TCP Performance in WCDMA-Based Cellular Wireless IP Networks

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Index Terms- Dynamic rate adaptation, variable spreading factor WCDMA system, TCP.

Abstract— **The performance of TCP (Transmission Control Protocol) is evaluated for downlink data transmission in a cellular WCDMA (Wideband Code Division Multiple Access) network where variable rate transmission is supported at the RLC (Radio Link Control)/MAC (Medium Access Control) level. A simple rate search procedure (based on the number of simultaneous TCP connections and the channel condition) is proposed for the RLC/MAC level transmission rate selection for downlink data transmission. The dynamic rate variation is assumed to be achieved by using single-code transmission with variable spreading factor, where the spreading factor varies inversely with the transmission rate. A novel 'mean-sense' approach to calculate inter-cell interference in such an environment is developed assuming homogeneous traffic load (in terms of active TCP connections) in different cells. The impact of the different physical layer, RLC/MAC layer and TCP parameters on the end-to-end throughput performance are investigated by simulating the system dynamics under multiple concurrent TCP connections.**

I. Introduction

WCDMA systems (e.g., ETSI WCDMA, cdma2000) will be the major radio transmission technologies for IMT-2000 (International Mobile Telecommunications 2000). The core network in an IMT-2000 system will be IP (Internet Protocol) based, which will evolve through GSM/GPRS-based core network architecture [1]. Standardization efforts in 3GPP (Third Generation Partnership Project) are now directed in this direction. Since the transport layer protocol performance is one of the most critical issues in data networking over noisy wireless links ([2]-[3]), the performance of TCP, which is the flagship protocol in today's Internet, would be crucial in such an environment.

The performance of TCP for wireless Internet access in a packet-switched cellular WCDMA environment would depend on the service provided by the underlying RLC/MAC protocol which allows variable rate packet data transmission for achieving high radio spectrum utilization. Interference calculation for TCP performance evaluation is non-trivial in such an environment, particularly for heterogeneous traffic load in different cells.

In this paper, the performance of TCP is evaluated for downlink packet data transmission in cellular WCDMA networks assuming homogeneous traffic load (in terms of active TCP connections) in the different cells. The RLC/MAC layer frame transmissions are assumed to be based on a *sub-optimal rate selection procedure* and the transmission rate to an MS (Mobile Station) can be controlled on a frame by frame basis, depending on the number of concurrent TCP connections passing through the BS (Base Station). Variable rate transmission to a mobile station is assumed to be achieved through single-code transmission with variable spreading gain ([4]-[6]). A novel 'mean-sense' approach is used for inter-cell interference calculation under such a condition where the number of instantaneous TCP connections in a cell may vary while the average number of active TCP connections over all the cells is assumed to be kept fixed[1]. Performance evaluation is carried out for wide-area TCP connections for two different wireless channel models ([11]-[7]), namely, *multipath channel with equal path gain* and *multipath channel with unequal path gain*.

The impacts of channel impairments and different physical layer parameters along with the effects of variations in the different TCP parameters, e.g., TCP

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[1] This can be done by the RNC (Radio Network Controller) in a WCDMA network.

window size (W), transmission delay in the wired-network or Internet delay (D_{wd}) on the throughput of a target TCP connection are investigated.

The issue of transmission rate variability at the RLC/MAC layer (and hence the issue of interference modeling under variable rate transmission) was not considered in the earlier works on wireless TCP in a DS-CDMA environment (e.g., [8]-[9]). In addition, in most of the cases, system dynamics under single TCP connection was dealt with.

II. System Model

A. TCP Model

A C-coded event-driven simulator that supports the TCP congestion and error control algorithms, including *slow-start*, *congestion avoidance*, *fast retransmit* and *fast recovery*, is used to imitate the TCP behavior. The RTO (Retransmission Time Out) value is based on RTT (Round Trip Time), which is estimated by exponential weighted averaging. The RTT is measured for each successfully received unretransmitted packet. Based on these measurements, a moving estimate of the round trip time (RTT_{mean}) is made according to the following: $RTT^{i+1} = c \times RTT_{measured} + (1-c) \times RTT^{i}$. The value of the low-pass filter gain parameter c is assumed to be 0.1 in this paper. Conventional TCP implementations update the RTO value as the sum of the smoothed average and four times the standard deviation of the RTT values (*Jacobson's Algorithm*).

A sender-based one way traffic scenario is considered where the mobile stations act as TCP sinks. It is assumed that the ACKs generated by the TCP sinks are not dropped in the wired part of the network although the ACKs may be lost in the wireless link. The ACK packets undergo no extra queueing delays in addition to the propagation delay. All of the TCP connections in a particular simulation scenario are assumed to experience the same Internet delay.

B. Radio Link Layer Model

A TCP data unit is typically equivalent to several RLC/MAC layer frames. For example, in IS-99, the CDMA circuit-mode data transmission standards, the radio link layer frame size is 24 *bytes* (with 19 *bytes* of payload) and the TCP segment size is 536 *bytes*. In a GPRS-based UMTS environment, a TCP packet will be forwarded to the RLC/MAC layer after IP, SNDCP (Subnetwork Dependent Convergence Protocol) and LLC (Logical Link Control) overheads have been appended to it.

During each frame-time (or timeslot), the downlink transmission rate to a mobile (i.e., the number of basic link layer frames) is determined by a sub-optimal rate selection procedure (as will be described later) based on the number of simultaneous TCP connections present at that time. The number of RLC/MAC layer frames to be sent in a timeslot is varied according to the transmission rate used.

Let us assume that the length of a slot, denoted by T_s, is fixed and that the transmission rates can be selected from the set of rates $\{v_1, v_2, \ldots, v_\varphi\}$. If it is assumed that $v_m = mv_1$ $(m = 2, \ldots, \varphi)$ [2], and that only one frame (of fixed length of M bits) corresponding to the smallest (basic) rate v_1 can be sent in a slot, then for a transmission rate of v_m, m frames can be sent in a timeslot. To achieve this variable rate transmission, a variable spreading factor (VSF) WCDMA system is used where the basic factor is given by N chips per bit, and for rate v_m, the spreading factor is reduced to N/m chips per bit. Note that the signal energy per bit (E_b) is kept constant to achieve almost the same bit error rate (BER) performance.

The best performance can be obtained if the simultaneously transmitting users choose the optimum combination of transmission rates. The RLC/MAC level throughput (β) can be expressed by

$$\beta(n_1, n_2, \ldots, n_\varphi) = \sum_{m=1}^{\varphi} m n_m P_{c,m} \quad \text{frames/slot} \tag{1}$$

where the probability of correct reception of a frame $P_{c,m}$ is dependent on the physical layer BER (Bit Error Rate) performance $P_{b,m}$ (and hence on the channel interference and fading conditions) and on the error control protocol employed. Channel interference conditions largely depend on the dynamically selected transmission rates in the different cells. The probability of correct reception of a frame $P_{c,m}$ for a user transmitting at rate v_m can be expressed as

$$P_{c,m} = \sum_{e=0}^{t} \binom{M}{e} P_{b,m}^{e} (1 - P_{b,m})^{M-e} \tag{2}$$

where M is the frame size (in bits) corresponding to the smallest (basic) rate v_1.

A one-step rate selection procedure [10] is used here for a specified rate vector $\mathbf{v}$ assuming n simultaneous TCP connections. The rate selection procedure determines the value of v_m for which the RLC/MAC

[2]For the rest of the paper, it is assumed that $v_m = mv_1$ so that the normalized value of v_m with respect to the basic rate v_1 is m.

layer throughput (in terms of the number of basic RLC/MAC frames) is maximized when the same transmission rate v_m is selected for all the TCP connections.

An ACK/NAK-based RLC/MAC level error control is assumed where the error recovery is similar to the conventional SR-ARQ protocol although it is more complex due to variable rate transmission. To illustrate, flow diagram of the SR-ARQ protocol under variable rate transmission is depicted in Fig. 1 for transmissions from a single user, assuming that the acknowledgement delay is T_s (i.e., one timeslot) and that the data rate v_m can be selected from the set $\{v_1, v_2, v_4\}$. Here, a heavy traffic condition is assumed so that newly generated frames are always available and can be transmitted along with the old frames (which are being retransmitted) so that the variable rate transmission can be fully exploited from slot to slot.

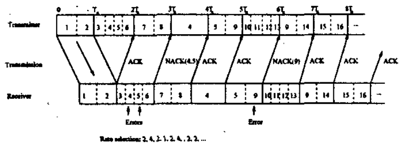

Fig. 1. SR-ARQ based RLC/MAC level error control in variable rate transmission systems.

RLC/MAC level error recovery continues until R_{max} transmission failures occur in succession where *all the frames transmitted in a timeslot are garbled.* At this point the whole TCP packet is discarded and the TCP at the sending host performs end-to-end error recovery. The rationale behind this assumption is, in the case that all the transmitted frames in a timeslot have not failed, the channel condition can be assumed to be still *not too bad* so that persisting on retransmission may be beneficial to avoid end-to-end error recovery.

III. Downlink SINR Modeling and BER Calculation

Assume that the transmitted signal from the BS is affected by the L-path Rayleigh fading with path gains $\{a_l\}$ with $\sum_{l=1}^{L}\sigma_l^2 = 1$, $\sigma_l^2 = \mathbf{E}\{a_l^2\}$ ($\mathbf{E}$ denotes an expectation). All mobiles are assumed to be uniformly located in a cell. For synchronous transmission in the downlink of a target cell (while asynchronous transmission is assumed between cells), with rate selection being independent of the location of their corresponding mobiles, the average output signal-to-interference-plus-noise-ratio $\overline{(SINR)}_{o,i}^{(l)}$ for the lth path of ith mobile can be modeled as (3) [10].

$$\overline{(SINR)}_{o,i}^{(l)} = \frac{1}{\left[\frac{x}{3N}\left(\frac{1}{\sigma_l^2}-1\right)+\frac{\eta\alpha G}{3N\sigma_l^2}+\left(\frac{2\sigma_l^2 E_b}{N_o}\right)^{-1}\right]}. \quad (3)$$

Here, η is the frequency reuse factor in downlink, $x \triangleq \sum_{m=1}^{\varphi} m n_m$ with n_m = number of mobiles choosing the rate v_m, G = average offered load (i.e., average number of active TCP connections per cell) and $\alpha \triangleq \mathbf{E}\{m\}$, which accounts for the average rate selection in other cells. Note that the background noise with p.s.d. $N_o/2$ is also included, but the transmission power of any of the control channels, e.g., the pilot channel, is not included in (3).

In the case of multipath Rayleigh fading channel with equal path gain (*channel model-A*), an L-path Rayleigh fading channel with uncorrelated scattering and equal average path power is considered. For this model, the average output $\overline{(SINR)}_{o,i}^{(l)}$ is given by (3) with $\sigma_l^2 = 1/L$ and the BER P_b is given by [7]

$$P_b = \left[\frac{1}{2}(1-\zeta)\right]^L \sum_{l=0}^{L-1} \binom{L-1+l}{l} \left[\frac{1}{2}(1+\zeta)\right]^l \quad (4)$$

where $\zeta = \sqrt{\overline{(SINR)}_{o,i}/[2+\overline{(SINR)}_{o,i}]}$.

In the case of multipath Rayleigh fading channel with unequal path gain (*channel model-B*), the BER can be expressed as [7]

$$P_b = \frac{1}{2}\sum_{l=1}^{L} \pi \left[1-\sqrt{\frac{\gamma_l}{1+\gamma_l}}\right] \quad (5)$$

where $\pi = \prod_{l'=1, l'\neq l}^{L} \gamma_l/(\gamma_l - \gamma_{l'})$ with $\gamma_l = \frac{1}{2}\overline{(SINR)}_{o,i}$. Here, $\overline{(SINR)}_{o,i}$ is as given in (3).

IV. Simulation of TCP

A. Simulation Assumptions and Parameters

The buffer size at the BS is assumed to be infinite so that packet loss can occur only due to errors in the wireless channel. Per-destination queueing with FIFO (First In First Out) scheduling (within each queue) is assumed for the TCP packets at the BS. The RLC/MAC layer frames corresponding to the TCP packets are buffered in the link layer queues (Fig. 2). From each of the RLC/MAC frame queues, m_o frames are transmitted simultaneously during each timeslot, where m_o is determined using the rate selection procedure previously described. The set of permissible rates is assumed to be $\{v_1, v_2, \cdots, v_8\}$ with $v_m = mv_1$. Mobile specific channelization code and the cell specific scrambling code are used for downlink transmission.

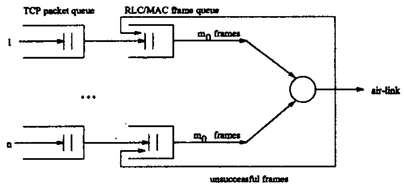

Fig. 2. Queueing of TCP packets and RLC/MAC layer frames at the BS for downlink transmission.

The different physical layer simulation parameters are: maximum spreading gain (N), outer-cell interference factor (η), FEC (Forward Error Correction) parameter (t), ratio of bit energy and AWGN noise spectral density (E_b/N_o), number of resolvable multipaths (L) and tapped-delay-line parameters (for channel model-B). Parameters for channel model-B are based on the vehicular-B model [12] for macro-cell.

The different simulation parameters at the TCP and RLC/MAC level are: system load G in terms of the average number of TCP connections in the network, TCP segment size (MSS), TCP maximum window size (W), TCP fast retransmit threshold (K), TCP timer backoff parameter (Q), initial RTO value ($RTO_{initial}$), allowable transmission rates ($\mathbf{v}$), wired-network (or Internet) delay (D_{wd}), number of concurrent TCP connections (N_c), fast retransmit parameter (K), RLC/MAC layer frame size M corresponding to the basic rate v_1, frame-length in time (T_s), and the maximum number of retransmissions allowed at the RLC/MAC layer (R_{max}). The assumed values for some of these paraemters are: $MSS = 576$ *bytes*, $K = 3$, $Q = 2.0$, $M = 16$ *bytes*, $T_s = 10$ *ms*, $N = 128$, and $L = 4$ (for channel model-A).

The parameter R_{max} is to be chosen properly so that the RLC/MAC layer retransmissions do not interfere with the end-to-end retransmission. The transmission time for a link layer ACK is assumed to to be one timeslot (T_s). A similar assumption is made on the transmission time of TCP ACK from the mobile station. The parameter D_{wd} accounts for the delay experienced by the TCP packets in the wired part of the network and hence affects the RTT value of the corresponding TCP connection. During each simulation, the initial value of RTT is chosen as follows: $RTT^0 = 2 \times (D_{wd} + \Delta) + MSS \times T_s$. Here, Δ = guard time = 5 *ms*.

The performance metric being considered here is the *TCP throughput (β_{TCP})*, which is measured as the total number of bytes received per unit time at the TCP sink.

B. Simulation Results and Discussions

The impact of variations in the frequency reuse factor (outer-cell interference coefficient) η and the average offered load G on TCP throughput are demonstarted in Figs. 3 - 4. With a TCP packet size of 576 *bytes* and a RLC/MAC frame size of 16 *bytes* (corresponding to the basic rate v_1 and frame period of 10 *ms*), the maximum per-connection throughput achievable in an error-free channel would be 92.16 *Kbps*. Because the RLC/MAC level rate selection would allow 8 frames to be transmitted within a frame-time (i.e., $m_o = 8$) in this case. For a single TCP connection, with $W = 5$ and $D_{wd} = 50$ *ms*, here, TCP throughput $\beta_{TCP} \approx 84, 80$ *Kbps* for channel model-A and channel model-B, respectively. As the number of simultaneous TCP connections (N_c) increases, throughput per connection (β_{TCP}) falls off rapidly. The observed improvement in β_{TCP} due to a reduction in the outer-cell interference coefficient and/or average system load is not significant.

The effects of variations in E_b/N_o and t on β_{TCP} are demonstrated in Figs. 5 - 6 for channel model-B. TCP throughput improves when the ratio of received bit energy (E_b) to background noise power spectral density ($N_o/2$) is increased, but the rate of improvement diminishes with increasing E_b/N_o. For small number of connections, an increase in the value of the FEC parameter (t) may reduce the per-connection *effective TCP throughput*[3] (Fig. 6). This would become more pronounced as the maximum TCP window size W decreases and/or Internet delay D_{wd} increases. But when the number of concurrent TCP connections is relatively large, the effective throughput increases monotonically with t. The effect of variation in R_{max} on β_{TCP} is shown in Fig. 7.

The effects of the maximum TCP window size (W) and the Internet delay (D_{wd}) on TCP throughput under varying number of simultaneous TCP connections are demonstrated in Figs. 8 - 9. As is evident from Fig. 8, for a particular value of D_{wd}, the value of W can be selected such that the throughput is maximized. If t_{TCP} is the transmission delay of a TCP

[3]It is calculated using the Varsharmov-Gilbert bound [13] for each successfully received RLC/MAC layer frame with t-bit error correction capability.

packet (from BS to MS) and t_{ACK} is the corresponding ACK delay (from MS to BS), then the minimum value of the maximum TCP transmission window size W_{min}[4], for which the 'packet pipe' corresponding to a connection would be full, is given by

$$W_{min} = 1 + \frac{2 \times D_{wd}}{t_{TCP}} + \frac{t_{ACK}}{t_{TCP}}. \quad (6)$$

As the number of simultaneous connections increases, t_{TCP} increases and hence W_{min} decreases. Again, large values of W may cause more frequent invocation of the TCP 'congestion control' mechanism and more timeouts, and consequently, the packet transmission rate corresponding to a TCP connection may decrease. This causes degradation in the achieved throughput performance.

As D_{wd} increases, the value of W need to be increased to keep the transmission 'packet pipe' full. For this reason, for a particular value of W, throughput falls off as D_{wd} increases, especially when the number of connections is small (Fig. 8). As the number of TCP connections increases, the performance difference becomes insignificant, because due to the smaller rate selection at the RLC/MAC layer, t_{TCP} increases in this case. As a result, for a particular W, even if D_{wd} increases, the corresponding values of W_{min} (as given in (6)) remain smaller than W. Under such a condition, connections with different round trip delay experience the same throughput.

V. Outlook

The performance of TCP has been evaluated in a WCDMA-based cellular network which supports variable rate transmission at the RLC/MAC layer. The dynamic rate selection at the RLC/MAC layer is based on a one-step sub-optimal rate search procedure. A homogeneous traffic scenario has been assumed where the mean number of TCP connections averaged over different cells is *not* time-varying, although the instantaneous number of connections in a cell can vary. The impacts of different physical, link and transport layer parameters on the achieved throughput performance have been evaluated. Since the number of concurrently active TCP connections determines the RLC/MAC layer rate selection and hence the achieved TCP throughput, the TCP throughput for wide-area TCP connections can be improved by employing 'intelligent' RLC/MAC layer scheduling policies. We are currently investigating this issue.

[4]For this value of W, the BS transmitter would never remain idle.

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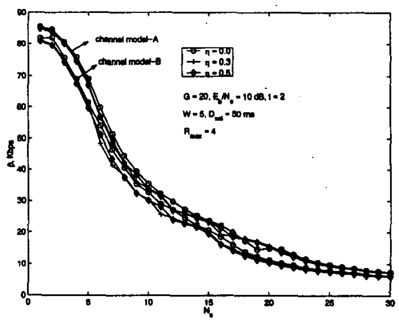

Fig. 3. Variation in β_{TCP} with N_c (for different η).

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