The Qualcomm CDMA Digital Cellular System

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Introduction

Qualcomm, Inc. has developed and tested a digital spread spectrum cellular telephone system that will supplant and eventually replace the existing analog FM cellular system. TIA has recently standardized this "CDMA" (Code Division Multiple Access) as TIA IS-95, and several cellular carriers have already announced plans to deploy the service.

The original impetus for CDMA's development was the enormous popularity of existing narrow band analog FM cellular telephone systems. There is only so much radio spectrum available to deal with the flourishing demand for cellular service, and severe congestion already exists in several major service areas. A IS-95 system can carry about 10-15 times as many voice calls as an analog system in the same spectrum.

Although Qualcomm specifically designed IS-95 for voice telephony, it is easily adapted to packet data transmission. It can provide a service comparable to those of several existing and proposed metropolitan area wireless data networks with better performance, greater reliability, and lower cost.

A Note on Terminology

The term CDMA ("Code Division Multiple Access") is generic. It applies to any spread-spectrum multiple access system where different spreading codes (or different portions of the same spreading code) allow receivers to discriminate between multiple transmitters using the same frequency channel at the same time. For several years, the cellular industry has used the term to refer specifically to the Qualcomm-developed digital cellular telephone system based on CDMA techniques. Now that the technology is a standard, the preferred term is TIA IS-95 (Telecommunications Industry Association Interim Standard 95). In this paper I will tend to use "CDMA" to refer to the general characteristics of spread spectrum multiple access systems and "IS-95" to refer to the specific Qualcomm-developed CDMA digital cellular system.

CDMA System Advantages

CDMA's advantages over conventional narrow band systems include the following:

1. Automatic Transmitter Power Control

IS-95 adjusts mobile transmitter power with a fast "closed loop" power control system. It uses only the power actually needed at any instant (+/-1 dB) to produce an acceptable bit error rate at the cell receiver. This compares with conventional systems that need substantial transmitter power margins (often well over 20 dB) to "ride through" fade nulls. The much lower average transmitter power required by IS-95 results in considerably less interference to other users sharing the same channel, and correspondingly greater system capacity and mobile battery life.

2. Forward Error Correction

IS-95 uses very strong forward error correction (FEC), decreasing required transmitter power still further. The typical E_b/N_0 (energy per bit to noise spectral density ratio) required for good performance is 6 dB or less, while FM typically requires a signal-to-noise of at least 17 dB.

3. Universal channel reuse

Narrow band systems cannot reuse every channel in every cell. Typically only 1/7 of the channels allocated to a carrier are usable in any given cell due to the need to protect neighboring cells. The inherent interference resistance of spread spectrum, however, allows every IS-95 cell to use every channel.

4. Variable rate speech coding

Narrow band cellular systems statically allocate transmission resources to each user for the duration of a call. Proposals exist for the dynamic reallocation of channels among users according to voice activity, but they are hampered by the inherent overhead. The problem is fundamental. It is similar to that of contention-based packet radio networks with short packets and long feedback delays.

CDMA, on the other hand, assigns each user a unique code (spreading sequence) from a set that is for all practical purposes infinite. There is no limited pool of single-user frequency channels or time slots to carefully manage. When a CDMA transmitter has data to send, it simply sends; when it no longer has traffic, it stops (or slows to an "idle" speed, as in IS-95). To be sure, the shared wide band channel still has a total capacity limit, but it is only the sum of many users' instantaneous demands that matters. The law of large numbers makes this sum much more predictable and uniform than the individual demands of each user. This allows each wide band spread spectrum channel to operate much closer to its capacity limit than if it was rigidly subdivided into fixed narrow band channels.

The IS-95 system uses a variable rate voice coder (vocoder). When the user speaks, the vocoder runs at a relatively high rate; when the user stops talking, the vocoder idles at a low rate. Every 20 ms, the vocoder produces one of four frame sizes: 16, 40, 80 or 171 bits, thus continuously adapting to the speaker's speech patterns. In normal conversation, the average data rate required by the variable rate vocoder is only about 40% of the peak rate.

To keep the transmitted energy per bit constant, IS-95 transmits with power proportional to the data rate. For example, it sends 1/8 rate data frames with 9 dB less power than full rate frames. This reduces average transmitter power, reducing the interference to the other users, increasing system capacity and prolonging battery life while allowing the closed-loop power control system to continue functioning.

5. Soft Handoff

IS-95 supports a novel "soft handoff" feature that sets up individual calls through several cells simultaneously. This allows the mobile to combine the independently fading signal components from several cells, and the base station to select the best cell to receive the mobile on a frame by frame basis. The system takes down a path through an old cell only when the mobile becomes firmly established in a new cell. As long as the two cells' service areas overlap, this "make before break" feature makes soft handoffs completely undetectable to the user. It also allows the use of less RF power for the same grade of service.

A single IS-95 RF channel is 1.25 MHz, the spreading bandwidth of the system. Each 1.25 MHz RF channel in a cell supports up to 61 traffic channels (simultaneous calls), but mutual interference limits the aggregate user data rate. That is, one can support as many as 61 simultaneous calls per channel per sector, as long as the users do not simultaneously transmit full rate frames. In practice, the independence of the speakers plus the law of large numbers reduce the probability of mutual interference under normal operating conditions.

IS-95 is similar to the TASI (Time Assigned Speech Interpolation) scheme that increases the carrying capacity of expensive undersea cables beyond that possible by dedicating transmission resources to each user. Both schemes are related to statistical multiplexing, the basis of packet data switching.

Adapting IS-95 for Data Services

Although Qualcomm originally designed IS-95 specifically for voice, its high performance digital radio modem and its use of variable data rates make it well suited for either circuit or packet-switched data. I have already demonstrated TCP/IP over IS-95, using the IS-95 radio channel as an access link to a router connected to the base station ahead of the vocoder. A radio link protocol (RLP) layered on top of the existing IS-95 architecture carries general purpose variable-length packets over the IS-95 radio channel. These packets can contain Internet datagrams or packets belonging to any other desired protocol suite, e.g., OSI CLNP or Appletalk.

This approach has two major advantages that should minimize cost and speed deployment. First, it minimizes the changes required to the existing IS-95 system architecture. The data service uses IS-95 only as a simple access link to a packet switch; the data packets themselves carry all network addressing information. Second, it maximizes use of existing and proposed Internet facilities, including those of special interest to mobile users such as the Mobile IP and IP Security protocols.

A Radio Link Protocol (RLP) For IS-95

In any mobile radio system, quality and system capacity are direct design tradeoffs and IS-95 is no exception. IS-95 provides an average frame erasure (loss) rate of 1-2% under credible full-load conditions. This figure maximizes system capacity without excessive degradation of voice quality with the chosen vocoder. However, when one considers that a 1 kilobyte data packet is about 50 full-rate IS-95 frames, and that at a frame erasure rate of 2% the probability of getting 50 consecutive frames across the link without any erasures is only about 36%, relying totally on end-to-end error recovery from protocols like TCP is clearly not a good idea. We need a little help from the link layer. This is the main job of the proposed Radio Link Protocol (RLP).

The author is still a strong believer in the End-to-End Principle, and did not design RLP for absolute reliability. In particular, it bears no resemblance to LAPB, the over-designed and inefficient link layer from X.25 that keeps popping up in "new" protocols, with little or no thought given to its appropriateness for the task at hand.

RLP is a "lightweight" protocol intended only to improve performance by complementing existing end-to-end error recovery mechanisms in protocols like TCP. RLP can still lose packets from several causes, but they are rare enough that relying on TCP to recover from them is appropriate; handling them at the link layer is well beyond the point of diminishing returns. Among the possible causes of packet loss are: dropped IS-95 calls (usually caused by the user moving outside the coverage area); errors undetected by the relatively weak frame CRCs already in IS-95 (12 bits for full rate, 8 bits for half rate); data errors within the IS-95 base station; and excessive requests for retransmission of a particular erased IS-95 data frame.

RLP uses negative acknowledgments (NAKs) to request selective retransmission of individual IS-95 frames. Since IS-95 frames get through much more often than not, this makes much more efficient use of the back channel than the traditional practice of sending a positive acknowledgment (ACK) for every successfully received frame. (Recall that IS-95 sends lower rate frames such as idles at a lower power level.)

RLP first encodes user packets in a PPP subset. As in conventional PPP, RLP adds a 1-byte Protocol ID to the front of the packet, adds a 16-bit CRC and a flag to the end, and queues the resulting byte stream for transmission. Byte stuffing maintains transparency in the user data wherever it contains values special to the framing technique (such as the flag, 0x7e).

RLP then divides the byte stream produced by PPP into IS-95 frames for transmission. Each IS-95 frame that carries user data is sequence numbered modulo 256. RLP increments the sequence number by one after each data frame, regardless of size; at full speed, the sequence numbers wrap around in 5.12 seconds. The receiver monitors incoming sequence numbers, and as long as none are missing, quietly passes the data portion of each frame up to a PPP receiver routine for reassembly into complete packets. Missing sequence numbers trigger NAKs from the receiver, requesting the sender to retransmit the requested frame(s). NAKs are retransmitted up to three times before the receiver gives up. RLP puts data frames with sequence numbers beyond those needed next to complete a packet on a reassembly queue until they can be used.

Idle frames also carry sequence numbers, but RLP does not increment them; their purpose is to "flush out" a NAK from the receiver when the channel erases the last data frame before an idle period. Because RLP repeats the same sequence number as long as the channel remains idle, even a long series of erased idle frames will eventually trigger a NAK when the first unerased idle gets through.

IS-95's synchronous nature makes this pure-NAK scheme work. As long as the channel remains up, it needs at least a 2-byte frame to transmit every 20 milliseconds, and this frame might as well carry the current sequence number. In contrast, an asynchronous channel (one that goes completely idle between packets) needs a positive acknowledgment to guard against loss of the last data frame sent before the link goes idle.

The current RLP uses half- or full-rate IS-95 data frames to carry user data, and eighth- and quarter-rate frames for idle and control respectively. Future versions may expand the available rates for performance tuning purposes.

Because the basic IS-95 system is connection-oriented while the packet service provided by RLP is connectionless, RLP automatically brings up and drops IS-95 traffic channels as needed. X.25 and dialup circuits have long used this same technique, except that IS-95 can bring up a traffic channel in only a second or so. RLP drops channels after an idle timeout, but the exact duration of the timeout is not too critical because an idle channel consumes relatively little of the IS-95 channel capacity. Contention for physical hardware resources (the modem ICs at the cell sites) is more likely than channel capacity considerations to be the controlling factor in deciding when to close idle traffic channels.

Prototyping and Testing

The prototype IS-95 data service uses PC clones at both the mobile and base stations running the KA9Q NOS TCP/IP package, with RLP and IS-95 interface drivers added. Since NOS includes an IP router, it was straightforward to use the prototype to access the regular Internet from a laptop computer plugged into a IS-95 mobile. The mobile laptop also supports additional computers via SLIP or Ethernet connections, although all of the remote computers must share the bandwidth of a single IS-95 traffic channel.

In a public demonstration in February 1993, I constructed two mobile data stations, each with a PC (running NOS TCP/IP/RLP) and a Macintosh Powerbook (running the University of Melbourne's Appletalk Remote Network Service over UDP/IP/SLIP). The demonstration supported simultaneous usage of the PC and Mac. The latter mounted Appleshare disk volumes on Qualcomm's file servers across the IS-95 radio link provided by the PC.

Field tests demonstrate the RLP's effectiveness. In tests from a moving vehicle in the San Diego CDMA Validation System, the packet loss rate was typically one in 10,000. Throughput on file transfers (using FTP/TCP/IP over the RLP) is typically about 900-950 bytes/sec, depending on the IS-95 frame erasure rate. TCP segment size is also a factor, although Van Jacobson header compression reduces header overhead significantly. The RLP seems quite robust; it hardly loses any packets unless the user moves outside the cellular coverage area, in which case there is little for it to do until the physical layer is restored. There is reason to believe that the dominant component in the 1:10,000 packet loss rate mentioned above was bit slips in the back haul links between the cell sites and the central switch, but the rate was already low enough to not warrant serious attention.

Future Activities

We have submitted the packet data architecture and radio link protocol to the TIA TR45.5.1.5 working group on IS-95 data services, where they are currently under consideration. Among the immediate needs of the working group are ways to provide conventional data services such as access to asynchronous modems on the regular public telephone network and support for conventional Group 3 facsimile, both of which have been prototyped and demonstrated over TCP/IP and RLP/IS-95 with the same software package developed to provide packet mode services. In this way, IS-95 has shown itself capable of supporting traditional data services while at the same time positioning itself to support the packet-based services that will certainly dominate mobile computing in the future.

Obtaining Specs

The complete Qualcomm CDMA system specifications (plus a system overview) are available by anonymous FTP from ftp.qualcomm.com in directory /pub/cdma. The files are in gzipped Postscript format.