IEEE Australia–New Zealand Postgraduate Student Paper Competition 1995 – First Prize
Awarded at ANZIIS '96, 18–20 November 1996, Adelaide, Australia

Cochannel Reuse Ratio Distributions in Dynamic Channel Assignment Microcellular Systems

Brendan C. Jones, *Student Member IEEE*

Electronics Department, School of Maths, Physics, Computing and Electronics
Macquarie University NSW 2109 Australia

`email: brendan@mpce.mq.edu.au`

ABSTRACT: *This paper presents a novel analysis of cochannel reuse ratio distributions in DCA microcell systems, and compares the results with conventional FCA macrocell systems. Computer simulations show that DCA systems exhibit significantly closer channel reuse than FCA systems for a significant proportion of terminals. Mathematical analysis is used to show that this is a fundamental consequence of the microcell architecture and that the resultant interference distributions cannot be obtained using conventional cellular engineering techniques. A closed form expression for the cochannel reuse ratio distribution in DCA microcell systems is derived.*

1. INTRODUCTION

The concept of cellular telecommunications, where radio channels are reused at less than horizon distances, was developed by the Bell Telephone Laboratories in the early 1970's [1].

The capacity of cellular systems can be increased by splitting existing cells into smaller cells, thereby reusing frequencies more often in a geographic area. In practice, however, there is a capacity limit as cells cannot be split indefinitely. The lower cell radius limit for most conventional cell systems (herein referred to as 'macrocells') is in the range of 1 to 1.5 km [2].

Microcellular technologies are being developed to provide wireless communications to very large numbers of people at a much higher user density than is possible with macrocells [3]. Microcell architecture differs from macrocell architecture in three fundamental ways:

- The cells are typically less than 1 km in radius
- The mobile terminals radiate much smaller power levels
- The available channels are not partitioned (i.e. all channels are available in every cell)

In macrocell systems, channels are permanently pre-allocated in each cell and interference is controlled using channel reuse rules. This is called Fixed Channel Assignment (FCA).

It is impractical in a microcell system to preallocate channels using FCA. Instead, channels are allocated at call set up time by the mobile terminal or base station, with the aim of the channel assignment algorithm being the minimisation of interference. This is called Dynamic Channel Assignment (DCA).

In FCA systems there is a simple relationship between the cluster size *C*, and the signal to interference (*S*/*I*) performance of a receiver at a cell boundary in the presence of cochannel interferers [4–8]. However, no such simple relationship between cluster size and worst case *S*/*I* performance exists for microcells [7].

This paper compares the cochannel reuse ratio probabilities in microcell and macrocell systems through Monte Carlo simulation and theoretical analysis. The analysis provides a means of establishing a theoretical limit to cochannel reuse in DCA microcell systems, and therefore the quality of the radio coverage offered by the system.

2. CHANNEL REUSE RATIOS

The principle of channel reuse within a cellular communications system is shown in an idealised form in Fig. 1. In an FCA system, the available channels are divided into *C* sets (where *C* is called the cluster size), and each channel set is used within cells (represented by hexagons) in such a way that the distance between cells using the same channel set divided by the cell radius is a constant, called the cochannel reuse ratio (CRR). In Fig. 1, the FCA cluster size *C* is 3 and the nominal CRR is $\sqrt{3C} = 3.0$ but the minimum possible CRR is 2.0 due to the constraints designed into the system.

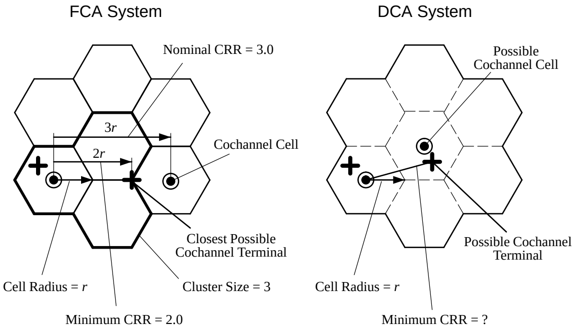


Fig. 1 – Cochannel Reuse Ratio in FCA vs DCA Systems

In FCA systems, the *S*/*I* requirement of the particular technology determines the minimum cluster size and the channel assignment pattern. This design principle, however, breaks down in DCA microcells because there is no channel partitioning. Every terminal has the capability of using any channel in any cell and there is not necessarily a guaranteed minimum CRR. The minimum CRR in a microcell systems is a function of pure RF blocking at a receiver (i.e. interference prevents the establishment of a radio link), and the reuse ratio probabilities cannot be predicted using macrocell design principles [9].

Generally researchers do not examine cochannel reuse ratio *probabilities* despite the fact that terminals are randomly located. For example, Linnartz [10] assumed all interfering terminals in an FCA system were located at the nominal reuse distance; Wang and Rappaport [11,12] assumed terminals were in the 'worst case' location in each cell; and Chuang [13] assumed terminals were located at regular fixed points throughout the service area. While this may be acceptable for an FCA system, it is not clear that it is appropriate for DCA systems.

2.1 Monte Carlo Simulation

A computer program has been developed to model arbitrary cellular networks [14–18]. The program can be loaded with the technical specifications for existing or proposed macrocell or microcell technologies, and perform a Monte Carlo simulation to estimate system performance parameters such as CRR probabilities.

In each simulation, a random sequence of call attempts can be made from mobile terminals randomly placed within the system service area. A mobile terminal's call attempt is deemed to fail if it doesn't meet the required signal to noise plus interference ratio $S/[N+I]$ on both the uplink and downlink. Initially successful mobile terminals can also drop out if the success of other terminals leads to an increase in interference and the $S/[N+I]$ ratio falls below threshold. In-cell channel reassignments can be performed if the mobile technology specification allows it.

Note that it is difficult to construct a fair experiment to compare different cellular technologies. Wherever there was not an obvious equivalent basis for comparison (e.g. offered traffic load), the simulation parameters were chosen so that any differences in system performance should be reduced rather than increased.

A system of 21 cells arranged in a regular, hexagonal pattern was simulated for four mobile technologies: GSM, CT2, DECT and PHS. For the FCA macrocell system (GSM) the cluster size was set to 3 and the cells were spaced by √3 km, giving a target cell radius of 1 km – a very small GSM cell. For the DCA microcell systems (CT2, DECT and PHS) the cells were spaced by 100√3 m, giving a target cell radius of 100 m. This is towards the lower end of microcell sizes, but not at the limit.

All systems were assumed to be synchronised, hence there was no intertimeslot interference. Interference between users was purely a result of RF channel spill from other users transmitting on the same timeslot.

For each technology simulated, the offered traffic level was set so that approximately 10% of the total number of channels available in that cell would be used simultaneously. Another possible way of performing a fair comparison would be to vary the offered traffic levels in each simulation to meet a fixed call loss rate of, say, 2%. This, however, tends to produce less conservative results.

In each simulation, terminals were randomly placed with a uniform area distribution within the 21 cell service area, and each terminal chose the 'best' server at call setup time on the basis of received signal strength indication (RSSI). A single exponent distance dependent path loss propagation model of the form $P_r \propto P_t d^{-\gamma}$ was used, with a path loss exponent $\gamma = 3.0$. Lognormal shadowing and multipath fading were not considered.

2.2 Cochannel Reuse Ratio Distributions

Simulations were performed to estimate the CRR probabilities for GSM, CT2, DECT and PHS. A total of 10000 static call attempts were made in each simulation, and whenever a pair of *successful* terminals were detected to be using the same radio channel and timeslot a 'cochannel event' was deemed to have occurred and the CRR was calculated. The CRR was calculated as the distance of the interfering terminal from the wanted link's fixed station divided by the nominal cell radius. The results of these simulations are summarised in Table I.

TABLE I
COCHANNEL REUSE RATIO SIMULATION RESULTS

Parameter	**GSM**	**CT2**	**DECT**	**PHS**
Cells	21	21	21	21
Terminals	525	84	252	630
Total Call Loss (%)	1.27	4.28	2.99	0.87
Cochannel Events	2252	6881	11508	7885
Mean CRR	4.17	4.73	4.35	4.54
Std. Dev. CRR	1.32	1.46	1.56	1.51
Maximum CRR	6.98	8.53	8.52	8.51
Minimum CRR	**2.04**	**1.33**	**1.20**	**1.25**

In the case of DECT there were more cochannel events than call attempts. This is because a single terminal can experience more than one cochannel interferer, especially when the total number of terminals exceeds the total number of available channels.

Although the average CRR was lower for GSM than the microcell systems, the *minimum* CRR was much lower in the microcell systems. Clearly the actual CRR distribution is critical, as the proportion of terminals successful with small CRRs will affect the radio coverage quality. The cumulative distribution of the CRR for each technology is plotted in Fig. 2 on a log probability scale to highlight the critical area of interest – the CRR for the last 10% to 1% of cochannel events.

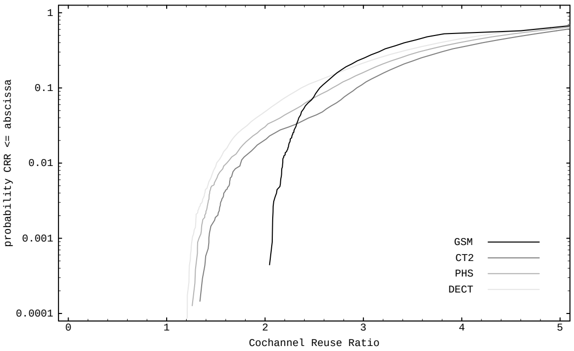


Fig. 2 – CRR distribution for four mobile technologies

Examining Fig. 2, it can be seen that the microcell systems exhibit similar CRR distributions, and that a significant proportion of cochannel terminals operated successfully at CRRs smaller than the smallest possible CRR of 2.0 for the GSM system modelled. The simulation results indicated that 2.1% of cochannel CT2 terminals, 3.0% of cochannel PHS terminals, and 4.5% of cochannel DECT terminals successfully operated at CRRs of less than 2.0.

Fig. 2 also suggests that RF blocking, or some other mechanism, does eventually place a limit on the minimum CRR in a DCA system, however the lower limit is at different points for each microcell technology (from 1.21 for DECT to 1.33 for CT2). In Sec. 3 a theoretical analysis is performed to quantify this lower CRR limit.

The physical nature of the CRR distributions in Fig. 2 can be illustrated by plotting the locations of the cochannel interferers with respect to the nominal, idealised, cell boundaries. Fig. 3 shows the location of the first 100 cochannel interferers to users in the central reference cell for the GSM and DECT simulations. The locations of the users in the reference cell are not shown.

The significance of the different CRR probabilities are immediately apparent in Fig. 3. Firstly, the operation of FCA in the GSM system prevents cochannel interferers establishing calls in cells adjacent to the reference cell, and only in six designated first tier cells. In DECT, however, it is clear that cochannel interferers do establish themselves in cells adjacent to the reference cell, and are not restricted in location in first tier cells.

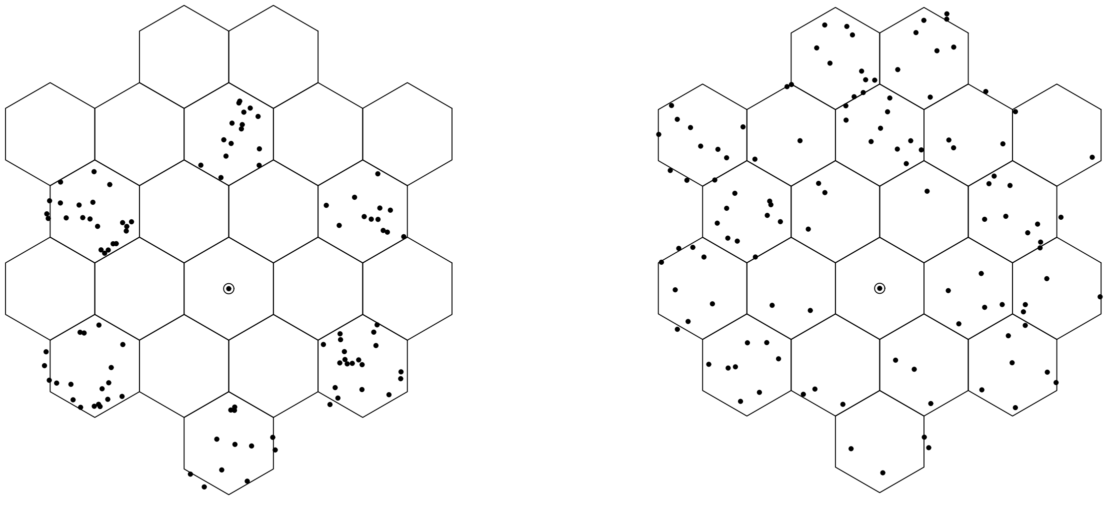
Even though the call loss rates were low for these systems, such close channel reuse compromises coverage quality because cochannel interference severely limits the terminal range [14,15]. In a DCA system, close cochannel reuse occurs through the statistical fortune of the specific location of the terminals in question (e.g. the wanted terminal is close to its fixed station and thus can tolerate high levels of interference). When those terminals move, their limited coverage range could force a handoff or in-cell channel reassignment, and as interference levels increase, the probability increases that such handoffs or reassignments could be unsuccessful [16,17].

3. COCHANNEL REUSE RATIO DISTRIBUTION ANALYSIS

The factors which influence the CRR probabilities include:

- The terminal distribution
- The cell layout and service area extent
- The channel assignment algorithm
- The probability of successful call establishment on a given channel

By making simplifying assumptions and following the channel reuse model as shown in Fig. 4, the CRR probabilities may be derived analytically. To calculate the reuse probabilities the *a priori* assumption is that a cochannel reuse event has occurred, hence the terminal M_0 must be in the reference cell (radius r) at some radius ρ from the reference cell site F_0. The interfering terminal M_i is assumed to be within the service area of radius R and is at some radius Π from F_0.



GSM ⦿ *Reference Cell* **DECT**

Fig. 3 – Location of the first 100 cochannel interferers for GSM and DECT

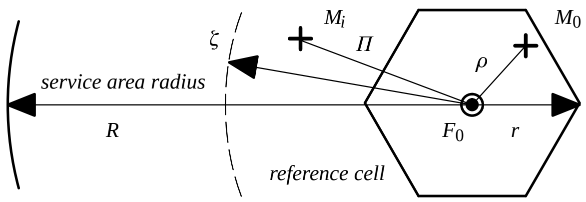


Fig. 4 – Channel reuse model

The signal received at F_0 from M_0 is denoted as s, the interference received at F_0 from M_i as i, and the signal to interference ratio s/i as z, with the random variable (RV) to which it belongs $\mathscr{Z}$. The CRR is given by $\Re = \Pi/r$ and the RV to which it belongs is denoted $\mathscr{R}$. For DCA systems the problem is to compute the conditional distribution of the CRR, which by definition is:

$$\begin{aligned} F_{\mathscr{R}}\left(\Re \mid z \geq Z\right) &= F_{\mathscr{R}}\left(\frac{\Pi}{r} \,\middle|\, \frac{s}{i} \geq Z\right) \\ &= \frac{p\left\{\frac{\Pi}{r} \leq \Re \ , \ \frac{s}{i} \geq Z\right\}}{p\left\{\frac{s}{i} \geq Z\right\}} \end{aligned} \tag{1}$$

where $p\{x\}$ is a probability of event x occurring and Z is the required signal to interference protection ratio for the particular technology.

The significance of the radius ζ in Fig. 4 is as follows. There will be some range $\Pi > \zeta$ at which the interferer M_i cannot generate sufficient interference at F_0 to cause M_0's link to fail, regardless of M_0's location. Thus when $\Pi > \zeta$, the signal to interference ratio z will always be greater than or equal to Z and the probabilities $p\{\Pi/r \leq \Re\}$ and $p\{s/i \geq Z\}$ in the numerator of Eq. (1) become independent. Conversely, for $\Pi \leq \zeta$ the probabilities in the numerator of Eq. (1) are *not* independent and therefore the computation of $p\{\Pi/r \leq \Re,\ s/i \geq Z\}$ becomes more complicated.

The value of ζ may be easily computed assuming a single-slope distance-dependent path loss propagation model. With this model $s = \kappa P_t \rho^{-\gamma}$ and $i = \kappa P_t \Pi^{-\gamma}$, κ is an RF constant, P_t is the transmit power and γ is the path loss exponent. The minimum possible signal power occurs when M_0 is at the periphery of its cell, i.e. $s = \kappa P_t r^{-\gamma}$, hence the minimum signal to interference ratio for M_0 is given by:

$$z = \frac{s}{i} = \frac{\kappa P_t r^{-\gamma}}{\kappa P_t \Pi^{-\gamma}} = \left(\frac{\Pi}{r}\right)^{\gamma} = \left(\frac{r\Re}{r}\right)^{\gamma} = \Re^{\gamma} \tag{2}$$

When $z = Z$,

$$\zeta = r\Re = rZ^{1/\gamma} \tag{3}$$

hence the conditional distribution of Eq. (1) is piecewise continuous about a reuse ratio $\Re = Z^{1/\gamma}$. It can be shown that when $\Re \leq Z^{1/\gamma}$, Eq. (1) can be written as:

$$\frac{p\left\{\frac{\Pi}{r} \leq \Re \ , \ \frac{s}{i} \geq Z\right\}}{p\left\{\frac{s}{i} \geq Z\right\}} = \frac{F_{\mathscr{R}}(\Re) - F_{\mathscr{R}\mathscr{Z}}(\Re, Z)}{1 - F_{\mathscr{Z}}(Z)} \qquad 0 \leq \Re \leq Z^{1/\gamma} \tag{4}$$

where $F_{\mathscr{R}\mathscr{Z}}(\Re, Z)$ is the joint distribution of $\mathscr{R}$ and $\mathscr{Z}$.

For the following derivation, it will be assumed that only *one* cochannel interferer exists for any particular cochannel event, and that it is the dominant interference source (i.e. other interferers and receiver noise n are negligible).

Examining Eq. (4), the first expression requiring evaluation is $F_{\mathscr{R}}(\Re)$. If it is assumed that M_0 is distributed within the reference cell (radius r) uniformly by area and that M_i is distributed within the service area (radius R) uniformly by area, it can be deduced from first principles that:

$$F_{\mathscr{R}}(\Re) = \left(\frac{r\Re}{R}\right)^2 \tag{5}$$

Next, the joint distribution function $F_{\mathscr{R}\mathscr{Z}}(\Re, Z)$ is defined as:

$$F_{\mathscr{R}\mathscr{Z}}(\Re, Z) = \int_0^{\Re} \int_{\alpha^{-1}\mathbb{R}^{\gamma}}^{Z} f_{\mathscr{Z}}\left(z \mid \mathscr{R} = \mathbb{R}\right) f_{\mathscr{R}}(\mathbb{R}) \, dz \, d\mathbb{R} \tag{6}$$

where $\mathbb{R} \in \mathscr{R}$ is a dummy variable. The density function $f_{\mathscr{R}}(\Re)$ is simply the derivative, with respect to $\Re$, of the distribution function $F_{\mathscr{R}}(\Re)$ of Eq. (5).

The conditional density function $f_{\mathscr{Z}}(z \mid \mathscr{R} = \mathbb{R})$ is the density function of the signal to interference ratio z given a specific reuse ratio and thus a specific amount of interference. Under these conditions the minimum possible value of z is $\mathbb{R}^{\gamma}$. Given the assumed distributions of M_0 and M_i the density functions of the signal and interference powers can be shown to be:

$$f_S(s) = \frac{2}{\gamma r^2}(\kappa P_t)^{\frac{2}{\gamma}} \, s^{-\frac{\gamma+2}{\gamma}} \qquad \kappa P_t r^{-\gamma} \leq s < \infty \tag{7}$$

$$f_I(i) = \frac{2}{\gamma R^2}(\kappa P_t)^{\frac{2}{\gamma}} \, i^{-\frac{\gamma+2}{\gamma}} \qquad \kappa P_t R^{-\gamma} \leq i < \infty \tag{8}$$

With appropriate transformations, the required conditional density function is given by:

$$f_{\mathscr{Z}}\left(z \mid \mathscr{R} = \mathbb{R}\right) = \frac{2\mathbb{R}^2}{\gamma} \, z^{-\frac{\gamma+2}{\gamma}} \qquad \mathbb{R}^{\gamma} \leq z < \infty \tag{9}$$

thus the joint distribution function as per Eq. (6) may be evaluated to be:

$$F_{\mathscr{R}\mathscr{Z}}(\Re, Z) = \frac{r^2}{2R^2}\left[2\Re^2 - \Re^4 Z^{-\frac{2}{\gamma}}\right] \qquad 0 \leq \Re \leq \frac{R}{r} \ , \ \Re^{\gamma} \leq Z < \infty \tag{10}$$

The density function of the signal to interference ratio $z = s/i$ is given by:

$$f_{\mathcal{Z}}(z) = \int_{-\infty}^{\infty} |i| \; f_{SI}(zi, i) \; di = \int_{-\infty}^{\infty} |i| \; f_S(zi) \; f_I(i) \; di \quad (11)$$

as s and i are independent. It can be shown that $f_{\mathcal{Z}}(z)$ is piecewise continuous about $z = (R/r)^{\gamma}$, with the expression:

$$f_{\mathcal{Z}}(z) = \begin{cases} \dfrac{r^2}{\gamma R^2} \; z^{\frac{2-\gamma}{\gamma}} & 0 \le z \le \left(\dfrac{R}{r}\right)^{\gamma} \\[2ex] \dfrac{R^2}{\gamma r^2} \; z^{-\frac{2+\gamma}{\gamma}} & \left(\dfrac{R}{r}\right)^{\gamma} < z < \infty \end{cases} \quad (12)$$

The distribution function $F_{\mathcal{Z}}(z)$ can be obtained by integrating Eq. (12) with respect to z over the appropriate limits.

The CRR distribution for $\Re \le Z^{1/\gamma}$ is then computed from Eq. (4). For brevity, the derivation of the CRR distribution when $\Re > Z^{1/\gamma}$ is omitted, however it can be shown that the complete CRR distribution is given by:

$$F_{\Re}\left(\Re \;\middle|\; z \ge Z\right) = \begin{cases} \dfrac{r^2 \Re^4 Z^{-\frac{2}{\gamma}}}{2R^2 - r^2 Z^{\frac{2}{\gamma}}} & 0 \le \Re \le Z^{1/\gamma} \\[2ex] \dfrac{2r^2 \Re^2 - r^2 Z^{\frac{2}{\gamma}}}{2R^2 - r^2 Z^{\frac{2}{\gamma}}} & Z^{1/\gamma} < \Re \le \dfrac{R}{r} \end{cases} \quad (13)$$

Eq. (13) represents the theoretical CRR limit for a DCA system with interference protection ratio Z and cells of radius r operating in a service area of radius R. In practice, channel reuse may not approach this limit, as it was based upon the assumption that a single interferer dominated. Typically, there will be some additional interference which is not negligible [11]. For example, it has been shown that adjacent channel interference can affect the performance of heavily loaded systems [12,19–22].

Note that Eq. (13) only applies if $R/r \ge Z^{1/\gamma}$. If $R/r < Z^{1/\gamma}$ a different formulation of the original probability expression, i.e. Eq. (4), is required. However, for typical values of Z (less than 20 dB) and systems comprising more than a few cells, $R/r \ge Z^{1/\gamma}$.

The distribution of Eq. (13) is a fundamental consequence of the lack of channel partitioning in DCA. This result proves that the CRR distribution in DCA systems cannot be predicted using macrocell engineering techniques.

To compare Eq. (13) with the Monte Carlo simulation results, the service area radius R needs to be computed. Examining Fig. 3 it is clear that the service area is not circular and is not centred on the reference cell. As an approximation, the service area comprising hexagonal cells may be replaced with a circle of radius R of equal area centred on the reference cell. It can be shown that for T tiers of a C cluster hexagonal cell system:

$$R = \sqrt{\frac{3\sqrt{3}\, r^2 C (1 + 3T + 3T^2)}{2\pi}} \quad (14)$$

For the simulation of Sec. 2.2, $C = 3$, $T = 1$, $r = 100$ m, $R = 416.7$ m and $\gamma = 3.0$. $Z = 14$ dB for CT2 [23], 12 dB for PHS [24], and 10 dB for DECT [25]. In all three systems $Z \le (R/r)^{\gamma}$ and therefore Eq. (13) is applicable.

The above CRR distributions were plotted and then superimposed upon the Monte Carlo simulation graph of Fig. 2. The result is shown in Fig. 5 below.

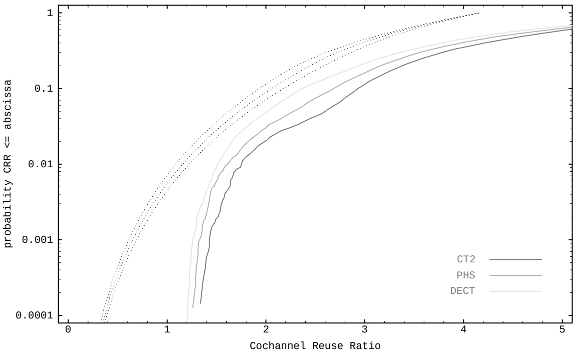


Fig. 5 – Theoretical CRR distributions (dotted lines) compared with Monte Carlo results (L to R the theoretical curves are for DECT, PHS, and CT2).

The effect of the assumption of only one dominant cochannel interferer can be seen. The Monte Carlo curves for all the microcell technologies are inside the theoretical curves due to additional, unaccounted for, interference. This has the effect of reducing the probability of successful link establishment at all reuse ratios. This means, however, the theoretical curves represent the absolute *lower limit* to the CRR in each case as the minimum amount of cochannel interference is that caused by a single cochannel interferer.

Note that the maximum CRR for the theoretical distributions is R/r (i.e. 4.17 for the current examples) while in the simulations CRRs of over 8.0 occurred. This is a consequence of the fact that the Monte Carlo simulation sampled *all* cochannel events, not just those in relation to the reference cell. While this affects the accuracy of the theory at large CRRs, it has little effect at small CRRs, which is the area of interest.

Eq. (13) therefore enables analytical determination of the minimum possible reuse ratio for a given proportion of cochannel terminals in a DCA microcell system. This is an important result and will assist in the characterisation of radio coverage performance in microcell systems.

4. CONCLUSION

Cochannel reuse ratio distributions in DCA microcell systems exhibit very different properties to those found in FCA macrocell systems. Computer simulations and mathematical analysis has shown that DCA systems exhibit significantly closer cochannel reuse than FCA systems for a significant proportion of terminals. This is a fundamental consequence of the lack of channel partitioning in DCA.

Theoretical analysis has provided closed form expressions for cochannel reuse ratio distributions in DCA systems, which in turn establishes a theoretical lower limit to the channel reuse ratio in DCA systems. It has been shown that the resultant reuse ratio distributions cannot be obtained using conventional macrocell engineering principles.

REFERENCES

[1] W.R. Young, “Advanced Mobile Phone Service: Introduction, Background and Objectives”, *Bell System Technical Journal*, vol 58 no 1, Jan 1979, pp 1–14.

[2] J. Sarnecki, C. Vinodrai, A. Javed, P. O’Kelly, K. Dick, “Microcell Design Principles”, *IEEE Communications Magazine*, vol 31 no 4, Apr 1993, pp 76–82.

[3] D.C. Cox, “Wireless Network Access for Personal Communications”, *IEEE Communications Magazine*, vol 30 no 12 , Dec 1992, pp 96–115.

[4] W.C.Y. Lee, “Estimate of Channel Capacity in Rayleigh Fading Environment”, *IEEE Transactions on Vehicular Technology*, vol 39 no 3, Aug 1990, pp 187–189.

[5] J.G. Gardiner, “Second Generation Cordless (CT2) Telephony in the UK: Telepoint Services and the common air interface”, *Electronics and Communication Engineering Journal*, Apr 1990, pp 71–78.

[6] I. Goetz, “Transmission Planning for Mobile Telecommunication Systems”, *6th IEE International Conference on Mobile Radio and Personal Communications*, Coventry, UK, 9–11 Dec 1991, pp 126–130.

[7] W.T. Webb, “Modulation Methods for PCNs”, *IEEE Communications Magazine*, vol 30 no 12, Dec 1992, pp 90–95.

[8] V.H. MacDonald, “The Cellular Concept”, *Bell System Technical Journal*, vol 58 no 1, Jan 1979, pp 15–41.

[9] R. Saunders and L. Lopes, “Performance Comparison of Global and Distributed Dynamic Channel Allocation Algorithms”, *44th IEEE Vehicular Technology Conference* (*VTC ’94*), Stockholm, Sweden, 8–10 Jun 1994, pp 799–803.

[10] J.–P.M.G. Linnartz, “Exact Outage Analysis of the Outage Probability in Multiple–User Mobile Radio”, *IEEE Transactions on Communications*, vol 40 no 1, Jan 1992, pp 20–23.

[11] S.–W. Wang, S.S. Rappaport, “Signal to Interference Calculations for Corner Excited Cellular Communications Systems”, *IEEE Transactions on Communications*, vol 39 no 12, Dec 1991, pp 1886–1896.

[12] S.–W. Wang, S.S Rappaport, “Signal to Interference Calculations for Balanced Channel Assignment Patterns in Cellular Communications Systems”, *IEEE Transactions on Communications*, vol 37 no 10, Oct 1989, pp 1077–1087.

[13] J. C.–I. Chuang, “Performance Limitations of TDD Wireless Personal Communications with Asynchronous Radio Ports”, *Electronics Letters*, vol 28 no 6, 12 Mar 1992, pp 532–534.

[14] B.C. Jones and D.J. Skellern, “Spatial Outage Analysis in Cellular and Microcellular Networks”, *Wireless ’95*, Calgary, Canada, 10–12 Jul 1995, pp 1–18.

[15] B.C. Jones and D.J. Skellern, “Outage Contours and Cell Size Distributions in Cellular and Microcellular Networks”, *45th IEEE Vehicular Technology Conference* (*VTC ’95*), Chicago, United States, 26–28 Jul 1995, pp 145–149.

[16] B.C. Jones and D.J. Skellern, “Interference Distributions in Microcell Ensembles”, *6th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC ’95)*, Toronto, Canada, 27–29 Sep 1995, pp 1372–1376.

[17] B.C. Jones and D.J. Skellern, “System Design for Contiguous Coverage in High Density Microcellular Networks”, *International Symposium on Signals, Systems and Electronics (ISSSE ’95)*, San Francisco, United States, 25–27 Oct 1995, pp 263–266.

[18] B.C. Jones and D.J. Skellern, “Influence of Terminal Distributions and Channel Spills on Microcell Coverage”, *IEEE 1995 Global Telecommunications Conference (Globecom ’95)*, Singapore, 13–17 Nov 1995, pp 17–21.

[19] D. Everitt, D. Manfield, “Performance Analysis of Cellular Mobile Communications Systems with Dynamic Channel Assignment”, *IEEE Journal on Selected Areas of Communications*, vol 7 no 8, Oct 1989, pp 1172–1180.

[20] P.T.H. Chan, M. Palaniswami and D. Everitt, “Dynamic Channel Assignment for Cellular Mobile Radio System using Self–Organising Neural Networks”, *6th Australian Teletraffic Research Seminar*, Wollongong, Australia, 28–29 Nov 1991, pp 89–95.

[21] J.P. Driscoll, “Relevance of Receiver Filter Performance and Operating Range for CT2/CAI Telepoint Systems”, *Electronics Letters*, vol 28 no 13, 18 Jun 1992, pp 1200–1201.

[22] J.P. Driscoll, “Some Factors Which Affect the Traffic Capacity of a Small Telepoint Network”, *5th IEE International Conference on Mobile Radio and Personal Communications*, Coventry, UK, 11–14 Dec 1989, pp 167–71.

[23] European Telecommunications Standards Institute (ETSI), “Common Air Interface Specification between cordless telephone apparatus in the frequency band 864.1 MHz to 868.1 MHz”, I–ETS 300–131, Sep 1991.

[24] Research & Development Centre for Radio Systems (RCR) (Japan), “Personal Handy Phone System RCR Standard”, RCR–28 Version 1, Dec 1993.

[25] European Telecommunications Standards Institute (ETSI), “DECT Radio Receiver Interference Performance”, DECT CI Part 2 Version 7.06 Section 6.4, 1991.