♦ Forward Link Performance Analysis of the CDMA2000* 3G1X Data System

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Performance analysis of data networks based on the code division multiple access (CDMA) air interface including the CDMA2000 3G1X and the Universal Mobile Telecommunications System (UMTS) requires development of new methodologies distinct from those used to analyze voice networks. In this paper, we present a set of analytical and simulation techniques of different complexity that are used to investigate different aspects of data system performance on the forward link. We demonstrate how the static-snapshot simulation model is used to obtain statistically significant system-level results valid for multi-cell wide area network deployment. These simulations are complemented by the dynamic model, which takes into account details of data traffic arrival and resource management algorithms on the air interface. It also provides insight into each individual user's experience under different network loads when running different data applications over the CDMA2000 air interface. Key results of simulation models are verified via theoretical analysis techniques that demonstrate the consistency of the results obtained via different methods. © 2003 Lucent Technologies Inc.*

Introduction

In this paper, we focus on performance aspects pertaining to the forward link of the CDMA2000* 3G1X [2]. The air interface allows coexistence of voice and high-speed data users on the same carrier. We limit the scope of this paper to the scenario in which only data traffic is present on the carrier. The data service is supported by a number of physical channels on the air interface. We consider an implementation of high-speed data where the 9.6-kb/s fundamental channel (FCH) is used by the data call to carry signaling and control information. This channel is established for each user before a high-rate connection can start. We assume that FCH uses either radio configuration 3 or radio configuration 4 (RC3 or RC4). The FCH can reduce its rate according to the data source activity to reduce co-channel interference to other users. In other words, the FCH reverts to the 1/8 rate when there is no data or signaling to transmit. In order to support high-rate data bursts, a forward link supplemental channel (F-SCH) can be established using the following physical transmission rates: 19.2, 38.4, 76.8, and 153.6 kb/s for RC3 and 4 and 307.2 kb/s for RC4 only.

We introduce an analytical approach and static-snapshot simulation that allow predicting aggregate sector throughput. We also present a dynamic simulation approach that enables us to gain additional insight into each individual user's throughput and rate distributions for different applications.

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Analysis Approach and Assumptions

The performance analysis and simulation results presented in the paper are based on a system model and a common set of assumptions with respect to radio frequency (RF) conditions, mobility profiles, physical link performance, and system configurations. The system-level performance analysis and simulations utilize the results from link-level physical-layer simulations to obtain the channel transmit power fraction requirement as a function of geometry (to be defined later) for each mobile under the simulated conditions. Physical-layer simulations at the link level describe physical-layer performance of a base station–mobile or transmit–receive pair. The details of power control, channel estimation, and forward error correction algorithms are included in this simulation. The simulations are performed separately for each data rate, channel condition of interest, target frame error rate, and geometry.

The physical-layer simulation assumptions are outlined in **Table I**.

It is known that the mobile RF condition is determined by many factors such as:

- *Location of the mobile*—Shorter distance between the mobile and its serving base station leads to less path loss on the radio link and therefore a smaller fraction of the base station power required to serve the mobile. This power requirement is also impacted by the shadow fading experienced by the mobile and the interference created by the signals received from surrounding non-serving base stations. The concept of *geometry* is introduced to capture this aspect. It is defined as the ratio of the total mobile received power from its serving sectors *and* the noise plus the total interference received from all other sectors within the network.
- *Channel fading characteristics*—A mixed channel model composed of static propagation (AWGN) channels and 1-path and 2-path Rayleigh fading channels is used. The details of the model are shown in **Table II**.
- *Mobility*—Mobile speed profile affects the Doppler spread and alters the dynamic evolution of the fading channel. It varies in different geographical areas. The mobile speed distribution used in this paper is shown in Table II.

The overall system configuration and assumptions are listed in Table II.

The system-level simulations model interaction between a network of base stations and a number of uniformly distributed mobiles. The forward link transmission power to each mobile is derived from the physical-layer simulation results based on the mobile handoff state, geometry, and propagation channel. The sector transmit power is the summation of the

Table I. Physical layer simulation assumptions.

Simulator:	Symbol level
Frequency band:	Band class 1 (1.96 GHz)
Multi-path profile:	AWGN, 1-path, and 2-path Rayleigh
Pilot strength:	−7 dB
Power control rate:	Mode 001 (400 Hz) for data FCH and SCH
Data rate:	Radio configuration 3: 9.6, 19.2, 38.4, 76.8, and 153.6 kb/s; Radio configuration 4: 19.2, 38.4, 76.8. 153.6, and 307.2 kb/s
Transmit diversity	None

FCH—Fundamental channel
SCH—Supplemental channel

Panel 1. Abbreviations, Acronyms, and Terms

CDMA—code division multiple access
FCH—fundamental channel
F-SCH—forward link SCH
FTP—file transfer protocol
HTTP—hypertext transfer protocol
IP—Internet protocol
MUX—multiplexer
PDU—protocol data unit
RC—radio configuration
RF—radio frequency
SCH—supplemental channel
UMTS—Universal Mobile Telecommunications System
WWW—World Wide Web

Table II. System configuration and assumptions.

Number of BSs	19
Sectors/BS	3
Max Tx Ec/Ior per FCH	−7 dB
Max Tx Ec/Ior per SCH	−3 dB
Propagation path-loss model	3.76
Propagation site-to-site correlation	50%
Antenna pattern	Real pattern with 17 dBi gain and 90 degree HBW
Max BS Tx power	16 W
Max mobile Tx power	23 dBm
Mobile speed distribution	0 km/h: 25%, 3 km/h: 37.5%, 30 km/h: 22.5%, 100 km/h: 15%
Multi-path profiles—FCH Soft/softer handoff is allowed	AWGN: 25%, 1-path Rayleigh: 5%, 2-path Rayleigh: 70%
Multi-path profiles—SCH Simplex transmission assumed	AWGN: 25%, 1-path Rayleigh: 25%, 2-path Rayleigh: 50%
Channel encoder	Turbo/convolutional
RLP PDU type	MUX PDU type 3 and MUX PDU type 5
Target frame error rate	1% for 9.6 kb/s, 2% for 19.2 and 38.4 kb/s, 5% for 76.8, 153.6 and 307.2 kb/s
Capacity evaluation metric	5% sector power outage

AWGN—Additive white Gaussian noise
BS—Base station
FCH—Fundamental channel
HBW—Horizontal beam width
RLP—Radio link protocol
SCH—Supplemental channel
MUX—Multiplexer
PDU—protocol data unit
Tx—Transmit

overhead channel power and traffic power consumed by all mobiles that it serves. After power control convergence, the sector power stabilizes at a level that depends on the number of active users, their locations, and the channel data rates they are transmitting. By controlling the average sector power outage within a target threshold, the system capacity in terms of the number of active users or sector throughput can be evaluated.

System-level analysis and dynamic simulation utilize the geometry distribution generated from the static system-level simulation. The use of geometry distributions provides a reasonable compromise for reducing complexity and runtime of the dynamic model. This allows confining the modeling of resource allocation and data traffic interactions to one typical sector in the system while the impact of the interference from other sectors is captured through geometry distribution. Geometry distribution obtained from the static simulation with the full loading on adjacent sectors is shown in **Figure 1**. This distribution is modified further to account for various self-interference factors in transmit and receive chains as recommended in [1]. The limiting self-interference factor of −13 dB is used.

Numerical Analysis

The theoretical analysis based on numerical analysis is performed to estimate the range of the data capacity and associated coverage constraints for different SCH data rates. The result of this analysis provides theoretical guidelines and serves as a reference to subsequent simulation work.

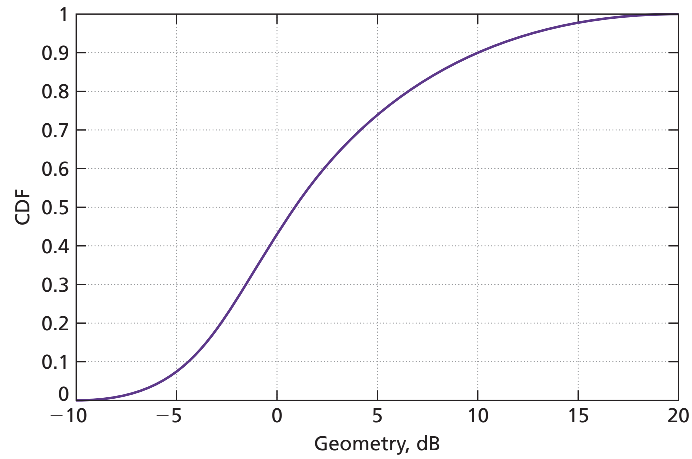

Figure 1.
Cumulative distribution function of geometry used in numerical analysis and dynamic simulation.

The objective of the analysis is to estimate the average number of SCHs that can be supported in the network for each data rate. Based on the SCH power requirement from physical-layer simulations and initial geometry distribution, the power distribution for each SCH data rate can be obtained per channel condition and mobile speed. Then the average power is obtained based on the mixed channel model and mobile speed distribution. The sector power outage and loading are estimated and the outage is compared to the target threshold. To ensure consistent sector loading throughout the network, the procedure is iterated to ensure that the summation of the powers of all mobiles in the center cell is the same as that of the interference. The details of the numerical analysis are described in the Appendix.

For this analysis, we assume that all SCHs use the same data rate and that there are no limitations on the maximum number of available channel resources. A methodology for throughput evaluation in the mixed system with Walsh code constraints is presented in the "Rate Distribution Model and Throughput" section below.

The analysis results for RC3 and RC4 data capacity and coverage are shown in **Table III**.

Table III. Analysis results of 3G1X data channel capacity.

Rate (RC3)	Coverage Area Relative to FCH	Channel Capacity within Coverage
19.2 kb/s	98%	8.0
38.4 kb/s	92%	4.4
76.8 kb/s	85%	2.7
153.6 kb/s	66%	1.6
Rate (RC4)	**Coverage Area Relative to FCH**	**Channel Capacity within Coverage**
19.2 kb/s	95%	6.0
38.4 kb/s	88%	3.5
76.8 kb/s	83%	2.4
153.6 kb/s	63%	1.4
307.2 kb/s	32%	1.0

FCH—Fundamental channel
RC—Radio configuration

The results show reduction of coverage for higher data rates and reduction of channel capacity for RC4 compared to RC3. This capacity reduction is due to a weaker channel coding in RC4. The channel capacity of a single-rate SCH system can be used to obtain the sector throughput in a mixed-rate SCH system as described in the following section.

Static Simulation

The static simulation uses a large number of system snapshots to arrive at the performance characterization. Since the dynamic interaction of rate assignment algorithms cannot be captured, the distribution of data rates has to be either assumed or modeled based on some assumptions. There are a number of possible approaches for static simulation of a mixed-rate data system. One approach is to simulate users with different data rates coexisting in the same system. This requires specifying a scheduling rule or priority among users. Another approach is to simulate a single-rate system and to repeat it for each data rate. The aggregate throughput of the system is obtained by combining single-rate throughputs via a mixed-rate model. In this paper, we adopt the latter approach.

Single-Rate Simulation

The simulated wireless network is a two-tier network with a total of 19 three-sector cells. The cell radius is determined by IS-95 voice reverse link footprint. Mobile users are placed uniformly over the entire network. The locations of mobiles are static during one simulation trial, and each simulation run is independent from trial to trial.

The simulation starts with an initial number of mobile users. The forward link transmission power to each mobile is based on its handoff state, geometry, and propagation channel. A user is dropped if the mobile's required traffic power exceeds a predetermined limit. The total transmission power is the summation of the overhead channel power and traffic power consumed by all mobiles that it serves. The simulation performs iterations to stabilize base-station transmission powers and then increments the number of mobiles in the system until the transmission power outage probability exceeds its limit.

Table IV summarizes channel capacity achievable within the coverage areas of the corresponding SCH rate and does not represent aggregate sector throughput over the whole sector coverage area.

Table IV. Static simulation results of 3G1X channel capacity.

Channel Rate and RC	Coverage Area Relative to FCH	Channel Capacity within Coverage
9.6 kb/s (RC3)	100%	12.4
19.2 kb/s (RC3)	99%	8.7
38.4 kb/s (RC3)	95%	4.4
76.8 kb/s (RC3)	86%	2.7
153.6 kb/s (RC3)	72%	1.7
307.2 kb/s (RC4)	40%	1.0

FCH—Fundamental channel
RC—Radio configuration
SCH—Supplemental channel

Close agreement with the analytical model results presented previously can be observed.

Rate Distribution Model and Throughput

In this section, we describe a model used to compute rate distribution probabilities and the throughput in a mixed-rate system. The fraction of the total available traffic transmit power in the sector used for data transmission can be written as:

$$P = \sum_{i=1}^{6} x_i P_i, \qquad (1)$$

where P_i is the average fraction of the total available traffic transmit power of the rate R_i channel, and x_i is the number of channels of the rate R_i, with $R_i = 2^{i-1}9.6$ kb/s and $i = 1, 2, \ldots, 6$. Note that P_i can be computed by dividing the total available traffic transmit power by the single-rate SCH channel capacity obtained via the analytical model (Table III) or via the single-rate static-snapshot system simulation (Table IV) described previously.

Based on the simulations and field experience, we further assume that, in the typical fully loaded system, three-quarters or more of the total available traffic transmit power is used for traffic channels, which results in the following constraint on power:

$$0.7 \le P < 1. \qquad (2)$$

Additionally, the number of simultaneous forward link channels of different rates is constrained by the Walsh code availability as follows:

$$x_i \leq \begin{cases} W_i - \sum_{n=0}^{5-i} 2^{6-n-i} x_{6-n} + 2^{5-i} x_6 & \text{for } i = 1, 2, \ldots, 5 \\ W_6 & \text{for } i = 6 \end{cases} \quad (3)$$

where W_i is the maximum number of Walsh codes of appropriate length available to support the forward link channel at rate R_i when there are no other traffic channels present. The maximum number of available Walsh codes at each data rate takes into account the codes used by the IS-95 and CDMA2000 forward link overhead channels such as the pilot, paging, and synchronization channels and is equal to 61, 30, 14, 6, 2 and 2 for 9.6, 19.2, 38.4, 76.8, 153.6 (all RC3), and 307.2 (RC4) kb/s channels, respectively.

Using the power and Walsh code constraints in (2) and (3), we find all valid combinations of numbers of channels x_i, $i = 1, 2, \ldots, 6$, through an exhaustive search in integer space. Since each channel data rate has a different coverage probability, each valid combination of x_i has a probability of occurrence determined by the probabilities of coverage of channel rates that constitute this combination as follows:

$$p_j = \frac{1}{N_p} \prod_{i=1}^{6} c_i^{x_{ij}}, \quad j = 1, 2, \ldots, N, \quad (4)$$

where p_j is the probability of occurrence of j-th valid combination of data rates, c_i is the probability of coverage of the channel rate R_i, x_{ij} is the number of channels of rate R_i in the j-th combination, N is the total number of valid combinations of data rates found via exhaustive search in integer space using constraints (2) and (3), and N_p is the normalization factor found from $\sum_{j=1}^{N} p_j = 1$.

The probability of the rate R_i in a mixed-rate system could be found from the probabilities of occurrence of valid rate combinations and the number of times the rate R_i is present in each combination as follows:

$$q_i = \frac{1}{N_q} \sum_{j=1}^{N} x_{ij} \quad p_j, \quad (5)$$

where q_i is the probability of rate R_i and N_q is the normalization factor found from $\sum_{i=1}^{6} q_i = 1$.

Finally, the sector throughput T in the mixed-rate system can be obtained as:

$$T = \sum_{i=1}^{6} q_i \quad T_i, \quad (6)$$

where T_i is the sector throughput in the system with all channels having only a single-rate R_i. Note that the single-rate sector throughputs T_i can be found by means of theoretical analysis or using static simulation approach as described previously in this paper.

Sector throughput T in (6) can be found for a given number of simultaneous channels. This allows evaluating throughput dependency on the number of users. The mixed-rate model introduced in this section reflects the fact that, as the number of active users increases, the system downgrades high data rate users to transmit at a lower data rate in order to accommodate more users. When the number of simultaneously transmitting users is large, most of the users are assigned low-rate SCH channels or are limited to the FCH channel only. **Figure 2** shows the sector throughputs in a mixed-rate system for MUX PDU types 3 and 5 obtained from (6). Note that the throughput results presented in this figure do not include gains that are achievable on the forward link of the CDMA2000 packet data system via scheduling techniques.

The approach described above can be extended to include traffic model considerations. The average user rate R_U at the radio link protocol (RLP) layer can be related to that of the physical layer as follows:

$$R_U = \sum_{i=1}^{6} q_i \quad (1 - e_i) \quad (1 - \delta_i) R_i, \quad (7)$$

where e_i is the target frame error rate and δ_i is the combined physical, multiplex, and RLP layer overhead for the channel of data rate R_i.

Assuming that the typical user traffic consists of a series of data downloads with the average size of L bits each, separated by reading or "think" periods with average duration t_{IDLE} seconds, the average offered user traffic T_U can be defined as follows:

$$T_U = \frac{L}{\frac{L}{R_U} + t_{ACT} + t_{ACCESS} + t_{IDLE}} \equiv \alpha R_U, \quad (8)$$

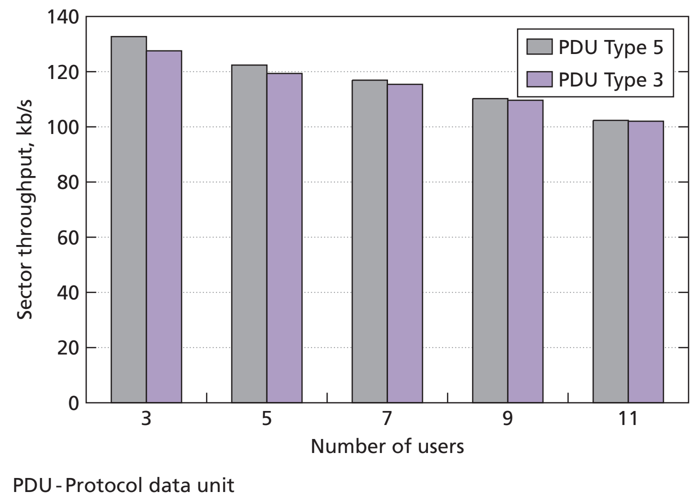

Figure 2.
Sector throughput as a function of number of simultaneously transmitting users in a mixed-rate system without scheduling gain.

where t_{ACT} is the dormant-to-active activation latency that accounts for the scenarios when user session goes into dormant state during the reading period, t_{ACCESS} is the network access latency, and α is defined as the session activity factor. The offered traffic in the sector can be obtained by multiplying the offered user traffic T_U by the number of user sessions in the sector.

The maximum carried traffic in the sector is equal to the loaded sector throughput T in (6) and Figure 2 with the number of sessions equal to the ratio of the number of simultaneously transmitting users and the session activity factor α.

In **Figure 3**, the offered sector traffic and the maximum carried traffic are shown for the World Wide Web traffic model (L = 40 KB, t_{IDLE} = 40 s, t_{ACT} + t_{ACCESS} = 2.5 s), which is also used below in the dynamic system-level simulation. The intersection of the offered traffic and the maximum carried traffic curves provides the maximum number of sessions the system can support. The maximum number of sessions in Figure 3 is 21, and the corresponding sector throughput is about 114 kb/s. Note that these results assume equal throughput per user and do not take into account any scheduling gain.

Dynamic Simulation

In the previous sections, we presented throughput analysis through theoretical and static-snapshot simulation approaches. One of the advantages of the two approaches is the simplicity. However, the resultant throughput does not include the possible gains from the use of scheduler. For this purpose, a more complex dynamic simulation can be used.

Methodology and Assumptions

In the 3G1X system, the SCH bursts dynamically share RF and system resources unoccupied by voice and data FCHs. Traffic burstiness is exploited to improve throughput efficiency by dynamically reassigning system resources from the users that are instantaneously inactive to the users that have data to transmit. The system serves multiple users that need to access resources simultaneously. The simulation model assumes best-effort operation in the multi-user environment. By controlling the rate and duration of SCHs, it ensures that none of the active users monopolize radio resources and supplies all users with an adequate share of air-interface capacity.

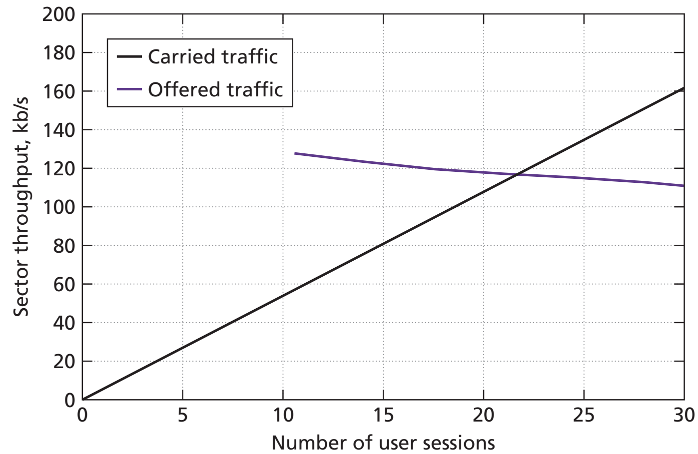

Figure 3.
Sector throughput as a function of number of user sessions using WWW traffic model without scheduling gain.

In the dynamic simulation, the geometry of users is picked from the distribution periodically such that the final results are representative of various combinations of mutual simultaneous user locations. Between these updates, geometry is varied according to the slow fading model with exponential spatial correlation coefficient as described in [1]. This model provides a mechanism to include the effect of power control tracking of slow fading at different mobile speeds.

The dynamic simulation adopts two generic models, which are called the "full buffer model" and the "WWW model." The full buffer model is characterized by continuous data stream per user. The WWW model simulates a generic bursty traffic having the following parameters: fixed-sized packets of 576 B (at the IP layer), exponentially distributed packet interarrival time with mean of 200 ms, exponentially distributed page size with 40 KB mean, and exponentially distributed reading or "think" time between page downloads with 40-s mean.

For each user data session, an inactivity timer is started when there is no data left to send. The expiration of this timer triggers transition from active to dormant state and the release of all air interface resources associated with the session. The timeout period is assumed to be 15 s. When data arrives again, an activation process is initiated and the FCH is reinstated. Reactivation delay of 2.5 s is assumed to transition the session back into the active state.

Dynamic Simulation Results

In **Figure 4**, we compare aggregate throughput when using RC3 and RC4 with MUX PDU type 3 and, when using RC3 for all rates up to 153.6 kb/s and RC4 for the 307.2 kb/s rate, with MUX PDU type 5. The first option is also known as Release 0, while the second one is known as Release A. With the full buffer traffic model, it is possible to achieve higher throughputs than with the WWW model for several reasons. In the full buffer case, there are no inefficiencies associated with more frequent rate changes, which occur in the WWW case. Further, since the full buffer model does not pose any restriction on the amount of traffic that can be delivered to the user and since the resource-sharing algorithm in the sector is implemented in such a way as to fairly distribute the time users are allowed to use SCH resources, the users in the high data rate coverage areas are able to achieve higher throughputs leading to higher overall sector throughput. On the other hand, the WWW model imposes restrictions on how much data each user can receive, therefore reducing the scheduling gain observed in the full buffer case. The full buffer model is also characterized by a smaller overhead not directly associated

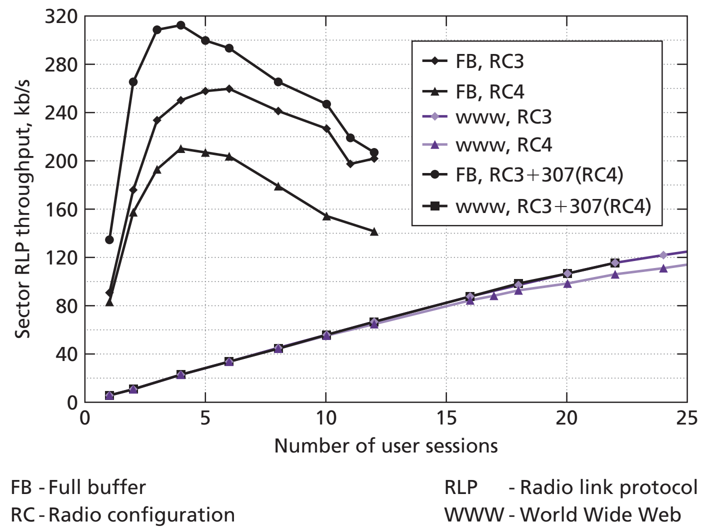

Figure 4.
Sector RLP throughput as a function of number of sessions using FB and WWW traffic models with RC3 and RC4 and Release 0 and Release A features.

with the data transmission. This overhead includes FCHs not transmitting data, reverse link power control bits, and signaling messages transmitted on FCH. This overhead is larger for the WWW model resulting in a smaller aggregate throughput. The impact of this overhead on the full buffer model can be observed in that, after reaching a peak value, the throughput reduces as more users are added to the sector.

From Figure 4, it is observed that Release A features such as 307-kb/s SCH rate and MUX PDU type 5 result in some moderate gains for the full buffer traffic model and a small number of data sessions. Smaller gains are observed with larger numbers of users due only to the MUX PDU type 5 reduced RLP overhead compared to MUX PDU type 3. The 307-kb/s SCH in this region does not contribute to the aggregate throughput gain due to the negligible probability of this rate when the number of the users contending for resources is high. Very little difference is observed between Release 0 and Release A aggregate sector throughput for the WWW model because the improvements in overhead and peak rate do not affect performance when most of the transmission is done on the fundamental or low rate SCHs.

The maximum number of user sessions and the maximum aggregate sector throughput are determined by the FCH blocking criterion. If addition of a new FCH in the sector leads to power amplifier overload with the probability of 5% or larger, the number of data sessions supported may not be increased. In **Figure 5**, we present the probability of FCH blocking based on power outage as a function of the number of user sessions. The number of user sessions at which 5% power outage is reached is used in Figure 4 to evaluate the sector throughput for the maximum number of users. For example, for the WWW model using RC3 Release 0, the maximum number of user sessions is close to 24 and the aggregate sector throughput at the RLP layer is approximately 120 kb/s. This is consistent with the results of theoretical analysis and static simulations discussed in preceding sections, and it highlights the fact that the WWW model allows only for a very limited scheduling gain that could be achieved in the sector. The full buffer model, which allows the system to take advantage of scheduling gain to a larger degree, results in throughput in the range of 190 to 260 kb/s for RC3 Release 0.

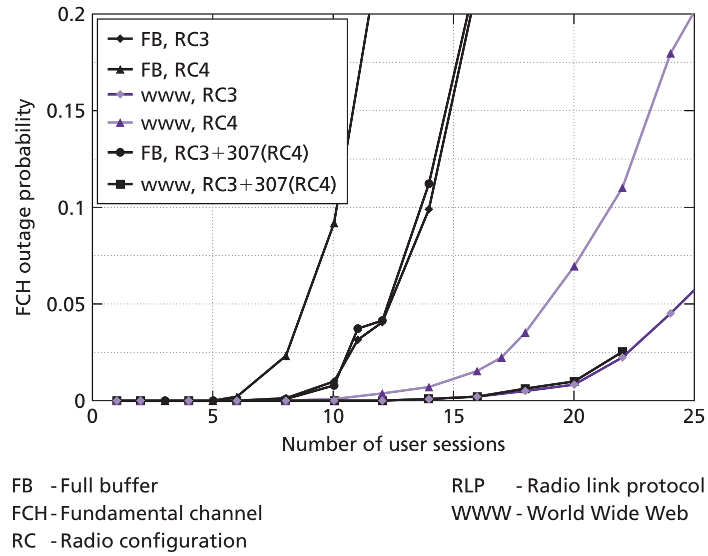

Figure 5.
Probability of FCH blocking as a function of number of user sessions using FB and WWW traffic models with RC3 and RC4 and Release 0 and Release A.

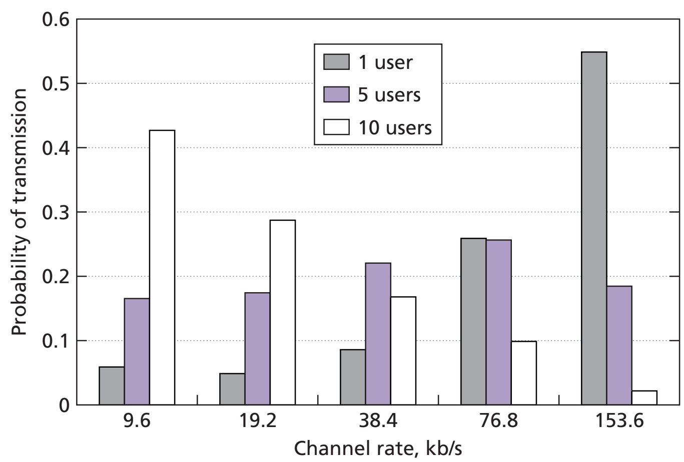

Figure 6.
Rate distributions as a function of number of user sessions for full buffer traffic model, RC3, Release 0.

In **Figure 6** and **Figure 7**, rate distributions are presented for the full buffer traffic model using Release 0 and Release A and for the FTP and HTTP traffic models using Release 0. These distributions are shown as a function of the number of user sessions. As explained above, the full buffer model allows evaluating an effective coverage probability of each data rate. Note that this coverage probability is slightly different from the one based on the analytical approach described above, because it uses additional real-time criteria and realistic delays and signaling overhead for assigning SCH rates. The probabilities of high rate assignment

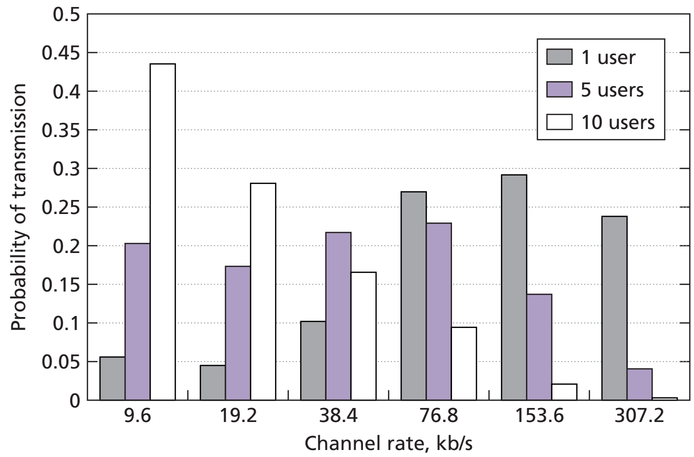

Figure 7.
Rate distributions as a function of number of user sessions for full buffer traffic model, Release A.

are somewhat lower than the ones predicted by the analytical approach.

Conclusions

In this paper, several techniques of different complexity are presented to investigate the forward link performance of 3G1X data system. The theoretical analysis and the static-snapshot simulation techniques are simple to use and can yield reasonable system throughput predictions. However, the predicted throughput does not include the scheduler gain that can be obtained by using an optimized scheduler in the system. To obtain system throughput that includes the scheduler gain, the more complex dynamic simulation technique can be used. Based on the presented analysis, the system throughput of 3G1X data system is in the range of 100 to 300 kb/s, depending on the assumptions of the traffic model and the scheduler gain.

Appendix: Details on Numerical Analysis

The main idea of obtaining the throughput of 3G1X data system through numerical analysis is based on the assumptions that users are moving uniformly in a cell area and that they are identically distributed and statistically independent. With these assumptions, we can obtain the transmit power distribution of each user first. The distribution of the total transmit power of a cell can then be obtained through convolution of the distribution of each user. For any given outage criterion, the average throughput can then be obtained from the total transmit power distribution.

In general, the user transmit power is a function of the transmit data rate and RF conditions. The RF channel type, mobile speed, the effects of the fast Rayleigh fading and transmit data rate are captured through the user required E_b/N_t. The user distribution in the cell and the effects of slow shadow fading are captured through the value of geometry.

Transmit Power Distribution of Single Channel

It is known that the average fractional power E_c/I_{or} transmitted on the forward link of a given user is related to the required E_b/N_t and the geometry g of one- or two-path channel model by the following equation [4]:

$$\frac{E_c}{I_{or}} = \frac{E_b/N_t}{G_p g}(1 + \alpha g), \qquad \text{(A-1)}$$

where E_b/N_t is the required energy per bit to the interference and noise ratio, G_p is the processing gain, α is the fraction of the multipath interference, and g is the geometry defined as $g = I_{oc}/\hat{I}_{or}$, where I_{oc} is the interference from other cells and $\hat{I}_{or}$ is the total user received power.

Through simulation with the RF conditions as given by Table II, it appears that the geometry for a fully loaded system can be closely modeled by the following formula:

$$f_{\hat{g}}(\hat{g}) = \begin{cases} \dfrac{c}{\hat{g} - a}\exp\left\{-\dfrac{(10\log_{10}(\hat{g} - a) - m)^2}{2\alpha^2}\right\} & \hat{g} \geq a \\ 0 & otherwise \end{cases} \quad \text{(A-2)}$$

where $\hat{g}$ is the geometry in dB domain, a is the minimum geometry considered and c is the normalization factor, m and σ are the mean and standard deviation of the log normal distribution.

If the network is not fully loaded, the geometry distribution should be adjusted based on the pre-assumed average network loading $\hat{l}$ as $\tilde{g} = \hat{g} - 10\log_{10}(\hat{l})$, where $\hat{l} \in [l_{\min}, 1]$. $l_{\min}$ is the minimum loading determined by the overhead channels power fraction S_{OH}.

Further, it is observed that the mobile receiver usually generates self-interference due to imperfect filtering and nonlinearity. Consequently, the maximum achievable geometry at the receiver is usually limited to a certain value. To take this effect into account, the geometry distribution curve is constrained with following conversion [1]:

$$g^{-1} = (g_{\max}^{-1} + \bar{g}^{-1}) \quad g_{\max} = 13\ dB \quad \text{(A-3)}$$

Denote $u = E_c/I_{or}$, where u is the fractional power and is a function of g from (A-1). By performing the function transformation as defined in (A-3) the distribution given by (A-2) becomes:

$$f_u(u \mid r, c, s) = f_g(g)\left|\frac{du(g)}{dg}\right|^{-1}. \quad \text{(A-4)}$$

Note that the distribution of u is conditional on channel data rate (denoted as r), channel type (denoted as c) and mobile speed (denote as s).

In practice, the channel fraction power will be limited to a maximum value $u_{\max}$ to protect the power amplifier and maximize the capacity. With this restriction, certain data rates may be supported only within a portion of the cell. In this analysis, we are interested in the cases where all mobiles are confined within their coverage. The coverage C is defined as the percentage of the cell area that supports the data rate, and it can be derived from the geometry distribution and the minimum geometry $g_{\min}$ that supports this data rate with a given fading channel c and mobile speed s:

$$C = C(c, s) = \int_{g_{\min}}^{g_{\max}} f_g(g)\, dg, \qquad u(g_{\min}) = u_{\max}. \quad \text{(A-5)}$$

Finally, in a multi-user system, different mobiles are under different fading conditions and mobility speeds, thus the channel fractional power distribution can be estimated from a probabilistic mix. The channel fractional power distribution of a given data rate r within the coverage can be obtained from

$$f_u(u \mid r) = \sum_{c,s} q_c q_s f_u(u \mid r, c, s)/C(c, s), \quad u \in (0, u_{\max}], \quad \text{(A-6)}$$

where q_c and q_s represent the probability of the channel type c and mobile speed s respectively. The values of q_c and q_s used in this analysis are included in Table II.

Sector Capacity as Supported Number of Channels

If there are n active channels with data rate r in the sector, the sector power distribution is the convolution of the individual channel power distribution assuming the channels are independent:

$$f_s(S \mid n, r) = \underbrace{f_u(S \mid r) \otimes f_u(S \mid r) \otimes \cdots \otimes f_u(S \mid r)}_{n}, \quad \text{(A-7)}$$

where S is the sector power. The sector power outage p_{out} and average sector loading l can readily be evaluated.

$$p_{out} = 1 - \int_0^{S_{\max}} f_s(S \mid n, r)\, dS, \quad S_{\max} = 1 - S_{OH} \quad \text{(A-8)}$$

$$l = E_s\{s \mid n, r\}, \quad \text{(A-9)}$$

where $E_v\{\cdot\}$ represents the statistical mean based on distribution of random variable.

Clearly, both p_{out} and l are depended on the number of channels n in the sector. Provided that the users are uniformly distributed within a multi-cell network, the number of channels n in each sector can be modeled by the Poisson distribution with mean of N, where N represents the average number of channels per sector in the network.

Using (A-8) and (A-9), the network-wide average sector power outage P_{out} and loading L can be determined as

$$P_{out} = E_n\{p_{out}(n) \mid N\} \quad \text{(A-10)}$$

$$L = E_n\{l(n) \mid N\}. \quad \text{(A-11)}$$

Under the capacity criterion $P_{out} \leq Threshold$, the average channel capacity N can be estimated.

It should be noted that to obtain the correct channel capacity, the pre-assumed average sector loading $\hat{l}$ should be consistent with the output L when the channel capacity is reached. This implies that iterations are needed for the above procedures to adjust $\hat{l}$ until the consistent loading is reached.

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