On the Capacity of CDMA Cellular Networks

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Abstract

The code division multiple access (CDMA) system is an interference-limited system in which link performance depends on the ability of the receiver to detect a signal in the presence of interference. In this paper procedures for calculating the capacity of the uplink and downlink of a CDMA system are given.

Introduction

Viterbi in [1] compared the capacity of CDMA with the traditional technologies FDMA & TDMA for satellite applications and suggested a reasonable edge in capacity for the latter two more conventional techniques. As FDMA and TDMA both are bandwidth limited, CDMA is only interference limited and any reduction in interference directly gives an increase to the capacity of CDMA. Gilhousen [2] has shown it and the edge suggested by [1] become illusory. Since voice signals are intermitted with a duty factor of approximately 3/8 [3], capacity can be increased by an amount inversely proportional to this factor by suppressing transmission during the quiet periods of each speaker. Similarly any spatial isolation through use of multi-beamed or multi-sectored antennas, which reduce interference, also provides a proportional increase in capacity. These two factors, voice activity and spatial isolation are sufficient to render CDMA capacity at least double that of FDMA and TDMA under similar assumptions for a mobile satellite application. Not only in satellite application CDMA also exhibits its greatest advantage over FDMA and TDMA in terrestrial digital cellular systems, for here isolation among cells is provided by path loss, which in terrestrial UHF propagation typically increases with the fourth power of the distance. Consequently, while conventional techniques must provide for different frequency allocation for contiguous cells, CDMA can reuse the entire spectrum for all cells, thereby increasing capacity by a large percentage of the normal frequency reuse factor. The net improvement in capacity, due to all of the above features, of CDMA over digital TDMA or FDMA is of the order of 4 to 6 and over analog FM/FDMA it is nearly a factor of 20.

CDMA is a very attractive technique for wireless communication provided the synchronization and power control problem can overcome. Its advantage over other multiple-access schemes includes higher spectral reuse efficiency, greater immunity to multipath fading, gradual overload capability, simple exploitation of sectorisation and voice inactivity and more robust handoff procedures [4], [5]. As early as 1978, a CDMA system had been proposed for mobile communication [6], however, interest was limited until Qualcomm demonstrated the feasibility of implementing such systems [7]-[9]. Since then there

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has been an explosion in CDMA research mainly concentrating on the design and performance analysis of receivers, coding and modulation techniques and power control algorithms. Higher layer issues such as call admission control, analysis of soft handover and effects of gradual overload and imperfect power control on capacity have also begun to receive attention [10] & [11]. A technique to access the uplink traffic capacity and its sensitivity to various propagation and system parameters has been given by Jamie [12]. Analysis of outage and capacity performance of an interference based admission control strategy in cellular CDMA systems had been evaluated by Anand [13].

The paper is organized as follows. We begin with the single cell CDMA capacity. Uplink capacity of a single cell system is given then. We then move to the case of a multicell system, which of course is more complex than the single cell system. Both uplink and downlink case of a multicell system is taken.

Single Cell CDMA Capacity

We begin by considering a single cell system. Each user of a CDMA system occupies the entire allocated spectrum, employing a direct sequence spread spectrum wave form.

At the cell-site transmitter, the spread signals directed to the individual subscribers are added linearly and phase randomness is assured. The receiver processors in both subscriber and cell site receivers provide the inverse bandwidth functions, which are of course more complex then the transmitter base band functions. One other key feature of the cell-site transmitter is the inclusion of a pilot signal in the forward direction. This provides for acquisition by the mobile terminals, including initial power control by the mobile terminals, which adjusts its power inversely to the total signal power it receives.

Uplink Capacity in a Single Cell System

In case of a single cell site with power control, all uplink signals are received at the same power level. Let there be a total of N users in the cell. In the absence of thermal power the required (E_b/I_t) for a single cell:

$$(E_b/I_t)_{reqd} = v_f \cdot S \cdot G_p/I_0$$

$$= v_f \cdot S \cdot G_p/(M_a-1) \cdot v_f \cdot S$$

$$= G_p/(M_a-1) \qquad \ldots(1)$$

Here M_a is the number of active users in a single cell system, G_p is the processing gain=R_c/R, R is mobile transmission rate in bps, R_c is the chip rate, I_t is total noise plus interference spectral density, E_b is energy per bit, S is signal power of each mobile at the BS receiver and v_f is the average uplink activity factor.

Uplink Capacity in a Multicell System

CDMA multiple cell networks use the same frequency band in all cells, as opposed to other access technologies in which frequency used in a given cell is reused only in sufficiently distant cells to avoid co-channel interference. To compare CDMA with other multiple access schemes, capacity is determined as the total number of users in the multiple cell network rather than the number of users per bandwidth or per isolated cell, we have just gone for. The CDMA link performance depends upon the ability of the receiver to discern a signal in the presence of interference. For satisfactory performance of a CDMA link, an FER of about one percent is recommended. The key issue in a CDMA network design is to minimize multiple-access interference. Power control is critical to multi-access interference. Each cell controls the transmit power of its own mobiles. However, a serving cell is unable to control the power of mobiles in the neighboring cells. The mobiles in the neighboring cell introduce additional interference, thereby reducing the capacity of uplink. We introduce this effect by a factor f. The interference from the other cells determine the actual reuse factor of the CDMA system. CDMA networks are designed to tolerate a certain amount of interference, and therefore have a capacity advantage in this regard as compared with TDMA (time division multiple access) or FDMA (frequency division multiple access) networks.

Power control to a given mobile is exercised by the cell whose pilot signal power is maximum to that mobile, it follows that if the path loss were only a function of distance from the cell site, then the mobile would be power controlled by the nearest cell site, which is situated at the center of the hexagonal in which it lies for an idealized placement of cell sites. The loss is proportional to other effects as well, the most significant being shadowing. The generally accepted model is an attenuation which is the product of the fourth power of the distance and a log-normal random variable whose standard deviation is 8 dB. That is, the path loss between the subscriber and the cell-site is proportional to $(10)^{(\xi/10)}r^{-10}$, where r is the distance from subscriber to cell site and î is the Gaussian random variable with standard deviation 6 = 8 and zero mean. Fast fading (due largely to multipath) is assumed not to affect the average power level.

The required SNR (signal-to-noise ratio) for a multicell system will be:

$$(SNR)_{reqd} = \left(\frac{E_b}{I_t}\right)_{reqd.} \frac{R}{R_c}$$

$$\left(\frac{E_b}{I_t}\right)_{reqd} = \frac{v_f.S.G_p}{I_o + I_{oc}}$$

$$= \frac{v_f.S.G_p}{(M-1).v_f.S + f.M.v_f.S}$$

where I_0 is the own cell interference and I_{oc} other-cell-interference, and M is active number of mobiles in the cell.

$$\left(\frac{E_b}{I_t}\right)_{reqd} = \frac{G_p}{(M-1)+f.M} \quad \ldots (2)$$

comparing (1) and (2), it can be noticed that the capacity of a single-cell system is higher than that of a multi-cell system.

Down Link Capacity

An important feature of CDMA that contributes to the added capacity on the uplink is soft handoff. In a CDMA network, a mobile can be served by multiple cells simultaneously. However, the same feature puts an additional burden on the downlink. Since multiple cells have to provide service to the same mobile, additional resources are allocated on the downlink. The downlink performance differs vastly from that of the uplink for the following reasons:

- Access is one-to-many instead of many-to-one.
- Synchronization and coherent detections are facilitated by use of a common pilot channel.
- Interference is received from a few concentrated large sources (cells) rather than many distributed small ones (mobiles).

To maximize the capacity of downlink, it is essential to control the power of the cell so as to allocate the power to individual mobiles according to their needs. More power is provided to those mobiles that receive highest interference from the neighboring cells. Mobiles on the boundaries may be in soft handoff, in which case they are receiving signal power from two or more cells. Power control on the downlink is accomplished by measuring the mobile power received from its serving cell and the total received power. In IS-95, the information about these two power values is transmitted to the serving cell.

For the downlink a figure of merit is defined for various channels. The figure of merit is the difference between the received (rec) and specified (sp) E_b/I_t. the link safety margin parameter for each of the channels on the downlink in IS-95 is defined as

$$M_{pilot} = (E_c/I_t)_{rec} - (E_c/I_t)_{sp} > 0$$
$$M_{traffic} = (E_b/I_t)_{rec} - (E_b/I_t)_{sp} > 0$$
$$M_{sync} = (E_b/I_t)_{rec} - (E_b/I_t)_{sp} > 0$$
$$M_{paging} = (E_b/I_t)_{rec} - (E_b/I_t)_{sp} > 0 \quad \ldots (3)$$

For the pilot channel, E_c/I_t is used instead of E_b/I_t since the pilot channel does not carry any information. Energy per chip, E_c, is used, chip rate being 1.2288 Mcps.

The downlink budget is used to confirm that quantities in these questions are positive and there is sufficient margin for the downlink to perform efficiently. Out of M_{pilot}, $M_{traffic}$, M_{sync}, and M_{paging}, the first two are more critical. If these two are positive then the other two are also likely to be positive. For perfect link balance all margin parameters should be zero, particularly M_{pilot} and $M_{traffic}$. The suggested values for the specified E_b/I_t and E_c/I_t parameters are

- Pilot channel: $(E_c/I_t)_{sp}$ = - 13 dB
- Traffic channel: $(E_c/I_t)_{sp}$ = 7 dB
- Sync channel: $(E_b/I_t)_{sp}$ = 7 dB
- Paging channel: $(E_b/I_t)_{sp}$ = 7 dB

Following assumptions are made for the CDMA downlink budget calculations:

- All mobiles are
  - at the cell edge
  - at least in two-way soft handoff
  - traveling at a medium speed
  - (E_b/I_t) = 7 dB for 1% FER
- Power control is working perfectly for all mobiles
- Total downlink traffic channel power is equally divided among all mobiles

The forward link capacity depends on the power that is available for the traffic channels. The power allocation to each overhead channel (i.e. P_{pilot}, P_{sync}, and P_{paging}) is determined from field tests. The suggested power allocations for the forward link channels are

- P_{pilot} = 15 % to 20% $P_{cell\text{-}site}$
- P_{sync} = 10% of P_{pilot} = 1.5% to 2% $P_{cell\text{-}site}$
- P_{paging} = 30% to 40% of P_{pilot} = 7% $P_{cell\text{-}site}$
- $P_{traffic}$ = [1 – (0.2+0.02+0.07)]
  = 71% to 76.5% $P_{cell\text{-}site}$

P_{paging} and $P_{traffic}$ represent the total allocated power for all the paging and traffic channels, respectively, and $P_{cell\text{-}site}$ is the total transmit power of the cell site.

$$P_{(traffic)/(mobile)} = P_{traffic}/(M_{total} \cdot \alpha_{chan}) \quad \ldots (4)$$

$$M_{total} = M(1+\xi_{co}) \quad \ldots (5)$$

where

M = number of active mobiles per sector

ξ_{co} = channel overhead factor for extra traffic channels required for mobiles in different types of soft handoffs

α_{chan} = channel activity factor

$$P_{(paging)/(channel)} = P_{paging}/N_p$$

where

N_p = number of paging channels

$P_{(traffic)/(mobile)}$ is a nominal value. Actual power allocated for each mobile can be upto ± 4 dB, depending upon the downlink power control for each mobile. On the downlink, extra traffic channels are required for the mobiles in various types of soft handoffs. The percentage of the coverage area in a handoff is the design criterion. The extra number of traffic channels in a handoff can be related to the area in the handoff.

Pilot Channel

The mobile continuously measures E_c/I_t of the pilot channel and compares it against threshold values of the handoff parameters, T_ADD and T_DROP (E_c is the energy per chip and I_t is the interference plus noise density measured on the pilot channel). The mobile reports the results of these comparisons to the serving cell. The serving cell decides whether the mobile needs handoff. The E_c/I_t of the pilot channel is needed to determine whether the mobile is within the coverage area of the particular cell. The pilot signal from a cell is transmitted at relatively higher power as compared with those of the other downlink channels (i.e.

paging, sync, traffic). In order to set up a call, the mobile must successfully receive the pilot signal. The pilot channel acts as a coherent phase reference for demodulation of other channels on the downlink. Since, E_c/I_t effectively determines the coverage area of a cell or sector, it is essential that the E_c/I_t be sufficiently large.

Traffic Channel

Let $(S_1)_m$ = power received by the mth mobile from the cell/sector providing maximum power (i.e. serving cell), and $(S_2)_m$ .... $(S_Q)_m$ = power received by the mth mobile from neighboring cells. Thus, $(S_1)_m > (S_2)_m >$ .... $(S_Q)_m > 0$

We assume that the power received from Q cells or sectors is significant and the power from all other cells is negligible. We assume that all cell sites beyond the second ring around a serving cell contribute negligible received power, so that $Q \leq 18$. The received bit energy-to-interference plus thermal noise for the mth mobile will be

$$\left(\frac{E_b}{I_t}\right)_m \geq \left(\Phi_t.\frac{B_w}{R}.\frac{\omega_m(S_1)_m}{\sum_{j=1}^{Q(S_j)m}(S_j)_m + N_0 B_w}\right) \quad \text{... (6)}$$

where

Φ_t = fraction of total cell site power assigned to traffic channels

$(1-\Phi_t)$ = fraction of total cell power assigned to transmission of overhead channels (pilot, sync, and paging channels)

N_0 = thermal noise density

B_w = spreading bandwidth

R = data rate

G_p = processing gain = $B_w/R = R_c/R$

ω_i = fraction of total power allocated to the ith mobile

M = number of users in mobile's own cell or sector

$$\sum_{i=1}^{M}\omega_i \leq 1$$

From equ. (6) the weighting factor ω_m is given by

$$\omega_m \leq \frac{(E_b/I_t)_m}{\Phi_t G_p}\left[1+\left(\frac{\sum_{j=2}^{Q}(S_j)}{(S_1)}\right)\frac{\sigma_n 2}{(S_1)_m}\right] \quad \text{... (7)}$$

where σ_n^2 = thermal power

Since $\Phi_t S_1$ is the maximum total power allocated to the cell/sector containing the given mobile and M is the total number of mobiles in the cell/sector, we define the relative received cell power as

$$f_m = 1+\left(\frac{\sum_{j=2}^{Q}(S_j)}{(S_1)}\right)_m \quad \text{... (8)}$$

Next we combine the last two equations (7) and (8), and get

$$\sum_{i=1}^{M} f_i \leq \left(\frac{G_p\Phi_t}{E_b/I_t} - \sum_{i=1}^{M}\frac{\sigma_n 2}{(S_1)_i}\right) = \Delta f \quad \text{... (9)}$$

In general, back ground noise is well below the total largest received cell site signal power (second term of equ. (9)) and is typically neglected relative to the first term. The capacity can be estimated from the outage or blocking probability, defined as

$$P_{out} = p_r\,[BER > (BER)_{sp}] \quad \text{... (10)}$$

where

$(BER)_{sp}$ = specified bit error rate for which E_b/I_t is equal to $(E_b/I_t)_{sp}$

Conclusion

The necessary equations to calculate the downlink and uplink capacity of CDMA IS-95 system were given.

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