A Comparison of CDMA and TDMA Systems

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Abstract

In this reports two candidates for high capacity cellular systems are simulated and analysed, one CDMA and one TDMA system. Simulations of the CDMA example indicate a high sensitivity to variations in certain system parameters.

The TDMA example is a GSM system using random frequency hopping and operating without frequency planning. The simulations show that the TDMA system has at least the same capacity as the CDMA candidate. Soft capacity, efficient use of voice activity and diversity are features available in both systems.

1 Introduction

CDMA has been introduced as a candidate for high capacity cellular systems [1, 3]. Another atractive alternative is to refine todays TDMA systems already in operation into high capacity cellular TDMA or hybrid TDMA/CDMA systems for the future.

Introduction of dynamic channel allocation has been suggested as an evolution of TDMA [4, 5]. Another alternative is the frequency hopping TDMA system presented below. It can be seen as a TDMA/CDMA hybrid.

In this report, the issues of system capacity, flexibility and operational features are investigated for the CDMA system example and a comparison is made with the frequency hopping TDMA system.

2 The CDMA system

A description of the CDMA system is given in [3]. A direct sequence spreading technique is used, spreading the $R = 8$ kbps user data over the bandwidth $W = 1.25$ MHz trough a low-rate convolutional encoder and a Walsh-Hadamard transform.

Scrambling the data with PN-sequences provides decorrelation of the different users. The result is that the interference from all co-existing channels will add to a noise-like interference which is efficiently supressed in the despreading process.

The wide channel bandwidth allows a high resolution when extracing multipaths. Thus, a high degree of path diversity is availiable. For complexity reasons however only a few paths will be resolved. The remaining paths have to be supressed.

The analysed system is specified with a re-use factor of 1, i.e. the same frequency can be re-used in all base stations (BSs). This configuration is possible by the inherent interference diversity. Since the co-channel interference will be the average interference from several mobile stations (MSs), the worst case interferer will no longer determine the re-use factor as it does in conventional TDMA- and FDMA schemes.

For a CDMA system to work, the users sharing the same carrier must be received with equal power levels. Otherwise some users will jam the others. This makes heavy demands on the up-link design where the power control must have a wide dynamic range to compensate for the near/far effect. The power control must also be very fast since it has to compensate the multipath fading for slowly moving MSs. For fast moving MSs this is not necessary since the interleaving and coding probably provides sufficient quality in this case.

In [3] BS controls the MS power trough a closed loop. Every millisecond a command is transmitted to the MS demanding either an increase or a decrease by 0.5-1.0 dB of its power level. The algorithm is claimed able to track Rayleigh fading for vehicle speeds up to 25-100 mph.

Power control in the down-link is not as critical as in the up-link. Here all signals propagate along the same path, naturally giving balanced signal levels. It may however be used to increase capacity.

A study of the performance and capacity of the CDMA system is made in [1] and [2]. In both papers analytical expressions are used for the capacity calculations. Here, Monte-Carlo simulations are performed, allowing the introduction of hand-off margin, power control limitations etc. The evaluation is limited to the up-link since this is the most critical connection in the system.

A system comprising one local BS and three rings of interfering BSs is simulated. A hexagonal omni-cell pattern is assumed, and the MSs are randomly spread with uniform distribution in a circle having an equivalent area of the 37 hexagons. For each MS the power attenuation to each of the BSs are calculated. A distance dependent path-loss $r^{-\alpha}$ is used where α is the propagation exponent. The shadowing effects are modelled by independent, log-normally distributed random variables having a standard deviation of 8 dB. Hand-off is made to the BS resulting in the least attenuation.

In each simulation the C/I-level for the MSs con-

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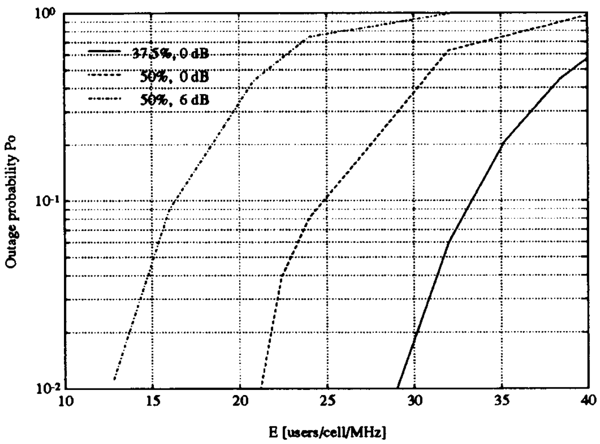

Figure 1: CDMA outage probability vs spectrum efficiency. *Right*: Ideal. *Middle*: canging channel activity to $\vartheta = 50\%$. *Left*: adding handoff margin $\Delta_{HO} = 6$ dB.

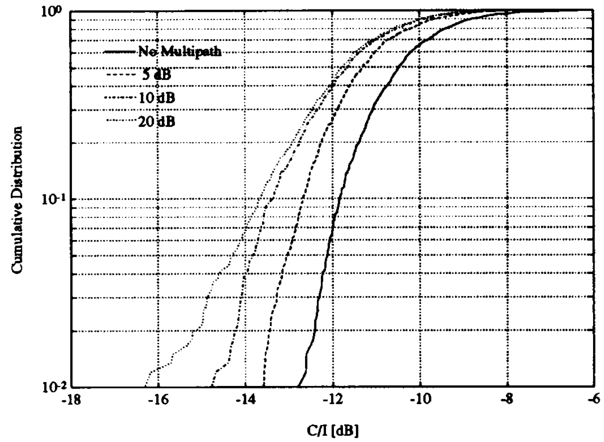

Figure 2: CDMA C/I-distributions in Rayleigh fading environment with max MS power limits $\nu = 5, 10$ and 20 dB.

nected to the local BS is calculated. Here C is the received power from the desired MS and I is the sum of undesired powers from all MSs sharing the same bandwidth. C/I-values for MSs not connected to the local BS are discarded due to boundary effects. Repeated simulations give a C/I-distribution.

The capacity is constrained by the minimum acceptable transmission quality $BER \leq 10^{-3}$ after decoding. In [1] this is claimed to be reached at $E_b/N_0 \geq 7$ dB. Assuming neglegible background noise this is directly translateable to the minimum C/I-level

$$\gamma = \frac{R \cdot (E_b/N_0)}{W} \qquad (1)$$

which for the vocoder bitrate $R = 8$ kbps is $\gamma = -14.9$ dB. The probability of having a C/I-level below γ is called the outage probability P_O and is found from the C/I-distribution. Note that outage implies that *all* MSs connecetd a the BS have unacceptable transmission quality.

Simulated values of P_O vs different values of spectrum efficiency E (users/cell/MHz) are given in Figure 1. The rightmost curve yields the parameter values used in [1]. For $P_O = 1\%$ the capacity is found to be $E = 29$ users/cell/MHz which gives 36 users/cell according with the result in [1]. However, this capacity figure is achievable only under idealized conditions. Choosing slightly more pessimistic parameter values reduce performance significantly.

The voice activity factor of $\vartheta = 37.5\%$ claimed in [1] seems very optimistic. In [2] the value $\vartheta = 60\%$ was used instead. Here $\vartheta = 50\%$ has been used giving the expected capacity reduction of 30% shown in Figure 1.

The choice of propagation parameters is known to depend heavily on geography. Own measurements gave path loss exponents mainly between $\alpha = 3$ and 4, but also values as low as 2 and as high as 5 occured. Changing the path loss exponent from 4 to 3 in the simulations gives a capacity reduction of 20%.

In deep fading dips the MSs must dramatically increase their output power levels in order to compensate the multipath fading. If a MS is located close to a neighbouring BS this may cause severe interference to the MSs at that BS. In the simulations a Rayleigh distributed fading is assumed. It is modeled by scaling the signals with independently Nakagami-2 distributed random variables corresponding to ideal, two-antenna diversity. All MSs will perfectly handle the fading, i.e. move at speeds less than 25 mph. However, parts of the deepest fading dips will remain due to an upper limiting of the MS output power. C/I-distributions for the upper limits $\nu = 5, 10$ and 20 dB are given in Figure 2. For the most realistic power limit, $\nu = 10$ dB, the C/I performance is reduced by 2 dB compared to a non-fading environment. Translated to capacity this is a reduction of 45%, implying that power control of the Rayleigh fading may cause severe problems to the system.

Perfect power control has been assumed in the capacity calculations in [1]. Here long-term power control er-

Table 1: Relative capacity degradation for variations in CDMA simulation parameters

Parameter:	Ideal[1]	Test value	Capacity change
Voice activity ϑ	37.5%	50%	−30%
Path-loss α	4	3	−20%
Multipath fading	No	Yes	−45%
HO-margin Δ_{HO}	0 dB	6 dB	−40%
Power control σ_{err}	0 dB	1 dB	−35%

rors are included by scaling the MS transmit-powers with an independent, zero mean, log-normally distributed random variable, having standard deviation σ_{err}. Simulations show that the degradation is large. For the moderate error value $\sigma_{err} = 1$ dB the capacity is reduced by 35%, demonstrating an extremely high accuracy needed in the power control to maintain operation.

To prohibit too frequent hand-offs, a hysteresis has commonly been used in cellular systems. This has been obtained by prohibiting the hand-off until a BS occures that gives more than Δ_{HO}dB reduction in path loss. Soft hand-off is an alternative to using hand-off margins, however, this has not been a prefered solution since connecting the MSs to more BSs simultaneously results is a dramatic increase in network complexity. The leftmost curve in Figure 1 shows P_O vs E for the CDMA system using hard hand-off with $\Delta_{HO} = 6$dB. A capacity reduction of 40% is observed compared to the case of ideal hand-off implying that soft hand-off is mandatory in this system.

Table 1 is a summary of the sensitivity to parameter variations. All capacity changes cannot be added, but the total picture is that the optimistic capacity claims in [1] are unrealistic. Accounting for the reduced voice activity of $\vartheta = 50\%$ and including the effect of multipath fading gives the capacity $E = 12$ users/cell/MHz. This can be compared to the AMPS analog 30 kHz system which with a 21 re-use frequency plan has the capacity 1.6 users/cell/MHz. Thus, a realistic CDMA capacity gain would probably be somewhat less than 10 compared to AMPS.

3 Frequency Hopping TDMA

Comparisons between CDMA and TDMA systems have been made by several authors [2, 4, 6].

Results reported by Baier et.al. [2] suggest that TDMA and CDMA system capacity is similar. They proposed a TDMA system using slow frequency hopping to provide interferer diversity [6]. The cluster size K was varied continously to simulate a continous set of spectrum efficiency values E. The interference level in [2] was calculated as the average interference over all frequencies used for hopping, i.e.

$$I = I_{external} = \frac{1}{N_f} \sum_i I_i \qquad (2)$$

where N_f is the number of frequencies used for frequency hopping and I_i is the interference contribution from the ith external user. The system parameters used were taken from the GSM-system with a half-rate speech codec, see Table 2.

Here we will simulate TDMA in the same way but with a fixed cluster size $K = 1$, i.e. all frequencies are re-used in all sites and no frequency planning is required. By varying the subscriber load, different values of E can be simulated. Random frequency hopping is performed over N_f=8 frequencies. The frequency hopping patterns

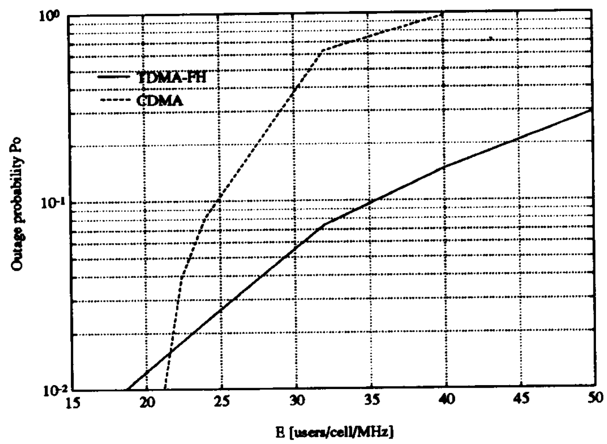

Figure 3: TDMA and CDMA outage probability vs. spectrum efficiency.

within the cell are strictly orthogonal, while the patterns are uncorrelated between the cells. Power control is used to achieve equal received powers at the site.

Each BS serves on the average N_s users per TDMA time slot, where $N_s \leq N_f$. N_s determines the spectrum efficiency E in users/cell/MHz:

$$E = \frac{N_s M}{N_f W} \qquad (3)$$

where M is the number of TDMA time slots and W is the bandwidth, see Table 2. The maximum available capacity of a BS is $E = 80$ users/cell/MHz.

The simulation model is in all other aspects equivalent to the one used for the CDMA simulations, including the ideal power control used. Up-link C/I-distributions are calculated and used to derive the outage probability. The result is plotted in Figure 3 together with the middle CDMA curve from Figure 1. The TDMA system capacity is 19 users/cell/MHz at 1% outage probability, while the corresponding CDMA figure is 21 users/cell/MHz. This shows that TDMA using 8 frequencies for interferer diversity has the same capacity as the CDMA system in [1]. The conclusion is confirmed in [2].

The GSM recommendation specifies a TDMA system with options for random frequency hopping and adaptive

Table 2: TDMA system parameters.

TDMA multiplex factor	M	16
No. of frequencies	N_f	8
User bit rate	R	6.5 kbit/s
Bandwidth	W	200 kHz
C/I limit [2]	$(C/I)_{req}$	6 dB
Channel activity	ϑ	50 %
HO-margin	Δ_{HO}	0 dB

power control. This indicates that one-cell frequency re-use could be possible in GSM. Further simulations of the GSM air interface operating in frequency hopping conditions will be needed to verify this.

4 System Comparison

The two system proposals presented above have approximately equal spectrum efficiency under the assumptions made. Below is a comparison of other system aspects that should be considered.

A TDMA system with random frequency hopping and a re-use factor of one gives interferer diversity much in the same way as CDMA does. The interference power will be the average from many interferers instead of a few possibly large ones. Interferer diversity makes it possible to exploit channel activity to get a capacity increase.

Frequency diversity in the CDMA system requires a multi-tap Rake receiver to exploit the wide bandwidth. In the TDMA system, the random frequency hopping inherently provides frequency diversity. Other diversity schemes such as antenna diversity, transmitter diversity and path diversity can be implemented in a TDMA system as well as in CDMA. The path diversity in TDMA can be provided by an equaliser.

In the CDMA system, a tight up-link power control is essential for operation. The TDMA system uses power control to reduce power comsumption in the mobiles and to gain capacity, but it is not as critical as in CDMA.

A CDMA system does not have a hard capacity limit. This is also true for the TDMA-proposal since it only uses 10-30% of the frequencies available at full capacity. Figure 3 shows that more soft capacity is available in TDMA since the outage probability increases more slowly.

The soft capacity also makes TDMA very flexible to unequal cell loading. A number of cells forming a line can be loaded up to 200% of the normal capacity if the surrounding cells have a 65% load. The high flexibility is due to the internal interference always being zero. In CDMA, the interference is mostly internal making it harder to increase capacity at peaks, since the cell will jam itself. A line of cells in the CDMA system can be loaded to 120% of nominal capacity, making it necessary to decrease the surrounding cells to 30%.

In the simulations presented in Section 3, 8 frequencies are used for frequency hopping. If the number is increased and averaging of interference can be performed, the system capacity will increase above that of the CDMA reference system. A TDMA system with a specific N_f will always have a higher spectrum efficiency than a similar CDMA system with the same interference diversity factor (processing gain). The reason is that the users within each cell are orthogonal i TDMA [6].

In a cellular system including both micro and macro-cells, MSs in the macro cells will use higher power levels and create high interference in the micro cells. The solution is to use different frequencies in macro and micro cells. This is a disadvantage in CDMA if mobile assisited hand-off is used, since transmission is continous and no time slots are available for measurement such as in TDMA.

5 Conclusion

This report points out some strong and weak points in CDMA by simulation of a system example. The results indicate that performance can be severely degraded when assuming non-ideal conditions. A comparison is made with a frequency hopping TDMA system.

Simulations show that the capacity of the TDMA system is equal to or even better than in the CDMA example in ideal conditions. It also has most of the advantages that CDMA has, concerning e.g. frequency diversity and use of voice activity. The soft capacity properties of the TDMA system is superior to CDMA, making operation in inhomogeneous cell loads more efficient.

The conclusion is that when comparing CDMA and TDMA as multiple access schemes, capacity is not the only issue. The main point is how to exploit the capacity potential and achieve the system features wanted.

The overall picture is that a very careful system design is necessary to utilize the full potential of CDMA as well as TDMA systems. Further simulations are needed to verify the properties of both candidates.

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