Radio Link Protocol Layer For CDMA 2000 Wireless Systems

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Abstract— In this paper the modeling of the RLP layer in CDMA2000 is presented, which uses the NAK based ARQ scheme for Random Error Channels. The RLP performs a partial link recovery through limited number of RLP frame transmission in case of frame error. In case when the RLP fails due to excessive frame error, the control is passed on to the higher (TCP) layer. The TCP layer provides the complete end-to-end recovery. Thus the reliable performance at the TCP/RLP is essential to maintain the required Quality of Service in the DS-CDMA wireless links.

The modeling is done for the performance analysis of the system in terms of the throughput and the mean extra delays, which are calculated analytically and are compared with the results generated by the simulations. This paper studies the effect of the random errors over different types of RLP frame formats and also the performance of the NAK based ARQ mechanism used under these conditions. The simulation provides with the over all characteristics of the throughput and the mean extra delay in terms of realistic environment parameters like Eb/No and probability of packet error (PE), based on the channel conditions.

I. INTRODUCTION

The rise in demand for faster wireless communications to access the Internet for data services like email, web browsing, telnet etc has triggered immense advances in this area. The Transport Control Protocol (TCP) is a reliable end-to-end transport protocol in the Internet Protocol (IP) suite for wire line networks but when used with wireless channels, which are characterized by high frame error rates (FER), the performance of TCP is severely affected [Balakrishnan et al, 1996]. In order to reduce the FER observed for the TCP layer on the wireless links, a Radio Link Protocol (RLP) is generally introduced at the link layer, i.e., above the physical layer and below the TCP layer.

The RLP uses an Automatic Repeat Request (ARQ) error recovery mechanism to reduce the FER. For example CDMA asynchronous data and packet data applications uses a Negative Acknowledgement (NAK) based ARQ scheme as standardized in TIA/EIA/IS-707-A. In a NAK-based ARQ scheme, the receiver does not acknowledge correct data blocks, i.e. no ACK message is sent over the feedback channel. It only requests the retransmission of data blocks that were not received, through a NAK message. The NAK message will be sent again if the requested data blocks are not received successfully after a predefined time period, which is typically greater than a round trip delay (RTD) time. This link recovery is carried out through a limited number (N=3) of RLP frame retransmissions in case of frame errors. When the RLP fails to get the correct frame, the control is passed to the higher layers (TCP), which is ultimately responsible for providing complete end-to-end recovery. This way ARQ mechanism at the RLP and TCP interacts with each other and affects the overall system performance depending on the channel conditions.

II. RADIO LINK PROTOCOL (RLP)

The Radio Link Protocol (RLP) Type 3 [TIA/EIA/IS-707-A-1, Nov 1998] is used with CDMA2000 Traffic Channel to support CDMA data services. RLP provides an octet stream transport service over forward and reverse traffic channels. RLP is unaware of higher layer framing; it operates on a featureless octet stream, delivering the octets in the order received.

RLP has procedures to substantially reduce the error rate exhibited by CDMA traffic channels. There is no direct relationship between higher layer packets and the underlying traffic channel frames; a large packet may span multiple traffic channel frames, or a single traffic channel frame may contain all or part of several small higher layer packets. RLP fames can be carried as primary or secondary traffic. An RLP frame supplied to the multiplex sub-layer to be carried in a fundicated (fundamental/dedicated channel) data block is called a Fundicated RLP frame. Similarly, an RLP frame supplied to the multiplex sub-layer to be carried in a supplemental data block is referred to as a Supplemental RLP frame.

A. RLP Frame Formats

The RLP frames that can be supplied to the multiplex sub-layer are Frame Format A, B, C, D, Blank Frame and Idle Frame. The number of bits supplied to the multiplex sub-layer for the RLP Frame Format A is as shown in the Table 1. Upon command, RLP shall supply a Blank RLP frame, which contains no bits, or supply a non-blank Fundicated RLP frame of whatever rate the multiplex sub-layer commands.

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The Table 1 below shows the Frame Format A for the Primary and Secondary Traffic Channels for CDMA2000 supplied to the RLP and to the multiplex sub-layers. The Frame Format A is considered in the following simulations for the Random and the Fading Channels. The formats used for information and TYPE in Table 1 is as follows:

Information: Control or data frame, formatted according to the control and data frame formats [TIA/EIA/IS-707-A-1, Nov 1998]

TYPE: Frame Type, its set to '001' or '01' for Frame Format A.

Table 1. Primary/Secondary Traffic RLP Frame Format A

Field	Primary Traffic Length (bits)		Secondary Traffic Length (bits)	
	Multiplex Option		Multiplex Option	
	Odd	Even	Odd	Even
Information	168	264	165	260
TYPE	3	2	3	2

B. Frame Priority of Traffic Channel:

RLP shall classify frames into three priority classes. In order of priority they are (with highest priority first) as follows:

1. RLP control frames.
2. Retransmitted data frames (i.e. data frames being resent in response to received NAK control frames).
3. New data frames (i.e. data frames being sent for the first time).

When the multiplex sub-layer indicates that it is ready to send RLP frames on a traffic channel, RLP shall supply it with the highest priority RLP frames available with the following exceptions:

1. A control frame, idle frame or fill frame shall only be supplied as a Fundicated RLP frame.
2. Identical retransmitted data frames should not be supplied in the same 20 ms time slot, but instead should be supplied in consecutive time slots, in order to reduce the likelihood that all retransmitted copies will be lost due to a burst error.
3. RLP may supply a fill frame at any time.

When RLP frames are carried as primary traffic and no RLP frames in the above three priority classes are available, an idle frame or a fill frame shall be generated and supplied if a Fundicated RLP frame is needed, and a Blank RLP frame shall be supplied if a Supplemental RLP frame is needed. In case of secondary traffic the value of the round-trip frame counter is also checked to be greater than zero.

C. RLP System Model and Operation

The RLP when transferring data is a purely NAK based automatic repeat protocol [TIA/EIA/IS-707-A-1, Nov 1998]. Conventionally ARQ (ACK/NAK-based) and NAK-based ARQ have the same forward channel data transmission procedure, but they differ in the transmission of the feedback messages (ACK and NAK) through the feedback channel. That is, the receiver does not acknowledge correct RLP data frames; it only requests the retransmissions of RLP data frames that were not received correctly.

In case of a frame error, RLP performs a partial link recovery through a limited number of frame retransmissions. Since the number of allowed retransmissions of an erroneous RLP frame is finite, RLP cannot completely eliminate all detectable errors. The undetectable errors, which can be generally bounded to a very small value by proper selection of CRC, are not considered here. The unrecovered errors at the RLP layer will be recovered by the higher layer i.e. TCP layer.

Fig. 1 shows the NAK transmission scheme for RLP. The RLP, when at the receiving end finds a frame in error (or is missing), it sends back a NAK requesting retransmission of the lost frame. A NAK retransmission is set for the lost frame and a guard interval is added to the retransmission timeout in order to account for the buffering delays and the segmentation of retransmitted frames [TIA/EIA/IS-707-A-1, Nov 1998]. When the retransmission timer expires for the first time, RLP resets the timer and sends back NAK twice. Each NAK received at the transmission end triggers a retransmission of the requested frame. When the timer expires for the second time, RLP resets the timer and sends back three NAKs. This process continues until the number of timer expirations reaches a certain limit (n=3 by default in CDMA2000). RLP aborts the attempt after 'n' unsuccessful retransmissions and passes control to the TCP layer.

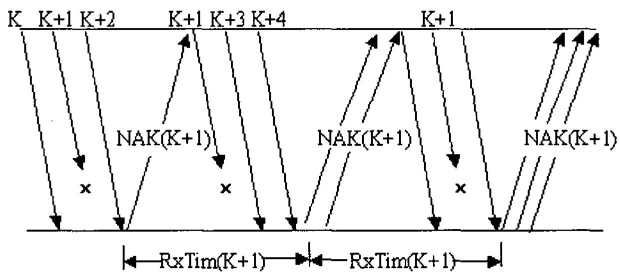

Fig. 1 NAK Transmission Scheme for RLP.

During the data transfer phase (i.e., excluding the link set-up and tear down phases), RLP maintains a 8-bit sending sequence number count V(S), and two sequence numbers V(R) and V(N) for receiving. All operations on these RLP frame sequence numbers are carried out in unsigned modulo 4096 arithmetic. V(S) is incremented whenever a new RLP data frame of non-zero bytes is sent out. That is, V(S) is the sequence number of the next frame to be sent. V(R) contains the sequence number of the next new frame expected to be received. V(N) is the next needed frame for sequential delivery. In other words, V(N) is the oldest sequence number of the missing frames.

By denoting the sequence number of a newly received frame by i, the RLP transmission procedure can briefly be described by the following rules [TIA/EIA/IS-707-A-1, Nov 1998]:

- If i < V(N) or if the frame is already stored in the resequencing buffer, discard the frame.
- If i = V(N), update V(N) to the next oldest missing frame sequence number. Pass received frames up to V(N) – 1 to the upper layer.
- If V(N) < i < V(R), store frame i in resequencing buffer if it is missing.
- If i = V(R) = V(N), pass all received frames up to V(R) to the upper layer.
- If i = V(R) ≠ V(N) or i > V(R), increment V(R) and store frame i into resequencing buffer.
- For all cases, send NAKs of missing frames if their retransmission timers are not yet set or expired.

D. Theoretical Analysis and System Assumptions

Most of the earlier work done on performance evaluation of data block transmissions, e.g. in data-link protocols, the block transmissions were assumed to be independent and identically distributed (i.i.d.) [Wang, 1994]. So one of the assumptions was that the frame error distribution is i.i.d; in this paper an effort has been made to model data transmissions for the CDMA2000 for a random error channel. Performance analysis is done by comparing the throughput and mean extra delay for the RLP got from the analytical expression and the simulation done under varying conditions and assumptions for the random error channel.

The analytical calculations are done using the RLP Frame Format A for the Primary and Secondary Traffic (Table 1). Certain equation were derived and taken into consideration for the performance analysis of the RLP based on the throughput and mean extra delay. Also some assumptions are made for the model of the RLP stack.

The frame error distributions can be considered as independent for each packet transmitted by the transmitter. The feedback channel is considered to be a noisy channel, i.e. the NAK control message may be received incorrectly during the feedback due to random feedback errors. The data block error probability is taken as to be P_e whereas the feedback error probability is taken as to be P_f. The throughput for this channel is can be derived in terms of the block error probability P_e [Yao, 1999], given by S :

$$S = 1 - P_e. \quad (1)$$

When a NAK message is received incorrectly and also when a data block is received incorrectly , extra delay are introduced . Here considering up to three RTDs (up to three retransmissions of the NAK) [TIA/EIA/IS-707-A-1, 1998], the probability density function of the extra delay [Yao, 1999] is given as:

$$p_T(i) = \begin{cases} 1 - P_e & i=0 \\ P_e(1-P_f)(1-P_e) & i=1 \\ P_e P_f (1-P_f)(1-P_e) + P_e^2(1-P_f)(1-P_e) & i=2 \\ P_e P_f^2(1-P_f)(1-P_e) + 2P_e^2 P_f(1-P_f)^2(1-P_e) + & i=3 \\ P_e^3 P_f^3(1-P_e) & \end{cases} \quad (2)$$

The mean extra time delay (considering up to three RTDs) can be expressed as [Yao, 1999]

$$T \approx p_T(1) + 2p_T(2) + 3p_T(3). \quad (3)$$

The approach used to find the block error probability P_e, is to first establish the single bit error probability P_{ch} for the random error channel. This single bit error probability P_{ch} [Proakis, 1989] is given as:

$$P_{ch} = \left(\frac{1-\mu}{2}\right)^L \sum_{k=0}^{L-1} \binom{L-1+k}{k} \left(\frac{1+\mu}{2}\right)^k \quad (4)$$

where L = antenna diversity at the base-station, is assumed equal to 1 and

$$\mu = \left(\frac{\gamma}{1+\gamma}\right)^{1/2}$$ with the average SNR $\gamma = E_b/N_o$.

$$\therefore \quad P_{ch} = \frac{1 - \left(\frac{\gamma}{1+\gamma}\right)^{1/2}}{2} \quad (5)$$

The block error probability P_e [Zorzi et al, 1997] can be now found using the single bit error probability given by P_{ch}.

$$P_e = \sum_{i=e+1}^{n} \binom{n}{i} [P_{ch}]^i [1 - P_{ch}]^{n-i} \quad (6)$$

Where n = number of bits in a packet and e = error correction capability of the block code in the packet.

The probability of the feedback error P_f is assumed to be 0.001 and the number of frame error correction capability e is assumed to be equal to 3. The range of values for average SNR (Signal to Noise Ratio Eb/No) γ is varied from 6.5 to 16.5 dB. The single bit error probability P_{ch} is evaluated using eqn. (5) and is used to calculate the frame error probability P_e for each of the different frames(Table 1) using the eqn. (6). The throughput is calculated based on these frame error probabilities P_e, using the eqn(1).

From these values it is clear that the summation of all the delay probabilities in eqn. (2) does not add up to 1. The calculation of mean extra delay using the eqn. (3) does not provide accurate analytical values for the values of Pe generated fro the different RLP frames. The mean extra delay is calculated analytically for the Pe values ranging from 0.001 to 0.0015(0.1% to 0.15%) using eqn.(3) and the result is shown in Fig. 4. Based on all the values obtained from equations 1 through 6, the graphs are drawn for both primary and secondary traffic and are compared with the simulation results. The following graphs are drawn for RLP Frame Format A:

1. Throughput Vs. Eb/No
2. Throughput Vs. Frame Format Error (Pe)
3. Mean Extra Delay Vs. Eb/No.

E. Simulation:

The Random Error Channel is simulated using C++ to get the throughput and average mean delay for the NAK based ARQ used in the Radio Link Protocol for CDMA2000.

The simulation maintains a time clock, used to keep track of the transmissions and retransmissions of the RLP frames due to the channel errors. There are four queues used in this simulation, two at the transmitter and the other two at the receiver. The queues at each end act as a transmission and retransmission buffer. The packet arrival at the transmitter is taken to be Poisson-distributed arrival with the arrival rate of one for one unit of time. The packet error and the feedback error are generated using a random function and also the signal to noise ratio. The bit error correction capability of the RLP frame packets is taken as three.

Any packet having bit errors more than this is considered to be in error and a retransmission is requested from the transmitter for this packet. The successful retransmission request (NAK) is based on the probability of error for the feedback channel and is taken to be 0.001, as used for the analytical calculations also. If the number of retransmission attempts used for a packet is three and it is still in error then the packet is removed from the system as a bad packet that cannot be retrieved. All the other packets are considered to be successfully delivered to the receiver, with zero delay or with specific time delay due to the number of retransmissions done for the packet.

Important parameters needed for the simulation are initialized at the start of the program and variables are used to store the results of the simulation. Each packet used for the simulation is so designed to store information like the packet number, the number of NAK's used, the start time and the end time for the packet. This information is used to calculate the throughput and the average mean delay at the end of the simulation.

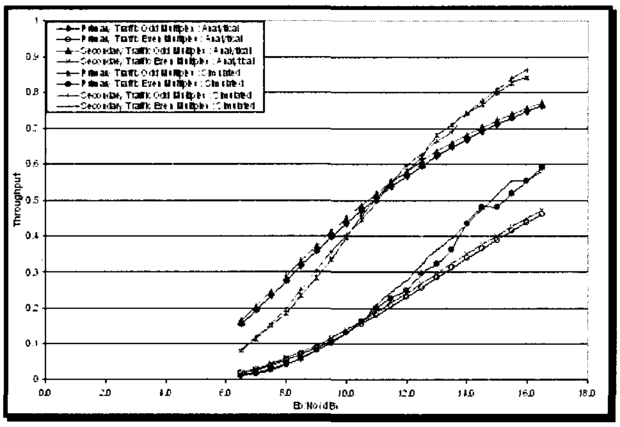

Fig. 2 Throughput vs Eb/No for RLP Frame Format.

The simulation is done for the four different RLP packet types shown in Table 1. The total numbers of packets used for the Simulation were varied from 1000 to 5000 packets and it was done several times for the convergence of the simulation results. The results of the simulation for the throughput analysis are plotted in the Figs 2 and 3 to compare with the results generated from the analytical calculations. Where as the Fig. 4 shows the mean extra delay for the different packet types as a function of Eb/No.

F. Results:

The results of the simulations and analytical calculations for the random error channel are as shown in the Figs. 2, 3 and 4 in the form of graphs of throughput versus the signal to noise ratio (Eb/No) and frame error probability Pe, and also the extra delay versus the Eb/No.

As seen in the graph (throughput vs. Eb/No) in Fig. 2, the throughput increases with increase in received signal to noise ratio (Eb/No). The throughput is higher for the frames used by the odd multiplex, as the number of bits in the frames is less as compared to the even multiplex. Hence the effect of the random errors in the channel affects the packets with larger size as the probability of error increases and this results in their reduced throughput performance. The value of Eb/No when varied from 6.5 to 16.5 dB, the throughput shows a marked increase, which shows that maintaining a relatively higher value of Eb/No can enhance the throughput performance.

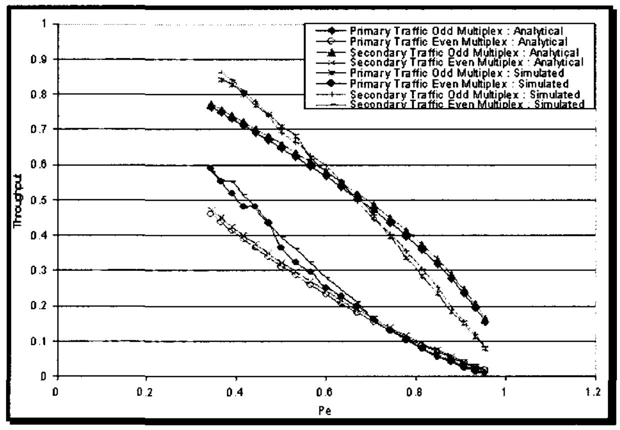

Fig. 3 Throughput vs Frame Error Pe for RLP Frame Format A.

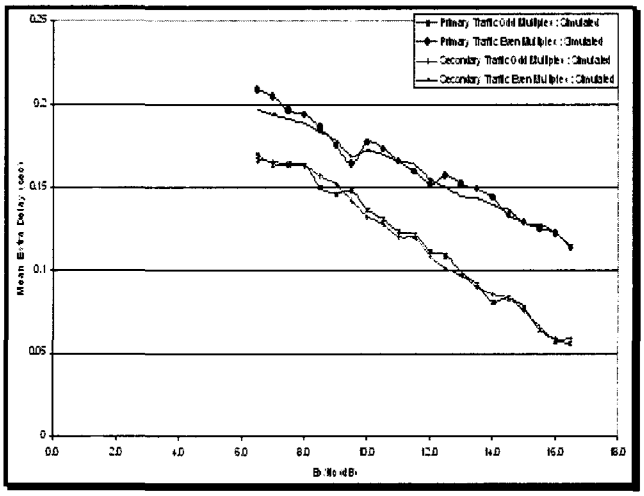

Fig. 4 Delay vs. Eb/No for RLP Frame Format A.

The Fig. 3 shows the throughput as a function of the frame error rate. This is a representation of equation (1). The frame error rate Pe is based on the equation (6) with the assumption of no antenna diversity (i.e. L=1). This figure shows the decrease in throughput performance for the system as the frame error rate increases. Again the throughput of the frames for the odd multiplex option has a better performance as compared to the even multiplex frames in accordance with the Fig. 2. As the frame error increases the number of the retransmissions requests for the incorrect frames also increase and this affects the end-to-end throughput performance.

The Fig. 4 shows the mean extra delay in seconds as a function of the Eb/No for the simulated results. Here the feedback error probability P_f is assumed to be equal to 0.001. From the figure it is clear that the average mean extra delay for the system increases with the increase in the frame error rate at lower Eb/No values. This shows that as the frames received in error are requested for retransmission by the RLP, the delay performance becomes worse with the increase in the error rate. The packet with larger number of bits has higher delay as compared to the smaller packets, as the probability of retransmissions are more for the larger packets.

IV. CONCLUSIONS

The following conclusions can be drawn from the analytical and simulated results of this paper:

The throughput performance for a NAK based ARQ scheme improves with decrease in the frame error rates. The presence of feedback channel errors does not affect the throughput performance, as it is a function of only Pe. The throughput is also independent of the number of retransmissions done by the RLP upon the reception of frame errors. In the random error channel case, as the frame size increases the probability of single bit error increases and this in turn increases the frame error rate, which results in lower throughput performances.

The frame error distribution for fast fading channels ($f_DT > 0.2$) can be considered to be independent of each other and can be considered to be a random error channel. The received signal to noise ratio plays an important role in determining the frame error rates. Higher Eb/No results in better throughput, but other factors like power control, intra cell interference and cell capacity and sector loads have to be taken into consideration while using higher values of Eb/No.

The mean extra delay increases with the higher frame error rates for lower values of Eb/No. The delay also increases with the presence of feedback channel errors as shown in Fig. 7. Here the mean extra delay is evaluated using a constant value of the feedback error probability P_f.

The present study is groundwork for future analysis of the RLP layer for the cdma2000 systems. Future studies of the RLP layer can analyze functions and aspects that were not covered as a part of this research. They mainly include:

- The modeling of the block error probability as the i.i.d. would not be true for slow fading channels or in burst error channel conditions. For such channels it is necessary to study the correlation properties, and it can be modeled as a one-step Markov process whose transition probabilities are a function of the channel characteristics. Such a channel modeling is indispensable for high rate data transmissions and also because of the multi-path radio environments.
- The feedback channel error probability should be varied depending on the channel conditions while evaluating the performance of the system.
- The presence of antenna diversity can be incorporated into the analysis of the system performance.
- Increased frame sizes corresponding to the higher data rates needs to be evaluated for performance analysis.

The usage of error correcting codes like the turbo codes or the burst error codes can be investigated for the fading processes based of the Rayleigh fading channel.

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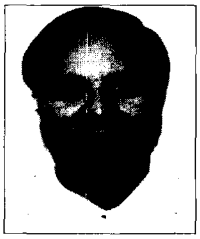

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