NETWORK VALIDATION

for CDMA 2000 1X EV-DO TECHNOLOGY

Technical Handbook Report

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PRIMERA EDICIÓN

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In accordance to the requirements of the Request for Engineering, we carried out several information and asks in Panama, China, Sweden, USA, Norway, Finland, Korea and Taiwan. These locations are home to equipment suppliers, network operators or product regional representatives.

The tasks outlined for compliance were defined as:

1- Revision, testing, analysis and recommendation of initial terminal equipment for use in the local IMT-2000 network. Compilation of accurate on the field information on troublesome equipment.

2- Secure availability of terminal equipment to synchronize with the new IMT-2000 platform.

3- Interpretation and recommendation of a product release information listing that will be able to interact with the majority of available terminals, particularly low-end supplies, without affecting GoS/QoS.

4- Cellular tests and measurements. Perform data throughput tests with terminals in working IMT-2000 networks. Sensitivity and Performance measurements.

5- Revision, testing, analysis and recommendation of testing equipment to be used for engineering purposes in the IMT-2000 network at terminal level (level 1,2,3) and network level.

6- Conduct laboratory testing and measurements on network equipment (including antennas) and terminals.

7- Purchasing of spare parts of key components of the IMT-2000 network.

8- Pursuing adequate training relevant to the technology and vendor for know-how transfer to network operator.

9- Testing and analysis of IMT-2000 networks in the countries visited with hardware and software tools.

In meetings with manufacturers of IMT-2000 terminals were held, model compatibility was observed and technical training received by the manufacturers of equipment. The training included RF and programming matters on each of the manufacturer's platforms and devices. This training was conducted in laboratories and on the field on currently existing Ericsson platforms. Also, work sessions with worldwide mobile terminals manufacturers were held to establish the network parameters. These network parameters included:

- Network definitions for PRI,
- RF configuration,
- PRL,
- ERI definitions,
- NVR definitions,
- WAP definitions,
- and functionality description of terminals to be replicated in the network.

Extensive training and analysis of existing networks running Ericsson CDMA 1X EVDO platforms was conducted to replicate the scenarios in the local network. Sessions with network engineers were held to gather information regarding shortcomings of their networks with the intention to avoid these in the local network implementation. Specific problems in the local network were reviewed with manufacturers with the objective of correcting them. These allowed the team to have the latest know-how and be able to transfer it to the local network operator, which is an operator responsibility.

Software interfaces were also analyzed and basic programming training on PST for each device was conducted.

With testing equipment to be recommended for purchase, visited IMT-2000 networks were tested and analyzed in order to replicate implementation locally. Network problems, throughput, performance, latency, congestion, etc. were observed.

Korea demanded most of the resources, as two major manufacturers are located in this country, and many others have assembly plants too. While noticeable, network correlation to local implementation was not exact (due to different frequency allocations),

terminal testing was mandatory.

Also tested were microwave links, antennas, repeaters, filters, combiners, etc. as key components to the IMT-2000 network under development from important suppliers around the world, in order to purchase spare equipment for redundancy matters in the network.

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The information collected, training received, equipment, spare parts, software, hardware and know-how has been forwarded to the local operator, which should be invaluable for the operatorś growth and customer satisfaction. The objectives described in the RFE were successfully achieved and exposed accordingly in a PFE.

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NETWORK VALIDATION

Introduction

The process of measuring performance of networks in production and compare them against the focus infrastructure is known as “network validation”. Because efficient use of resources is a key design problem for any cellular network, in general, and code division multiple access (CDMA) networks, in particular, where the number of simultaneous calls that can be admitted in one cell depends on the number of simultaneous calls in many cells in the network, network validation becomes a must perform process.

The focus infrastructure is usually a new or recently implemented network. Network validation is necessary to match network planning and configuration to “sturdy” (or immune) networks. These networks are grade of service proven and in production. The know-how transferred in this process is one of the single most important factors for network fine tune-up and used as a parameter to validate the network design and implementation based on the comparison of performance against other networks.

Objectives

The objectives of this project were to gather information, perform tests, take measurements, run simulations, perform accurate benchmark of application performance over such commercially deployed environments, implement and characterize the impact of various optimization techniques across different layers of the protocol stack, quantify their interdependencies under realistic scenarios, issue results in production networks in order to validate the implementation of the local network as requested in the RFE documentation. The results and analysis concluded in this reports are to be used for validation of the local network. This report does not comprehend the local network validation, but provides the tools to perform this task. The production networks in consideration are located in different countries that have embraced the CDMA 2000 1X EV-DO technology.

One of our goals is to obtain parameters to maximize the throughput in the network and provide consistent grade-of-service (GoS), i.e., the call blocking rate, for all the cells in the network while at the same time maintaining the quality-of-service (QoS), i.e., the probability of loss of communication quality, for all the users.

Summary

To provide a firm validation foundation for the technical and commercial measures that would play a critical role in the operation of the third-generation – “3G” – network, running under CDMA 2000 1X EV-DO.

It was anticipated that this would be in the context of comparison with ERICSSON platforms, but since has judged fundamental to compare the ERICSSON technology with that one of other suppliers as a main issue in the network validation, great care has been taken to consider this matter. By taking this opportunity, the work plays a vital role in setting critical components of the network.

The close association with major key players in the industry at the operator level and implementer level, and the unbiased position of the firm towards any supplier, is a key major advantage, particularly important since it is likely that global influence can accidentally bias most consulting firms.

The tasks performed were related to the process of validation of the network installation for phase II per RFE.

The validation process was performed in China, Chile,

USA and Canada.

Ericsson IMT-2000, Nortel Networks, Lucent, Huawei,

Daxian, Samsung, LG and Motorola operating platforms

were analyzed in particular with emphasis on Ericsson

platforms.

In general terms, the team had the purpose of validating

network implementation by considering several factors like:

• frequency planning,

• trunk network planning,

• time frame,

• propagation,

• channel capacity,

• noise performance,

• interference (frequency reuse, co-channel, adjacent

channel, from other systems),

• intermodulation,

• blocking,

• BS control and signaling,

• grade of service (GoS) in other networks

for later comparison to the local installation with the

intention of:

- applying corrections where necessary,

- improving network efficiency,

- maximize investment usage.

At production network locations, the following processes were conducted (not exclusive):

1-

Analysis of PNs distribution and general distribution of noise in the carrier wave.

2-

Evaluation of the GoS of the access channel and GoS of the voice channel as a sole parameter.

3-

FER measurements.

4-

Handoffs, Hard Hand-off parameters where there is more than one carrier wave.

5-

Analysis of calls dropped, on-net completed calls, off-net completed calls, completion rate,

6-

RBS location analysis, RF engineering, signal strength measurements, fade pathway

7-

Channel allocation, spectrum usage, channel congestion.

In locations where Ericsson was not the technology supplier, benchmark analysis with other platforms was performed, more specifically with Nortel Networks platforms installed on those networks. The performance

obtained from these networks were used to validate the Ericsson IMT-2000 behavior.

Also analyzed were cellular billing system, fraud (roaming fraud was particularly observed) and fingerprinting techniques used in those networks.

The interaction with the Switch/BSC was observed, calibration of test equipment conducted and also personnel performance to match against the service levels reported locally.

The process of validation did require traveling through entire networks coverage area, performing measurements including particularly troublesome locations. The results were to conclude on the results on the first listing of this document.

System balance, Load balance, interconnection, power distribution systems, protection, grounding, switching at all levels (including hierarchy), roaming services, contents, authentication, signaling and synchronization factors were observed for validation of the local network. Infrastructure like frames, masts, poles, and civil works were also observed.

In conclusion, the division performed these tasks in order to comply with the RFE. As a result, a PFE in being developed.

NETWORK VALIDATION

Project Overview

Wireless cellular networks are being upgraded world-wide to support 2.5G and 3G mobile data services. For example, CDMA 2000 and UMTS networks in Europe, and CDMA 1xRTT and CDMA 2000 networks in the USA and Asia are currently being deployed and tested to provide wireless data services that enable ubiquitous mobile access to IP-based applications.

CDMA2000 1xEV-DO (1X Evolution Data-Only) wireless technology introduces a new air interface with a peak data rate of 2.4Mbps and an average throughput of about 600 Kbps on the forward link providing operators with up to three times more data capacity than current CDMA2000 1X networks. 1xEV-DO is optimized for the bursty, high-speed, broadband access characteristics of the Internet data model. Enhancements to the 1xEV-DO standard, referred as Revision A, increase data speeds, reduce latency and provide QoS mechanisms making the standard viable for real time applications such as VoIP. All these considerations were taken into deciding which networks to analyze for performance. Since our costumer will operate as an EV-DO environment, great care was taken into observing the data progress in CDMA networks.

Measurements taken in the networks of well-known carriers implied at times agreements with those carriers but also 60% of the networks analyzed were done without signing any agreement. This was done to make random measurements of well-known operators and observe all the problems and constraints their networks have without being directed by the carrier itself towards their trouble less installations only.

In matters of our results, it was measured that networks such as Verizon Wireless, MTC

Mobility and Sprint PCS occupy a first tier in quality performance. AllTel, Western

Wireless, US Cellular, Metro PCS have minor problems.

Our results also indicated that SmartcomPCS, Leap, China Unicom had at the time

measurements were performed problems with network throughput.

The results obtained are valid to be used for network validation.

Abbreviations and Acronyms

AAA

Authentication, Authorization, and Accounting

AAL5

ATM Adaptation Layer Type 5

ANSI-41

American National Standard Institute

ATM

Asynchronous Transfer Mode

BSC

Base Station Controller

BSS

Base Station Sub-system

BSSAP

BSS Application Part

BTS

Base Transmission System

CDMA

Code-Division Multiple Access

DHCP

Dynamic Host Configuration Protocol

DSC

Data Switching Center

FA

Foreign Agent

FR

Frame Relay

FW

Fire Wall

GOS

Grade Of Service

GRE

Generic Routing Encapsulation

HA

Home Agent

HDLC

High-level Data Link Control

HLR

Home Location Register

IKE

Internet Key Exchange

IOS4.0

Inter-operability Specification Version 4.0, also see IS2001

IP

Internet Protocol

IPv4

IP Version 4

IPv6

IP Version 6

IPsec

IP Security

IS2001

Interim Standard 2001: Defines Protocols for A1, A7, A9, A11-

Interfaces for CDMA

IS-41e

Interim Standard 41: Defines Protocols for D-Interface for CDMA

IS-95

Interim Standard 95: Defines Protocols for U-Interface for CDMA

IWF

Inter-Working Function

LAC

Link Access Control

M3UA

MTP 3 User Adaptation

MAC

Medium Access Control

MAP

Mobile Application Part

MIP

Mobile IP

MMSC

Short Message Switching Center

MS

Mobile Station

MSC

Mobile Switching Center

MSS

Mobile Service Subscriber

MTP-Adapt

Message Transfer Part Adapter

P.S0001

Specification for Wireless IP based protocols

PCF

Packet Control Function

PDSN

Packet Data Serving Node

PL

Physical Layer

PPP

Point-to-Point Protocol

PSTN

Public Switched Telephone Network

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RADIUS

Remote Authentication Dial In User Service

RAN

Radio Access Network

SCCP

Signaling Connection Control Part 11

SCMG

SCCP Management

SCTP

SCCP Transport Protocol

SMS

Short Message Service

SS7

Signaling System No. 7

SSSAR

Service Specific Segmentation and Reassembly Sub-layer

TCAP

Transaction Capabilities Application Part

TCP

Transmission Control Protocol

UDP

User Datagram Protocol

VLR

Visitor Location Register

1xRTT

1x chip rate of 1.2288 Mcps for Radio Transmission Technology

1xRTT EV-DO

1xRTT Evolution-Data Only

3xRTT

3x chip rate of 1.2288 Mcps for Radio Transmission Technology

2G

2nd Generation of Mobile telecommunication

2.5G

“2.5” Generation of Mobile telecommunication

3G

3rd Generation of Mobile telecommunication

3GPP

3rd Generation Partnership Project

3GPP2

3rd Generation Partnership Project 2

AMPS

Advanced Mobile Phone System

ARIB

The Association of Radio Industries and Businesses (Japan)

CDMA-HDR

CDMA High Data Rate

CDMA-MC

CDMA Multi Carrier

cdmaOne

CDMA for 2G

EDGE

Enhanced Data rates for GSM Evolution

ECDMA 2000

CDMA 2000 for EDGE

FDD

Frequency Division Duplex

GPRS

General Packet Radio System

GSM

Global System for Mobile Communication

HSCSD

High Speed Circuit Switched Data

IMT2000

International Mobile Telecommunications for the 2000s

IS136

Interim Standard 136: Defines Protocols for TDMA (AMPS)

IS136B-HS

IS136B High Speed

IS-634b

Interim Standard 634b: Defines Protocols for A-Interface for

CDMAone

PDC

Personal Digital Cellular (Japan)

TDMA

Time Division Multiple Access

TIA

Telecommunications Industry Association

UMTS

Universal Mobile Telecommunication/Telephone System

UWC136

Universal Wireless Communications for IS136

W-CDMA

Wide-band CDMA

CC

Call Control

MM

Mobile Management

P-H

PDSN to Home Agent Interface

R-P

RAN to PDSN Interface

SDU

Signal Data Unit

U

Air interface between MS and BTS

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Data Gathering

Data gathering or mining from network measurements was performed as follows:

Country

Locations

Operator

Notes

Santiago

Chile

Concepción

SmartCom PCS

Valparaíso

Viña del Mar

Durham, Wilmington NC.

Comscape

Phoenix, AZ.

Leap

Phoenix, AZ.

Alltel

Denver, CO.

Leap

New York City, NY.

Verizon

U.S.A.

New York City, NY.

Sprint PCS

St. Louis, MO.

Verizon

Atlanta, GA.

Metro PCS

Atlanta, GA.

Sprint PCS

Los Ángeles, CA.

Sprint PCS

Los Angeles, CA.

Western Cellular

Stillwater, OK.

US Cellular

Miami, FL.

Sprint PCS

Miami, FL.

Verizon

Fort Lauderdale, FL.

Metro PCS

Port Charlotte - Fort Myers, FL.

Metro PCS

West Palm Beach, FL.

Metro PCS

Athens, GA

Metro PCS

Monterrey-Salinas, CA.

Metro PCS

Altona

Bonnet

Grandview

Canadá

Morris

MTS Mobility

Polonia

Rusell

Steinbach

Woodside

AnHui

Beijing

Henan

Henan

China

Jiangsu

China Unicom

Liaoning

Shanghai

Sichuan

Yunnan

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Table 1- Networks in Production measured

Network Affiliation

The following service providers were measured:

Operator

Country

US Cellular

United States

Metro PCS

United States

Sprint PCS

United States

MTS Mobility

Canada

SmartCom PCS

Chile

China Unicom

China

Comscape

United States

Leap

United States

Verizon Wireless

United States

Table 2- Network Affiliation

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Terminal Clients

The following clients were used to perform our measurements and testing.

Client

Model

Notes

Kyocera

2255

Data Capable, SMS

Data Capable, BREW 2.0,

Kyocera

KE413/KX414 Phamton

SMS

Kyocera

2235

Data Capable, SMS

Kyocera

S14

Data Capable, SMS

Audiovox

CDM 8300

Data Capable, SMS, WAP

Audiovox

CDM 9155

Data Capable, SMS, WAP

Data Capable, SMS, Push

Sanyo

PM-8200

To Talk, MMS, WAP

Sanyo

SCP-8100

Data Capable, SMS, WAP

Data

Capable,

JAVA

Motorola

V720

enabled

Data

Capable,

BREW,

Motorola

T730

gpsOne

Samsung

SCH-N255

Data Capable, SMS

Data

Capable,

BREW,

Samsung

SCH-A610

gpsOne, SMS, MMS

Data Capable, gpsOne,

Samsung

SCH-A310

SMS

Data

Capable,

BREW,

LG

VX-4400

gpsOne, WAP 2.0, SMS

Data

Capable,

BREW,

LG

VX-6000

gpsOne, WAP 2.0, MMS,

SMS

Nokia

2270

SMS

Table 3 - Clients Devices

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Client per Operator

Client

Model

Operator

Kyocera

2255

Leap, China Unicom

Kyocera

KE413/KX414 Phamton

Leap

Kyocera

2235

Smartcom PCS

Kyocera

S14

Metro PCS, Leap

Audiovox

CDM-8300

Comscape

Audiovox

CDM-9155

AllTel

Sanyo

PM-8200

Sprint PCS

Sanyo

SCP-8100

Sprint PCS

Motorola

T730

MTS

Samsung

SCH-N255

Western Cellular

Samsung

SCH-A610

China Unicom

Samsung

SCH-A310

Verizon Wireless

LG

VX-4400

US Cellular

LG

VX-6000

Verizon Wireless

Smartcom

PCS,

Metro

Nokia

2270

PCS

Table 4 - Clients used at networks

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Technology

Protocol

Networks

Notes

IS-95A

None tested

-

IS-95B

None tested

-

All

networks

had

developed into EV-DO.

IMT-2000

None alone

Some were developing

into EV-DV

Most networks were EV-

IMT-2000 1X EV-DO

Some

DO enabled

Although there were EV-

DV networks in operation

IMT-2000 1X EV-DV

None tested

in the US, did not test

these.

Table 5 - Technology Protocols

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Frequency Channel Allocation

Frequency

Carrier

800

Verizon, SPRINT PCS, China Unicom,

Smartcom, AllTel, Commnet

1800

Verizon, Western Wireless, Commnet

SPRINT PCS, China Unicom, SmartCom

1900

PCS, Verizon, US Cellular, Metro PCS,

Leap, MTS Mobility, AllTel

2100

China Unicom

Table 6 - Frequency Channel Allocation

Work package 1

The rental or acquisition of sophisticated equipment was considered in order to measure the networks parameters. It was considered that the key tools to:

a) Measure RF parameters

b) Measure and Tests Calls performance

o calls completed

o calls dropped

o calls failed

o jitter

o echo

o interference

o noise

c) Phase Noise

Work package 2

Extensive measurements preparations were also observed for:

a) MBS

b) MSC

c) BSC

d) BTS

e) BSS

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f) SMSC

g) DSC

h) MSS

i) RAN

For these tasks, it was established that the items on Table 7- Measurement

Equipment for testing were necessary.

Item No.

Equipment

Model / System

Options / Notes

Portable Spectrum Agilent E443A PSA

With options 226 (Phase

LE1290

Analyzer

Noise

Measurement),

option

B78

(CDMA

2000), option 204 (1xEV-

DO Measurement).

LE1315

Test Drive Set

E7477A Cdma 2000 Support for 850 MHz, 1.8

Network

Drive System

GHz

and

1.9

GHz,

Optimization

Agilent E6474A

1XRTT/SR1

Platform

Option

E6474A-740

(WAMS)

Allows testing of MMS,

SMS, Video, WAP, HTTP,

FTP

LE1337

Wireless

Base E7495A/B

Option CDMA2000 Tx

Station Test Set

CDMA over the air test

tool

Nortel CDMA test SW

Power Meter

Interference analysis

LE1501

Laptop Computer

Toshiba

Satellite Serial ports, CDRW, LAN

Centrino

Software includin:

EDX PCS Analyzer

LE1601

Software

Specialized software

Marconi Planet

MapInfo

Integrated Analyzer for

LE1702

Analizador CDMA

NetTek Analyzer

CDMA

Table 7- Measurement Equipment for testing

• Item LE1290 Portable Spectrum Analyzer

This item, the portable spectrum analyzer Agilent E443A PSA with the option to measure

phase noise, and IMT-2000 with 1xEV-DO extension. This is the heart of the

measurement configuration and the single most powerful tool to measure spectrum

usage. Our preference for Agilent against other brands reviewed (especially Ando) was

based solely in a cost-benefit analysis.

• Item LE1315 CDMA Test Drive Set

The Test Drive Set is a specialized tool that allows engineers to literally drive around the

network coverage. It allows the engineers to obtain RF coverage, service performance

and data test measurements for wireless communications networks that use the

advanced CDMA 2000 technology. The system runs on a laptop PC that interfaces with

an Agilent digital receiver and/or a CDMA 2000 mobile phone. The system can control

up to four receivers and four phones simultaneously. The drive test system is a platform

product which provides the following features: carry-around testing, indoor testing, real-

time mapping as well as measurements capabilities in other technologies such as IS-

95, CDMA, TDMA and CDMA-2000.

The engineering team chose Agilent because this is the best test drive tool in the market

for CDMA 2000 networks.

• Item LE1337 Wireless Base Station Set

The base station test set is the most functional one-box tool for wireless and wireline test available today, eliminating the need for technicians to carry, manage, and learn multiple test tools. Consolidating the most used frequently used tools into one box dramatically increases the technicianś productivity. This helps reduce the asset costs, tracking costs, calibration and maintenance costs, and training costs associated with learning the specifics of separate instruments.

It supports CDMA One and CDMA 2000 Tx analysis. It contains an antenna tester (to include one port and two port insertion loss, return loss, and distance to fault measurements), spectrum analyzer, internal GPS receiver, and a set of accessories (cables, attenuators, opens, shorts, etc.).

The option included:

- Power Meter
- CW and CDMA reverse link signal generator
- CDMA over the air test tool
- NEM specific test software (Nortel CDMA test SW)
- 12 Volt DC Bias Output

- Interference analysis

• Item LE1501 Laptop Computer

Toshiba Satellite with serial ports running Windows OS and Toshiba Satellite running Linux. Both machines were powered by Intel Pentium IV Centrino chips, 512Mb RAM.

• Item LE1601 Software

Diverse software used as MapInfo and Marconi Planet.

Planet uses the most advanced architecture and design components based on

Microsoft NET. It is easy customizable and allows to work with 3rd party vendors.

MapInfo is our preferred mapping and cartography application.

• Item LE1702 NetTek Analyzer

The NetTek Analyzer is a base station transmitter and interference analyzer. The

Tektronix NetTek analyzer is a revolutionary portable field tool. The YBT250 test module

tailors this system for fast trouble resolution and easy transmitter verification of cellular,

DCS/PCS and 3G base stations and Node Bs.

The NetTek Analyzer with the YBT250 test module is not an expensive, do everything

solution: instead, the NetTek test module is optimized to perform the day-to-day RF and

demodulation measurement tasks that occupy the majority of a technician's time.

Data Performance

For Data performance measurements and analysis, IMT-2000 ftp/web traces were

collected over the networks above offering 1X services. The client were described as

mobile phone terminals in use in the networks examined. any CDMA 2000 3G-1X

FTP/Web traces were collected over the mobile phones data connection in CDMA 2000

3G-1X Network in the networks analyzed. The clients used are established before as

designated terminals (Samsung, LG, Sanyo, Nokia, Kyocera, Motorola, Audiovox). In all

cases, the terminals were set with maximum ideal downlink rate of 144Kbps and the

network operating at 1900Mhz. For web downloads we used the standard websites

hosted in our remote Lab in the United States. In addition, some CDMA 2000 3G-1X

traces logged in data centers in the countries of location of the networks were used but in this case we have the sender (server side) tcpdump traces collected. Traffic tcpdump traces taken over higher data-rate CDMA 2000 EV-DO and measured when available.

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We have conducted detailed performance studies of different applications over commercial WWAN networks. We primarily focus on the performance of web browsing applications in these environments. Our experiments show that all standard web browsers operating in their default settings significantly underutilize the limited resources of the WWAN wireless link. This is surprising in the context of prior work, which showed that TCP, the underlying transport protocol used by HTTP, makes efficient use of the WWAN wireless link. In fact, these results are also re-confirmed by our experiments. We explain this performance discrepancy based on inefficiencies in session and application layers. Our experiments show that suitable optimizations implemented in these layers can significantly improve application performance over WWAN environments. Our results also demonstrate that collective suite of optimizations applied at different layers of the protocol stack in many cases improves end-user web-browsing experience by at least a factor of two.

To precisely quantify the causes of poor performance over WWANs, we first benchmarked standard web browsers, protocols, and techniques with respect to their performance. Through our experiments we have measured the different components that contribute to the latencies during web downloads for a range of popular websites (ranked in www.100hot.com). Subsequently, we examined a large number of optimization choices that are available at different layers of the protocol stack.

Specifically we study the following aspects of these optimizations for WWANs:

• Application layer

We quantify the benefits of using schemes like HTTP pipelining, extended hash-based caching, delta encoding and dynamic content compression overWWAN.

• Session layer

We study the impact of multiple simultaneous transport connections as typical in standard web browsers, examine the impact of techniques like DNS-Rewriting and URLrewriting and of server-side 'parse-and-push'. Transport layer, We evaluate the performance of standard TCP, a recently proposed and implemented link-adapted TCP variant suited for WWAN environments and a customized UDP based solution.

• Link layer

We study the interaction between link-layer retransmissions (ARQ) and forward error correction (FEC) schemes using trace-based simulations for different applications in WWAN environments. To conduct this study we implemented all necessary techniques (including three different proxies) for our WWAN infrastructure.

The results presented in this project summarizes our experiences and lessons learnt through deployment and operation of our WWAN testbed in the CDMA networks. The Network Validation for CDMA 2000 1X EV-DO Technology Technical Handbook Report

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following were some of our interesting observations: (1) Although TCP itself is relatively

efficient even in WWAN environments, the default HTTP protocol significantly underutilizes the WWAN wireless links. (2) Appropriate application layer and session layer mechanisms are necessary to correct the significant mismatch between transport and application performance. (3) Proxy based optimizations are crucial to realize many of the performance benefits over WWAN.

• Key Contributions

o We highlight the main contribution of this work as follows: We present the

first detailed evaluation of application performance over commercial WWAN

environments.

o We implement and study a wide selection of optimization techniques at

different layers and their cross layer interactions on application performance.

In our experiments, we placed the proxy in our laboratory and then use a well

provisioned IPSec VPN to 'back haul' the traffic from the cellular provider's network. The

mobile client connects to the web servers through this proxy. We present an experiment

methodology based on virtual web hosting that is essential for performing reproducible

and repeatable experiments over WWAN environments.

Tested and Methodology

The experiments reported in this paper have primarily been performed on CDMA-2000

1X EV-DO based WWAN networks, which are widely deployed in different parts of the

world. The SGSN acts as a packet switch that performs signaling similar to a mobile

switching center (MSC) in CDMA networks, along with cell selection, routing, and

handovers between different Base Switching Centers (BSCs). It also controls the Mobile

Terminal (MT)'s access to the CDMA network and routes packets to the appropriate

BSC. The GGSN is the gateway between the mobile packet routing of CDMA and the

fixed IP routing of the Internet. We have also experimentally evaluated application

performance on the next generation (3G) cellular networks, which are currently being deployed in different parts of the world. Wireless links using these 3G technologies have

higher data rates than existing 2.5G technologies. Our preliminary study conducted

over two different 3G networks, CDMA 2000 and W-CDMA UMTS, are presented in

Section 5. These results indicate that our observations and evaluations presented in this

paper apply also to these higher data rate 3G environments.

In this setup, a mobile terminal (MT), e.g. a laptop, connects to the WWAN network

through a mobile device – a PCMCIA CDMA 2000 1X. card or a phone. In order to use

the WWAN network, the MT first attaches itself to the GGSN (PDSN in CDMA 2000)

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through a signaling procedure and establishes a Point-to-Point Protocol (PPP)

connection with the GGSN. The MT is dynamically assigned an IP address and the

WWAN network is responsible for switching data back and forth to this IP address as

the MT moves through the network.

In our experiments the MT (or mobile client) downloaded web content over the WWAN

link from different content locations: (1) directly from the real web servers, e.g. CNN,

Yahoo, and (2) virtually hosted web-servers (explained later in this section) that were

located in our laboratory.

In either case, the data from the mobile client to the servers traverse through the cellular

service-provider’s network as well as the public Internet, before it is finally ‘back-hauled’

to our laboratory. To study the different optimization techniques at different layers of the protocol stack and their overall impact on application (web) performance, our experiments required us to implement optimization specific proxies.

Based on the use of proxies, our experiments can be classified into three modes:

• No Proxy Mode

In this case the client directly connected to the server and the experiments did not require any intervening proxy. These optimizations are the easiest to deploy.

• Transparent Proxy Mode

This mode is used for those experiments here the client need not be aware of the existence of a proxy and the cellular provider's network transparently guides the client's connections through a proxy as necessary. Transparent proxy solutions are also easy to deploy, since they require o changes or configuration to be made in the mobile clients themselves.

• Explicit Proxy Mode

This mode was used in experiments which require the mobile client to be aware of the proxy in the network (in this case called the 'server-side' proxy). This requires either (a) explicit browser configuration or (b) software updates at the mobile client to enable it to interact with the server-side proxy. The software update is a 'client-side' proxy and hence we refer to this approach as a dual-proxy solution.

In the proxy-based optimizations the proxy needs to be deployed within the cellular provider's network. Since it was not practical for us to install our own equipment inside a commercial cellular network, we instead placed the proxy in our laboratory and used a well provisioned IPSec VPN to 'back haul' CDMA traffic to it directly from the cellular provider’s network. This ensured that the path between the proxy and the cellular

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provider’s network was never the bottleneck. In the proxy-based experiments, the mobile client connects to the web servers through this proxy.

Experimental Methodology

We use virtual web hosting to emulate real web downloads. Virtual web hosting is an important construct to perform repeatable web browsing experiments over WWAN links involving fast-changing websites.

Contents of popular websites change very frequently (e.g. in CNN content changes within minutes). If real web-download experiments were to be conducted over low-bandwidth WWAN links involving such web-sites, then different download attempts may notice significant differences in the downloaded content structure and volume. The total number of downloads required for each website considered in this work was more than 500 (including at least 20 downloads for each configuration). This translates to a duration of over 1500 minutes to perform the experiments, leaving side setup times, transient network congestion, unavailable wireless link conditions, etc. Hence it would not have been feasible for us to make meaningful comparisons performed directly using real websites. To avoid this problem we implemented a virtual web hosting system in our laboratory, where we replicated the contents of the popular websites into a set of web servers (in our laboratory) with public domain names. Thus a mobile client can access the virtually hosted webpages using WWAN networks just as they would from actual servers in a repeatable and reproducible fashion. A snapshot on the main webpage of a popular news web-site like CNN shows that it has more than 100 embedded objects. While some of these objects may be hosted on the main content servers, there's are hosted by CDN servers, e.g. Akamai.

When a user attempts to download http://www.cnn.com, the browser first performs a DNS lookup to resolve cnn.com and downloads the main webpage. Subsequently it performs further DNS lookups to resolve the CDN servers that hold some of the embedded objects in that page, and performs appropriate downloads for these objects.

Downloads from popular websites sometimes involves a large number of DNS lookups,

which significantly affect the download performance over WWAN links. Hence, in the virtual web hosting setup, it was necessary to faithfully replicate the distributed web content and its overall structure. For each server in the original website, we assigned a separate web server in our laboratory to "virtually" host the corresponding content. The

domain names of these virtual web-hosting servers were constructed from their original

domain names by pre-pending Web-page.

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Benchmarking Performance

Our experimental evaluation is focused on the web-browsing performance over WWAN

network. We have experimented with different standard web- browsers available (e.g.

Internet Explorer 6, Netscape 7.0). Some other web browsers for handheld devices (e.g.

Blazer, Pocket IE) may have additional features such as progressive rendering and smart caching. While there are some variations in their implementations, we observed that their behavior is roughly similar. In the experimental results reported in this paper, we use the Mozilla browser version 1.4. In its default setting Mozilla opens up to 8 simultaneous TCP connections per web-server using HTTP 1.0 and up to 2 TCP connections using HTTP/1.1. Mozilla also supports proposed experimental features in HTTP/1.1, e.g. pipelining. Due to its open source nature, it was easier to alter the default browser to suit experimental needs.

The experiments reported in this paper were performed using a laptop with a 1.4 GHz processor running Linux (kernel 2.4.20) which connects to the WWAN CDMA 2000 network using a '3+1' CDMA phone. The WWAN operates in the 1.8-1.9 GHz band and supports the use of CS-2 coding scheme for Forward Error Correction (FEC). CS-2 is a 'good compromise' coding scheme giving an ideal downlink data rate of 39.6 Kbps for a '3+1' phone. (Note the actual payload throughput seen by the Radio Link Control – RLC layer is slightly lower than this value). The reliability (retransmissions) offered by the RLC layer was kept enabled. Furthermore, we saw no evidence of network resource contention (CDMA time-slots) in our WWAN cell. This is perhaps due to the small number of CDMA-2000 1X users and generous time-slot provisioning by the WWAN operator. In all our experiments the mobile host (laptop) was kept stationary to avoid link variations. Measured signal quality at the local File Size (KB) FTP-throughput (Kbps).

These results indicate that there are significant opportunities for optimizing web browsing performance for WWAN networks.

Performance Optimizations

We have examined and characterized the performance of a wide selection of optimization techniques that have been proposed at the different layers of the protocol stack — application, session, transport, and link. As discussed some of these optimization techniques relied on a transparent or explicit proxy that was located in our

laboratory.

We will quantify the relative benefits observed by each of these techniques, except for the explicit dual-proxy techniques in most cases. The dual-proxy techniques works with

very different assumptions of deployment and hence it is not possible to make a fair

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comparison of these techniques with the no-proxy or single-proxy techniques. Therefore,

we will present the benefits of the dual-proxy schemes individually and comment on their combined effects in the summary of results.

Application Level Techniques

We consider three application-level optimization techniques. First, we examine content compression and its impact on web download performance. Our results show that web content is highly compressible, but this does not translate to commensurate benefits in web download performance over WWAN. Next, we examine the various choices available through the HTTP protocol, e.g. HTTP/1.1 with persistent connections and HTTP request pipelining]. Our results show that the default configuration parameters of

most browsers (typically chosen to work well in wired networks or wireless LANs) perform poorly in WWAN environments.

Finally, we also explore some advanced techniques including delta encoding and extended caching.

Ø **Dynamic Content Compression**

The total size of content of many webpages is quite large relative to the downlink data rate of WWAN networks. Hence, content compression is a natural candidate to further reduce download latencies. We first examine the "compressibility" of the different websites. We classify content into two parts—fixed fidelity content (includes all HTML,

CSS, JS, files) and variable fidelity content (includes all images). For all fixed fidelity data we applied lossless data compression, using gzip and for all variable fidelity data we applied loss data compression, by reducing the depth level of images.

Note that other forms of data compression, e.g. html reformatting, image resizing, etc. could also be applied here. However, we do not employ such techniques in our proxy, since they require significant knowledge of the content semantics. We implement dynamic content compression using an application-level proxy operating in the transparent as well as the explicit dual-proxy mode. Website Fixed-fidelity Variable-We present the performance benefits of content compression of web download latencies. When lossless compression is used, the client needed to perform an uncompressed operation. (Note that the extra CPU overhead to uncompressed, say a 100 KB data file, is of the order of a few milliseconds for most handheld devices and is

insignificant.) We can observe that although the content in the different websites are very compressible, the benefits of compression on application performance i.e full web-

page download time is not as substantial (except for Yahoo).

We can explain this apparent anomalous behavior based on the object size distribution of the webpages. We can observe that most of the objects in the webpages are small, e.g. nearly 60% of the objects in CNN are less than 1 KB (typically 1 TCP segment for 1400 byte payload IP packets). Any amount of compression would clearly not change the number of segments below one. Furthermore each GET request for such segments will incur an overhead of at least one WWAN round trip time. Therefore, the total overhead of issuing individual GET requests for each of these objects in the web-page sequentially over the TCP connections starts dominating the overall transfer time of these objects and hence improvement in the web-page download latency due to compression will be minimal in these cases. In contrast, the distribution of object sizes in the Yahoo website is skewed towards larger values (the average object size is 3.8KB in Yahoo, as opposed to 2.2 KB and 2.8 KB for Amazon and CNN respectively). We can

observe here that the impact of content compression is significantly greater since the number of objects in Yahoo web-page are relatively few (hence reduced RTT overheads

of issuing GET requests) while the average image size large (thereby yielding greater compression factor per image object where most objects are large). Hence the improvement in response time by reduction in the payload offered by

Ø **Mechanism Description**

HTTP/1.0 Use of separate TCP conn. For each object downloaded HTTP/1.1-def. Use of two “persistent” TCP conn. to download all objects. HTTP/1.1-Pipelining Use of 2 “persistent” TCP conn. with simultaneous GETs HTTP/1.1-Opt. Use of 6 “persistent” TCP conn. compressing the objects in case of Yahoo is far greater than the overhead of issuing individual GETs – data compression has a significantly better impact on download latencies of such websites.

Ø **Optimizing HTTP using Pipelining**

Many current web browsers continue to use non-persistent connections (HTTP/1.0), which opens-up new TCP connection for every object downloaded. In contrast, HTTP/1.1 in its default mode opens two TCP connections to each server which are used to download all the objects from that server. Our results show that HTTP/1.1-default suffers from significant under-utilization of the WWAN link. Therefore we now study the impact of the HTTP1.1-Pipelining feature which is an experimental option in the standard.

In Table 5 we summarize the different variants of the HTTP protocol that we study. A browser that implements HTTP request pipelining is allowed to issue new GET requests without waiting for the entire response of the previous ones. Hence a browser can use this mechanism to issue simultaneous GET requests and ensure that the TCP connection are fully utilized for data transfer. This is in contrast to the HTTP/1.1-default (non-pipelined) which issues GET requests sequentially over each open TCP

connection. In fact, it is precisely this ‘stop-and-go’ GET behavior of HTTP/1.1-default which leads to significant of under-utilization of the WWAN link.

In Table 6 we can see that HTTP Pipelining provides between 35% to 56% benefit for the different websites. The benefit is particularly high for large websites like CNN with many objects in their webpage. We explain this using the distribution of object sizes shown earlier. Most of the objects in these popular webpages have a large number of small objects (e.g. CNN has more than 60% of the objects less than 1 KB in size). The default HTTP/1.1 protocol gets each of these small objects sequentially over its two TCP connections, and waits numerous times between the completion of each GET request and the beginning of the next.

In contrast, pipelining allows many GET requests to be issued simultaneously y the mobile client and hence the objects are fetched without any intervening gaps. TTP pipelining is an experimental technique in the HTTP/1.1 standard and we found that, unfortunately, most browsers do not enable this feature by default. Additionally, our experiments show that the web servers of many popular websites currently do not respect this pipelining feature. Therefore, the real performance benefits of this mechanism on wireless web browsing can be quite limited. In all our subsequent experimentation, we will ignore HTTP/1.1-pipelining technique for this reason and re-visit it in our summary of results. We will study the impact of a session layer technique in which we vary the number of simultaneous TCP connections and show how it can approximate the behavior of HTTP pipelining.

Ø **Extended Caching and Delta Encoding**

In this explicit, dual-proxy based optimization, we evaluated extended content-hash based caching and delta encoding schemes. In this scheme, a ‘client-proxy’ software was installed in the mobile device which interacted with the ‘server-side’ proxy located in the WWAN infrastructure. In the extended caching scheme, the client as well as the server proxy indexes web objects by their SHA-1 fingerprint, which we call Content Hash Key (CHK). Each time the client attempts to download a webpage, it gets a CHK list of all the objects in the webpage from the server-side proxy. Using this information,

the client makes request for only single instance of objects, even if they point to multiple

URLs (same response but aliased to multiple URLs). Experiments have shown that in

many dynamically generated websites (e.g. bbc.co.uk) such a phenomenon is

commonplace (also known as response aliasing). Hence, CHK-based caching is able

to eliminate redundant data transfer over WWAN, save disk space and also improve

overall web download times.

When the data being downloaded is a different version of the same object previously

cached (i.e. same URL but different CHK), a delta encoding scheme is used. Delta

encoding is a standard technique in which the server (in our case the server-side proxy)

sends only the differences between the new and old versions of a document to the client.

This technique is very useful for websites like cnn.com and bbc.co.uk, where the

content changes incrementally, but frequently (e.g. time-of-day strings). Our experience

shows that the use of CHK-based caching and delta-encoding on average improves

real web-browsing performance by about 3-6% in such fast-changing web-sites. Note

that individual benefits from CHK-based caching and delta encoding depends largely

on the type of web-site and its content. In general these are expected to vary for different

web-sites. The figures reported here are benefits users can nominally expect for our

example web-sites during real web-browsing sessions.

Session layer Techniques

The goal of the session-layer optimizations is to mitigate the link ‘idle time’ effects incurred during DNS lookups and some other factors during web downloads. We performed a detailed study of the performance enhancement schemes for:

(1) impact of multiple simultaneous transport connections as typical in standard web browsers,

(2) impact of DNS look-ups on web download, and,

(3) server ‘parse-and-push’ technique. We study URL-rewriting/DNS Rewriting with the transparent proxy, and Parse-and-Push scheme as an explicit dual-proxy approach.

Ø **Varying Number of TCP Connections**

We showed that the HTTP pipelining feature has significant impact on web browsing performance in WWAN mail TCP connections for the web browser was varied.

Download times normalized with respect to the HTTP/1.1 default of two TCP connections.

(The default connection settings in Web browsers leads to significant under-utilization over WWAN.) environments. Unfortunately, the pipelining feature is not faithfully supported by many commercial web servers. Therefore we look at an alternative session layer technique where we treat each HTTP download as a single session and optimally choose the number of simultaneous TCP connections opened by the client to the server. The normalization was done with respect to HTTP/1.1-default (two connections). In all the cases, we found the best performance when 6 connections were used (we call this HTTP/1.1-Opt). The download latency for HTTP/1.1-Opt reduced by 35-42% for the different websites. The number of parallel GET operations increase with the number of connections, thus, decreasing the total ‘idle time’ on the wireless channel.

However, we observe no additional benefits of increasing the number of connections beyond six, at which point the download performance is limited by other inefficiencies (e.g. DNS lookups, TCP 3-way handshake and slow start effects, etc.). In fact, the performance degrades due to adverse interactions and overhead from the TCP connections.

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The optimal number of TCP connections that minimizes download latency is a property of the wireless interface and the network. Our results indicate that 6 TCP connections provide maximum throughput when using a GRPS network with an ideal downlink data rate of 39.6 Kbps. The optimal number of TCP connections can vary for a CDMA 2000 3G-1X network with an ideal downlink data rate of 144 Kbps or for a UMTS 3G network with maximum downlink data-rate of 384 Kbps, and we recommend an empirical configuration of the optimal settings in browsers based on such properties of the WWAN network. Increasing the number of simultaneous TCP connections is an aggressive behavior. However, for bandwidth-depleted environments like WWAN environments, such a behavior leads to significant improvement in the user experience (i.e. for CNN the download latency reduces from 196.3 seconds to 123.0 seconds).

We can observe that the use of HTTP/1.1-Opt (6 connections) leads to significant performance benefits for web downloads. While the performance improvement of HTTP/1.1-Opt is similar to that of HTTP/1.1-Pipelining, it is somewhat lower in some cases. This is because HTTP/1.1-Opt is only able to approximate the behavior of

HTTP/1.1-Pipelining by carefully choosing the number of simultaneous TCP connections.

Includes App. Opts: Full Compression

The goal of both these optimizations, in the WWAN context, are similar — to reduce the number and overall duration of idle times between successive GET requests over each TCP connection. Since most web servers currently do not support the HTTP pipelining option, HTTP/1.1-Opt is an alternative approximation that may be used by WWAN clients to realize similar benefits.

• **URL Rewriting/DNS Rewriting**

These are two almost equivalent techniques that transparently reduce the DNS lookup and TCP connection setup overheads at the mobile client. In the URL re-writing technique, the proxy in the cellular provider's network intercepts the GET request issued by the client for a webpage, say index.html, and makes appropriate server requests on the client's behalf. On receiving the index.html page, the proxy parses the contents, and identifies the names of all other servers that holds different embedded objects and replaces them with its own IP address similar to schemes employed by Content Distribution Networks. It then responds with this modified index.html to the client. The client now directly contacts the proxy using the latter's IP address for these embedded objects through subsequent GET requests. The proxy again (pre-) fetches these objects from the other servers and in turn serves them to the client, much like a web caching system. Thus the client needs to perform at most one DNS lookup. DNS-Rewriting achieves the same effect as URL re-writing, but by intelligently manipulating DNS queries from the client. By responding to the DNS queries with a fixed IP address, the

DNSRewriting technique implicitly forces the client to point to one single (proxy) server

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so that client can open an optimal number of TCP connections thereby improving overall

performance. Thus, we find that both schemes can benefit performance in two ways:

(1) by avoiding extra DNS Lookups, and,

(2) by minimizing the overhead of opening distinct TCP connections to different servers.

To quantify the benefits of these schemes, we implemented the DNS-Rewriting/URL-

rewriting proxy and performed download experiments for different websites. We present

the results.

Since we wanted to quantify the additional benefits of the different session level

techniques, we performed the application-level optimizations (not including HTTP/1.1-

pipelining since its prevalence is still limited in commercial web servers) in all these

experiments. As noted before, use of HTTP/1.1-Opt itself leads to significant

performance benefits, i.e. between 37-44%, while elimination of the DNS lookup

overhead adds another 5-9% improvement in the download latency. The combined

improvements due to these session layer techniques are between 53-65%.

• **Server side**

ParseandPush. Parse-and-push is a session-level, explicit, dual-proxy scheme where

the server-side proxy located at the other end of the wireless link in theWWAN network

attempts to speculatively 'push' objects Website App. + Session Opts: 1.1-Opt + DNS-b/URL-r Download time in seconds. None implies no transport optimizations, T1 is TCP-

WWAN and T2 is UDP-CDMA. Improvements with respect to None (first column)

towards the client that it knows the client will have to download. For example, when the

client makes a request for the index.html page, the server-side proxy will begin pushing

the various objects embedded in the index.html file even before the client makes explicit

GET requests for it. Parse-and-push emulates deterministic content pushing towards

the mobile client, when the wireless downlink would have been otherwise left idle. While

supporting parse and push mechanism requires explicit client-side software update,

the scheme helps to improve overall utilization of the link. Our experiments have shown

that parse-and-push can provide an additional between 5% to 12% improvement in the

web-page download latency for popular websites.

Transport layer Techniques

We now examine two optimization techniques in the transport layer that have been

proposed in recent literature. The first one is a transparent-proxy solution that attempts

to optimize TCP performance using a 'transparent' proxy located in the cellular

provider's network, we refer to this technique as TCPWWAN. The other is an 'explicit

dual-proxy' solution which defines a custom protocol based on UDP (we call it UDP-

CDMA.)

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While TCP is designed to operate over a wide-range of network and link conditions, the optimized protocols studied in this section specifically leverage the knowledge of the underlying WWAN wireless links and hence achieve improved performance. Due to space constraints we only summarize the key features of both these implementations.

• **TCP WWAN**

TCP WWAN defines a transparent proxy-based solution in which the proxy is located in the cellular provider's network. The proxy specifically addresses some of the main performance problems of TCP for web downloads over WWANs. For example, instead of using the TCP slow start, it uses a pre-determined value of the bandwidth-delay product and performs aggressive recovery during packet losses and link stalls. Note that such aggressive behavior can be very disruptive if implemented in the Internet. However, TCP-WWAN is implemented only within the cellular provider's network which already implement appropriate bandwidth sharing mechanisms (for CDMA 2000) between users at lower layer of the protocol stack. Standard TCP leads to large queue build-up due to generous buffer provisioning in WWAN networks. Long-lived TCP flows destined to mobile clients accumulate segments in these large queues causing Sender TCP RTO inflation that prolongs recovery during loss. Furthermore, WWAN links can be subjected to link 'stalls'. When such link stalls occur, undelivered TCP segments accumulate in these large WWAN queues, which are then correctly re-transmitted by the reliable link layer on link repair. However, this results in sender experiencing sudden 'delay spikes' that can cause spurious timeouts. Note that TCP-WWAN can estimate the

Download Latency (Norm.) FEC % Impact of dynamic link-layer FECs on Download Latency

WWAN links on bulk data downloads under different channel conditions. (WWAN trace-driven simulations) available bandwidth on the wireless link to sufficiently regulate the flow of TCP segments towards the mobile client. It avoids excess queue build-up inside WWAN networks and also prevents spurious timeouts should wireless link stalls occur.

We implemented a TCP-WWAN proxy for an experimental evaluation of this technique based on the description of Chakravorty, Katti, Pratt and Crowcorft.

• **Custom Transport Protocol**

UDP-CDMA 2000 is an explicit dual-proxy based scheme to improve the transport performance of web downloads. This scheme defines a reliable protocol using UDP and implements ordered, reliable, message transfer. The protocol is optimized specifically for CDMA networks by leveraging its knowledge of the CDMA 2000 wireless link. For

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example, this protocol is aware that the CDMA 2000 link layers offer reliable in-order data delivery. Hence it uses a selective repeat with Negative Acknowledgements for loss recovery. Using such specific properties and characteristics of CDMA 2000 links, this protocol responds efficiently even in the event of common patterns of packet losses.

Periodic messages are generated every few seconds which allow hosts to detect serious link stalls. If such a link stall is detected, the client disconnects and re-attaches to the CDMA 2000 network. Experience has shown that this action often repairs the link

failures.

An unaware transport protocol (e.g. standard TCP) will experience severe back-offs and

failures under similar circumstances. UDP-CDMA 2000, by design, also avoids TCP's

connection setup and slow start delays. While TCP has to operate over links with widely

varying qualities, being a custom solution UDP-CDMA 2000 can make many more

assumptions about the underlying network. For instance, since CDMA 2000 networks

implement a mechanism to share bandwidth between users, there is no need for the

UDP-CDMA 2000 protocol to implement its own congestion avoidance mechanisms.

Instead, it employs a simple credit-based flow control scheme. The credit value is so

chosen to ensure that the wireless link remains fully utilized even though the buffer

occupancy in the cellular network remains low. This avoids excess queueing that some

long lived TCP flows cause. We present the additional performance benefits of applying

the above transport-level optimizations. We can observe that TCP-WWAN achieves

between 5-13% additional benefits for the different websites. UDP-CDMA 2000

leverages its specific knowledge of the wireless link characteristics to improve the

download performance further (between 7-14% for the different websites).

Linklayer Techniques

We finally present an evaluation of link-layer mechanisms and their impact on user

performance. WWAN wireless links use two different schemes to provide reliability

across the wireless links over a wide range of channel noise conditions. The first of this

is a data encoding scheme with various levels of Forward Error Correction (FEC). For

example, CDMA 2000 networks use four different FEC schemes (CS-1 to CS-4). The choice of the appropriate encoding scheme is made statically by the Radio Link Control (RLC) layer. Most current CDMA 2000 WWANs make use of the CS-2 scheme, which allows good data protection in moderate to high noisy radio conditions. The second one is an Automatic Repeat Request (ARQ) scheme that works aggressively to recover any data transfer losses through re-transmissions. Since re-transmissions incur delays, all short term link outages are hidden from the higher layers and manifest as increased delays. The higher layers will detect losses only for

(1) deep fading that leads to bursty losses, or

(2) cell-reselection due to the cell update procedure that leads to ‘black-outs’ (or link stalls).

We study mechanisms that will allow the RLC to dynamically choose the encoding schemes in conjunction with the ability to enable or disable ARQ, and the impact of such mechanisms on applications. Performing actual experimentation for all of this study was difficult since we had no control on the encoding schemes used by the Base Station to transmit data to the mobile client. At the mobile client we only had the flexibility to enable or disable ARQ, and the ability to disable FECs. In order to study the trade-offs between ARQ-based and variable FEC-based link layer reliability approaches, in some cases we relied on trace-based simulations (the traces were generated from actual experiments on our testbed).

Our traces were generated as follows: we sent a stream of UDP packets from the proxy to the mobile client. The WWAN wireless link is the bottleneck in this system, and therefore, these UDP packets will queue at the base station. The RLC layer will appropriately fragment these UDP/IP packets into blocks and pace them out to the mobile client at the rate permissible by the wireless link. To generate our traces, we disable ARQ. Additionally we set the RLC layer at the mobile client to deliver all packets

up to the IP layer (including packets in error) 1. The RLC blocks are sub-divided into slots, and we can infer which slots are 1 Blocks with corrupted headers could not be correctly interpreted and hence was not delivered to the upper layers corrupted over the wireless link. We then apply various levels of FEC-based encodings and ARQ on these traces and observe their performance on the applications. We consider two kinds of applications:

(a) reliable data transfer applications (like ftp and web traffic), and,

(b) non reliable data transfer applications (like streaming media).

For reliable data transfer applications, we assume that the link layer can dynamically choose an amount of FEC (including none) to apply on the RLC data blocks. For ease of exposition, we assume that the FEC is applied at the granularity of slots. If there are 100 slots to a block and the amount of FEC applied is 5%, then 5 out of these 100 slots are used to redundantly encode the remaining 95. Slots that are not recovered after FEC is applied (due to higher channel error conditions) are recovered using the ARQ scheme. For the non-reliable data transfer applications we completely disable ARQ. Hence data that could not be recovered after FEC is applied, is lost.

• **Reliable Data Transfer Applications**

We plot the normalized data download latency for reliable data transfer for a large data file for different channel conditions and amount of FEC (the data is normalized with respect to the experiment with the best channel condition and no FEC). It is easy to see that for each different channel condition there is an optimal value of FEC that leads to the least download latency. For example a moderately poor channel, with an error rate of 0.9% on the CDMA 2000 channel, 5-6% FEC is the optimal choice to minimize download times. By doing so, the data latency reduces by about 21.9%. In a better channel (say with 0.2% error rate) the corresponding benefit is about 5%. The amount of required FEC for such optimal performance increases with increase in channel error rates. This data suggests that, instead of using a fixed value of FEC (e.g. CS-2 in CDMA),

networks should implement an RLC that can continuously monitor the channel conditions and dynamically choose the amount of FEC to be applied on reliable data transfers across the wireless links.

• **NonReliable Data Transfer Applications**

An important consideration for non-reliable data transfer applications like media streaming is the jitter experienced by the data stream. Our experiments indicate that use of ARQ schemes for data recovery incurs a high jitter on traffic — it can vary between 600 ms to 3 seconds depending on the number of re-transmissions attempted. For such non-reliable data applications we consider the scenario where ARQ is completely disabled. Only variable amounts of FEC is used to recover from link layer losses. Use of FEC incurs constant delay overheads even when the channel is loss free. While this would decrease the jitter between successive data packets in such media streams, under poor channel (high noise) conditions it would also incur losses.

We show how the choice of FEC impacts losses experienced by a streaming application.

We can see that even a low amount of FEC is sufficient to obtain a low loss performance

for streaming applications, while maintaining low jitter. However, a disadvantage of

using FEC to handle losses is a reduction in data throughput. For example, when the

channel error rate is 0.9%, 5-6% FEC is useful to eliminate most of the channel errors.

Nevertheless, this also leads to a reduction of useful data bandwidth by 5-6%. The gains

of such FEC-based approaches are in corresponding reduction in jitter.

Summary of Results

In the previous sections, we presented a number of different optimization techniques to

improve web download performance. Application and Session Layer optimizations

dominate performance improvements, we assume a reasonably good wireless link,

(error less than 0.2%) where dynamic FECs provide a latency improvement of upto 5%.

This value is derived from our trace-based simulations. The benefits of dynamic FECs

will increase with poorer wireless channel conditions and decrease with further

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improved channel conditions. We have explored two classes of optimizations — those

that require re-configuration or software update in the mobile client, i.e. uses an explicit

proxy, (called Client-reconf.) and those that have no such requirements (called No-

reconf.). We plot the relative contribution of the No-reconf. schemes when all of them

are applied simultaneously. The optimizations include, Full Compression, HTTP/1.1-Opt,

DNS-Rewriting/URL-rewriting, TCP-WWAN, and dynamic FECs. Website No-reconf.-I

No-reconf.-II Client-reconf.

The improvement provided by all the techniques applied simultaneously were the sum of these values, 63.0%, which brought the download latency from 76.4 seconds to 29.3 seconds. In general, we can observe that application and session layer techniques dominate improvements in web performance. They lead to 48-61% performance improvements for our example websites. Thus our work demonstrates that the application and session level mechanisms currently deployed for web browsing applications make poor use of the relatively efficient lower layers. Employing appropriate optimizations at these layers can help bridge this performance gap observed between the upper and lower layers.

Note that transport and link layers optimizations typically provide 5-10% additional performance improvements, which is still significant for web downloads over WWAN links.

We distinguish between two different No-reconf. solutions: No reconf.-I uses HTTP/1.1-

Opt while No reconf.-II uses HTTP/1.1-Pipelining. Note that these two techniques are interchangeable since they have the same goal with somewhat similar effect. In both these solutions we also apply all the other No. reconf. solutions at the different layers. The Clientreconf. solution includes Full compression, Delta encoding and extended caching, Parse-and-push, and UDP-CDMA 2000. As we would expect, the Client-reconf.

solution leverages extra functionality between the client and the server-side proxy to achieve better performance than the No-reconf. techniques. Additionally we can observe that between the two No-reconf. solutions, the pipeliningbased technique achieves better performance than the HTTP/1.1-Opt based technique. This indicates that pipelining is a very crucial technique to improve performance and should be enabled by all web servers.

Discussion

The results presented indicate that optimizations at individual layers of protocol stacks

are necessary to achieve significant performance benefits in CDMA 2000 environments.

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Also quantifies the specific benefits of performance optimizations at these different

layers. In this section we discuss the following related questions:

- Are these optimization-based benefits specific to 2.5G CDMA 2000 based WWAN networks or do we expect similar performance benefits in the next generation (3G) networks as well? Hence we first present a preliminary case study of 3G networks and demonstrate that our observations in this paper would largely extend to these environments.
- Are WWAN environments a special case of low-bandwidth high-latency networks? In particular should we expect that the optimizations studied in this paper in the context ofWWANs would also lead to equivalent performance improvements in wired dial-up environments? Hence we next present a similar study for web applications run over wired dialup environments to demonstrate that WWAN environments have significantly different characteristics and performance. We present these results for FTP and web throughputs respectively as we discuss later.
- Finally, we will conclude with a discussion of limitations of proxy-based solutions and the implications of such limitations in the context of the results presented.

• **Implications in 3G Networks.**

To evaluate the potential impact of our results on 3G WWAN environments, we conducted experiments over two different commercial class 3G networks – CDMA 2000

3G-1X network and W-CDMA UMTS 3G network. In these experiments we used a

Samsung VGA1000 handset for connecting to the 3G-1X network (maximum ideal

downlink data-rate of 144 Kbps) while for the UMTS 3G experiments we used a 3G

PCMCIA data-card (qualcomm chipset) for measuring FTP and web throughputs (ideal

UMTS downlink data-rate of 384 Kbps).

The goal of our study was to examine the potential benefits of optimizations to 3G

networks. Hence we present the FTP throughputs for different file sizes and the

unoptimized web throughput for the four websites and compare them with the

corresponding performance of our CDMA 2000 experiments. We quantify the under-

performance of the two data transfer protocols — the under-performance (in

percentage).

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We can observe that CDMA 2000 and 3G (both CDMA 2000 3G-1X and UMTS) networks

exhibit a significant additional under-performance between FTP and Web throughput.

For instance the FTP throughput in the 3G-1X case for a 200 KB file is about 36% less

than the ideal downlink data rate of 144 Kbps, whereas the web download of 186.8 KB

size CNN page shows a significantly greater under-performance. We can also contrast

the CDMA 2000 and 3G-1X (under) performance with that of UMTS 3G WWAN that

offers a maximum downlink data-rate of 384 Kbps. We find that for the case of UMTS

3G WWAN the average web download throughput of 62.3 Kbps (again downloading the

CNN web-page) is far below the average FTP throughput of 156.8 Kbps for a 200 KB file transfer.

Note that in these experiments we do not apply any performance optimizations at any layer. These results demonstrate that performance mismatch as seen over 2.5G CDMA 2000 WWAN are also present in 3G WWAN environments. Thus, even though 3G offers higher data rates than 2.5G, the high and variable link latency in WWAN impacts performance of web-based applications negatively leading to poor end-user experience. Appropriate use and choice of optimizations implemented at the different layers of the protocol stack as shown in this paper are necessary to improve performance and overall end-user experience. Hence we expect the benefits from such performance optimizations to extend to these higher data-rate 3G environments.

Wired Dial-up Environments. We also experimentally investigated performance of wired (dial-up) environments. We conducted experiments using a standard V.90 56Kbps dial-up modem. FTP and Web Download throughputs for CDMA WAN and wired dial-up links. Here degradation (in %) with respect to ideal downlink data rate. (No significant mismatch seen between TCP and HTTP in wired dial-up links.) Interesting to note in that there exists no significant mismatch between FTP and web throughputs in the wired dial-up scenarios. The performance degradation (with respect to the ideal data rate of 56 Kbps) of a 100 KB FTP is 19%, while that of a large website like CNN is 32%. This is very unlike the characteristics experienced in WWAN environments. We attribute this difference to the following reasons. First, the RTTs for dial-up modems (in the 100-150 ms range for 64 byte packets) is relatively lower in comparison to the significantly higher values encountered inWWAN links (nominally in the 400 ms to few seconds range for same packet size). Hence the ‘stop-and-go’ behavior of HTTP protocols in default settings leads to greater under-utilization in WWAN links than it does in dial-up wired environments. Clearly, the optimizations studied in this paper will lead to improvement in download performance over dial-up modems as well, but the impact of these techniques are significantly higher in WWANs. Second, the RTT variability on dial-up links is marginal when compared to that of WWAN links. Finally, losses encountered in wired dial-up links are few and far in between (unlike WWAN environments). Hence although the wired dial-up environments have low bandwidths, their impact on data transfer applications is relatively benign. It allows modems to implement additional

stateful packet and connection compression techniques that are more difficult to implement in WWAN environments.

Trade-offs in Proxy Deployments overWWANs. Our results demonstrate that proxy-based solutions provides significant performance benefits to the end-user experience over WWANs. However, the presence of proxy breaks the “end-to-end” properties of an application and has security and other related implications. For example, if the webpage contents are digitally signed by the content provider, then any updates e.g. URL-rewriting or content compression, will violate the security guarantees of the client.

Part of the problem would be solved if the content source itself implemented such proxy functionality. Even more realistically, it may be necessary to provide the clients with the

appropriate choice to trade-off performance against end-to-end guarantees. Thus, a client browsing news at CNN may accept some susceptibility to insecure data at the cost of significant performance improvements in download latencies. The same client may not use a proxy-based solution when downloading stock-quotes and instead prefer the rigid security properties of end-to-end encryption.

The explicit proxy based solutions define customized mechanisms to provide the best-known benefits to WWAN clients. However, client re-configuration or a client-side software update is an intrinsic requirement of such schemes. This increases the deployment overhead of such schemes higher than the other class of schemes.

In many cases it is expensive for cellular operators to provide such updates to existing client equipment. The price performance trade-off of the wireless cellular operators will

finally determine the deployment of such mechanisms in WWAN environments. The benefits available from using such intermediaries (proxy solutions) are also genesis to novel architectural proposals that espouse use of intermediaries in the realms of new Internet functions. Some interesting new proposals envisage functions for internetworking, transparent address extension or a layered naming architecture. Addressing such issues are necessary even for true mobile convergence. Thus, architectures that combine performance issues to address such trade-offs using proxies in WWAN benefits the 'mobile Internet' evolution.

Related Work

Researchers have examined various optimization choices at the different layers of the protocol stack in the context of both wired, wireless, and also for WWAN environments.

However, much of the prior research has focussed mainly on isolated performance

optimizations. Prior research in WWANs have primarily focussed on the following three

aspects:

(a) improving TCP performance over WWANs,

(b) passive analysis of TCP traffic traces, and,

(c) cross-layer interaction and optimizations of TCP with the link-layer.

Our work differs from all prior work in WWANs in several ways. In our study

(1) we quantify the causes of poor application performance and examine the user

experience over WWANs,

(2) we measure the different components that contribute to the latencies during web

downloads for a range of popular websites,

(3) we use virtual web hosting as an important construct to perform repeatable and

reproducible web browsing experiments over WWANs,

(4) we benchmark standard web browsers, protocols, and techniques with respect to

their performance, and,

(5) we implement and study a wide selection of optimization techniques at different

layers and their cross layer interactions on application performance.

At the link layer, TULIP describes a transport unaware ARQ mechanism to improve TCP

performance. A. Chokalingam and Ayanoglu examine the interaction between ARQ and

FEC-based link recovery mechanisms in the context of wireless networks through

detailed simulations and is related to our discussion. A. Gurtov and S. Floyd in discuss

comparative aspects of modeling different wireless links for transport protocols. A.

Kumar compare performance of versions of TCP over wireless links. H. Balakrishnan

use explicit loss notification (ELN), mostly in the context of wireless LANs, to improve

the performance of applications like HTTP. For the transport layer new mechanisms

have been defined to improve the performance of reliable (data) applications in wireless

LAN environments. Examples of this are Snoop, I-TCP, M-TCP etc. However, solutions

meant for wireless LANs may not work that well over WWAN.

Meanwhile, researchers have also demonstrated that the CDMA 2000WWAN link layer

and TCP do not adversely interact with each other. Experience with UMTS 3G networks

also show that TCP works well with link-layer (RLC) retransmissions. Similarly, link layer

(RLP) retransmissions in CDMA 2000 3G links ensure packet loss probability of less

than 1% and that also minimizes any impact (and adverse interactions) on TCP. While

our results agree with these above observations that the WWAN link-layer is generally

well-tuned for transport protocol TCP to operate over WWANs, the end-result (i.e. user

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experience) for TCP-based applications like web browsing remains ‘remarkably’

different. Our work also demonstrates that employing appropriate optimizations at the

application and session layers (as described in this paper) provides significant benefits

to actual user (web) experience.

In other important works, R. Ludwig et. al. examine the performance of TCP over CDMA cellular links and subsequently propose specific link layer mechanisms (e.g. frame size adaptations) that are necessary to improve TCP performance in such environments. P. Sinha et al. introduce WTCP as one of the first solution to overcome performance problems seen for TCP over CDPD-based WWAN links. Many of the link-related performance issues (high RTTs, link stalls etc.) observed in CDPD based WWANs are similar to that observed in CDMA 2000 and 3G-1X based WWANs. M. C. Chan and R.

Ramjee propose ACK Regulator for improving TCP performance over CDMA 2000 3G-

1X links. Unlike GSM-based CDMA 2000, 3G-1X links exhibit much higher rate and delay variations and transport-layer optimizations like ACK regulator can be used to significantly benefit TCP performance in such environments. IETF RFC 3135 and RFC

3481 provide further details of different mechanisms to improve TCP performance in different wireless environments. Research has also investigated some performance issues over CDMA 2000, e.g., a large-scale passive analysis of end-to-end TCP flows and some preliminary study of proxy performance in cellular networks. In a recent work

T. Bonald et al. in examine the performance of wireless data systems in the context of dynamic interaction of active flows in multi-cell scenarios.

Proxy and caching based schemes to improve web performance, similar to the ones we have explored in this paper for WWAN environments, have been already extensively

explored in the prior literature mostly in the context of wired (including dial-up) environments, e.g. Cache Digests, response-aliasing in web transactions etc. A detailed description of caching schemes is presented. Similarly, delta encoding is also a well-known and useful technique to improve HTTP performance. Web Express from

IBM defines some application level techniques, including caching, differencing, and header-reduction mechanisms, and is related to some of the techniques explored. In the context of WWAN environments, Liljeberg et. al. developed Mowgli Communication Architecture that uses a pair of proxies to employ a custom protocol tailored for the GSM wireless link. Their solution is similar to (UDP-CDMA 2000). The Wireless Application Protocol is another related mechanism that employ explicit proxies (optional but highly recommended) to improve web experience of WWAN users. The optimization choices discussed can be applied in the context of WAP 2.0, specifically for improvements suggested in “wireless profiled” TCP and HTTP.

CDMA has seen incremental improvements in capacity throughout this period. Now both types of networks are making a transition to third-generation (3G) systems around the globe, offering yet more capacity and data services. This description describes the Network Validation for CDMA 2000 1X EV-DO Technology Technical Handbook Report

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origins of CDMA technology and the emergence of 3G implementations such as cdma2000 1X and cdma2000 1x EV-DO. An overview of network topology is included, with a detailed explanation of the role of each element and interface in the network and of protocol testing to address the changing requirements of the network. We concludes with a discussion of some of the technical problems that can occur in CDMA networks and some proposed solutions.

Digital Revolution and Evolution

When the mobile communications industry began its transition from first-generation analog technology to second-generation (2G) digital architecture, manufacturers and operators chose sides: in Europe, frequency-hopping GSM architecture became almost universal, while in the U.S., parts of Asia, and elsewhere, spread-spectrum CDMA technology took a large share of the market. Because spread spectrum uses wide band, noise-like signals, they are hard to detect. They are also difficult to intercept or demodulate. Further, spread spectrum signals are harder to jam (interfere with) than narrowband signals. These Low Probability of Intercept (LPI) and antijam (AJ) features

are why the military has used spread spectrum for so many years. Both network implementations, GSM and CDMA, have advanced to keep pace with subscribers' demands for more bandwidth, features and reliability at lower cost. cdmaOne Helps 2G Mobile Communications Take Off The Telecommunications Industry Association (TIA/EIA) IS-95 CDMA standard published established the ground rules for a complete

end-to-end digital wireless communications system. The commercial network system architecture based on this standard is known as cdmaOne. TIA/EIA IS-95 and the subsequent IS-95A revision form the basis for most of the commercial 2G CDMA-based

networks deployed around the world. From the standpoint of voice services, cdmaOne technology offers important features for mobile network operators:

• An 8X to 10X increase in voice capacity increase compared to analog AMPS systems

• Simplified network planning, with the same frequency used in every sector of every cell

The early 2G CDMA infrastructure proved its effectiveness in delivering high-quality, low-loss voice traffic to subscribers. But it didn’t take long for mobile users to begin asking for basic data services, such as Internet and Intranet services, multimedia applications or high-speed business transactions, to supplement the voice services on their handsets. The TIA/EIA IS-95A standard answered this demand with its definition of the wideband 1.25 MHz CDMA channels, power control, call processing, hand-offs and registration techniques for system operation. TIA/EIA IS-95A brought true circuit-switched data services to CDMA subscribers; however, these were limited to a maximum speed of 14.4 Kbps per user.

A second round of revisions to the original specification produced the TIA/EIA IS-95B standard. This new development gave subscribers packet-switched data services at speeds up to 64 Kbps per subscriber in addition to the existing voice services. With this increased data rate, TIA/EIA IS-95B-compliant networks qualify as 2.5G CDMA technology.

CDMA 2000 Takes the Next Step

The transition to 3G networks, still underway, began with a profusion of newly proposed standards. Some were designed to build on GSM infrastructures and others emerged directly from CDMA technology. Ultimately the ITU took a position on the matter, defining an IMT-2000 standard that encompassed five different radio interfaces including cdma2000. Note that all of the IMT-2000 protocols use spread-spectrum techniques, which has implications about network installation, operation and maintenance.

The ITU defines a 3G network as one that delivers, among other capabilities, improved

system capacity and spectrum efficiency versus 2G systems. It supports data services

at transmission rates of at least 144 Kbps in mobile (moving) environments and at least

2 Mbps in fixed (indoor) environments. The cdma2000 architecture meets these

objectives and includes several implementations that an operator can select to best

serve a transition strategy based on competitive concerns, existing infrastructures, cost,

and other variables.

Among these implementations are cdma2000 1X and cdma2000 1xEV:

- cdma2000 1X doubles the voice capacity of cdmaOne networks, delivering

peak data rates of 307 Kbps per subscriber in a mobile environment.

- cdma2000 1xEV includes two variants, both backward compatible with

cdma2000 1X and cdmaOne technologies.

- dma2000 1xEV-DO (Data Only), capable of delivering data multimedia services

such as MP3 transfers and video-conferencing at peak data rates of 2.4 Mbps

per subscriber in a mobile environment;

- cdma2000 1xEV-DV (Data Voice), capable of delivering integrated voice and

simultaneous data multimedia services at peak data rates of 3.09 Mbps per

subscriber.

A Network Structure Designed for Packetized Communication

The Mobile Station (MS). In a cdma2000 1X network, the mobile station—the

subscriber’s handset—functions as a mobile IP client. The mobile station interacts with

the Access Network to obtain appropriate radio resources for the exchange of packets, and it keeps track of the status of radio resources (e.g. active, stand-by, dormant). It accepts buffer packets from the mobile host when radio resources are not in place or are insufficient to support the flow to the network. Upon power-up, the mobile station automatically registers with the Home Location Register (HLR)

in order to:

• Authenticate the mobile for the environment of the accessed network

• Provide the HLR with the mobile's current location

• Provide the Serving Mobile Switching Centre (MSC-S) with the mobile's permitted feature set after successfully registering with the HLR, the mobile is ready to place voice and data calls. These may take either of two forms, circuit-switched data (CSD) or packet-switched data (PSD), depending on the mobile's own compliance (or lack thereof) with the IS-2000 standard. This document defines protocols for several critical CDMA interfaces pertaining to packet transmission, namely A1, A7, A9, and A11.

Mobile Stations must comply with IS-2000 standards to initiate a packet data session using the 1xRTT1 network. Mobile stations having only IS-95 capabilities are limited to CSD, while IS-2000 terminals can select either the PSD or CSD. Parameters forwarded by the terminal over the air link (AL) to the network will determine the type of service requested. Circuit-switched data has a maximum rate of 19.2 Kbps and is delivered over traditional TDM circuits. This service allows users to select the point of attachment into a data network using ordinary dialled digits. Packet-switched data service has a maximum data rate of 144 Kbps. For each data session a Point-to-Point Protocol (PPP) session is created between the mobile station and the Packet Data Serving Node (PDSN). IP address assignment for each mobile can be provided by either the PDSN or a Dynamic Host Configuration Protocol (DHCP) server via a Home Agent (HA).

The Radio Access Network (RAN)

The Radio Access Network is the mobile subscriber's entry point for communicating either data or voice content. It consists of:

- The air link
- The cell site tower/antenna and the cable connection to the Base Station Transceiver Subsystem (Um)
- The Base Station Transceiver Subsystem (BTS)
- The communications path from the Base Station Transceiver Subsystem to the base station controller (Abis)
- The Base Station Controller (BSC)
- The Packet Control Function (PCF)

The RAN has a number of responsibilities that impact the network's delivery of packet services in particular. The RAN must map the mobile client identifier reference to a unique link layer identifier used to communicate with the PDSN, validate the mobile station for access service, and maintain the established transmission links. The Base Station Transceiver Subsystem (BTS) controls the activities of the air link and acts as the interface between the network and the mobile. RF resources such as frequency assignments, sector separation and transmit power control are managed at the BTS. In addition, the BTS manages the back-haul from the cell site to the Base Station Controller

(BSC) to minimize any delays between these two elements. Normally a BTS connects

to the BSC through un-channelized T1 facilities or direct cables in co-located equipment.

The protocols used within this facility are proprietary and are based on High-level Data

Link Control (HDLC).

The Base Station Controller (BSC) routes voice- and circuit-switched data messages

between the cell sites and the MSC. It also bears responsibility for mobility management:

it controls and directs handoffs from one cell site to another as needed. It connects to each MTX using channelized T1 lines for voice and circuit switched data; and to un-channelized T1 lines for signalling and control messages to the PDSN using the 10BaseT Ethernet protocol. The Packet Control Function (PCF) routes IP packet data between the mobile station within the cell sites and the Packet Data Serving Node (PDSN). During packet data sessions, it will assign available supplemental channels as needed to comply with the services requested by the mobile and paid for by the subscribers. A network that provides a “1x chip rate of 1.2288 Mcps for Radio Transmission Technology.”

The PCF maintains a “reachable” state for between the RN and the mobile station, ensuring a consistent link for packets; buffers packets arriving from the PDSN when radio resources are not in place or insufficient to support the flow from the PDSN; and relays packets between the MS and the PDSN.

The Core Network’s Role in the CDMA Infrastructure

The Packet Data Serving Node / Foreign Agent (PDSN/FA) The PDSN/FA is the gateway from the RAN into the public and/or private packet networks. In a simple IP network, the

PDSN acts as a standalone Network Access Server (NAS), while in a mobile IP network

it can be configured as a Home Agent (HA) or a Foreign Agent (FA).

The PDSN does the following activities:

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- Manage the radio-packet interface between the BSS (Base Station Subsystem

= BTS + BSC) and the IP network by establishing, maintaining and terminating

link layer to the mobile client

- Terminate the PPP session initiated by the subscriber

- Provide an IP address for the subscriber (either from an internal pool or through

a DHCP server or through an AAA server; see below)

- Perform packet routing to external packet data networks or packet routing to the

HA which optionally can be via secure tunnels

- Collect and forward packet billing data

- Actively manage subscriber services based on the profile information received

from the SCS server of the AAA server

- Authenticate users locally, or forward authentication requests to the AAA server

The AAA Server

The AAA (Authentication, Authorization, and Accounting) server is used to authenticate

and authorize users for network access and to store subscriber usage statistics for

billing and invoicing.

The Home Agent

The Home Agent (HA) supports seamless data roaming into other networks that support

1xRTT. The HA provides an anchor IP address for the mobile and forwards any mobile-

bound traffic to the appropriate network for delivery to the handset. It also maintains

user registration, redirects packets to the PDSN and (optionally) tunnels securely to the

PDSN. Lastly, the HA supports dynamic assignment of users from the AAA and (again

optionally) assigns dynamic home addresses.

Detecting and Solving Some Common Problems in cdma2000 1X

Networks

All of the features and capacities embodied in the modern 3G mobile network make for

a complex system with many modes, nodes, elements, interfaces, and protocols.

Problems, when they arise, may have their origins in either hardware or software. As

mobile Internet connectivity becomes common, the challenge of maintaining

uninterrupted data transactions will require new, more powerful monitoring solutions

and procedures, among other things. In this section, we will examine some common

problems that can occur in cdma2000 1X networks. Failure in Mobile Initiated Packet

Data Call Set-up and Mobile IP Registration in order to obtain packet data services, the

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mobile performs registration with the serving wireless network on the A1 interface and

then with the packet network on the A10/A11 interface. The mobile sends an Origination

Message to the BS that includes the packet data service option. This results in assignment of the traffic channel, establishment of the A10 connection, establishment of the link layer (PPP) and for the case where Mobile IP is used by the terminal, Mobile IP registration with the serving packet network. User data traffic can now be passed over the A10 connection encapsulated within GRE frames.

The PCF periodically re-registers with the selected PDSN by sending the A11 Registration Request message before the A10 connection Lifetime expires. A successful call set-up scenario is illustrated in Figure 2. This standard message sequence chart outlines a series of steps, summarized in items 1-12 to follow. Note that this explanation bypasses the radio reception/transmission activities of the BTS, concentrating instead on the protocol functions that begin with the Origination dialogue between the mobile and the BSC.

1. To register for packet data services, the mobile sends an Origination Message over the Access Channel to the BSS

2. The BS acknowledges the receipt of the Origination Message, returning a Base Station Ack Order to the mobile

3. The BS constructs a CM Service Request message and sends the message to the MSC.

4. The MSC sends an Assignment Request message to the BSS requesting assignment of radio resources. No terrestrial circuit between the MSC and the BS is assigned to the packet data call.

5. The BS and the mobile perform radio resource set-up procedures.

The PCF recognizes that no A10 connection associated with this mobile is available and selects a PDSN for this data call.

6. The PCF sends an A11-Registration Request message to the selected PDSN.

7. The A11-Registration Request is validated and the PDSN accepts the connection by returning an A11-Registration Reply message.

Both the PDSN and the PCF create a binding record for the A10 connection.

8. After the radio link and A10 connection are set-up, the BS sends an Assignment Complete message to the MSC

9. The mobile and the PDSN establish the link layer (PPP) connection and then perform the MIP registration procedures over the link layer (PPP) connection.

10. After completion of MIP registration, the mobile can send/receive data via GRE framing over the A10 connection.

11. The PCF periodically sends an A11-Registration Request message for refreshing registration for the A10 connection.

12. For a validated A11-Registration Request, the PDSN returns an A11-Registration Reply message. Both the PDSN and the PCF update the A10 connection binding record.

This necessarily complex process can be the source of some problems that affect service and quality. A rigorous monitoring scheme involving simultaneous observation of the A1 interface and the A10/A11 interface is the best way to detect and correct errors early. Here, a multi-interface call-trace application is especially productive, since it can trace and group all of the procedures related to the activity of each single subscriber in a CDMA network, even as the procedures evolve over multiple interfaces.

Within the call set-up process, an error in any element or procedural step can inhibit the remaining steps. For example, suppose that the MSC does not respond to the CM Service Request message (Step 3) sent by the BSC/PCF over the A1 interface. This is sometimes caused by internal MSC problems. If this prevents the CM Service Request from reaching completion, the BSC/PCF cannot assign radio resources to the mobile station, in turn preventing establishment of the connection. The user finds it impossible to make a data call—a service for which he or she has paid a premium.

Before a specific timer expires, the PCF sends periodically A11-Registration Request message (Step 11) to refresh the registration for the A10 connection. For a validated A11-Registration Request, the PDSN returns an A11-Registration Reply message (Step 12). Here again, internal problems in the PDSN can cause it to respond late or not at all.

As a result the process of establishing or maintaining the connection cannot continue. The user is once again unable to make a data call.

In both cases, a protocol analyzer connected to the A1 and A10/A11 interfaces can help track down the problem. The call trace application can distinguish the origin of messages and detect any failure to respond. This makes it easy to pinpoint the MSC and the PDSN, respectively in these examples.

Ø **Inefficiency in User Data Packet Transmission**

Frequently in a cdma2000 network the TCP user-plane packets have a small Window Size. This implies that end-to-end TCP connections are not stable. The more TCP packets lost in the network and not acknowledged, the smaller the Window Size, with the result that more TCP connections are dropped and re-established. The small TCP Window Size is a by-product of the soft-start mechanism built into the TCP protocol. To characterize this problem, it is necessary to capture the TCP/IP user plane packets flowing on the GRE tunnels on the A10 interface. Protocol filtering allows the tool to home in on just the data or interest. By applying different types of filtering with increasing

level of details, it is possible to “drill down” and isolate the root cause of the shrinking TCP packet Window Size. Routing Loops of User Data Packets in the Core Network “Tunnel router loops” are another class of cdma2000 network problems that can degrade the quality of service for subscribers. The problem is caused by misconfiguration in the PDSN routers. It can be detected by acquiring and analyzing IP traffic on the P-H interface.

To understand tunnel router loops, imagine a subscriber surfing the Web (WWW) with a laptop connected to a cdma2000 handset. Packets addressed to go to a specific HTTP proxy are routed (after passing through the PCF) from the PDSN/FA (Foreign Agent) to the Home Agent (HA) for de-tunneling. With certain incorrect internal routing configurations, packets destined for Port 80 WWW are not de-tunnelled by the HA. Instead, they are sent back downstream toward the PDSN/FA. As a result, multiple packets travel on the same network segment with the same packet ID, wasting precious bandwidth—and not reaching the intended destination. In addition, for each repetitive hop a packet takes between the PDSN/FA and HA nodes, the IP TimeTo Live (TTL) field is decremented. If the packet is stuck in a router loop, the TTL eventually decrements all the way to zero and the packet is discarded by the network nodes. “Lost” packets must be retransmitted, leading to excessive packet retransmission overhead and reduced throughput.

As in the earlier examples, the solution is to use protocol filtering to capture IP packets on the PH interface. Browsing through the captured data by applying increasingly fine levels of filtering, it is possible to see the repeating packets and resolve the problem.

Ø **Duplication of IP traffic**

PDSN configuration problems can give rise to other types of problems in addition to tunnel loops. One common issue is associating the PDSNś logical IP addresses with more than one physical MAC address. When this occurs, more than one hardware card has the same IP address. All traffic sent to that IP address goes to two different hardware entities and receives responses from both. This effectively doubles the amount of IP traffic associated with that single IP address on that segment. Once again, protocol filtering capabilities are required for effective troubleshooting.

A protocol analyzer should capture IP packets travelling to a specific IP destination address via the P-H interface. Browsing through the data and using filtering to successively narrow down the inquiry, the nature of the problem (the duplicated address) soon becomes apparent.

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Ø **Routing problems in the Core Network**

Sometimes internal problems can cause PDSN routers to go offline and come back online after a period of time. This can happen frequently and continuously in a cdma2000 core data network. When a router first comes online its routing table are not optimized. It takes time for the built-in OSPF (Open Shortest Path First) routing algorithm

to learn the best way to route packets depending on adjacent available routers. Until the routing tables are optimized, there will be degradation in quality of service. By capturing IP packets on the P-H interface with a protocol analyzer and applying filters on the OSPF routing messages, changes in designated router and changes in neighbours of a router can be easily identified. Using intelligent and detailed filtering capability on OSPF messages and information elements within these messages identifying routing problems on an IP network becomes an easy task.

Throughput Optimization

Ø Traffic and Mobility Model

A. Feasible States

There does not exist among researchers a unanimous consensus on whether the CDMA

system capacity is reverse or forward link limited. However, the majority of the literature

published on the subject is of the former view. In light of this, in this paper we consider

the reverse link capacity only. Consider a multi-cell CDMA network with spread signal

bandwidth of W, information rate of R bits/s, voice activity factor of A, and background

noise spectral density of No. To achieve a required bit error rate we must have (Eb/Io)

>= S for some constant S. Assuming a total of M cells with ni calls in cell i, the number

of calls in every cell must satisfy

ni + (MXj=1) nj_ji <= W/R/A (1/S – 1/Eb/No) + 1 = ceff ,

for i = 1, ...,M. (1)

where ji = Iji/nj is the per user inter-cell interference factor from cell j to cell i, and where

Iji denotes the relative average interference of cell j to cell i.

A set of calls n = (n1, ..., nM) satisfying the above equations is said to be a feasible call

configuration or a feasible state, i.e., one that satisfies the Eb/Io constraint. The right

hand side of (1) is a constant which is determined by system parameters and by the

desired maximum bit error rate, and can be regarded as the total number of effective

channels, ceff , available to the system. Denote by the set of feasible states. Define the

set of blocking states for cell i as

Bi = {n 2 : (n1, ..., ni + 1, ..., nM) 62 } . (2)

If a new call or a handoff call arrives to cell i, it is blocked if the current state of the network, n, is in Bi. The call blocking probability for cell i, Bi, is the probability that n 2

Bi.

B. Mobility Model

The call arrival process to cell i is assumed to be a Poisson process with rate _i

independent of other call arrival processes. The call dwell time is a random variable

with exponential distribution having mean 1/µ, and it is independent of earlier arrival

times, call durations and elapsed times of other users. At the end of a dwell time a call

may stay in the same cell, attempt a handoff to an adjacent cell, or leave the network.

Let qij be the probability that a call in progress in cell i after completing its dwell time

goes to cell j. If cells i and j are not adjacent, then qij = 0. Define qii as the probability

that a call in progress in cell i remains in cell i after completing its dwell time. In this

case a new dwell time that is independent of the previous dwell time begins immediately.

We denote by qi the probability that a call in progress in cell i departs from the network. This mobility model is attractive because we can easily define different

mobility scenarios by varying the values of these probability parameters. For example,

if qi is constant for all i, then the average dwell time of a call in the network will be

constant regardless of where the call originates and what the values of qii and qij are.

Thus in this case, by varying qii's and qij 's we can obtain low and high mobility

scenarios and compare the effect of mobility on network attributes (e.g., throughput).

Let Ai be the set of cells adjacent to cell i. Let _ji be the handoff rate out of cell j offered

to cell i. _ji is the sum of the proportion of new calls accepted in cell j that go to cell i

and the proportion of handoff calls accepted from cells adjacent to cell j that go to cell

i.

Thus _ji = _j(1 - Bj)qji + (1 - Bj)qji Xx2Aj_xj. (3)

Equation (3) can be rewritten as _ji = _(Bj , _j , qji) = (1 - Bj)qji_j , (4)

where _j , the total offered traffic to cell j, is given by

_j = _(v, _j ,Aj) = _j + Xx2Aj

_xj, (5)

and where v denotes the matrix whose components are the handoff rates _ij for i, j =

1, ...M. The total offered traffic can be obtained from a fixed point model, which

describes the offered traffic as a function of the handoff rates and new call arrival rates,

the handoff rates as a function of the blocking probabilities and the offered traffic, and

the blocking probabilities as a function of the offered traffic. For a given set of arrival

rates, we use an iterative method to solve the fixed point equations. We define an initial value for the handoff rates. We calculate the offered traffic by adding the given values of the arrival rates to the handoff rates. The blocking probabilities are now calculated using the offered traffic. We then calculate the new values of the handoff rates and repeat.

C. Admissible States

A call arriving to cell i is accepted if and only if the new state is a feasible state. Clearly

this requires global state, i.e., the number of calls in progress in all the cells of the network. Furthermore, to compute the blocking probabilities, the probability of each state in the feasible region needs to be calculated. Since the cardinality of is O(ceff M), the calculation of the blocking probabilities has a computational complexity that is exponential in the number of cells.

In order to simplify the call admission process, we consider only those which require local state, i.e, the number of calls in progress in the current cell. To this end we define a state n to be admissible if

ni _ Ni for i = 1, ...,M, (6)

where Ni is a parameter which denotes the maximum number of calls allowed to be admitted in cell i. Clearly the set of admissible states denoted 0 is a subset of the set of feasible states . The blocking probability for cell i is then given by

Bi = B(Ai,Ni) = ANi

i /Ni! Ni Pk=0

Aki /k!, (7)

where Ai = _i/µi = _i/µ(1 - qii). We note that the complexity to calculate the blocking probabilities in (7) is O(M), and the bit error rate requirement is guaranteed since 0 _ .

Throughput Optimization

The throughput of cell i consists of two components: the new calls that are accepted in

cell i minus the forced termination due to handoff failure of the handoff calls into

cell i. Hence the total throughput, T, of the network is T(B, _, _) = MXi=1 {_i(1 - Bi) - Bi(_i

- _i)} , =MXi=1 {_i - Bi_i} , (8)

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where B is the vector of blocking probabilities, _ is the vector of total offered traffic, and

_ is the vector of call arrival rates. We formulate a constrained nonlinear optimization

problem in order to maximize the throughput subject to upper bounds on the blocking

probabilities and a lower bound on the signalto-interference constraints in (1). The goal

is to optimize the usage of network resources and provide consistent grade-ofservice

(GoS), i.e., the call blocking rate, for all the cells in the network while at the same time

maintaining the quality-ofservice (QoS), i.e., the probability of loss of communication

quality, for all the users. In the optimization problem the arrival rates and the maximum

number of calls that are allowed to be admitted in the cells are the independent

variables. This is given in the following

max

(_1,...,_M),(N1,...,NM)

T(B, _, _), subject to B(Ai,Ni) _ _,

Ni + MXj=1 Nj_ji _ ceff ,

for i = 1, ...,M, (9)

The optimization problem in (9) is a mixed integer programming (MIP) problem. One technique to solve the MIP problem is based on dividing the problem into a number of smaller problems in a method called branch and bound. Branch and bound is a systematic method for implicitly enumerating all possible combinations of the integer variables in a model. The number of sub problems and branches required can become extremely large. By relaxing the integer variables Ni, i = 1, ...,M, to continuous variables,

the optimization in (9) is solved using a Sequential Quadratic Programming (SQP) method. In this method, a Quadratic Programming sub problem is solved at each iteration. A solution to the fixed point equations is calculated iteratively. An estimate of

the Hessian of the Lagrangian is updated at each iteration using the Broyden-Fletcher-Goldfarb-Shanno (BFGS) formula. A line search is performed using a merit function. The

Quadratic Programming sub problem is solved using an active set strategy. In order to use the SQP method, we need to evaluate the derivatives of T with respect to N and _.

T(B, _, _) is an implicit function of N = (N1, ...,NM) and _. We can obtain relations of total

and partial derivatives of the throughput by differentiating the fixed point equations.

These relations are manipulated to obtain a system of linear equations in the derivatives

of the offered traffic with respect to the number of calls admitted and the arrival rates.

We calculate the implied cost, i.e., the derivative of T with respect to the implicit variable

N. The calculation of the implied cost of T with respect to the new-call arrival rates is given in the Appendix.

Numerical Results

The base stations are located at the centers of a hexagonal grid whose radius is 1732 meters. Base station 1 is located at the center. The base stations are numbered consecutively in a spiral pattern. The COST-231 propagation model with a carrier frequency of 1800 MHz, average base station height of 30 meters, and average mobile height of 1.5 meters is used to determine the coverage region. We assume the following for the analysis. The path loss coefficient is 4. The shadow fading standard deviation is 6 dB. The processing gain is 21.1 dB. The bit energy to interference ratio threshold, _, is 9.2 dB. The interference to background noise ratio is 10 dB. The voice activity factor is 0.375. For more details on the choice of these parameters refer to. Per user inter-cell interference factors are evaluated numerically by dividing the whole area into small grids of size 150 m by 150 m. The blocking probability threshold, _, is set to 0.02.

We consider three mobility scenarios: no mobility, low mobility, and high mobility of users. The following probabilities are chosen for the no mobility case: $q_{ij} = 0$, $q_{ii} = 0.3$ and $q_i = 0.7$ for all cells i and j. For the low and high mobility case, the mobility probability parameters are given. In all three cases, the probability that a call leaves the network after completing its dwell time is 0.7. Thus, the average dwell time of a call in the network is constant regardless of where the call originates and the mobility scenario used.

In the following, we compare our results to a call admission control algorithm where the maximum number of calls that can be admitted in each cell is the same, i.e., N1 = N2 =

... = NM = N (irrespective of the call arrival rate profile in the network). We also optimize

the revenue for this algorithm subject to a lower bound on the bit energy to interference

ratio. In the sequel, the optimized algorithm is referred to as a

traditional call admission control (CAC) algorithm. Note that

LOW MOBILITY PROBABILITIES.

kAik	qij	qii	qi
3	0.020	0.240	0.700
4	0.015	0.240	0.700
5	0.012	0.240	0.700
6	0.010	0.240	0.700

HIGH MOBILITY PROBABILITIES

kAik	qij	qii	qi
3	0.100	0.000	0.700
4	0.075	0.000	0.700
5	0.060	0.000	0.700
6	0.050	0.000	0.700

• kAik is the number of cells adjacent to cell i.

• qij is the probability a call in cell i goes to cell j.

• qii is the probability a call in cell i stays in cell i.

• qi is the probability a call in cell i leaves the network. This algorithm will be optimal

in the sense of (9) in the case of equal call arrival rates, equal mobility probabilities for all the cells, and a network with a large number of cells (in which edge effects can be ignored).

We choose the call arrival rates to be equal to _ calls per unit time for all cells except those in Group A (i.e., cells 5, 13, 14, and 23) and Group B (i.e., cells 2, 8, 9, and 19). For Groups A and B the call arrival rates are equal to 5_ calls per unit time. The total offered traffic per cell (the sum of the call arrival rate and the handoff rate) is shown in brackets for the no mobility, low mobility, and high mobility cases. The maximum number of calls that can be admitted in each cell, calculated from equation (9), is shown in parentheses in the same figures. For the traditional CAC algorithm with the same blocking probability threshold, system parameters, and the bit energy to interference ratio requirement, the maximum number of calls that could be admitted in each cell would be 18. In our algorithm for the no mobility case, it can be seen that for the cells belonging to Groups A and B the maximum number of calls admitted has increased from 18 to 22-24, while for all other cells it has decreased from 18 to 7-9. It can be seen that our algorithm trades off the calls in the cells with low arrival rate for the calls in the cells with high arrival rate. As the mobility model changes from no mobility to high mobility, the handoff rates increase thus increasing the total offered traffic per cell. For the high mobility case, the maximum number of calls admitted now ranges from 20 to 23 for cells belonging to Groups A and B, and from 7 to 11 for all other cells.

The throughput of each cell resulting from our algorithm and the traditional CAC algorithm for the no mobility, low mobility, and high mobility cases are given in Figures 4, 5, and 6, respectively. In these figures, the circle and star at the two ends of a vertical bar indicates the throughput. Total offered traffic and maximum number of calls allowed to be admitted per cell for the twenty-seven cell CDMA network with no mobility of users, the traditional CAC algorithm and our algorithm, respectively, for the cell whose id is shown on the horizontal axis. The traditional CAC algorithm has a total network throughput equal to 96.03, 99.08, and 102.43 calls per unit time for the no mobility, low mobility, and high mobility cases, respectively. Our optimization increases the throughput for the network to 127.02, 131.40, and 136.52 calls per unit time for the no mobility, low mobility, and high mobility cases, respectively, which is a 32% increase in throughput over the traditional CAC algorithm for the same guaranteed blocking

probability threshold of 0.02. The value of _ calculated from (9) increases from 1.65 (in the traditional CAC algorithm) to 2.19 calls per unit time (in our optimization) for the no mobility case, from 1.70 to 2.27 calls per unit time for the low mobility case, and from 1.75 to 2.37 calls per unit time for the high mobility case. Due to its call trade-offs between low and high traffic cells, this algorithm is able to better accommodate the unequal call arrival rates in the network and achieve higher throughput in all the cells for the same guaranteed GoS.

CALCULATIONS

Calculation of the Implied Cost w.r.t. _

In what follows we determine the implied cost of the throughput with respect to the new-call arrival rates. The total derivative of the throughput function with respect to a new-

call arrival rate is given by

dT (B, _, _) d_k = 1 + MXi=1 _@T(B, _, _) @Bi

dB(Ai,Ni) d_k + @T(B, _, _) @_i

d_(v, _i,Ai)

d_k _. (10)

The partial derivatives needed are @T(B, _, _) @Bi

= -_i, (11) and

@T(B, _, _) @_i = -Bi. (12)

Then we get dB(Ai,Ni)

d_k= @B(Ai,Ni) @Ai @Ai @_i

d_(v, _i,Ai) d_k

Total offered traffic and maximum number of calls allowed to be admitted per cell for

the twenty-seven cell CDMA network with high mobility of users. Maximum throughput

in every cell for the network.

The total derivative needed in (13) and (10) can be obtained from (5) as follows

d_(v, _i,Ai) d_k = Xx2Ai

@_(v, _i,Ai) @_xi

d_(Bx, _x, qxi) d_k +@_(v, _i,Ai)

@_k , (14)

where @_(v,_i,Ai)

@_k

= I{i=k}. From (5) we get @_(v,_i,Ai) @_xi

= I{x2Ai}. Finally, from (4), the derivative of the handoff rate with respect to the call arrival rate is given by

d_(Bx, _x, qxi) d_k

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= @_(Bx, _x, qxi)

@Bx

dB(Ax,Nx)

d_k +@_(Bx, _x, qxi)

@_x d_(v, _x,Ax) d_k.

The partial derivatives needed in (15) are obtained as follows

@_(Bx, _x, qxi) @Bx

= -qxi_x, (16)

@_(Bx, _x, qxi) @_x

= (1 - Bx)qxi. (17)

The set of simultaneous linear equations can be solved and the results substituted back

in (10) along with equations (11) and (12). This completes the derivation of the implied

cost and the values of the derivatives of the throughput with respect to the call arrival

rates. Implied costs capture the effect of increases in the call arrival rate in one cell on

the throughput of the entire network.

RESULTS

The optimization of network throughput was one of the main results that presented in

this project.

- Some mobile operators have addressed the problem of jointly controlling the data

rates and transmit powers of the users, so as to maximize the throughput. They formulate a classical optimization problem, modeling the constraints arising from the data rate requirements and power budgets.

- Others formulate the throughput maximization problem in terms of the spreading gains and transmit powers of the users, and solve it using a nonlinear programming approach.

- Others investigate the maximum throughput that can be achieved through joint rate and power adaptation in a multi-rate CDMA system. They assume conventional matched filter detection with perfect channel information and an instantaneous BER constraint. They restrict their attention to multicode or multiple processing gain schemes.

Also, some companies work solutions for throughput optimization of data traffic for a power constrained voice/data CDMA system by scheduling of data users. It was found that under a given received power budget and the constraints of transmission powers, the throughput of data traffic is maximized by selecting simultaneous data users and allocating powers according to the descending order of their received power

capabilities, which is defined as the product between the transmission power limit and the channel gain. In this paper, we formulate a constrained optimization problem that maximizes the network throughput subject to upper bounds on the call blocking probabilities and a lower bound on the bit energy to interference ratio. We calculate the implied costs, which are the derivatives of the throughput function, and capture the effect of increases in the call arrival rates in one cell on the throughput of the entire network. We also take mobility of users into account and differentiate between the blocking of new calls and the blocking of handoff calls. The blocking probabilities are given by the fixed point model, which describes the blocking probabilities as a function of the total offered traffic, the total offered traffic as a function of the call arrival rates and the handoff rates, and the handoff rates as a function of the blocking probabilities and the total offered traffic. We obtain relations of the total and partial derivatives of the blocking probabilities by differentiating the fixed point relations. These are then used along with the implied costs in the solution to our throughput optimization problem.

CONCLUSIONS

We conducted a detailed comparative performance study of a wide selection of optimizations choices applicable for WWANs. Ours is the first significant study to have attempted to address important questions like: Why do web users experience poor performance over WWANs? Even though TCP is relatively well-tuned to perform efficiently in these environments, why is the performance of HTTP applications significantly worse? While prior studies have examined the problems of TCP in WWAN environments, we are not aware of any prior research that presents a detailed evaluation of application performance. Our performance study also provides important insights in understanding what optimization choices can yield how much benefit. The performance optimizations applied at each individual layer studied in this paper, leverage well-adapted and optimized lower layers. This avoids any inefficient cross-layer design including adverse inter-layer interactions.

The following are some of our important observations: Severe Mismatch between TCP and HTTP: There is a significant mismatch in the performance of default HTTP protocols

and its underlying transport mechanism TCP in WWAN. Unlike the wired (e.g. dial-up)

environments, we find that standard web browsers do not exploit the meagre resources of the WWAN links. The achieved throughput is sometimes 70% lower than the ideal downlink data rate.

Applications and Session Layers Dominate Benefits: Significant benefits to end-user experience can be realized (about 48-61% improvements) by suitable optimizations implemented at the application and session layers. Use of Proxy Beneficial: Proxy-

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based solutions are most effective in improving application performance than non-proxy

based approaches.

Our performance study has broad implications. The additional benefits resulting from using HTTP pipelining highlights the need to mitigate the impact of high and variable WWAN link latency by implementing this feature in all commercial class web servers and standard web browsers. Hence appropriate support from web server vendors, content providers and browser designers will go a long way in the success of the next generation 'mobile' Internet. We find that a collective suite of performance optimizations

implemented using proxies at different layers in many cases can reduce the response time by at least a factor of two. This is possible because the proxies are specifically aware of the characteristics of the WWAN environment and hence makes more 'intelligent' decisions to adapt the performance of data delivery mechanisms. Such awareness of link characteristics is crucial for improving the overall end user-experience. This can imply any one of the following two things:

(1) Proxy-based solutions should not be restrictively viewed as a short-term solution. Instead, cellular operators should design, implement and deploy such proxy solutions within their network and end-users should be given the choice to use such proxies, thus,

trading off security with performance. Such an approach may be acceptable in certain scenarios.

(2) The intelligence of the proxies should be implemented in the web servers, content providers, as well as the web browsers. Such an approach will maintain "end-to end" ness of the protocols, however, will require significant collaborative effort between all these diverse vendors of different applications.

Other than performance, it is important to consider the trade-offs between the cost and the ease of deployment associated with such proxy installations. As previously discussed in our study, transparent proxies are the easiest to deploy since they require no changes or configuration to the mobile clients. However, from a performance perspective, dual-proxy based solutions seems to provide the most significant benefits. Unfortunately, such an approach requires either a reconfiguration or a software update in the mobile client. This increases its deployment overhead. In many cases it is expensive for the cellular operators to provide such updates to the existing client equipment.

We believe that a further detailed characterization of these environments will be very useful. Our hope is that others will also perform similar studies of actual user experience

over other wireless environments (e.g. W-CDMA UMTS and CDMA 2000) so that extensive benchmarks could be obtained and eventually lead to adoption of a "best of both worlds" solution.

CDMA infrastructure is widespread and sure to form the basis for broad penetration of CDMA networks. Cdma 2000 and other 3G technologies bring telecommunications into the packet switched domain, adding a host of new services and network complexities in the process. Troubleshooting activities now require an understanding of both traditional “telecom” concepts related to the circuit-switched domain and new “datacom” concepts related to the packet switched-domain. Network operation and maintenance personnel must refine their processes to meet complex new troubleshooting challenges.

These range from misconfiguration problems to duplicated IP addresses and more.

Protocol analysis tools can play a bigger role than ever in keeping a network running efficiently. Features such as multi-interface call tracing and protocol filtering will become critical to the job of maintenance.

We have investigated the network performance by determining the throughput that the network can achieve for a given network topology and call arrival rate profile. We formulated a constrained optimization problem that maximizes the network throughput subject to upper bounds on the blocking probabilities and a lower bound on the bit energy to interference. Total offered traffic and maximum number of calls allowed to be admitted per cell for the twenty-seven cell CDMA network with low mobility of user’s ratio. The blocking probabilities are given by the fixed point model. We obtained relations of the total and partial derivatives of the blocking probabilities by differentiating the fixed point relations. They are used in the solution to the optimization problem which

yields the maximum network throughput as well as the maximum number of calls that should be admitted in each cell for the network to guarantee a given grade-of-service and quality-of-service requirements. For unequal call arrival rates, our optimization algorithm achieved a 32% increase in throughput over the traditional CAC algorithm.

NETWORK VALIDATION

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APPENDIX 1: Results

QUALITY VOICE CALLS

Quality

No.

F

Dropped

Incomplete

Echo

Jitter

Noise

Factor

Sprint

1900

18

5

29

16

41

0.96

Verizon

1900

35

8

31

21

47

0.92

Wireless

Metro PCS

1900

51

10

40

44

67

0.72

Leap

1900

55

12

48

20

81

0.70

US Cellular

1900

43

8

39

29

62

0.80

MTS Mobility

1900

26

9

25

18

52

0.90

AllTel

1900

39

8

32

22

48

0.86

Comscape

1900

57

11

41

34

79

0.69

Smartcom

1900

78

34

76

55

103

0.58

PCS

China

1900

71

46

81

51

98

0.60

Unicom

ANALYSIS PERFORMED ON 1000 CALLS. When more than one network for same carrier being analyzed, best results are taken into account into above table. Worst results are for measurements against local network differently and results can’t be

compared.

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DATA THROUGHPUT

Throughput

Throughput

10<,<64Kb

>64Kbps

Incomplete

<10 Kbps

Droppe

Quality

No.

F

ps

connection

d

Factor

Broad

Middle

Narrow

Sprint

1900

46

120

430

450

81

0.78

Verizon

1900

81

167

230

603

97

0.88

Wireless

Metro PCS

1900

92

231

571

198

167

0.62

Leap

1900

103

255

560

185

181

0.67

US Cellular

1900

108

278

671

51

162

0.75

MTS Mobility

1900

79

199

302

499

92

0.82

AllTel

1900

82

208

355

437

148

0.76

Comscape

1900

99

251

454

295

179

0.62

Smartcom

1900

267

334

615

51

303

0.43

PCS

China

1900

256

246

431

323

298

0.55

Unicom

ANALYSIS PERFORMED IN 1000 CONNECTIONS. NON-CONNECTIONS DO NOT

COUNT TOWARDS PERFORMANCE MEASUREMENTS. When more than one network

for same carrier being analyzed, best results are taken into account into above table.

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Worst results are for measurements against local network differently and results cant be

compared.

RF MBS Terminal

Handoff

RF Strength

Channel

Terminal

No.

F

MBS

Coverage

Noise

Efficienc

GoS

Efficiency

Sensitivity

y

Sprint

1900

0.31

0.76

0.98

-0.70

1.01

0.99

Verizon

1900

0.23

0.77

0.96

-0.75

1.00

0.98

Wireless

Metro PCS

1900

0.27

0.72

0.88

-0.92

0.99

0.95

Leap

1900

0.21

0.71

0.87

-0.81

0.96

0.95

US Cellular

1900

0.23

0.71

0.86

-0.77

0.98

0.92

MTS Mobility

1900

0.30

0.75

0.91

-0.78

0.97

0.97

AllTel

1900

0.31

0.70

0.93

-0.92

0.99

0.98

Comscape

1900

0.32

0.77

0.89

-0.97

1.01

0.91

Smartcom

1900

0.33

0.71

0.89

-1.07

0.98

0.88

PCS

China

1900

0.36

0.73

0.90

-1.04

0.97

0.87

Unicom

RESULTS FROM DIFFERENT MEASUREMENTS TAKEN ON THE FIELD.

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OVERALL NETWORK PERFORMANCE

Network

Evaluation

Performance Rank

Sprint PCS

Excellent

1

Verizon

Excellent

2

Wireless

MTS Mobility

Excellent

3

AllTel

Good

4

US Cellular

Good

5

Metro PCS

Good

6

Leap

Good

7

Comscape

Poor

8

China Unicom

Poor

9

Smartcom PCS

Poor

10

Network Validation for CDMA 2000 1X EV-DO Technology Technical Handbook Report

80

APPENDIX 2 : Plots

Dropped Calls Comparison

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Network

Incomplete Calls Comparison

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Network Validation for CDMA 2000 1X EV-DO Technology Technical Handbook Report

81

Echo Calls Comparison

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Noised Calls Comparison

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Network Validation for CDMA 2000 1X EV-DO Technology Technical Handbook Report

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Jittered Calls Comparison

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Quality Factor Voice Call Comparison

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83

Data Throughput Incomplete Connections

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Data Throughput Less than 10Kbps

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Network Validation for CDMA 2000 1X EV-DO Technology Technical Handbook Report

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Network Validation for CDMA 2000 1X EV-DO Technology Technical Handbook Report

85

Data Throughput between 10 and 64 Kbps

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sanu 600

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Data Throughput Equivalent to Broadband

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Network Validation for CDMA 2000 1X EV-DO Technology Technical Handbook Report

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Data Connections Dropped per thousand

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Handoff MBS Sensitivity

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Network Validation for CDMA 2000 1X EV-DO Technology Technical Handbook Report

88

RF Strength Coverage Factor (log)

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Terminal Efficiency (Compatibility)

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Network Validation for CDMA 2000 1X EV-DO Technology Technical Handbook Report

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Channel Efficiency (Spectrum Efficiency)

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acto 0.98

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Ef 0.95

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Network Validation for CDMA 2000 1X EV-DO Technology Technical Handbook Report

92

Grade of Service Factor

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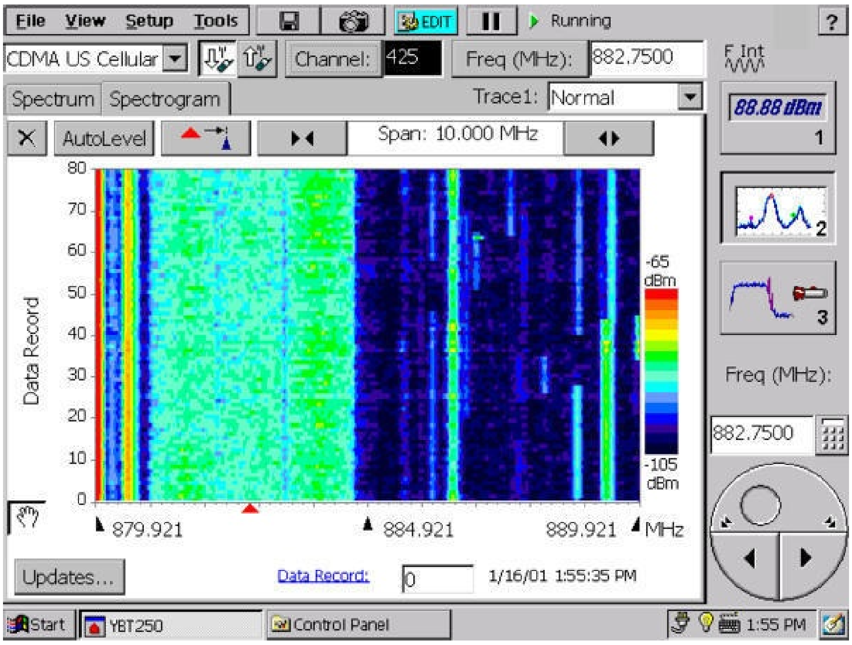
Network



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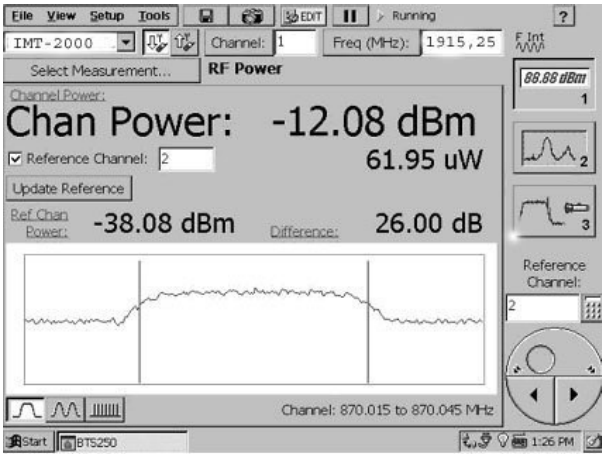
Measurements at US Cellular Network in 800 MHz



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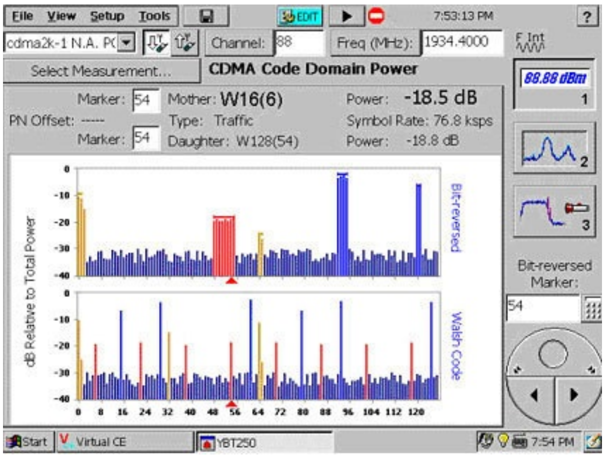

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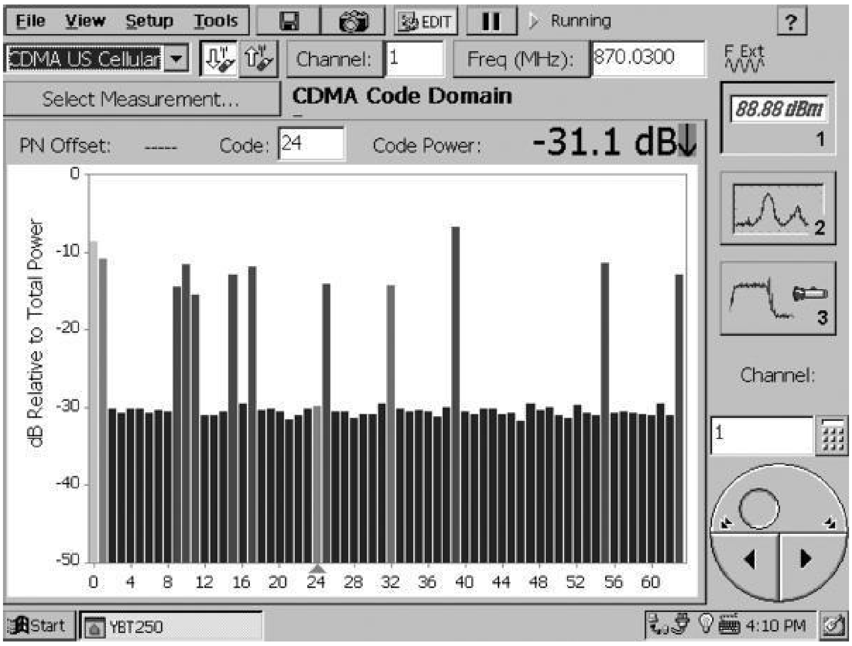

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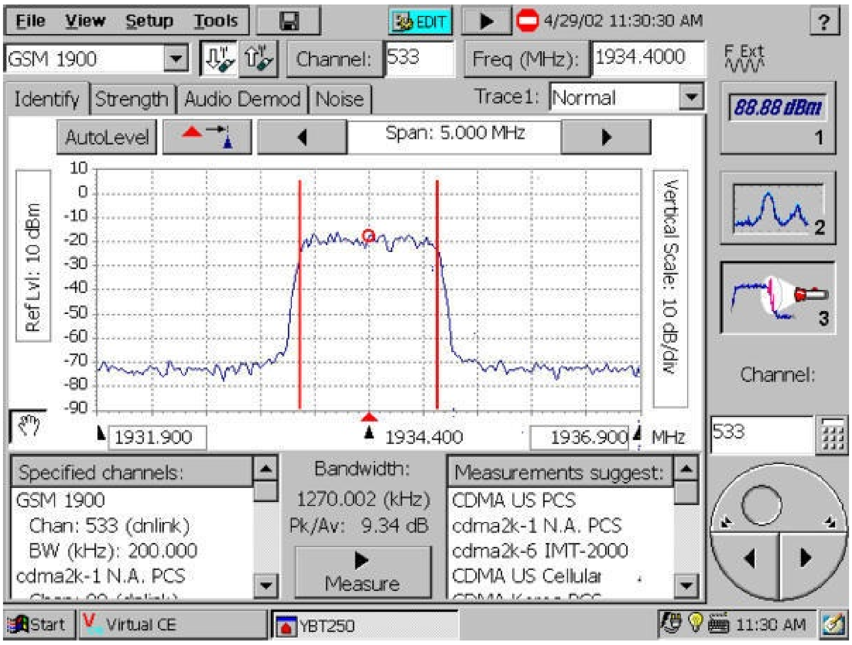

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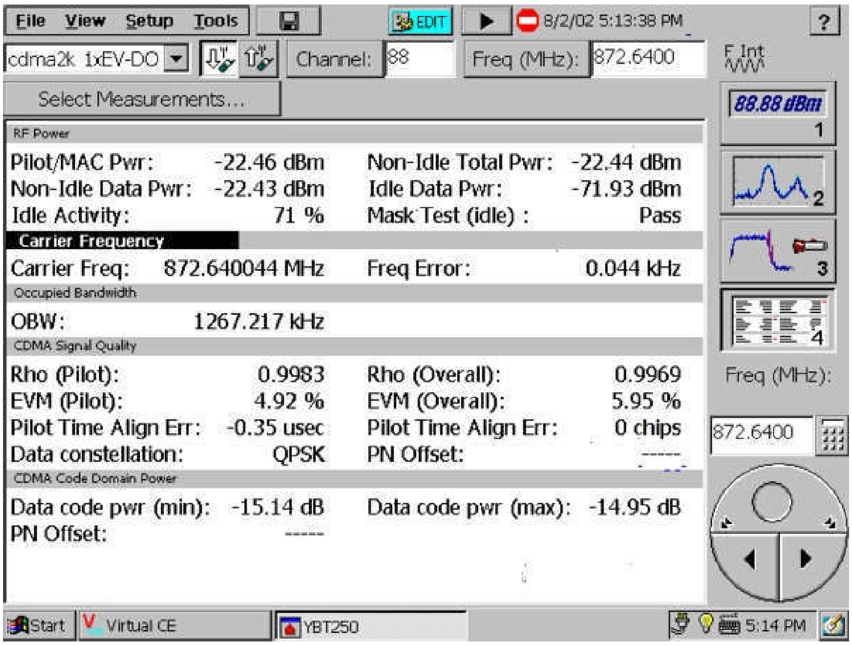

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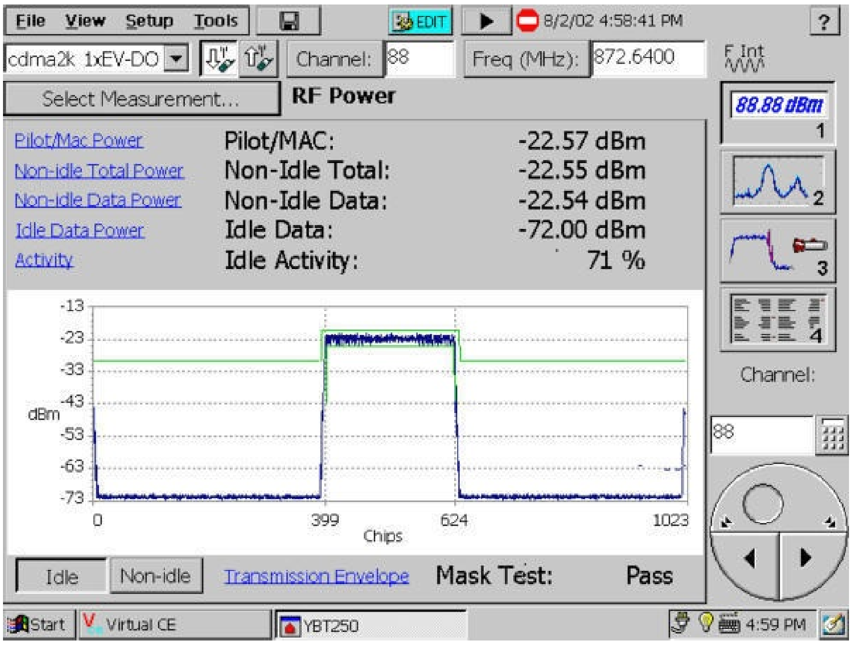

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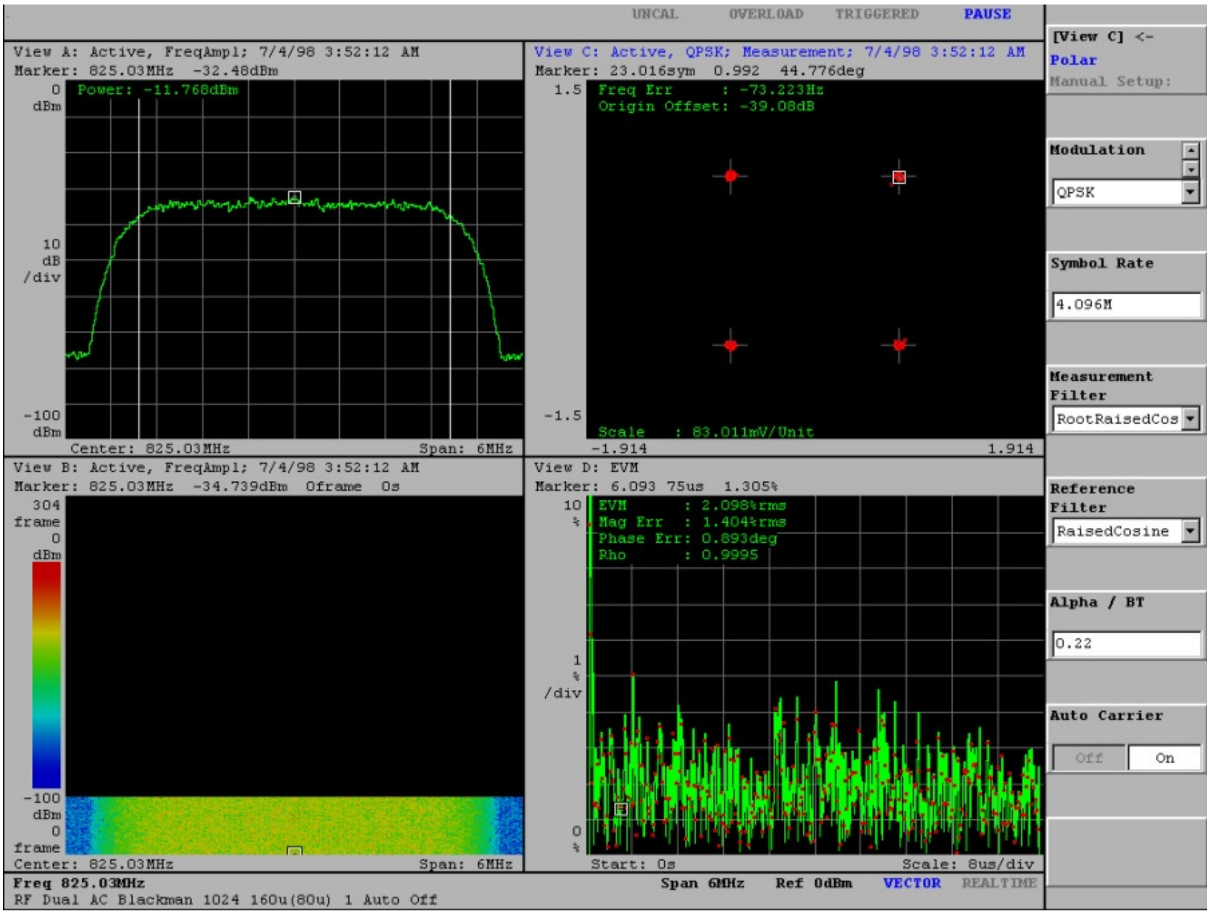

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Area Coverage Profile (Verizon Wireless)

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