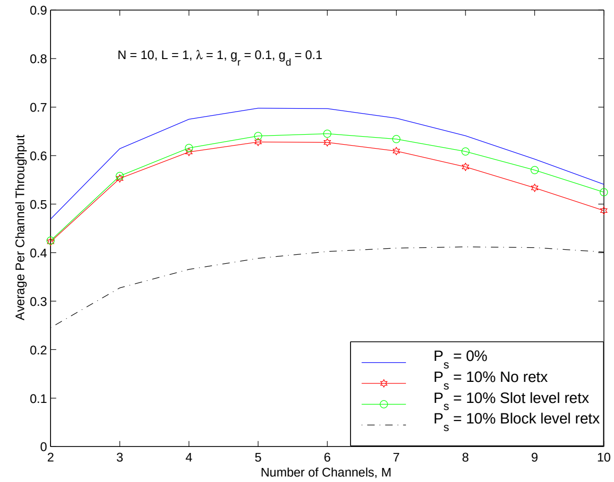

Fig. 6. Average per channel throughput, η_c versus number of channels, M. $N = 10$, $L = 1$, $\lambda = 1$, $g_r = 0.1$, $g_d = 0.1$.

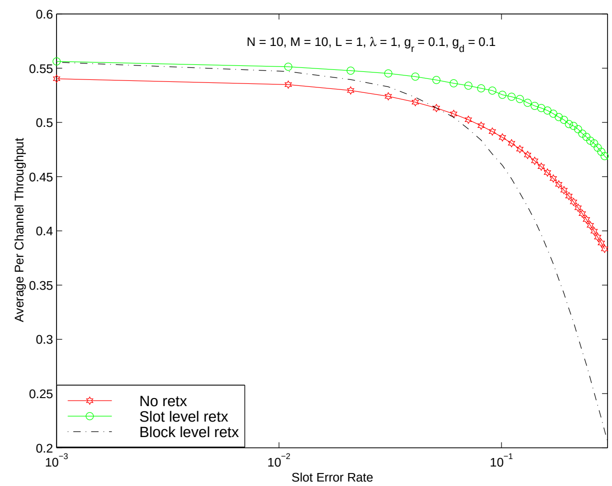

Fig. 7. Average per channel throughput, η_c versus slot error rate , P_s. $N = 10$, $M = 10$, $L = 1$, $\lambda = 1$, $g_r = 0.1$, $g_d = 0.1$.

(3) and (5) in the analysis. Also, the performance analysis of GPRS-MAC in conjunction with ARQs at both RLC as well as LLC layers is also under investigation.

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