TECHNICAL PAPER

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Authors:	Thrasivoulos (Sakis) Griparis, Tristan Lee—Bechtel Corporation
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THE CAPACITY OF A WCDMA NETWORK: A CASE STUDY

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Abstract—*This paper discusses the WCDMA radio capacity tests undertaken on trial and live networks to investigate both single-cell and network WCDMA radio capacity.*

Thrasivoulos
(Sakis) Gripari

tgripari@bechtel.com

Tristan Lee

tmlee@bechtel.com

INTRODUCTION

This paper begins by highlighting the theory behind radio loading in a code division multiple access (CDMA) network, the predicted capacity of a wideband CDMA (WCDMA) network in both the uplink (UL) and downlink (DL), and the factors affecting this capacity. The paper subsequently details the results of single-cell capacity tests and illustrates the ability to support multiple users in a single cell, including how this single-cell capacity could be used to estimate the capacity of a loaded WCDMA network.

To verify the estimated capacity, multiple tests were performed on myriad services, i.e., voice, 64 kbps, 128 kbps, and 384 kbps, in a fully loaded network.

THEORETICAL CELL CAPACITY

Uplink Cell Capacity

UL capacity is directly affected by the noise rise generated by users in the UL. Typically, an operator restricts the acceptable UL load to a certain UL noise rise. To assist in defining the theory behind UL cell capacity, it is helpful to define μ_{UL} as the UL load, NR_{UL} as the UL noise rise, I_0 as the noise floor of the cell, P_i as the received power from user i connected to the serving cell, and $P_{rx\text{-}total}$ as the total received power in the UL. The noise rise in the UL is the increase in noise compared to the noise floor of the Node B; thus:

$$NR_{UL} = \frac{P_{rx\_total}}{I_o} \qquad (1)$$

The total UL load is not a straightforward concept when considered with both intracell and intercell interferences. With N as number of users, and without intercell interferences, the following expression is considered:

$$\mu_{UL} = \frac{\sum_{i=1}^{N} P_i}{P_{rx\_total}} \qquad (2)$$

However, this does not take into account the load increase related to mobiles connected to other cells. The concept of noise rise means that an infinite noise rise must be considered when the load is 100 percent. In other words:

$$NR_{UL} = \frac{1}{1 - \mu_{UL}} \qquad (3)$$

And replacing NR_{UL} by its expression:

$$\mu_{UL} = 1 - \frac{1}{NR_{UL}} = \frac{P_{rx\_total} - I_o}{P_{rx\_total}} \qquad (4)$$

This expression shows that the load in UL is due only to the power received from the user equipment (UE) and not to the noise of the Node B. Indeed, the total received noise breaks down to:

$$P_{rx\_total} = I_o + I_{intracell} + I_{intercell} = I_o + (1 + F) \cdot \sum_{i=1}^{N} P_i \qquad (5)$$

With:

$$F = \frac{I_{intercell}}{I_{intracell}} = \frac{\sum_{j \in \text{users connected to other cells}} P_j}{\sum_{i \in \text{users connected to the same cells}} P_i} \qquad (6)$$

ABBREVIATIONS, ACRONYMS, AND TERMS

AMR	adaptive multirate
BLER	block error rate
CDMA	code division multiple access
CPICH_RSCP	common pilot channel received signal code power
DL	downlink
FTP	file transfer protocol
PS	packet switched
P-SCH	primary synchronization channel
RLC	radio link control
S/N	signal-to-noise (ratio)
S-SCH	secondary synchronization channel
TCP	transmission control protocol
Tx	transmit
UE	user equipment
UL	uplink
VAF	voice activity factor
WCDMA	wideband CDMA

where F is the intercell-over-intracell interference ratio and P_j is the received power from user j connected to another cell.

Finally, the UL load can be derived as:

$$\mu_{UL} = (1 + F)\,\frac{\sum_{i=1}^{N} P_i}{P_{rx\_total}} \tag{7}$$

With $F = 0$, the single-cell equation (Eq. 2) is obtained.

The power required for an individual user can be defined as follows:

$$P_i = \frac{(E_b/N_o)_i \cdot u_i}{PG_i}\,(P_{rx\_total} - P_i) \tag{8}$$

where u_i is the activity factor of user i, $(E_b/N_o)_i$ is the required energy per bit versus the noise spectral density, and PG_i is the processing gain of user i.

Note that P_i depends on the received interference. However, a user does not interfere with itself and therefore the equation can be rearranged as follows:

$$\frac{P_i}{P_{rx\_total}} = \frac{1}{1 + \left[PG_i/((E_b/N_o)_i \cdot u_i)\right]} \tag{9}$$

Finally, the UL load equation can be written as:

$$\mu_{UL} = (1 + F)\sum_{i=1}^{N} \cdot \frac{1}{1 + \left[PG_i/((E_b/N_o)_i \cdot u_i)\right]} \tag{10}$$

Assuming that all users have the same radio environment and use the same service (same E_b/N_o) and considering the case of a single cell, the simplified formula of UL load for N users is obtained:

$$\mu_{UL} = N \cdot \frac{1}{1 + \left[PG/((E_b/N_o) \cdot u)\right]} \tag{11}$$

This formula can be used to assess the UL E_b/N_o from the UL capacity curves. The UL capacity can also be expressed as the maximum number of users N, at which a defined UL load target (e.g., 4 dB) is reached.

Downlink Cell Capacity

DL capacity depends on the DL transmit (Tx) power, which is limited by the power of the Node B power amplifier. Each user uses part of the Node B Tx power, and the more users on the cell, the stronger the power required for each individual user. DL power required for a user i is given by:

$$P_{tx\_i} = \frac{(I_o + I_{intra} + I_{inter}) \cdot (E_b/N_o)_i \cdot \upsilon_i}{PG_i} \tag{12}$$

where I_o is the noise floor of the mobile, I_{intra} is the intracell interference, I_{inter} is the intercell interference, PL_i is the path loss for user i, and υ_i is the user i activity factor in the downlink.

A user does not interfere with itself, and DL spreading codes from the same cell are pseudo orthogonal. Note that the primary synchronization channel (P-SCH) and the secondary synchronization channel (S-SCH) are not spread and are therefore not orthogonal; however, this fact is negligible, given their activity factors compared with those of dedicated channels.

The DL intracell interference can be expressed as:

$$I_{intra} = \frac{\alpha \cdot (P_{tx\_total} - P_{tx\_i})}{PL_i} \quad (13)$$

where α is the orthogonal factor, using 0 as perfect orthogonal and 1 as not orthogonal, P_{tx_i} is the Tx power for user *i*, and P_{tx_total} is the total Tx power in the DL.

Intercell interferences can be simply expressed as a factor of the total DL power of the serving Node B, using F_{DL} as the intercell-over-intracell interference ratio in the DL:

$$I_{inter} = F_{DL} \cdot \frac{P_{tx\_total}}{PL_i} \quad (14)$$

From previous equations, the DL power of user *i* can be derived as:

$$P_{tx\_i} = ((E_b/N_o)_i \cdot \upsilon_i)/PG_i) \cdot \left[I_o \cdot PL_i + (\alpha + F_{DL}) \cdot P_{tx\_total} - \alpha \cdot P_{tx\_i}\right] \quad (15)$$

Since the total DL power is a sum of common channels and dedicated channels, and assuming that all users have the same radio conditions and require the same individual DL power, then:

$$P_{tx\_total} = P_{CCH} + N \cdot P_{tx\_i} \quad (16)$$

where P_{CCH} is the total power used for DL common channels and *N* is the number of users.

Then P_{tx_i} can finally be rearranged as:

$$P_{tx\_i} = \frac{I_o \cdot PL + (\alpha + F_{DL}) \cdot P_{CCH}}{(PG/((E_b/N_o) \cdot \upsilon) - \left[\alpha \cdot (N-1) + F_{DL} \cdot N\right]} \quad (17)$$

In a single-cell case at low path loss, the equation can be simplified to:

$$P_{tx\_i} = \frac{\alpha \cdot P_{CCH}}{(PG/((E_b/N_o) \cdot \upsilon) - \alpha \cdot (N-1)} \quad (18)$$

This formula can be used to assess the DL E_b/N_o of the mobile. Also note that this formula is valid only for the infinite DL power control range. However, allocated DL power can be limited by both maximum and minimum DL power for individual radio links, P_{max} and P_{min}. The required P_{tx_i} may be lower than P_{min}. Typically, if P_{min} is 16 dBm and the required P_{tx_i} is 15 dBm, then, in this case, $P_{tx\_i} = P_{min}$ at low path loss.

At low path loss, the required DL power for an individual link typically depends on the environment and not on the path loss.

SINGLE-CELL CAPACITY MEASUREMENTS

The network configuration consisted of only one cell on air, and admission control was disabled. All handsets were of similar brands and located indoors at a very low path loss (continuous common pilot channel received signal code power [CPICH_RSCP] around –70 dBm). Best efforts were made to keep the activity factor as close to 100 percent as possible (continuous tone for adaptive multirate [AMR] and file transfer protocol [FTP] download for packet-switched [PS] services). Connections were set up one at a time, with 1-minute intervals between each additional user.

Single-Cell Uplink Measurements—AMR 12.2 Kbps

The measured UL noise rise versus the number of calls for the single-cell case is shown in **Figure 1**. Given the results, the best match with the theory was obtained for an E_b/N_o = 5 dB.

Depending on the UL load target, the capacity figures are:

- *UL_load* = 3 dB -> 50 users
- *UL_load* = 4 dB -> 60 users

Note that these figures are given for 100 percent activity, which is not realistic in a real network. Values closer to 50–60 percent are typical and lead to a lower UL noise rise per user and a higher capacity for a single cell. Additionally,

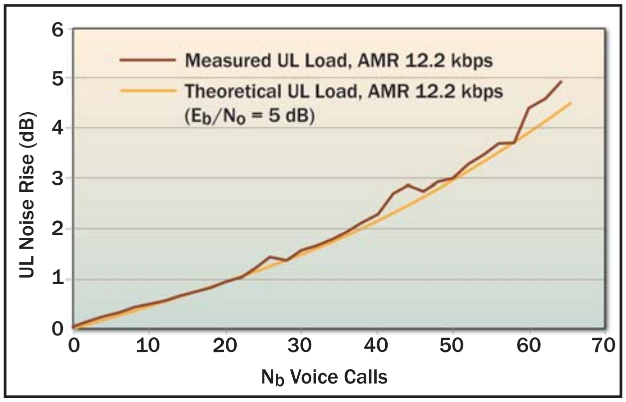

Figure 1. Measured Single-Cell UL Noise Rise (AMR Voice)

in a multicell environment some interference is generated by users connected to neighboring cells, leading to a lower number of users for the same noise rise.

In the UL, the influence of the path loss is minimal. Even at higher path loss rates, the capacity figures remain the same. As long as the UE does not reach its maximum power, the received P_{rx_i} is the same, as is the noise rise. The received P_{rx_i} increases only if the user reaches the cell edge. At this point, the UE Tx power starts to saturate and the UL signal-to-noise (S/N) ratio target rises.

> *Better quality is obtained at the expense of minimal capacity loss. Similarly, increasing* P_{max} *extends the DL cell range but diminishes capacity.*

Single-Cell Downlink Measurements—AMR 12.2 Kbps

DL capacity depends on the maximum and minimum DL powers for individual radio links, P_{max} and P_{min}, respectively. Assuming a low path loss, an infinite DL power control range is obtained with the following settings: $P_{max} = 31$ dBm and $P_{min} = 6$ dBm.

Given the results shown in **Figure 2**, the best match with theory was obtained for a DL E_b/N_o of 7.5 dB and assumed an orthogonal factor of 0.5. **Figure 3** compares DL capacity for various minimum and maximum power settings.

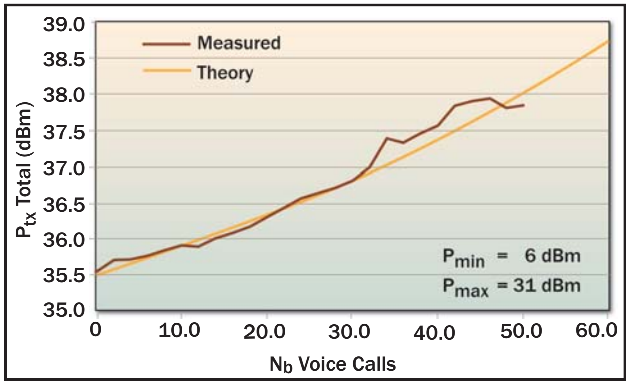

Figure 2. Measured Single-Cell DL Power Rise (AMR Voice)

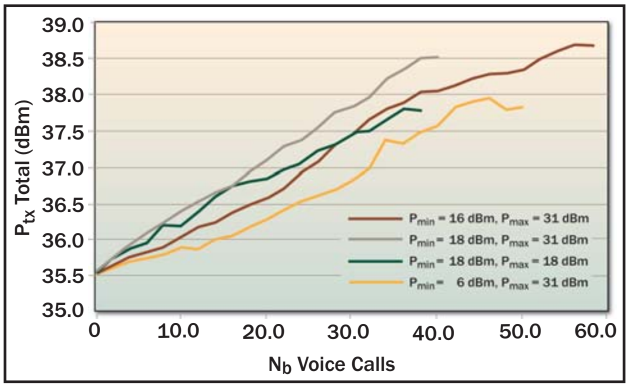

Figure 3. Measured Single-Cell DL Power Rises for Different P_{min} (AMR Voice)

As can be seen in Figure 3, the higher P_{min} is, the higher the load; similarly, the lower P_{max} is, the lower the load. A balance between capacity and quality must be achieved.

At low path loss, the required DL power for an individual link typically depends on the environment and not on the path loss. Theory can be applied to assess the required P_{tx_i}; using an E_b/N_o of 7.5 dB and an orthogonal of 0.5, P_{tx_i} is 15 dBm. Setting P_{min} greater than the required P_{tx_i} ensures that no dynamic power control is required at low path loss and that the block error rate (BLER) is null. Better quality is obtained at the expense of minimal capacity loss. Similarly, increasing P_{max} extends the DL cell range but diminishes capacity.

Single-Cell Downlink Measurements—PS Data

For PS services, activity was generated by means of FTP downloads. However, it was difficult to guarantee 100 percent activity using FTP, since the application throughput is driven by the transmission control protocol (TCP). Optimizing the TCP receive window size on the laptop helped improve the throughput and enhanced activity in the DL. The curve in **Figure 4** is for DL PS 128 kbps.

For PS 128 kbps, a maximum number of 15 users per cell was achieved. This limit was not due to the DL power rise, but, rather, to the code limit of the cell (code limit = spreading factor – 1).

With more than 11 users, the DL power is lower than expected, due to a reduction in the activity factor relative to increasing BLER. As detailed above, with nonoptimized TCP settings, radio link control (RLC) retransmissions can induce a reduction of application throughput.

With DL PS 384 kbps, the maximum power of the base station was reached. The saturation ratio is the ratio between the number of samples of total DL power at a maximum level (43.2 dBm) and the total number of samples; the overload ratio is the ratio between the number of samples of total DL power above an overload target (41 dBm) and the total number of samples.

As can be seen in **Figure 5**, with more than three users the maximum power of the base station is reached and, therefore, quality is not guaranteed to any of the cell users. Congestion can take place with only three or four users. It was possible to fit seven users on the cell; however, quality was seriously degraded, leading to increased retransmissions and lower throughput.

NETWORK CAPACITY MEASUREMENTS

Setup

Following the single-cell tests, a number of tests were performed in a loaded network environment to consider the effect of other cell interferences on the DL capacity of a cell. Using an experimental network, a test cell was chosen, and all cells surrounding the test cell were artificially loaded in the DL to 60 percent DL load. The test cell was then loaded with voice and data calls, and the power rises on the DL were logged.

Downlink Network Capacity—AMR 12.2 Kbps

Figure 6 shows the DL power rise and the number of users versus time. The graph illustrates that the cell was able to handle 38 voice calls (100 percent voice activity factor [VAF]) before reaching its maximum Tx power of 20 W.

Given a DL load target of 60 percent, Figure 6 also shows that approximately 30 voice calls (100 percent VAF) could be handled at this load. The result suggests that with a typical VAF of 60 percent, a cell in a network surrounded by cells loaded to 60 percent DL load would have a voice capacity of approximately 50 calls.

Similar DL capacity tests with the surrounding cells loaded were performed for PS data (64 kbps, 128 kbps, and 384 kbps with 100 percent DL activity). A summary of these results is given in **Table 1**.

Table 1. Loaded Network DL Capacity Results

Service (kbps)	Maximum Capacity (60% DL Load)
Voice (AMR 12.2)	50*
PS 64	14
PS 128	8
PS 384	3

*Estimation from 30 calls with 100 percent VAF

Clearly, the required DL E_b/N_o depends on terminal performance. Therefore, the above results are valid only for the single terminal type used during the trials. During the next few years, variations are likely to be seen in these figures for different terminals; however, in the longer term it is expected that the trend will be upward.

CONCLUSIONS

This paper has described the theory behind the UL and DL capacity in a WCDMA network. It has presented single cell and network capacity measurements using a commercial Node B and terminal. The actualized results obtained are limited to the test scenario and appear to be in line with theoretical estimates. ■

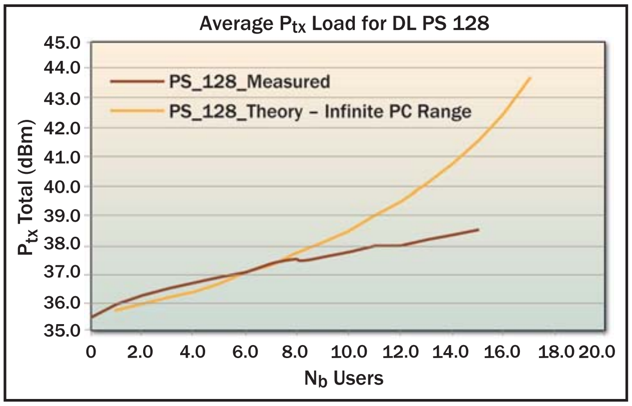

Figure 4. Measured Single-Cell DL Power Rise (PS 128 kbps)

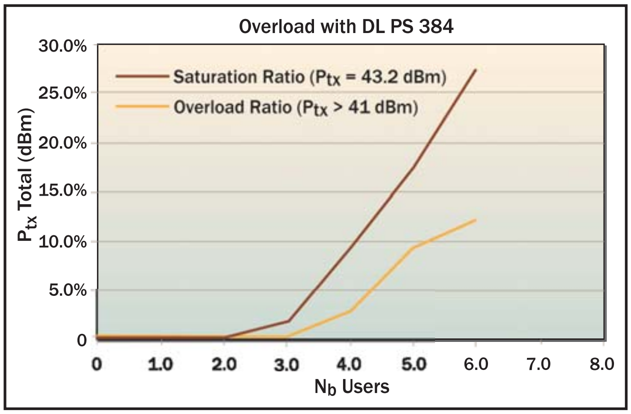

Figure 5. Measured Single-Cell DL Power Rise (PS 384 kbps)

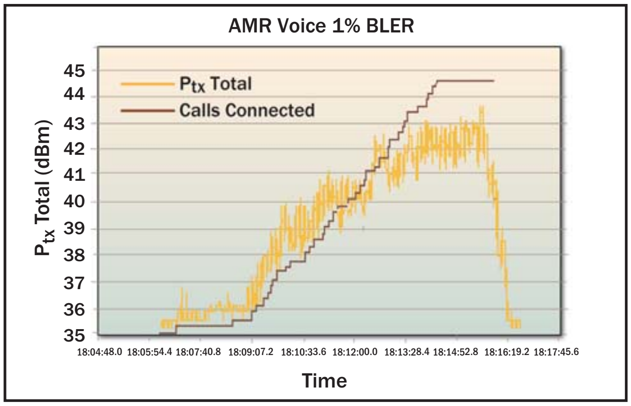

Figure 6. Measured Network DL Power Rise (AMR Voice)

ADDITIONAL READING

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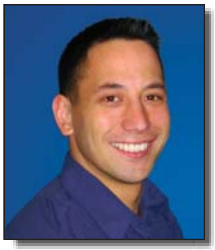
BIOGRAPHIES

Thrasivoulos (Sakis) Griparis joined Bechtel in July 2004 and is currently involved in the acceptance and optimization of a new 3G network built by Bechtel in Australia. Before this, he worked for about 6 years with various vendors and operators around Europe, mainly on preparing and deploying new UMTS networks. Projects for clients such as Siemens in Germany; PT-Telecomm, OniWay-Telecomm, and Nortel in Portugal; and Orange UK (Nokia) required his involvement in bids, network planning, network acceptance, parameterization, network optimization, and trial setup and testing.

Previously, Sakis spent 3 years as a researcher at Fujitsu Research Labs, working on WCDMA technology. His activities included designing and testing a WCDMA digital beam former hardware test bed and performing UMTS pilot trial testing in Japan (NTT DoCoMo), France (Alcatel), and the UK (Orange). Sakis initially became involved with UMTS at the Kings College Centre of Telecommunications Research, where he did research on channel estimation techniques for WCDMA receivers.

Sakis holds a degree in Electronic Engineering from National Technical University in Athens and a master's degree in Telecommunications from Kings College, London.



Tristan Lee is a senior RF engineer for the rollout of a Bechtel 3G project in Sydney, Australia. Specializing in WCDMA, he is currently responsible for RF governance and UMTS optimization in Australia. Before joining Bechtel in May 2005, Tristan worked for Orange UK during its 3G rollout. There, he was responsible for UMTS optimization guidelines. Previous roles include research and innovation (telecommunications) and software development.

Tristan graduated from the University of Birmingham (UK) with a degree in Mathematics.