Impact of Channel Errors on QoS of IP/cdma2000 Interconnections

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***Abstract*— The behavior of wireless links in third generation wireless data systems based on cdma2000 standard have profound impacts on the performance of transport layer protocols. This is due to greater variations in round trip times(RTTs) experienced by the TCP agents. In this work we present an exhaustive study of the nature and impacts of the variable delays on wireless links caused due to error recovery through link-layer retransmissions. We identify the conditions under which sharp delay variations and residual errors occur in presence of link layer recovery mechanisms and how they degrade the system performance and impact the TCP behavior. Finally, we show how our model could be used for channel allocation to optimize system performance and meet the desired QoS requirements of delays and packet losses.**

I. Introduction

It is now well understood that data services will dominate the cellular market in the future. Therefore, the current trend in IMT-2000 is to move towards new technologies and corresponding standards that provide enhanced data services in cellular networks. However, providing high data rate services through wireless cellular networks is challenged by problems specific to wireless networks viz. scarce channel resources and losses. In order to mitigate the problem of wireless losses and to provide reliable data services, several link layer retransmission mechanisms, e.g. Radio Link Protocol 3 (RLP)[13] in IS-2000, have been proposed to overcome the wireless losses through link layer retransmissions and hide these losses from the transport layer protocols. These mechanisms help in overcoming the frame losses at link layer but they pose an additional problem of high variability in delay over the wireless link. Some faster ARQ[5] mechanisms for newer standards like 1XTREME[3] have been proposed to overcome the losses with lesser delay variability, but the efficacy of all such mechanisms has to be thoroughly analyzed.

An accurate analysis of delays over wireless links is desirable for a variety of reasons. First local retransmissions are an additional overhead for the link and hence bring down the link's effective data rate. Under extreme error conditions or poorly designed retransmission settings, link layer might not be able to recover the losses and TCP might have to come into action for error recovery thereby causing prolonged delays and reduced throughputs. Also, the IP packets traversing over the link experience an additional delay due to retransmissions thereby resulting in inflation of the retransmission timeout (RTO) of TCP and hence delayed recovery in case of loss of a packet. Finally, there may be cases wherein the delay variability is so intense that it causes the TCP sender to timeout resulting in TCP's retransmission and hence an even greater loss in throughputs.

Several attempts have been made to model the impact of link-layer retransmissions on TCP [7], [8], [10]. However, these efforts lack completeness in one way or the other. An analytical model for RLP has been presented in [8] that is integrated with a too simplistic model for TCP and lacks much of the complexities of TCP. Also, these models have been developed for i.i.d. frame errors only and developing similar models for correlated block errors is a complex process and simulations are the only means to address the need for an accurate model. On the other hand, in another approach [7], [6], an extensive model for TCP is used but the link-layer details are simplified by means of introducing delays of desired durations at desired intervals. Such an approach is an oversimplification of delay introduced due to error recovery through link-layer retransmissions and lacks analysis for a given frame error rate(FER) with specific fading-induced correlation structure. Previous works in this area have thus been marked by oversimplified models at either transport or the link layer.

In this study we have developed a simulation tool for cdma2000 data network in widely used ns2[1] simulator. Our model[2] involves elaborate implementation of protocols like RLP, PPP and their integration with physical layer frame error models and transport layer protocols like TCP. In the following sections we will cover these protocols and their implementations. Our extension to the simulator helps in an accurate and broader analysis of additional delays induced over wireless links due to link layer error recovery.

The main focus of this paper is on an exact analysis of delay variability due to link-layer retransmissions for various values of FERs with varying correlation structure and its impact on performance of upper layer protocols. We note that for modest levels of FERs with little correlation, frame losses are effectively handled by link-layer error recovery mechanisms. We further observe that a smaller level of average FER with high degree of correlation produces similar throughputs as a high value of average FER with little correlation. We further derive conditions under which a high data rate supplemental channel may be assigned to a mobile based on its current FER and its tolerance for delay variability. In the following sections we first begin with description of the network setup we are analyzing and then proceed on to our results at various layers of commu-

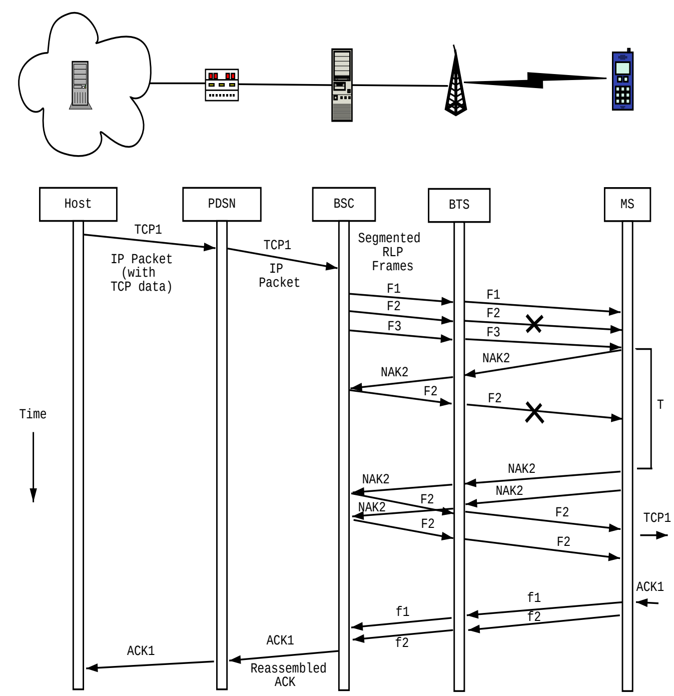


Fig. 1. An example of link-layer error-recovery through RLP retransmissions.

TABLE I
SIMULATION PARAMETERS

Description	Symbol	Value(s)
Application		FTP
TCP version		NewReno
TCP Segment Size	S_{tcp}	960 Bytes
Receiver's buffer size		32KB
TCP Segments per Ack		1
IP Packet Size	S_{ip}	1000 bytes
RLP NAK rounds	n	3
NAKs in each round	NC	$\{1, 2, 3\}$
Retransmit Timer	T	13
Abort Timer	A	13
One way radio delay (BSC to MS)	d_{radio}	40ms
One way wired delay (Host to BSC)	d_{wired}	30ms
Mobiles' data rates	R_{phy}	9.6 Kbps-153.6 Kbps
Error Models:		
(a) i.i.d. error rate	ϵ	0% - 40%
(b) correlated model	p	0.02, 0.05, 0.1
	q	0.08, 0.2, 0.4

nication protocol stack.

II. Background and Setup

The 3G-1X system based on IS-2000 standard uses a single-carrier 1.25 MHz channel. The base data rate for Rate Set 1 (RS1) is 9.6 Kbps. The supplemental channels (SCH) of higher data rates based on RS1 can correspond to one of the following rates - 9.6 Kbps, 19.2 Kbps, 38.4 Kbps, 76.8 Kbps and 153.6 Kbps based on the demand of a particular mobile and availability of resources. SCH allocations are made for certain durations (20ms - 5.2s) based on some scheme such as *finite-burst* mode [9]. It is desirable in a 3G-1X system to hide wireless losses from upper layer protocols like TCP. For this purpose link-layer recovery mechanisms such as RLP are used. A description of the protocol and modeling techniques can be found in the appendix.

Fig.1 shows an example of sending a TCP packet and receiving its Ack for a TCP connection with the two end-points being a host in external internet and a mobile that includes a lossy wireless link between base-station(BTS) and mobile(MS) and an underlying recovery mechanism at link-layer between base-station controller(BSC) and MSs. An incoming IP packet at the BSC, containing a TCP data packet, $TCP1$, is segmented into frames - $F1, F2, F3$ - out of which $F2$ is lost. NAKs are sent to recover this frame. The first NAK round is unsuccessful and eventually in the second round $F2$ is recovered leading to assembly of $TCP1$ at MS, which in turn repones with $ACK1$ which is again segmented into frames $f1, f2$. After successful receipt of these frames, $ACK1$ is assembled at BSC and routed back to its destination host in external internet.

Table I shows the simulation parameters used for analyzing the performance of cdma2000 data network. A single mobile user downloading a large file using FTP application is used for this purpose. The simulations are being performed using a cdma2000 data module in ns2[1] simulator, which we have implemented for the purpose of this analysis.

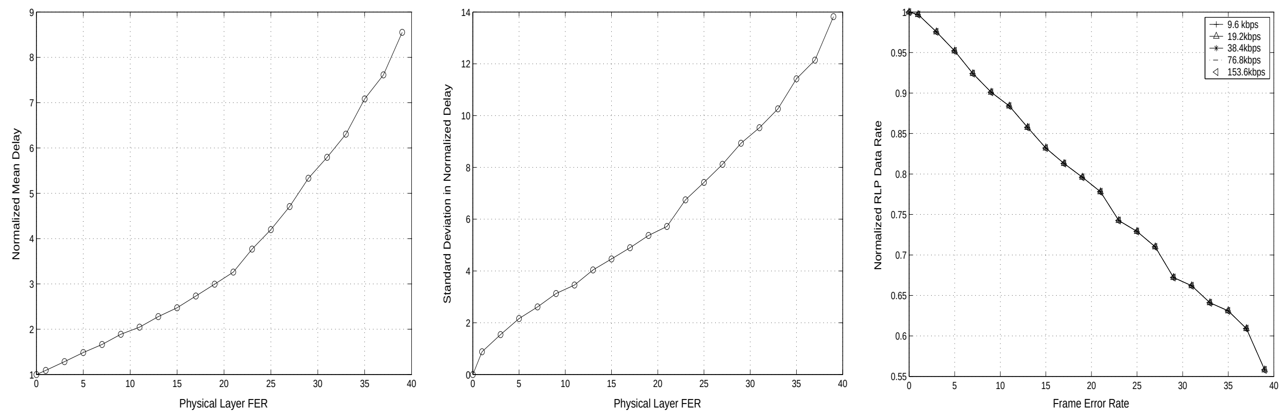
III. Results and Analysis

The impact of link-layer retransmissions can be understood at various levels. As we progressively go up the protocol stack, it manifests in different forms. Several major issues associated due to retransmissions are discussed in next sections.

A. Link Layer

As described earlier, error recovery in wireless networks is mainly done at link layer using protocols like RLP [13]. This layer locally hides the losses from upper layers using retransmissions. These retransmissions introduce several performance-related issues.

1) Delay Behavior: Fig. 2(a),2(b) show the normalized (as a ratio of transmission time of single frame, i.e. 20ms) values of mean delays for various values of frame error rates. It can be seen that both the average delay and deviation in it increase with increasing frame error rates, producing greater variability in delays. Previous works [8] focussed on mainly the mean values of delay. However it has to be clearly understood that increase in delay is not a major problem for higher layer protocols like TCP, instead it is the high variability in delay(Fig. 2(b)) that produces poor performance. As can be seen that for higher FERs, the effective delay over the link can increase manifold than its nominal value. For lower FERs, the variability is low and hence the moderate jitter can easily be absorbed in aggregate transmission.



(a) Normalized mean RLP delay due to various FERs (i.i.d.)

(b) Standard Deviation in normalized delay

(c) Effective RLP data rate due to retransmissions

Fig. 2. Impact of physical layer frame errors (i.i.d) at link layer.

From Eqn. 5 it can be understood that lower values of state transition probabilities,p and q, produce higher levels of correlation. Fig. 3 shows the normalized frame delay for FERs of varying correlations. It can be noted that correlated frame errors produce greater spikes in delays than i.i.d. errors of the same average FER, which indicates at greater degradation of performance due to fading resulting in correlated errors. Also note that extreme levels of correlation can lead to loss of a frame after all the NAK rounds and link layer is unable to retrieve the frame which will eventually lead to loss of the IP packet.

In general, the total normalized delay experienced by an RLP frame, d_{total}, is comprised of three parts:

- Nominal delay corresponding to transmission of frame and latency of link, $d_{nom} = d_{trans} + d_{radio}$. The transmission delay, d_{trans}, is simply the transmission time of frame and is simply ratio of frame size, S_{rlp}, and physical layer rate, R_{phy}. d_{radio} is the latency over wireless link.
- Normalized detection delay, d_{det}, representing the delay in detection of loss of a frame. Suppose that a frame with $L\_SEQ = m$ is lost and the previous frame $(m-1)$ was sent successfully. The frame number m will be detected to be lost when one of the future frames $m+1, m+2, \ldots$, is received successfully. Until that instant the receiver would be not be able to detect the loss. For an i.i.d. FER model, this delay would be,

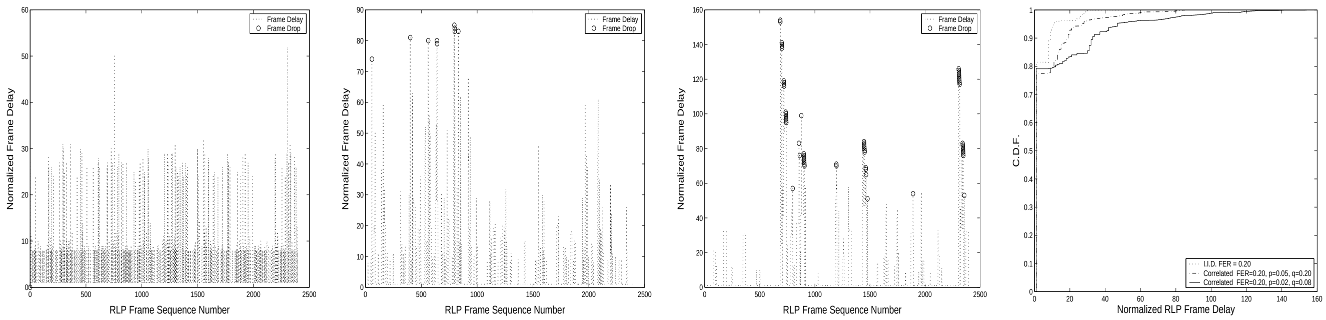
$$d_{det} = (1-\epsilon) + 2\epsilon(1-\epsilon) + 3\epsilon^2(1-\epsilon)\ldots = 1/(1-\epsilon). \quad (1)$$

  For correlated model this corresponds to the stay in *bad* state of the channel and can be found by replacing ϵ by $(1-q)$ in the above relation and turns out be the mean residence time in *bad* state, τ_{bad}. It can be verified that detection delay is not bounded above as it can attain any high value, although with a diminishing tail probability.
- Normalized recovery delay, d_{recov}. This delay is corresponding to the time spent by the receiver in retrieving the frame after first detection of loss of the frame. It can be in between zero (corresponding to successful original transmission) and sum of all the *retransmission* timers of receiver RLP. Since, for each of the NAK round, the retransmission timer is set to retransmit timer, T, plus the number of NAKs sent in the round, this condition bounds the upper limit of recovery delay as,

$$d_{recov} \leq \sum_{i=1}^{n-1} (T + NC(i)) + A, \quad (2)$$

  where A is the abort timer. This means that, after detection of loss of a frame, by the expiry of time equal to RHS in Eqn. 2, the receiver will either be able to recover the lost frame or give up doing so. A mean value of recovery delay is thus a function of FER structure and radio latency. For lower values of FERs, most of the lost frames will be recovered by first NAK round itself and hence the mean value of d_{recov} will be very low. However, for very high FERs, many frames will be recovered after several NAK rounds, some would not be recovered after all NAK rounds and the bound in Eqn. 2 will be attained for these frames.

The total delay experienced by a frame is thus dominated by the time spent in detection of frame loss and subsequent recovery. In our simulation setup as shown in Table.I, values of per-frame delays are shown in Fig. 3. Each round for this setup is of duration 13 units of frame transmission, so the upper bound on recovery delay for this setup using Eqn.2 comes out to 45 units. Fig. 3(a) shows the values of delays for an i.i.d. FER of 20%. It can be seen that for this scenario almost all of the frames are recovered within first two rounds and the retransmission induced delays occur frequently. Also, for this case, since the errors are well distributed, detection delay is negligible to few units and total maximum delay is thus in the vicinity of 50 units, close enough to the upper bound of 45 units as governed by Eqn. 2. Fig. 3(b), 3(c) show the delays for correlated case. Clearly, as the correlation increases, the loss-induced delays are more sharp in nature. The maximum delays are also very large, because with increasing correlation (i.e. decrease in p, q), the mean residence time in bad state is also very large, e.g. for a correlation model with $p = 0.02$, $q = 0.08$, τ_{bad} turns out to be 12.5 units, almost as much as the mean recovery delay. Fig. 3(d) shows the C.D.F. for frame delays for various levels of correlation. Clearly, variability increases with correlation of errors.



(a) I.I.D. FER, ϵ=0.20

(b) Correlated FER=0.20, p=0.05, q=0.20

(c) Correlated FER=0.20, p=0.02, q=0.08

(d) C.D.F. of Frame Delays

Fig. 3. Frame delays for various levels of correlation for a constant mean FER.

This can be summarized by noting that with increasing delays, the mean delay and variability in it both increase, and as the correlation increases, the delays tend to be more sharp and greater because of longer delays in detection of losses due to block errors.

2) Residual Frame Error Rate: As described earlier, RLP will not try to recover a lost frame after all the NAK rounds are over. Thus, despite RLP's elaborate recovery mechanism, it is not entirely error-free and reliable. All it does is to reduce the probability of errors below a desired level. In [8], authors report that the usual $\{1, 2, 3\}$ retransmission scheme helps to overcome the errors and show that, for i.i.d. errors, the residual RLP FER, ϵ_{rlp}, is well within 1% for a maximum FER of 40%. This result can easily be obtained using an i.i.d. FER and noting that residual RLP FER corresponds to all NAK rounds being unsuccessful, i.e.,

$$\epsilon_{rlp} = \epsilon^{1+\sum_{i=1}^{n} NC(i)}. \tag{3}$$

However, for correlated model, the residual FERs could be much higher because of sustained burst of errors. Fig. 3(b), 3(c) show this effect where, for a constant value of mean FER, as the correlation increases, the number of frames that could not be recovered after all NAK rounds increases and can not be neglected. In reality, residual FER for fading-induced correlated losses are difficult to be modelled analytically and simulations are the only means of getting an estimate. Table II shows the residual FER values for varying levels of correlation obtained using our simulation tool. It can be seen that for higher levels of correlation, RLP's retransmission scheme is unable to retrieve the lost frames and a residual FER of as high as nearly 5% can occur under such circumstances. This problem can be mitigated to an extent by using a more distributed retransmission setting, say $\{1, 1, 1, 1, 1, 1\}$ as in [10]. It is clear that high levels of correlation might lead to unsuitability of a particular retransmission setting and hence fading effects have to be adequately addressed while designing the network. Several approaches including one that adaptively changes retransmission settings[11] have been proposed to mitigate this problem.

3) Reduction in Data Rate: An immediate consequence of retransmissions is reduction in effective data rate. Since, under error conditions, some of the frames needs to be transmitted more than once, this leads to an additional overhead on the wireless resources. Fig. 2(c) shows the impact of retransmissions on the available data rate at link layer. It can be seen that at an i.i.d FER of 40%, the effective data rate goes to almost half its rate while operating under error-free conditions. An example of a poorly designed retransmission scheme that significantly alters the effective data rate is one in which too many NAK frames are sent in initial rounds for low levels of FER. This illustrates that retransmission settings are of utmost importance in retrieving lost frames with minimal overhead.

TABLE II

Residual RLP FER for various levels of correlation and constant mean FER.

FER parameters	Residual FER (%)
i.i.d., $\epsilon = 0.02$	0.0013
correlated, $p = 0.1$, $q = 0.4$	0.015
correlated, $p = 0.05$, $q = 0.2$	0.862
correlated, $p = 0.03$, $q = 0.12$	2.312
correlated, $p = 0.02$, $q = 0.08$	5.251

We will conclude this section by commenting on some of the deficiencies in the modeling techniques employed for link layer protocols. In [8], authors have modeled RLP and have ignored the additional queueing delays associated in detection of lost frames due to overdue *retransmit* frames. Also, in many modeling approaches, a constant value of round-trip time, R in sending a NAK and receiving the corresponding reply has been taken. Such an approach fails to capture additional queueing delays for NAK frames on receiver side due to other NAKs on one hand and the queueing delays associated with *retransmit* frames at the sender. Therefore, averaging out a value of R is impractical as it varies a lot with FER level, and at higher FER levels, the queueing delays mentioned above need to be taken into consideration for an accurate analysis. So, even though the analytical model provides rich insight into the behavior at low FERs, but at high FERs, in our view, simulations are the only way of accurately examining RLP behavior. It is our belief that our simulation tool will be effective in meeting this need for a robust and accurate model.

B. IP layer

At IP layer, apart from the error recovery, the delays are dependent on another factor - number of RLP frames per IP packet, $N_{rlp}(R_{phy}, S_{ip})$. Fig. 5 shows the results at IP layer. It can be seen that at lower data rates, when each of the IP packet is segmented into large number of frames, the delay jitter due to link layer retransmissions are absorbed to a great extent and the effective IP packet delay is never more than twice what it would take for an IP packet to traverse through error-free wireless link(Fig. 5(a)). This is due to the fact that large number of RLP frames are created for each IP packet and recovery in case of a loss can be mostly done while the original transmission of an IP packet's frames is going on. Correlated errors of same average FER however are more harmful leading both to loss of IP packets and greater spikes in delay(Fig. 5(b)). Fig. 5(c) shows that the delay jitter of link layer gets translated to delay spikes at IP layer if a high rate of 153.6 Kbps is used. This is because of the fact that fewer RLP frames are generated for an IP packet which, in case of loss, are mostly recovered when the sender is done with original transmission of IP packet and recovery might only be done when several future frames have been transmitted. However, link layer as before in Fig. 5(a) is effective in recovering the losses and no packet drops occur. So, a high level of correlation of errors and a high data rate can trigger spikes in packet delay that is harmful for wireless network performance. Fig. 5(d) illustrates that same level of physical layer of FER of 0.20 can trigger varying kinds of delay behavior at IP layer depending on the correlation structure and current data rate for the mobile.

Although, high data rates lead to greater delay variability, but a very low value of data rate is also not desirable as it magnifies the residual errors at link layer to those at IP layer, ϵ_{ip}. Note that residual IP layer error corresponds to scenario when any of the constituent RLP frames could not be recovered at link layer, i.e.,

$$\epsilon_{ip} = 1-(1-\epsilon_{rlp})^{N_{rlp}(R_{phy},S_{ip})} \approx N_{rlp}(R_{phy}, S_{ip})\cdot\epsilon_{rlp}. \quad (4)$$

Since number of RLP frames per IP packet is large for lower rates, so residual IP layer error rate decreases with increasing data rates, R_{phy}. However, the magnification of residual errors at IP layer occurs only at extremely low data rates and for a properly designed system with negligible residual RLP errors, only the delay variation needs to be considered for better performance.

C. TCP Performance

Fig. 6(a) shows the TCP traces for an error-free link. Fig. 6(b) shows the decrease in throughput due to reduced effective Link Layer rate as exhibited in Fig. 2(c). However link layer is able to recover all the lost frames and IP packet drops do not occur and the overall behavior is smooth. Fig. 6(c) shows further decrease in throughput due to correlated losses of same average FER. This is due to loss of packets due to failure of link layer to recover the lost frame after all NAK rounds. Fig. 6(d) shows that at higher levels of i.i.d. FERs packet losses do occur and the recovery is also very slow due to inflation of RTT. It can be seen that an i.i.d. FER of 0.35 offers roughly the same throughput ($\sim$ 200 TCP segments in $400s$) as a correlated FER of 0.20 and it establishes that fading effects have to be considered while modeling the delay of wireless links.

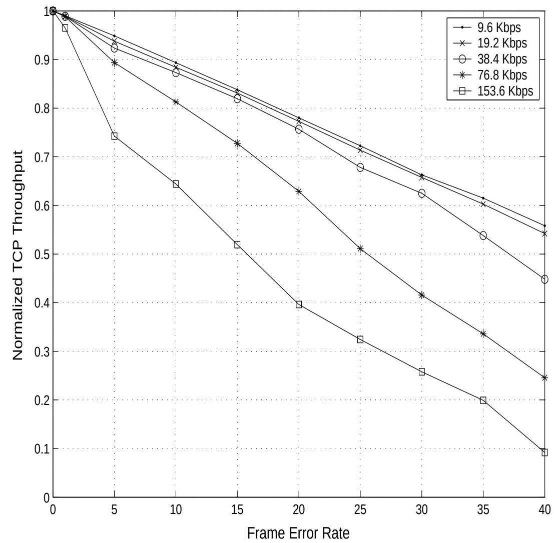


Fig. 4. TCP throughputs for various values of raw link rates and physical layer FERs (i.i.d.)

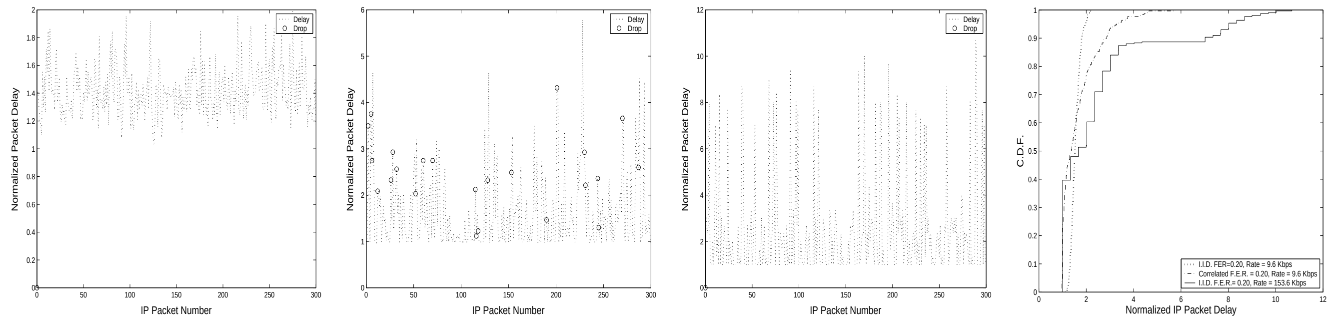
Fig.7 shows TCP behavior for a higher rate of 153.6Kbps. At this high rate when fewer frames are generated for each IP packet, delay variability is high and a modest i.i.d. FER of 0.20 that did not produce significant reduction in throughput for lower rate of 9.6Kbps(Fig. 6(a), Fig. 6(b)) is enough to significantly alter the available throughput as shown in Fig. 7(a) and Fig. 7(b). The ACK arrival times are not regular and show large variations. As mentioned earlier, for such high data rates, the delay variation has spike-like behavior and can trigger timeouts and one such timeout occurs at around $25s$. Fig.7(c), 7(b) show further degradation when correlation and mean FERs are increased respectively. Fig. 4 shows the TCP throughputs for various levels of FER (i.i.d) at various data rates for mobiles. It can be clearly seen that at higher data rates, TCP throughput reduces significantly more than lower rates due to higher delay variability leading to poor performance of TCP's window mechanism.

It can be clearly stated that TCP performance in presence of wireless losses and link-layer recovery is dependent on appropriate choice of design parameters viz. retransmission settings, retransmission timer. Fewer NAKs in high error scenarios will produce greater residual FER and degrade performance and an excessive number of NAKs for a low error case will again degrade throughputs by triggering unnecessary retransmissions. Also, the retransmit timer, T, has to be appropriately chosen so that RLP receiver waits for adequate time before entering the next NAK round.

A significant consideration in designing 3G wireless data system should be devoted towards SCH allocation to mobiles depending on wireless conditions. In the following section, we discuss one possible scheme for making channel allocation decisions.

IV. Supplemental Channel Allocation Decisions

It has been shown earlier that a high data rate SCH assigned to a mobile in poor wireless conditions significantly reduces the



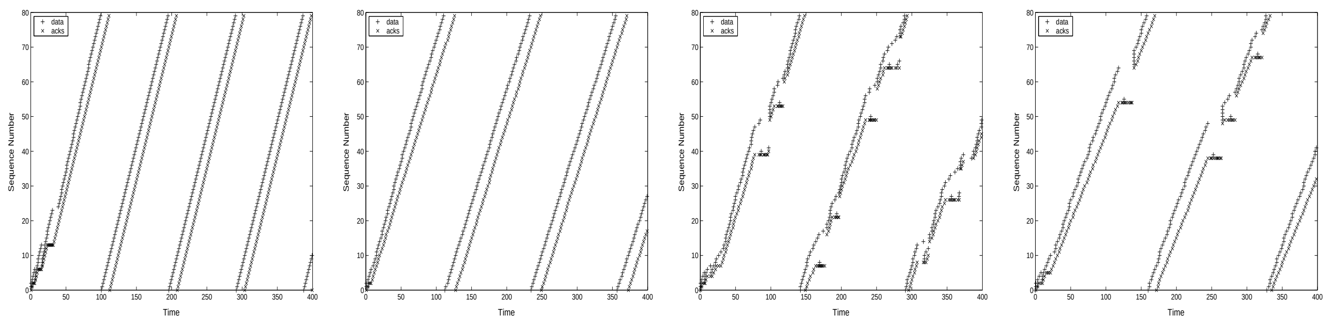
(a) I.I.D. FER ϵ = 0.20, R_{phy} = 9.6Kbps.

(b) Correlated FER = 0.20, p = 0.02, q = 0.08, R_{phy}= 9.6Kbps.

(c) I.I.D. FER = 0.20, R_{phy}= 153.6Kbps.

(d) C.D.F. of Normalized IP Packet Delays.

Fig. 5. Normalized IP packet delays.



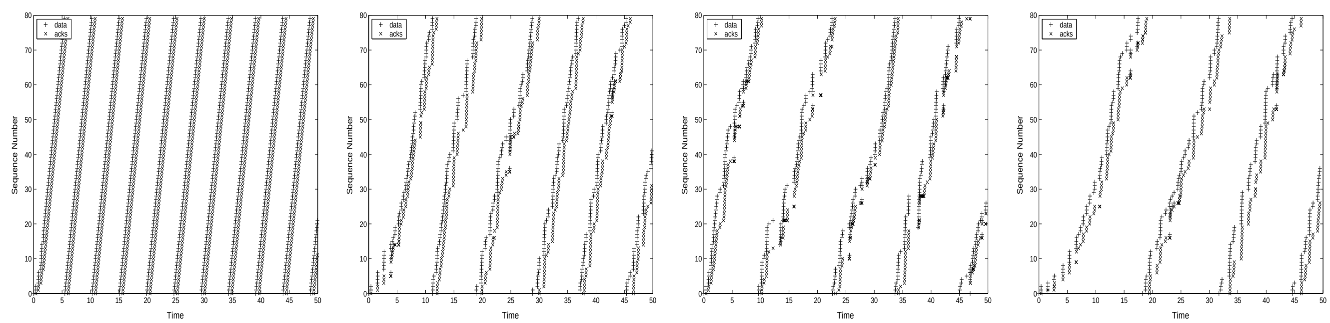
(a) ϵ = 0

(b) I.I.D. FER = 0.20

(c) Correlated FER = 0.20,p = 0.05,q = 0.20

(d) I.I.D. FER = 0.35

Fig. 6. TCP behavior for R_{phy} = 9.6Kbps (Sequence numbers are in *modulo*-80 fashion).



(a) ϵ = 0

(b) I.I.D. FER = 0.20

(c) Correlated FER = 0.20,p = 0.05,q = 0.20

(d) I.I.D. FER = 0.35

Fig. 7. TCP behavior for R_{phy} = 153.6Kbps(Sequence numbers are in *modulo*-80 fashion).

throughputs. So, the BSC should be able to make a decision as to how much resources could be allocated to the mobiles so that the scarce resources are not unnecessarily wasted for a mobile in poor radio conditions and the overall system performance is not seriously degraded. A straight way of making this decision would be to look at FERs, however the thresholds for FER making these decisions ought to have some logical connection with upper layer protocols. We discuss one possible way of doing so.

As an example, consider a conservative design with stringent QoS constraints wherein the system has to be designed in a manner for smooth operation as in Fig. 6(b) such that, like Fig.5(a), the maximum normalized delay of any constituent RLP frame of an IP packet, d_{tot}, is within transmission time for next IP packet, i.e. a maximum normalized delay of 2. Now using our simulator, we can calculate d_{tot} for different FER structures, retransmission settings and latencies, and based on that, a maximum level of sustainable SCH allocation can easily be calculated for this case by noting that the boundary condition for smooth operation is when last RLP frame of current IP packet is recovered just before the transmission of last frame of next IP packet, i.e., $d_{tot} < N_{rlp}(R_{phy}, S_{ip})$. This inequality together with Eqn.7 can be used for calculating the maximum allowable SCH allocation i.e. R_{phy} for a given FER structure and thus BSC channel allocation decisions can be made for the case under consideration. Similar arguments can be used to develop a system for a more liberal design with a wider delay spread and a range of FER structures, radio link latency and retransmission settings.

V. Conclusion and Future Work

In this work, we presented an accurate model for link layer in cdma2000 data networks. Fading-induced effects have been examined at various levels and an exact analysis for interaction of link layer protocols and upper layers has been presented based on our simulation tool. We illustrated the conditions under which link layer retransmissions produce the undesirable effects such as delay spikes, residual frame losses and reduced data rates. As future work, we will be using the developed model for developing an elaborate scheme for channel allocation based on specific QoS requirements.

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Appendix
Components of a 3G-1X system

A. Physical Layer Channel

The errors on the wireless links can be in either scattered form or in form of sustained blocks due to fading. The former can be easily modeled using an i.i.d. error model of a given frame error rate, say ϵ. For latter, the correlation exhibited by the Rayleigh fading can be modeled using a first-order two-state Markov chain[15] wherein the channel alternates between a *good* and a *bad* state with a transition matrix,

$$T = \begin{pmatrix} 1-p & p \\ q & 1-q \end{pmatrix}. \tag{5}$$

During the *good* state, all the frames are sent correctly over the channel and are all in error during a *bad* state. The mean FER for such a correlated model is $\epsilon = p/(p+q)$, and the mean residence times in good and bad states are, $\tau_{good} = 1/p$ and $\tau_{bad} = 1/q$, respectively.

The advantage of using this model is that there exists a direct mapping of fading margin, F, and normalized Doppler frequency, $f_D T$ (where f_D is the maximum Doppler shift and T is the duration of packet slot) to the parameters, p and q of the Markov chain. This scheme allows for simulation of any desired level of correlation of errors in the forward and reverse links of a particular mobile. In our simulations, we have put the error-model in the downlink only. However, similar results can be derived by putting an equivalent error-model in the uplink.

B. Radio Link Protocol

In order to mitigate the losses over the wireless link, several link-layer protocols are used to recover the lost data. For instance, cdma2000 systems use the Radio Link Protocol 3(RLP) [13] to overcome the losses. RLP performs the following two main functions.

1) Fragmentation and Assembly: Upon receiving an IP packet, RLP entity first puts it in the *new-data* buffer and after the packet leaves the queue, it is fragmented into RLP frames of size corresponding to the current data rate and puts other information viz. frame sequence number, L_SEQ, in its 5-byte header. The frame size is chosen in a manner so as to transmit the frame in a 20ms slot for current value of available data rate. Assuming that physical layer rate remains constant during the transmission of an IP packet, the fragmentation mechanism, for a given raw physical layer data rate, R_{phy} Kbps, slot duration for frame transmission, $slot$, frame header of hdr_len bytes, and an IP packet of size, S_{ip} bytes, will generate $N_{rlp}(R_{phy}, S_{ip})$ RLP frames of size S_{rlp} bytes each where,

$$N_{rlp}(R_{phy}, S_{ip}) = \lceil (S_{ip}/(((R_{phy} \cdot slot)/8) - hdr\_len)) \rceil \tag{6}$$

$$S_{rlp} = (R_{phy} \cdot slot)/8 \tag{7}$$

In case there is a waiting IP packet in *new-data* buffer, part of its data is put on the vacant space on the payload of last 20ms RLP frame of current IP packet. Frame size is strictly controlled by data rate and any change in it is immediately applied in determining the size of future frames. After transmitting each frame, the RLP sender puts the frame in a *retransmission* buffer, so that it can send the frame again in case the receiver demands so.

On the receiver RLP, the received RLP frames are put in a *resequencing* buffer until all the outstanding frames are received. The frames that are received in sequence are passed on to higher layer and in case a frame is detected to be lost, ARQ mechanism as explained next is used. If ARQ is unable to recover the lost frame, the link-layer passes the available data with holes to higher layers.

2) Automatic Repeat Request(ARQ): The ARQ mechanism employed in cdma2000 data networks is of selective repeat type. The RLP receiver does not acknowledge correctly received frames, instead it only requests those frames that it detects to be lost or finds to be in error. The RLP receiver maintains two variables, $L\_V(N)$ and $L\_V(R)$. The first one is the sequence number of frame needed for sequential delivery to upper layers and other one is the next frame expected by the receiver. Whenever the RLP receiver detects that incoming frame's sequence number, L_SEQ, is greater than $L\_V(R)$, it creates a NAK_LIST entry for each of the missing frames. A NAK_LIST keeps record of all the lost frames. Other setup parameters for link-layer are - number of NAK rounds, n, retransmit timer, T, and number of NAK frames to be sent in i-th NAK round, $NC[i]$. Upon receipt of every frame, NAK_LIST is updated by removing the entry for an outstanding frame that is received correctly on retransmission and sending NAK control frames for those missing frames whose retransmit timer, T, has expired for a particular round. If RLP is unable to recover the frame after $n-1$ rounds, it starts the n-th NAK round and starts an abort timer, A, to wait for the missing frame after which it passes the available data to the higher layers. Note that since all timers are frame counters, the specifications stipulate sending $IDLE$ frames when the sender has no data to send so that receiver does not have to wait indefinitely for its timers to expire.

C. Upper Layer Protocols

Point to Point Protocol(PPP) forms a data link between the BSC and MSs. Since IP packets are fragmented to RLP frames at BSC, PPP connection takes over the routing of data to its destination at BSC. PPP consists of variety of other options for setting up the link. Transmission Control Protocol (TCP) is a transport-layer protocol that provides reliable transport of data between two end-points. Several applications like File Transfer Protocol(FTP) can be run over TCP. A detailed description of these protocols can be found in [14].