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市街地とビル構内で周波数 2 重再利用するデジタルセルラ方式

― 単一携帯機方式の概念設計改善モデル ―

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あらまし 先に提案した周波数 2 重再利用方式の概念設計近似度を向上させるために電波伝搬モデルに新たに 2 個の設計パラメータを導入した。 この導入により、クラスタサイズが 10 以下のデジタル方式でも、ビル構内システムのマイクロセル半径や周波数利用効率の概念設計精度が改善される。

キーワード 周波数二重再利用, セルラ方式, 概念設計、周波数利用効率

Frequency Double Reuse for Indoor and Urban Digital Cellular Telephone Systems

– Enhanced Conceptual Design Model for Single Handset Systems –

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Abstract To improve the accuracy of the conceptual design model for the previously proposed frequency double reuse system, two parameters are added to the wave propagation model. The addition of these parameters improves the design accuracy of the cell radius and spectral efficiency of indoor microcellular systems even for cluster sizes less than ten.

Keywords frequency double reuse, cellular system, conceptual design, spectral efficiency

1 Introduction

In 1989, the first author proposed the frequency double reuse technique, which allows urban frequency channels to be also used in indoor wireless PBX systems [1][2]. This technique makes it more convenient to be able to access both urban and indoor systems with a single handset. Moreover, compared to conventional systems, which use adjacent frequency bands, and dual band systems, which have two sets of wireless circuits built into a single handset, it is possible to design a system with higher spectral efficiency. Analog frequency double reuse systems have already been standardized and are in use in the United States [7]. In Japan, analog systems have been field tested and the standardization of digital systems has been begun by the ARIB.

In previously reported results on the conceptual design of frequency double reuse systems [7], cluster sizes of 10 or more for analog systems were considered. However, for digital systems with a cluster size of less than 10, an improved model is necessary.

In this paper, we introduce two new parameters in the wave propagation model. These parameters represent the distance after which the propagation of the interference waves from the urban system to the indoor system and vice-versa changes. By introducing these parameters, we show that it is possible to apply the enhanced design model to digital systems as well.

2 Frequency Double Reuse

The concept of frequency double reuse (DR) is shown in Fig. 1. The large "A" represents a macrocell where the frequency **A** is used in an urban cellular system. The small "A" represents a microcell where the frequency **A** is used with small power in an indoor cellular system. In the conventional cellular system, the frequency "A" is reused at a certain distance from the present cell. However, inside the thick lines in the figure, which define clusters, different frequencies, e.g., **B**, **C**, are used. The frequencies are reused in adjacent clusters. In the proposed system, these frequencies are reused again inside the clusters for an indoor cellular system, so this scheme was named frequency double reuse (DR).

The first design parameter in a DR system is the number of "white" cells, i.e., the number of macrocells which contain no microcells in each cluster. These white cells provide the urban system protection from the indoor cellular system. Inside these white cells, frequency **A** is not reused, but other frequencies can be reused. We denote the number of guard cells C_g. Since the guard cells are placed evenly around the macrocell antenna, the number of guard cells can be represented in terms of the number of guard layers, s as

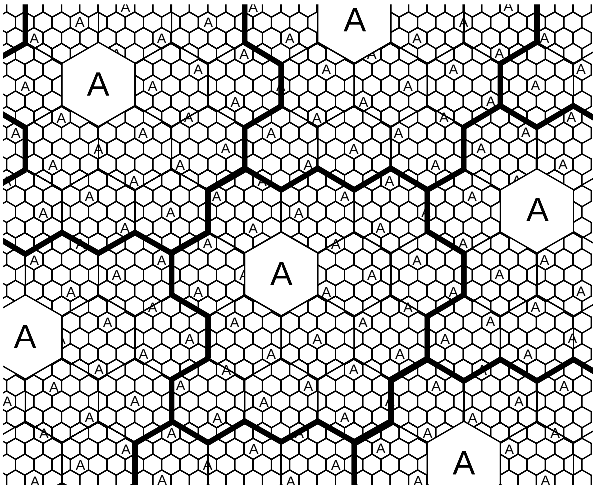

Fig. 1: A typical frequency double reuse system. The large "A"s show the macrocells where the frequency **A** is used. The small "A"s show the microcells where the frequency **A** is reused with low power for the indoor cellular system.

$$C_g = 1 + \sum_{k=0}^{s} k. \tag{1}$$

Therefore, in Fig. 1, $s = 0$ and $C_g = 1$.

The number of frequency channels used in the urban cellular system is denoted by C_1 and referred to as the cluster size. In Fig. 1, $C_1 = 13$.

The basic design criterion for DR systems is that the signal to interference ratios (SIRs) of the urban and indoor cellular systems that use the same frequency are the same. In mathematical terms, this condition can be written as

$$\frac{S_1}{I_1 + J_{21}} = \frac{S_2}{I_2 + J_{12}}, \tag{2}$$

where S_1 and S_2 are the signal powers at the macrocell and microcell edges, respectively, I_1 and I_2 are the self cochannel interferences for the urban (macrocell) and indoor (microcell) systems, respectively, J_{21} is the mutual cochannel interference that the indoor system causes on the urban system and J_{12} is the mutual cochannel interference that the urban system causes on the indoor system. This criterion means that the service quality is the same for both systems. The SIRs for the microcell and macrocell systems are worst at the edges of the cells, so the design equations are derived when (2) is satisfied at the cell edges.

In this paper, the subscript “1” refers to the urban system, while the subscript “2” refers to the indoor system. The subscripts i and j that appear later can take a value of 1 or 2 to refer to the urban or indoor system, respectively.

The next design parameters are β_1 and β_2, which are defined as

$$\beta_1 = \frac{J_{21}}{I_1} \quad \text{and} \quad \beta_2 = \frac{J_{12}}{I_2}. \tag{3}$$

These parameters are decided when the transmission power of the indoor cellular system and the microcell radius is designed. This will be explained later.

3 Enhanced Design Propagation Model

It is well known that the mean signal power at a distance r from an antenna in a fading environment is given by

$$S_i = K_i \frac{P_i}{r^{\alpha_i}}, \tag{4}$$

where P_i is the transmitter power, α^i is an attenuation parameter and K_i is a constant (Appendix A). The self and mutual cochannel interferences are calculated by adding the effects of many base station antennas using the same frequency.

In Fig. 2, the propagation model that is used to calculate the mutual interferences in this paper is shown. The signal strength, S, is plotted as a function of the distance from the base station antenna, r. The signal strength decreases with a propagation exponent of $\alpha = 2$ from the base station antenna for the line–of–sight distance Λ_i. After that, it is well known that the signal strength decreases with $\alpha_1 = 3.5$ for urban propagation, [4] and $\alpha_2 = 4.5$ for indoor propagation in a typical steel reinforced concrete building [5].

In this paper, two new parameters, ρ_1 and ρ_2 are introduced. The parameter ρ_1 is the distance after which the propagation of the interfering wave from the urban system to the indoor system changes, while ρ_2 is the corresponding distance for the interfering wave from the indoor system to the urban system. However, the propagation of the waves involved in cochannel interference, i.e., in the calculation of I_i, does not change.

In (2), if the two systems do not affect each other, i.e., $J_{12} = J_{21} = 0$, then the communication quality of the two systems is determined by only the ratio of the signal strength and cochannel interference S/I. In this case, from the criterion that the communication quality of the two systems is the same, i.e., $S_1/I_1 = S_2/I_2$, the cluster size of the indoor cellular system, C_2, can be calculated from the urban system’s cluster size using [1] [2]

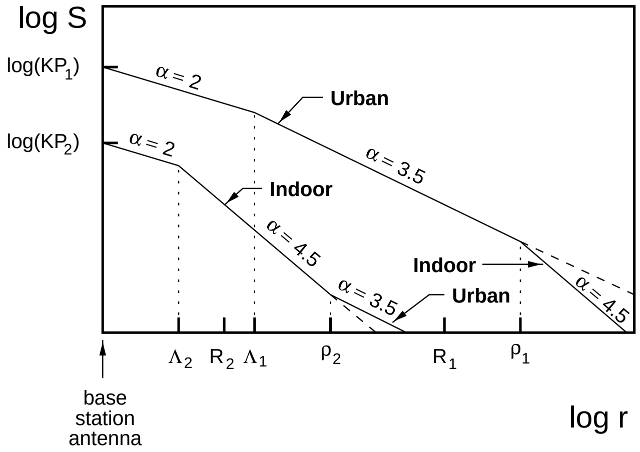

Fig. 2: The signal propagation model used in this paper. The parameters ρ_1 and ρ_2 are introduced to take into account the change in propagation from an indoor environment to an urban environment and vice–versa. The model used in previous papers in shown with a dashed line [1][2][7].

$$C_2 = 0.71418 C_1^{7/9}. \tag{5}$$

Since the attenuation in the indoor system is greater than that in the urban system, the indoor system can achieve the same communication quality with a smaller cluster size.

Next, in order to use the same frequency channel in both systems, we rewrite (2) for the case when $\beta_1 = \beta_2 = \beta$ as

$$\frac{J_{21}}{S_1} = \frac{J_{12}}{S_2}. \tag{6}$$

In this paper, we imagine the situation when there is an infinite number of evenly distributed cells in the indoor system. The solution of (6) gives us the conceptual design formula for a DR system.

4 Indoor System Conceptual Design Formula

4.1 Power Ratio

The calculation of the self and mutual cochannel interferences are shown in Appendix B. Using these results, we can derive the following conceptual design formula from (6): (Appendix C)

$$\frac{P_2}{P_1} = \left(\frac{R_2}{R_1}\right)^{\frac{\alpha_2}{2}+1} \left(\frac{\sqrt{\rho_1 \rho_2}}{\Lambda_2}\right)^{\alpha_2-\alpha_1} \left(\frac{\Lambda_1}{\Lambda_2}\right)^{\alpha_1-2} E(C_2, C_g), \tag{7}$$

where E is a function that depends only on the structure of the cell model and the propagation constants α_i. If this function is calculated once and tabulated, it is possible to perform a conceptual design easily.

4.2 Frequency Utilization Efficiency Calculation

The frequency utilization efficiency per unit area, γ, is defined by

$$\frac{\text{phone traffic[erlangs]}}{\text{bandwidth[MHz]} \cdot \text{area[km}^2]}. \tag{8}$$

For DR systems, the frequency utilization efficiency relative to that of conventional systems, γ_r, is given by

$$\gamma_r = (1+\beta)^{\frac{-2}{\alpha_1}} + (1+\beta)^{\frac{-2}{\alpha_2}} \left(1 - \frac{C_g}{C_1}\right), \tag{9}$$

where β is given by (Appendix D)

$$\beta = \left(\frac{R_2}{R_1}\right)^{\frac{\alpha_2}{2}-1} \left(\frac{\rho_1}{\rho_2}\right)^{\frac{\alpha_2-\alpha_1}{2}} H(C_2, C_g). \tag{10}$$

Here, H is a function that only depends on the structure of the cell model and α_i. Similarly to E, if this function is tabulated, a conceptual design can be easily done.

5 Numerical Results

The parameters introduced in this paper, ρ_1 and ρ_2 are strictly speaking a function of the microcell coordinates. However, in order to be able to get some results in this analysis, we assume the parameters are constants. As a result, these parameters appear as a product in (7) and a ratio in (10).

In digital cellular systems, the cluster size is smaller than in analog systems. In practice, 3–sector cells are used in cellular phone systems. The number of sectors can be thought of as approximately the same as the cluster size.

The values of E and H were calculated and the results are shown in Table 1. For comparison, the values when $\alpha_1 = \alpha_2 = 3.5$ are also shown.

In order to complete a conceptual design, the parameters shown in the propagation model in Fig. 2, Λ_i and ρ_i, must be decided. To keep the estimate of the mutual interference conservative, we assume $\rho_1 = 2R_1$ and $\rho_2 = 0.5R_2$. This results in values of β twice as large as when $\rho_1 = R_1$ and $\rho_2 = R_2$. From previous work [1][2], we use $\Lambda_1 = 120m$ and $\Lambda_2 = 3m$. Using these values, numerical results are shown in Table 2.

TABLE 1
$E(C_2, C_g)$ AND $H(C_2, C_g)$

C_g	C_1	E	H	E	H
		($\alpha_1 = \alpha_2 = 3.5$)		($\alpha_1 = 3.5, \alpha_2 = 4.5$)	
1	3	1.23	2.44	0.654	0.84
	4	1.16	3.06	0.590	0.96
	7	1.08	4.63	0.511	1.23
	9	1.14	6.01	0.539	1.52
	12	1.26	8.27	0.586	1.98
	13	1.30	9.07	0.602	2.13
	16	1.41	11.6	0.647	2.60
	19	1.52	14.2	0.689	3.07
	21	1.59	16.1	0.715	3.38
	25	1.72	19.9	0.763	4.00
7	12	1.47	2.03	0.476	0.39
	13	1.47	2.32	0.487	0.39
	16	1.30	2.72	0.403	0.41
	19	1.18	2.98	0.343	0.41
	21	1.17	3.29	0.340	0.45
	25	1.16	3.86	0.334	0.50

TABLE 2
MICROCELL RADIUS R_2 AND FREQUENCY UTILIZATION EFFICIENCY γ_r

C_1	7	9	16	16
C_2	3.2	3.9	6.2	6.2
C_g	1	1	1	7
$E(C_2, C_g)$	0.511	0.539	0.647	0.403
$H(C_2, C_g)$	1.23	1.52	2.60	0.41
R_2	50.5 m	49.8 m	47.4 m	53.8 m
γ_r	176%	177%	198%	153%
β	0.115	0.141	0.232	0.042

$P_1 = 3W$, $R_1 = 3km$, $P_2 = 10mW$

An indoor cellular system with a base station transmission power of $P_2 = 10mW$ has a cell radius of approximately $50m$. Therefore, even for digital systems with macrocell cluster sizes less than 10, it is possible to obtain service area values that are close to the values obtained from experience [1][2][7].

The parameters, ρ_1 and ρ_2 are roughly the same order as the cell radii of the two systems. For macrocell cluster sizes of 7 or less, it is necessary to rewrite the conceptual design formula when sector cells are used. This is especially true for spread spectrum systems.

The frequency utilization efficiency is close to the theoretical limit of 200%. The reason for this is that the urban cellular system and the indoor system can be thought to be designed to have a very high degree of electrical screening.

In previous work [5][6], outdoor positioning of microcells was also considered, but from the viewpoint of frequency utilization efficiency, the microcell antennas should be positioned indoors. Since waves propagate to the outside through windows etc., outdoor service with the microcell system is entirely possible. A value of $\rho = 0.5R_2$ means that the waves radiate outdoors at a distance less than the microcell radius.

6 Conclusions

In this paper, a conceptual design formula for digital frequency double reuse cellular systems with cluster sizes less than 10 was derived and numerical results shown. This was made possible by introducing two new parameters in the propagation model to improve the calculation of the interference. These parameters are roughly the same as the cell radii of the urban and indoor systems. For sector cell systems, it is necessary to derive a different formula with a new cell model. In future work, the analysis of spread spectrum double reuse systems will be done.

Appendices

A Received Signal Strength

The received signal strength, S, of UHF band signals in urban environments is given by (4) and for a distance, r, of 1 to 10 km, α is approximately 3.5. The constant K_i in (4) is given by

$$K_i = \left(\frac{\lambda}{4\pi}\right)^2 G_t G_r \Lambda_i^{\alpha_i - 2}, \tag{11}$$

where λ is the wavelength of the signal, G_t and G_r are the transmitter and receiver antenna gains, respectively, and Λ_i is the distance over which inverse square law propagation applies, i.e., the line of sight distance.

In Fig. 2, the signal strength for distances greater than ρ_i is given by

$$S_i = K\rho_i^{\alpha_i - \alpha_j}\frac{P_i}{r^{\alpha_i}}, \quad r > \rho_i. \tag{12}$$

B Self and Mutual Cochannel Interference

The self cochannel interferences, I_1 and I_2, are calculated by adding the signal powers from all cells using the same frequency. If these cells are numbered $\{1, ..., \infty\}$, the cochannel interference can be written as

$$I_1 = \sum_{m=1}^{\infty} K_1 \frac{P_1}{r_{1m}^{\alpha_1}} \quad \text{and} \quad I_2 = \sum_{m=1}^{\infty} K_2 \frac{P_2}{r_{2m}^{\alpha_2}}, \tag{13}$$

where r_{1m} is the distance from the mth interfering cell to the mobile user using the macrocellular system and r_{2m} is the corresponding distance for the microcellular system. Here, we assume that the propagation exponent for the cochannel interference between macrocells and between microcells does not change after Λ_2 and Λ_1, respectively.

Normalizing r_{1m} and r_{2m} by the macrocell and microcell radii, respectively, results in

$$I_1 = K_1 \frac{P_1}{R_1^{\alpha_1}} \sum_{m=1}^{\infty} \frac{1}{\underline{r}_{1m}^{\alpha_2}} \tag{14}$$

and

$$I_2 = K_2 \frac{P_2}{R_2^{\alpha_2}} \sum_{m=1}^{\infty} \frac{1}{\underline{r}_{2m}^{\alpha_1}}, \tag{15}$$

where

$$\underline{r}_{1m} = \frac{r_{1m}}{R_1} \quad \text{and} \quad \underline{r}_{2m} = \frac{r_{2m}}{R_2} \tag{16}$$

The summations above now only depend on the attenuation exponents and the distances between cells of unit radii. We define the summation part of the above equations as $\bar{I}_1$ and $\bar{I}_2$, which results in

$$I_1 = K_1 \frac{P_1}{R_1^{\alpha_1}} \bar{I}_1 \quad \text{and} \quad I_2 = K_2 \frac{P_2}{R_2^{\alpha_2}} \bar{I}_2, \tag{17}$$

where

$$\bar{I}_1 = \sum_{m=1}^{\infty} \frac{1}{\underline{r}_{1m}^{\alpha_2}} \quad \text{and} \quad \bar{I}_2 = \sum_{m=1}^{\infty} \frac{1}{\underline{r}_{2m}^{\alpha_1}}. \tag{18}$$

The mutual interference is the interference that the urban and indoor cellular systems cause on each other. The interference from the urban system on the indoor system, i.e., macrocell on microcell, is denoted by J_{12}, while microcell on macrocell interference is denoted by J_{21}.

If we denote the distance from the microcell system user to the mth macrocell antenna as d_{2m}, we can write J_{12} as

$$J_{12} = K_1 \rho_1^{\alpha_2 - \alpha_1} P_1 \sum_{m=1}^{\infty} \frac{1}{d_{2m}^{\alpha_2}}. \qquad (19)$$

To calculate J_{21}, we assume that the microcell antennae which are inside a macrocell are located at the center of the macrocell. The average number of interfering microcells in a macrocell can be approximated by

$$l = \frac{1}{C_2} \left(\frac{R_1}{R_2} \right)^2. \qquad (20)$$

Therefore, if we denote the distance from the macrocell user to the center of the mth macrocell which contains microcells as d_{1m}, J_{21} can be written as

$$J_{21} = K_2 \rho_2^{\alpha_1 - \alpha_2} P_2 l \sum_{m=1}^{\infty} \frac{1}{d_{1m}^{\alpha_1}}. \qquad (21)$$

Here, we normalize the distances by R_1 to get

$$J_{12} = K_1 \rho_1^{\alpha_2 - \alpha_1} \frac{P_1}{R_1^{\alpha_2}} \bar{J}_{12} \qquad (22)$$

and

$$J_{21} = K_2 \rho_2^{\alpha_1 - \alpha_2} \frac{P_2}{R_1^{\alpha_1}} l \tilde{J}_{21}, \qquad (23)$$

where

$$\bar{J}_{12} = \sum_{m=1}^{\infty} \frac{1}{\underline{d}_{2m}^{\alpha_2}} \quad \text{and} \quad \tilde{J}_{21} = \sum_{m=1}^{\infty} \frac{1}{\underline{d}_{1m}^{\alpha_1}} \qquad (24)$$

and

$$\underline{d}_{1m} = \frac{d_{1m}}{R_1} \quad \text{and} \quad \underline{d}_{2m} = \frac{d_{2m}}{R_1} \qquad (25)$$

C Power Ratio Derivation

Substituting (4), (22) and (23) into (6) gives,

$$\frac{P_2}{P_1} \frac{K_2}{K_1} \frac{R_1^{\alpha_1}}{R_2^{\alpha_2}} = \frac{K_1}{K_2} \frac{\rho_1^{\alpha_2 - \alpha_1}}{\rho_2^{\alpha_1 - \alpha_2}} \frac{P_1}{P_2} \frac{C_2 R_2^2}{R_1^2} \frac{R_1^{\alpha_1} \bar{J}_{12}}{R_1^{\alpha_2} \tilde{J}_{21}}. \qquad (26)$$

Rearranging terms gives

$$\frac{P_2^2}{P_1^2} = \frac{K_1^2}{K_2^2} (\rho_1 \rho_2)^{\alpha_2 - \alpha_1} \frac{R_2^{\alpha_2 + 2}}{R_1^{\alpha_2 + 2}} \frac{\bar{J}_{12}}{\tilde{J}_{21}} C_2. \qquad (27)$$

From (11), $K_1/K_2 = \Lambda_1^{\alpha_1 - 2}/\Lambda_2^{\alpha_2 - 2}$. Substituting this into the above equation and taking the square root gives the desired result:

$$\frac{P_2}{P_1} = \left(\frac{R_2}{R_1} \right)^{\frac{\alpha_2}{2} + 1} \left(\frac{\sqrt{\rho_1 \rho_2}}{\Lambda_2} \right)^{\alpha_2 - \alpha_1} \left(\frac{\Lambda_1}{\Lambda_2} \right)^{\alpha_1 - 2} E(C_2, C_g), \qquad (28)$$

where

$$E(C_2, C_g) = \sqrt{\frac{\bar{J}_{12}}{\tilde{J}_{21}} C_2}. \qquad (29)$$

D Interference Ratio Derivation

Substituting (22) and (17) into (3) gives

$$\beta = \frac{K_1 (\rho_1)^{\alpha_2 - \alpha_1} \frac{P_1}{R_1^{\alpha_2}} \bar{J}_{12}}{K_2 \frac{P_2}{R_2^{\alpha_2}} \bar{I}_2}. \qquad (30)$$

Rearranging terms gives

$$\beta = \frac{K_1 P_1}{K_2 P_2} \rho_1^{\alpha_2 - \alpha_1} \left(\frac{R_2}{R_1} \right)^{\alpha_2} \frac{\bar{J}_{12}}{\bar{I}_2}. \qquad (31)$$

Using (27) to replace $K_1 P_1/(K_2 P_2)$ results in the desired result:

$$\beta = \left(\frac{R_2}{R_1} \right)^{\frac{\alpha_2}{2} - 1} \left(\frac{\rho_1}{\rho_2} \right)^{\frac{\alpha_2 - \alpha_1}{2}} H(C_2, C_g), \qquad (32)$$

where

$$H(C_2, C_g) = \frac{1}{\bar{I}_2} \sqrt{\frac{\tilde{J}_{21} \bar{J}_{12}}{C_2}}. \qquad (33)$$

References

[1] Y. Kinoshita, T. Tsuchiya, and S. Ohnuki, "Frequency common use between indoor and cellular radio – research on frequency channel doubly reused system," *Proc. 1989 IEEE Vehicular Tech. Conf.*, pp. 325–329, May 1989.

[2] Y. Kinoshita, T. Tsuchiya, and S. Ohnuki, "A common air interface between wide-area cordless telephone and urban cellular radio: frequency channel doubly-reused cellular systems," *Electronics and Communications in Japan, Part 1*, vol. 77, no. 6, pp. 101–111, 1994.

[3] V. MacDonald, "The cellular concept," *BSTJ*, vol. 58, pp. 15-41, Jan. 1979.

[4] K. Daikoku and H. Ohdate, "Optimal channel reuse in cellular land mobile radio systems," *IEEE Trans. on Vehicular Technology*, vol. VT-32, pp. 217–224, Aug. 1983.

[5] D. C. Cox, "Universal digital portable radio communications," *Proc. IEEE*, vol. 75, pp. 436–477, Apr. 1987.

[6] Y. Kinoshita and M. A. A. Henriques, "High density space division multiple access: double reuse of frequency channels," *Proc. 1994 IEEE International Conference on Universal Personal Communications (ICUPC '94)*, pp. 552–557, Oct. 1994.

[7] Y. Kinoshita (editor), *Personal Mobile Telephone Systems.* Tokyo: Triceps, 1996 (in Japanese).