ON THE SYSTEM DESIGN ASPECTS OF CODE DIVISION MULTIPLE ACCESS (CDMA) APPLIED TO DIGITAL CELLULAR AND PERSONAL COMMUNICATIONS NETWORKS

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Abstract

CDMA is a modulation and multiple access scheme based on spread spectrum communications techniques, a well established technology that has been applied only recently to digital cellular radio communications and advanced wireless technologies such as PCN [1]-[3]. It solves the near-term capacity concerns of major markets and answers the industry's long-term need for a next generation technology for truly portable communications in the most economic and efficient manner providing for a graceful evolution into the future generations of wireless technologies.

In the U.S., it is now widely believed that the first generation "Advanced Wireless Technologies" and "Personal Communications Network (PCN)" services will be provided by the cellular carriers using the next generation digital cellular system infrastructure and the cellular frequencies as a straightforward extension of the cellular system. A breadboard CDMA digital cellular was system developed by QUALCOMM and demonstrated in San Diego, CA in conjunction with PacTel Cellular to over 150 representatives of the cellular industry in November 1989. In February 1990, an extensive technical field trial was carried out in midtown Manhattan with NYNEX Mobile. For the purposes of carrying out the CDMA trials and demonstrations a total of 3 cell-site and 2 mobile prototype units were built. In each case, the demonstration system utilized two actual cell-sites and one mobile, and included A/B comparisons with the commercial analog system. The fundamental features of CDMA such as power control and soft hand-off were tested and proven in a variety of field conditions.

The CDMA Signal and Waveform Design

A CDMA system can also be a hybrid of FDMA and CDMA techniques where the total system bandwidth is divided into a set of wideband channels, each of which contains a large number of CDMA signals. Hybrids of TDMA and CDMA are also possible.

The CDMA digital cellular waveform design uses a Pseudo-Random Noise (PN) spread spectrum carrier. The chip rate of the PN spreading sequence is chosen so that the resulting bandwidth is about 1.23 MHz after filtering, is approximately one-tenth of the total bandwidth allocated to one cellular service carrier.

CDMA Forward Link Waveform Design

The CDMA CAI specifies a forward link CDMA waveform design that uses a combination of frequency division, pseudo-random code division and orthogonal signal multiple access techniques. Frequency division is employed by dividing the available cellular spectrum into nominal 1.23 MHz bandwidth channels. Normally, a cellular system would be implemented in a service area within a single radio channel until demand requires employment of additional channels.

Pseudo-random noise (PN) binary codes are used to distinguish signals received at a mobile station from different base stations. All CDMA signals in the system share a quadrature pair of PN codes. Signals from different cells and sectors are distinguished by time offsets from the basic code. This relies on the property of PN codes that the autocorrelation, when averaged over a few bit times, averages to zero for all time offsets greater than a single code chip time (approximately 1 μsec).

The PN codes used are generated by linear shift registers that produce a code with a period of 32768 chips. The PN chip rate is 1.2288 MHz, or exactly 128 times the 9600 bps information transmission rate. Two codes are generated, one for each of two quadrature carriers, resulting in quadriphase PN modulation. To avoid confusion between the system bandwidth, the PN chip rate, and the frequency assignment spacing, note that the PN chip rate is exactly 1.2288 MHz. The frequency assignment spacing, in multiples of 30 kHz, for two adjacent CDMA carriers is 1.23 MHz. Note that the 3 dB bandwidth is also 1.23 MHz.

The signals are bandlimited by a digital filter that provides a very sharp frequency roll-off, resulting in a nearly square spectral shape that is 1.23 MHz wide at the 3 dB point. Signals transmitted from a single antenna in a particular CDMA radio channel share a common PN code phase. They are distinguished at the mobile station receiver by using a binary orthogonal code based on Walsh functions (also known as Hadamard matrices). The Walsh function is 64 PN code chips long providing 64 different orthogonal codes. Orthogonality provides nearly perfect isolation between the multiple signals transmitted by the base station.

The information to be transmitted is convolutionally encoded to provide the capability of error detection and correction at the receiver. The code used has a constraint length (encoder memory) of nine, K=9, and a code rate of one-half (two encoded binary symbols are produced per information bit), r=1/2. To provide communications privacy, each data channel is scrambled with a user addressed long code PN sequence. Thus, a "channel" in the forward link of the specified CDMA system consists of a signal centered on an assigned radio channel frequency, quadriphase modulated by a pair of PN codes with an assigned time offset, biphase modulated by an assigned orthogonal Walsh function, and biphase modulated by the encoded, and scrambled digital information signal.

An important aspect of the forward link waveform design is the use of the pilot signal that is transmitted by each cell-site and is used as a coherent carrier reference for demodulation by all mobile receivers. The pilot is transmitted at a relatively higher level than other types of signals allowing extremely accurate tracking. The Pilot Channel signal is unmodulated by information and uses the zero Walsh function (which consists of 64 zeroes). Thus, the signal simply consists of the quadrature pair PN codes. The mobile station can obtain synchronization with the nearest base station without prior knowledge of the identity of the base station by searching out the entire length of the PN code. The strongest signal's time offset corresponds to time offset of the nearest base station's PN code. After synchronization, the pilot signal is used as a coherent carrier phase reference for demodulation of the other signals from this base station. Figure 1 shows an example of all of the signals transmitted by a base station on a particular sector antenna. Out of the 63 forward code channels available for use, the example shown in the figure depicts seven paging channels (the maximum number allowed) and 55 traffic channels. Other possible configurations could replace the paging channels one for one with traffic channels, up to a maximum of no paging channels and 63 traffic channels.

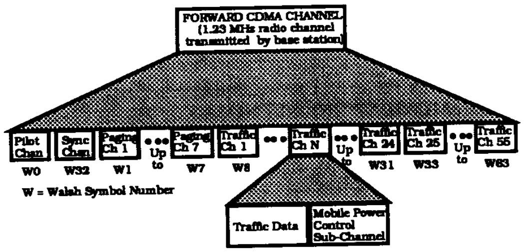

Figure 1. Example of Logical Forward CDMA Channels Transmitted by a Base Station

The remaining synchronization details and other system information are communicated to the mobile station by the base station's synchronization channel. This channel has a fixed assigned Walsh function. Once the sync channel has been received, the mobile station can select one of the paging channels to listen for other system information and pages.

CDMA Reverse Link Waveform Design

The CDMA reverse link also employs PN modulation using the same 32768 length binary sequences that are used for the forward link. Here, however, a fixed code phase offset is used. Signals from different mobile stations are distinguished by the use of a very long $(2^{42} - 1)$ PN sequence with a user address determined time offset. Because every possible time offset is a valid address, an extremely large address space is provided. This also inherently provides a reasonably high level of privacy.

The transmitted digital information is convolutionally encoded using a rate 1/3 code (three encoded binary symbols per information bit) of constraint length nine. The encoded information is grouped in six symbol groups (or code words). These code words are used to select one of 64 different orthogonal Walsh functions for transmission. The Walsh function chips are combined with the long and short PN codes. Note that this use of the Walsh function is different than on the forward link. On the forward link, the Walsh function is determined by the mobile station's assigned channel while on the reverse link the Walsh function is determined by the information being transmitted.The use of the Walsh function modulation on the reverse link is a simple method of obtaining 64-ary modulation with coherence over two information bit times. This is the best way of providing a high quality link in the fading channel with low Eb/No where a pilot phase reference channel cannot be provided. Note that on the forward channel the Pilot Channel signal is shared among all the users of the forward channel. This is not possible on the reverse channel.

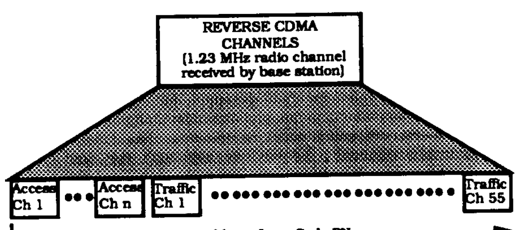

Figure 2. Example of Logical Reverse CDMA Channels Received at a Base Station

A "channel" on the reverse link of the specified CDMA system consists of a signal centered on an assigned radio channel frequency, offset quadriphase modulated by a pair of PN codes, biphase modulated by a long PN code with address determined code phase, and biphase modulated by the Walsh encoded and convolutionally encoded digital information signal.

Figure 2 shows an example of all of the signals received by a base station on a particular sector antenna. Each Reverse CDMA Channel can have up to 62 Traffic Channels and up to 32 Access Channels per supported Paging Channel.

The CDMA System Design

In a co-channel interference limited environment such as cellular telephone, CDMA provides much better frequency reuse.

CDMA For Greatly Increased Capacity

In CDMA, frequency reuse efficiency is determined by the signal-to-interference ratio resulting from all the system users within range, not just those in any given cell. Since the total capacity becomes quite large, the statistics of the users are what is important, not any single user. The "law of large numbers" can be said to apply. This means that the net interference to any given signal is simply the average of all the users' received power times the number of users. As long as the ratio of received signal power to the average noise power density is greater than a threshold value then the channel will provide an acceptable signal quality. With TDMA and FDMA, interference is governed by a "law of small numbers" in which "worst-case" situations determine the percentage of time in which the desired signal quality will not be achieved.

The primary parameters that determine the CDMA digital cellular system capacity are processing gain, the E_b/N_0 (with the required margin for fading), the voice duty cycle, the CDMA omni-directional frequency reuse efficiency, and the number of sectors in the cell-site antenna. Additionally, for a given blocking probability, the larger number of voice channels provided by CDMA results in a significant increase in trunking efficiency, serving a larger number of subscribers per voice circuit.

The complete equation for determination of capacity in QUALCOMM's CDMA system given by equation augmented by the additional system capabilities to provide the following equation for CDMA capacity [3]:

$$N = \frac{W}{R} \cdot \frac{1}{\frac{E_b}{N_o}} \cdot \frac{1}{d} \cdot F \cdot G$$

Where:
N = Calls Per Cell ••••••• Assuming: Rayleigh Fading, Reverse Link
W = Spread Spectrum Bandwidth ••••••••••• Assuming: 1.25 MHz
R = Data Rate in kbps •••••••••••••••••••• Assuming: 9600 bps
Eb/No = Bit Energy+Noise Power Spectral Density • Assuming: 6.0 dB
D = Voice Duty Cycle ••••••••••••••••••••••• Assuming: 50%
F = Frequency Reuse Efficiency ••••••••••••••• Assuming: 60%
G = Number of Sectors in Cell ••••••••• Assuming: 3 sectors (120°)
Radio Capacity Per Cell •••••••• 120 CDMA Channels in 1.25 MHz
Erlang Capacity Per Cell (2% Blocking) •••• 107 Erlangs in 1.25 MHz

CDMA Power Control

In CDMA mobile telephone systems, the objective of the mobile transmitter power control process is to produce, at the cell-site receiver, a nominal received signal power from each mobile transmitter operating within the cell. If all the mobile transmitters within a cell-site's area of coverage are so controlled, then the total signal power received at the cell-site from all mobiles will be equal to the nominal received power times the number of mobiles.

It is very desirable to maximize the capacity of the CDMA system in terms of the number of simultaneous telephone calls that can be handled in a given system bandwidth. It can readily be seen that the system capacity is maximized if each mobile transmitter's power is controlled so that its signal arrives at the cell-site with the minimum required signal-to-interference ratio. If a mobile's signal arrives at the cell-site with too low a value of received power, the bit-error-rate will be too high to permit high quality communications. If the received power is too high, the performance of this mobile unit will be acceptable, but interference to all the other mobile transmitters that are sharing the channel will be increased, possibly resulting in unacceptable performance to other users unless their number is reduced.

CDMA Reverse-Link Open-Loop Power Control

Each mobile unit attempts to estimate the path loss from cell-site to the mobile unit. In the CDMA approach to multiple access, all the cell-sites in a region transmit, on the same frequency, a "pilot" signal that is used by all mobiles for initial synchronization and as a frequency and time reference for demodulation of digital speech signals is also transmitted by each of the cell-site stations.

The mobile telephone measures the power level of both the pilot signal from the cell-site to which it is connected and also sum of all the cell-site signals receivable at the mobile telephone. This latter measurement is necessary to handle cases in which the mobile might temporarily obtain a better path to a more distant cell-site than to its normally preferred, close-by cell-site. Figure 3 shows a typical situation as a mobile drives away from the cell-site. Depicted are both log-normal shadowing and Rayleigh fading.

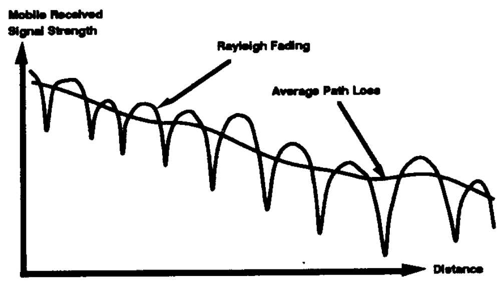

Figure 3. Mobile Received Signal Strength in Log-Normal Shadowing and Rayleigh Fading

Based on these measurements, the outbound link path loss is estimated. This estimate is then used to permit a rapid response to a sudden improvement in the channel while disallowing a rapid response to a sudden degradation in the channel. This is important because if the channel for one mobile suddenly improves, then the signal received at the cell-site from this mobile will suddenly increase in power causing additional interference to all the other signals sharing the same wide-band channel. The approach to solving this problem is to tolerate a temporary degradation in one mobile in order to prevent a degradation of all mobiles.

A typical example of a sudden improvement occurs when a mobile is moving through an area that is shadowed by a large building or other large obstruction and then drives out of the shadow. This can take place in a few tens of milliseconds. As the mobile drives out of the shadow, the outbound signal received by the mobile will increase in strength.

The reverse link path loss estimate at the mobile is used by the mobile to adjust its own transmitter power. The stronger the received signal, the lower will be the mobile's transmitter power. Reception of a strong signal from the cell-site indicates that the mobile is either close to the cell-site or has an unusually good path to the cell-site. This means that relatively less mobile transmitter power is required to produce a nominal received power at the cell-site from this mobile transmission. In the case of a sudden improvement in the channel, the open loop power control mechanism, which is analog in nature and has about 85 dB or more dynamic range, provides for a very rapid response over a period of just a few microseconds. It adjusts the mobile transmit level downward, preventing the mobile transmitter power from being at too high a level.

The rate of increase of mobile transmit power must generally be limited to the rate at which the closed loop power command from the cell-site, described below, can reduce the power. This prevents a sudden degradation which affects only the outbound path from causing a mobile transmit power to increase to a level significantly higher than required for communication. Figure 4 shows the effect of the open loop power control.

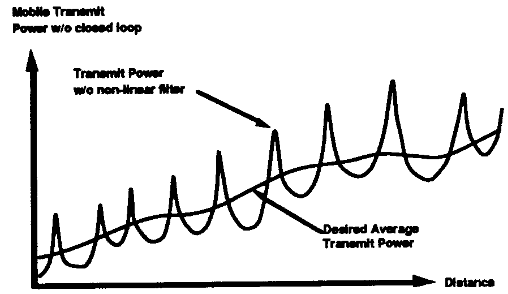

Figure 4. Transmit Power w/o Closed Loop Control and without Non-Linear Filtering

The cell-site transmits information as to its characteristics and number of active calls on its setup channel. The mobile receives this information when first obtaining system synchronization and continues to monitor the messages being transmitted.

In addition to measuring the received signal strength in the mobile, it is also desirable for the microprocessor in the mobile to know the cell-site's transmit power and antenna characteristics and the number of calls active from the cell-site. This allows the mobile's microprocessor to compute the reference power level for the local power setting function. This capability allows the system to have cell-sites with differing transmit power levels and antenna gains (ERP levels) corresponding to the size of the cells. For example, a small radius cell need not transmit as high a power level as a large radius cell. However, when the mobile is at a certain distance from a low power cell, it would receive a weaker signal than from a high power cell. It would respond with a higher transmit power than would be necessary for the short range. Hence, the desirability of having each cell-site transmit information as to its characteristics for power control.

CDMA Reverse-Link Closed-Loop Power Control

In cellular systems, the full-duplex radio channel is provided by using one frequency band for transmission from the cell-site to the mobile telephones and a different frequency band for transmission from the mobile telephones to the cell-sites. The frequency separation allows a mobile telephone's transmitter and receiver to be active simultaneously without feedback or interference from the transmitter into the receiver. The frequency separation has very important implications for the power control process. It causes the multipath fading on the inbound and the outbound channels to be independent processes. This is because the 45 MHz frequency separation greatly exceeds the coherence bandwidth of the channel. This means that a mobile unit cannot measure the path loss of a received signal and assume that the exactly the same path loss is present on its transmitted signal, particularly when the mobile is stationary. The above measurement technique provides the correct transmit power on the average, but additional provisions must be made for the effects of independent Rayleigh fading.

To account for the independence of the Rayleigh fading on the forward and the reverse link, which the mobile cannot estimate, the mobile transmitter power is also controlled by a signal from the cell-site. Each cell-site demodulator measures the received signal strength from each mobile. The measured signal strength is compared to the desired signal strength for that mobile and a power adjustment command is sent to the mobile in the outbound channel addressed to that mobile unit. This power adjustment command is combined with the mobiles' open loop estimate to obtain the final value of the mobile's transmit radiated power.

The cell-site power adjustment command signals the mobile unit to increase or to decrease the mobile power by a predetermined amount, nominally about 0.5-1 dB. The power adjustment command is transmitted at a relatively high rate, on the order of one command every millisecond. The rate of transmission of the power adjustment command must be high enough to permit the Rayleigh fading on the inbound path to be tracked. It is also desirable for the outbound Rayleigh fading process that is impressed on the inbound signal to be tracked. One command per millisecond is adequate to track fading processes for vehicle speeds up to 25-100 miles per hour for 850 MHz band mobile communications. It is important that the latency in determining the power control signal and in the transmission process be kept small so that the channel conditions will not change significantly before the control bit can be received and acted upon.

The system controller residing at the MTSO provides each cell-site controller with a value of desired signal strength to use based on the overall system information available. The cell-site controller maintains the desired signal strength information for each mobile that is active within that cell. This level is passed to each of the cell-site demodulators where it is used along with the available information on instantaneous vs. the expected value of the bit error rate of the received signal to determine whether to command a particular mobile to increase or to decrease its transmitter power. This mechanism is called the CDMA closed-loop power control.

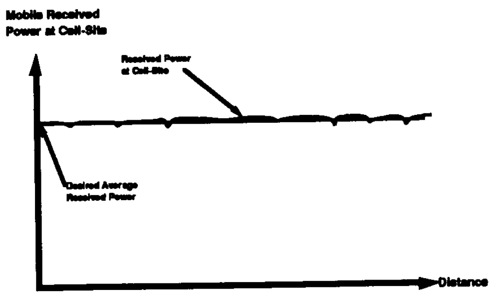

Figure 5. Mobile Power Received at Cell-Site

The nominal power level can be adjusted up or down to accommodate variations from the average conditions. For example, a cell-site in an unusually noisy location might be allowed to use a higher than normal inbound power level. This will result in a higher level of interference to the immediate neighbors of this cell. This can then be compensated for by allowing these neighbor cells a smaller increase in inbound power than for the cell in the high noise environment. Figure 5 shows the net result of the open and closed loop power control processes. Notice that the return link channel has its own independent Rayleigh fading process.

CDMA Forward-Link Power Control

It is also desirable to provide a means for controlling the relative power used in each data signal transmitted by the cell-site in response to control information transmitted by each mobile. The primary reason for providing such control is to accommodate the fact that in certain locations, the link from cell-site to mobile may be unusually disadvantaged. Unless the power being transmitted to this mobile is increased, the quality may become unacceptable. An example of such a location is a point where the path loss to one or two neighboring cells is nearly the same as the path loss to the cell-site communicating with the mobile. In such a location, the total interference would be increased by three times over the interference seen by the mobile at a point relatively close to its cell-site. In addition, the interference coming from these neighboring cell-sites will not fade in unison with the desired signal as would be the case for interference coming from the desired cell-site. This situation may require 3-4 dB additional signal power to achieve adequate performance.

In another situation, the mobile may be located where several strong multipath signals arrive, resulting in larger than normal interference. In such a situation, increasing the power of the desired signal relative to the interference may allow acceptable performance. At other times, the mobile may be located where the signal-to-interference ratio is unusually good. In such a case, the cell-site could transmit the desired signal using a lower than normal transmitter power, reducing interference to other signals being transmitted by the system. To achieve these objectives, the design includes a signal-to-interference measurement capability within the mobile receiver. This measurement is performed by comparing the desired signal power to the total interference and noise power. If the measured ratio is less than a predetermined value the mobile transmits a request for additional power to the cell-site. If the ratio exceeds the predetermined value, the mobile transmits a request for a reduction in power.

The cell-site receives the power adjustment requests from each mobile and responds by adjusting the power allocated to the corresponding cell-site transmitted signal by a predetermined amount. The adjustment would usually be small, on the order of 0.5 dB, or 12%. The rate of change of power would be somewhat slower than that used for the mobile to cell-site link, perhaps once per vocoder frame, or nominally once per 15-20 milliseconds. The dynamic range of the adjustment would also be limited approximately to a plus or minus 6 dB range around the nominal power. The cell-site must also consider the power demands being made on it by all the mobiles in deciding whether to comply with the requests of any particular mobile. For example, if the cell-site is loaded to capacity, requests for additional power might be granted but only by 6% or less instead of the normal 12%. In this regime, a request for a reduction in power would still be granted at the normal 12% change.

Additional Features of CDMA

The CDMA system has many other features that do not relate directly to capacity, but rather to ease of system operation, grade and cost of service. As mentioned earlier, in the cell-site to mobile direction, or forward link, the CDMA signal design uses convolutional encoding with constraint length K=9 and code rate 1/2. The optimum decoder for this type of code is the soft decision Viterbi algorithm. A standard design is used for this purpose.

In the mobile to cell-site link, or reverse link, since the modulation scheme employs 64-ary orthogonal signalling based on the set of Walsh function sequences, the demodulation is based on the use of the Fast Hadamard Transformers (FHT) as an optimum receive filter for the Walsh function. In the cell-site receiver, the correlator output is fed to a FHT processor. This processor produces a set of 64 coefficients for every 6 symbols. The 64 symbols are then multiplied by a weighting function and passed to a diversity combiner. The weighted 64 symbols from each antenna's receiver are added to each other. The resulting set of 64 coefficients is tested to determine the largest coefficient. The magnitude of the result, together with the identity of the largest of the 64 is used to determine a set of decoder weights and symbols for a Viterbi algorithm decoder. The Viterbi decoder, a constraint length K=9, code rate 1/3 decoder, determines the most likely information bit sequence. For each vocoder data block, nominally 20 msec of data, a signal quality estimate is obtained and transmitted along with the data. The quality estimate is the average signal-to-noise ratio over the frame interval.

A unique capability of direct sequence CDMA is the exploitation of multipath to provide path diversity. The wide bandwidth PN modulation allows different propagation paths to be separated when the difference in the path delays for the various paths exceeds the PN chip duration (or 1/bandwidth). This is because the PN sequence has zero correlation for time offsets greater than one chip time. For a PN chip rate of 1.2288 MHz as employed in the present design approach CDMA system, the full spread spectrum processing gain, equal to the ratio of spread bandwidth to system data rate, can be employed to discriminate against paths that differ by more than one microsecond.

If two or more paths exist with greater than 1 microsecond differential path delay, then multiple PN receivers can be employed to separately receive the strongest of signals in multiple paths. The number of signals (or paths) is equal to the number of PN receivers provided. Since these signals will typically exhibit independence in fading, i.e., they usually do not fade together, the outputs of the receivers can be diversity-combined so that a loss in performance only occurs when all receivers experience fades at the same time. This type of diversity not only mitigates Rayleigh fading but also fades caused by blocking of the signal path by physical obstructions. A one microsecond path delay differential corresponds to differential path distance of 1000 feet. Signals arriving with larger than 1 microsecond delay spread will likely also arrive from different directions. Signals coming from different directions will be affected differently by obstructions in the immediate physical environment of the mobile. This effect is especially pronounced in heavily built-up urban areas. The urban environment typically provides differential path delays ranging from less than one microsecond up to 10-20 microseconds in some areas.

CDMA Soft Hand-off's "Make Before Break"

In the CDMA cellular telephone system, the same channel center frequency is used in all cells. The CDMA waveform properties that provide processing gain are used to discriminate between signals that occupy the same channel. This means that the mobile unit need not switch frequencies when being handed-off from one cell-site to another. Therefore, there is a smaller probability that the call will be dropped if the hand-off command is received in error.

The new cell-site assigns a modulator-demodulator (modem) unit, consisting of digital modulator and digital data receiver(s) functions, to the call while the old cell-site continues to handle the call. While the mobile is located in the transition region between the two cell-sites, the call can be switched back and forth between them as signal strength dictates with no disrupting effects on the mobile. Only when the mobile is firmly established in the new cell will the original cell-site discontinue handling the call. In this regard, the analog system (and the digital TDMA based systems) can be said to provide a break-before-make switching function whereas the CDMA based soft handoff system provides a make-before-break switching function.

Call Setup

The pilot carriers are transmitted by each cell-site using the same code but with a different spread spectrum code phase offset, allowing them to be distinguished. The fact that they all use the same code allows the mobile to find system timing synchronization by a single search through all code phases. The strongest signal found corresponds to the code phase of the nearest cell-site.

After acquisition of the pilot carrier, the mobile searches for the setup channel. This requires that the mobile search through all the different codes used for this purpose. When the mobile finds the setup channel, the system information is received and the mobile monitors the setup channel for control messages that indicate a call is waiting for this mobile. Also, the mobile continues to scan the pilot code at the code offsets corresponding to the neighboring cell-sites to determine if one of the neighbor cells is becoming stronger than the cell-site signal first determined to be strongest. If, while in this call inactive mode, a neighbor cell-site pilot signal becomes stronger than the initial cell's pilot, the mobile will acquire that cell-site's setup channel. When a call is initiated, a PN code address is determined for use during the course of this call. The code address is assigned based on the identity of the mobile unit.

Mobile-Assisted Soft Hand-off

The mobile can be permitted to initiate the hand-off request and to determine the best new cell from the old cell's neighbors. After a call is initiated, the mobile continues to scan the neighboring cells' pilots to determine if one of these signals becomes stronger than the first cell's pilot. When this happens, it indicates to the mobile that it has entered the new cell's coverage area and that a hand-off could be initiated. The mobile transmits a control message to the cell-site handling the call with the information that a new cell-site's pilot is now stronger along with the identity of the new cell-site.

The system controller can now begin the hand-off process. The PN code address need not change. The system controller begins the hand-off process by assigning a modem located in the new cell-site to the call. The modem is given the PN address of the call. The cell-site modem searches for and finds the mobile's signal. The cell-site modem also begins transmitting the outbound signal to the mobile. The mobile searches for this signal. When the new cell-site signal is found, the mobile can switch over to listening to this signal. The mobile then transmits a control message indicating that the hand-off is complete. The system controller then switches the call over to the new cell-site and allows the old cell-site modem to enter the pool of idle modems available for reassignment.

In addition to the above, the hand-off process can introduce a second mode of operation, called cell-site diversity mode. In this mode of operation the call is allowed to linger in the in-between state when the call is being processed by two cell-sites. In the path from mobile to the two cell-sites, path diversity reception is also obtained by having two or three cell-sites demodulate the signal from the mobile. All cell-sites forward their demodulated data signals to the system controller along with an indication of the signal quality in the receiver. The system controller then compares the two or three versions of the mobile's signal and selects the signal with the best quality indication. It is also possible, although more complex, to transmit the undecoded or even the undemodulated signals to the system controller to allow a better diversity combining process to be utilized.

In hand-off with cell diversity mode, the process is initiated as before, by the mobile determining that a neighboring cell-site has a signal strength high enough to allow good quality demodulation. The mobile transmits a control message to the cell-site (which relays it to the system controller) indicating the identity of this new cell-site and requests the cell diversity mode. The system controller responds by connecting the call to a modem in the new cell-site. The system controller then performs diversity combining of the signals received by the two cell-sites (on a vocoder frame by vocoder frame basis) and the mobile performs diversity combining of the signals received from the cell-sites.

The cell diversity mode continues as long as good signals are received from all the cell-sites. The mobile continues to search for other cell-sites. If a new cell-site becomes stronger than one of the original cell-sites, a control message will be transmitted indicating the identity of this cell-site. The system controller will then drop the weakest cell-site and continue with the strongest cell-sites. Note that if the mobiles are equipped with three data demodulators, then a triple cell-site diversity mode results. The cell diversity mode is terminated when the mobile determines that only one cell-site is providing adequate signals for quality reception. The mobile sends a control message indicating the cell-site it wishes to remain with at the end of cell-diversity mode. Cell diversity mode might be terminated by the system controller if the system were to become overloaded and insufficient number of modems were available to support all requests for this mode. The mobile initiated hand-off has the advantage that mobile becomes aware of changes in the paths between itself and the various neighboring cell-sites much sooner and with less effort than the cell-sites.

Variable Data Rates

The appearance of the modulated signal does not change if the baseband data rate is changed. For example, a wide range of voice codec (or vocoders) rates can easily be introduced over time and offered to subscribers as different grades of voice quality which can be priced accordingly, with no impact on system operation or costly redesign of the system. It is anticipated that, at least initially, vocoders employing baseband data rates of 8 and 4.8 kilobits per second are likely to be used in the system. It is highly desirable for all of these rates to be simultaneously usable in the system by different mobiles. It is envisioned that the cellular operator would maintain a bank of vocoders, operating at different rates such as the ones mentioned above, as a shared resource at the MTSO. A wide range of new non-voice services (e.g., data, facsimile, imaging, ISDN, etc.) requiring different data rates, possibly at much higher or lower rates than the ones employed by the vocoders, can be accommodated simultaneously.

The capacity of the CDMA system is directly proportional to the basic vocoder data rate. It is strongly believed, based on CDMA system demonstrations and field trials to date, that a CDMA system utilizing an 8 Kbps vocoder could provide for a much higher voice quality most of the time, in the intended area of coverage, compared to a wide area FDMA or TDMA system utilizing, for example, 32 Kbps ADPCM in a dispersive fading channel without the use of power control, multipath parallel correlator "Rake" receiver or soft (and softer) hand-off. QUALCOMM is implementing its QCELP 8 Kbps vocoder on a VLSI ASIC with an I/O driver module and some additional functions residing on a general purpose microprocessor that is a part of either the subscriber unit or the channel element at the cell site. Therefore, in terms of cost, power consumption, size/packaging considerations, and complexity to incorporate its use in the design of the microportable, the 8 Kbps vocoder would not be substantially different than, for example, the circuitry that supports a 32 Kbps ADPCM vocoder, once a low cost and low power 8 Kbps vocoder ASIC is available.

Personal Communications Systems

Although first terrestrial application of the CDMA is for the development of the next generation digital cellular system, it is important to realize that the CDMA technology being developed, and the chip-set "engines", could be cost-effectively used in many other important applications. The major wireless personal communications applications are:

- CDMA for Private Microcellular Systems,
- Public Cordless Systems (e. g., CT-2)
- Wireless Local Loop, and
- Wireless PABX

Current and future cellular radio systems must be able to operate in an environment of increasing spectrum congestion and interference levels. One efficient way of using the available spectrum is to reduce the cell size and tailor its shape to the teletraffic demands. This dramatically increases the capacity of the system, reduces the radiated power levels (a biological plus) and reduces the equipment complexity. There is no universally accepted definition of a microcellular system. For some, it is a conventional cellular system with smaller cells, designed mainly for areas with dense teletraffic demands. Microcells may be classified as either one-, two-, or three-dimensional, depending on whether they are along a road or a highway, covering an area such as a number of adjacent roads, or located in multilevel buildings, respectively. The number of microcells per cluster may be much higher than with current systems. Recent studies conducted at QUALCOMM demonstrated that with transmit power levels of less than 18 milliwatts in the CDMA mobile, it is possible to provide coverage to street blocks of 500 meter in length. Similar power level and coverage results are obtained for in-building (3-dimensional) and hot spots (2-dimensional) microcells.

CDMA also holds great promise for Wireless PBX applications. Using the same basic hardware used for the CDMA microcellular telephone system, a very high capacity digital wireless PBX system can be constructed. This, together with an innovative new antenna approach (that can only be employed with CDMA) leads to a remarkable new concept. The proposed system has the following features:

- Simple interface to ISDN PBX switch
- Higher capacity
- Much simpler antenna system
- Excellent coverage
- Transparent handoff between antennas
- Competitive cost
- Inter-operates with CDMA cellular system

The Distributed Antenna

The key concept in the wireless PABX and for the wireless local loop is the CDMA distributed antenna. In this concept, a set of simple antennas are fed by a common signal with only time delay processing to distinguish signals. The transmit output of the cell transmitter is fed down a coaxial cable to a string of radiators. The radiators are connected to the cable using a power splitter. The resulting signal, amplified if necessary, is fed to the antenna. The salient features of this antenna concept are:

- Extremely simple and inexpensive,
- Neighboring antennas have time delays inserted in feed structure so signals received from two antennas are distinguishable by PN temporal processing,
- Exploits direct sequence CDMA's ability to discriminate against multipath,
- Creates deliberate multipath that satisfies discrimination criteria providing path diversity.

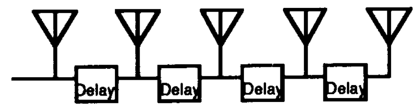

Figure 6. CDMA Distributed Antenna Concept

In the distributed antenna processing, each antenna taps into the distribution cable somewhat like a cable TV system. Broadband gain is provided as needed at the antennas or at the cable taps. Note that the cable system might consist of two cables, one for transmit signals and one for receive signals, although this is not necessary provided that the normal 45 MHz frequency separation of uplink and downlink bands in cellular telephone is used. In many cases, the necessary delay will be provided naturally by the distribution cable and no additional delay elements will be necessary. When additional delay is necessary, simple lumped delay elements can be employed.

A very important feature of this architecture is that no signal specific processing is necessary. In particular, no filtering, mixing translation or other complex signal processing operations need be performed. Only amplification is needed and that is provided "in bulk" to all of the signals in the cable with a single amplifier at each location where gain is required.

It is also possible to distribute the signal without the use of coaxial cable. For example, the system might have a central distribution location with an antenna in sight of all the remote antenna sites. The remote site would have a high gain antenna pointing to the central distribution antenna. The signal is then amplified, delayed and connected to the local distribution antenna. The local distribution antenna is configured so as to cover an area not in view of the central distribution antenna. If an overlap in coverage is possible between two adjacent local distribution antennas, then differing delays should be used so as to allow the signals to be distinguished by receivers in the overlap area.

Another advantage is that little site specific engineering is required for installation. Normally, antenna placement will be determined only by physical constraints, together with the requirement that every location desiring service must be covered by at least one antenna. There is no concern for overlap. In fact, overlapping coverage is desirable in that it provides diversity operation to all terminals in the overlap area. Overlap is, however, not required.

[1] Allen Salmasi, " Future Public Land Mobile Telecommunication Systems (FPLMTS) Employing Code Division Multiple Access (CDMA) and Advance Modulation and Coding Techniques," Information Paper to the Sixth meeting of CCIR IWP 8/13, Harrogate, U.K., July 1990.

[2] K.S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver, and C. E. Wheatley, "On the Capacity of a Cellular CDMA System," to appear in IEEE Transactions on Vehicular Technology, May 1991.

[3] Allen Salmasi, "An Overview of Code Division Multiple Access (CDMA) Applied to the Design of Personal Communications Networks," Proceedings of the Second Rutgers University WINLAB Workshop on Third Generation Wireless Information Networks, East Brunswick, New Jersey, USA, October 18-19, 1990.