Perfect Cell Partitioning Scheme for Micro-Cellular Networks

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***Abstract*— A perfect cell partitioning (PCP) scheme is described for controlling the transmission power of base stations in a cellular communication system to prevent radio frequency interference among adjacent base stations. A base station using this scheme can use its entire frequency range, while one using the conventional scheme can use only a quarter of it. Simulation and analytic results showed that the PCP scheme is more effective than the conventional one when the node density is lower than 6. However, the probability of successful communication is relatively low. A modified version of this scheme in which the base station sacrifices the nodes near its border has a significantly higher probability. Simulation and analytic results showed that the success probability of the modified scheme is as much as 0.67 higher than that of the original one when the occupation ratio is 1.2 and that a base station using the modified scheme can use its frequency range more effectively than one using the original or conventional scheme.**

***Index Terms*— perfect cell partitioning, transmission power control, mobile communication, high-speed data transfer, information distribution, radio frequency interference**

I. INTRODUCTION

Mobile communication technologies [1]–[3], which play important roles in ubiquitous networks, have attracted extensive research efforts in recent years. In conventional mobile communication services, voice and mail data account for the largest portion of traffic. Such data can be transmitted at a relatively low bit rate. In recent years, cellular phone service providers have begun offering flat-rate plans [4] in which the fee charged is independent of the amount of traffic consumed. Such plans promote the downloading of short movies and music. As a result, downlink transmission to nodes within a certain area is significant. For example, a shop may want to send promotional information to potential customers, that is, to people within a certain distance of the shop. In both cases, network capacity and transmission rate are more important.

A mobile communication system has a cellular structure [5]–[7]. Each mobile phone is a node and communicates through a base station. The service region is divided into subregions, called “cells”. A base station is located at the center of every cell, and it communicates with the nodes in the cell using a wireless connection. A base station can smoothly communicate with the nodes by avoiding conflicts with the adjacent cells in the usage of network resources (frequency range, time slots, orthogonal code sequence, etc.). From the viewpoint of four-color theory [8], however, the original network resource must be divided into at least four sub-resources [9], [10]. In this paper, we focus on the frequency range resource, but our discussion is also applicable to other network resources.

In the conventional cellular system, the cell size (diameter) is from several hundred meters to several kilometers. The larger cells are called “macro-cells” [11]. A system administrator designs the sizes of the macro-cells so that the service area is fully covered by the macro-cells with some overlap allowed [12], [13]. This structure is effective for calling because a node can communicate no matter where it is in the service region. There have been several studies about cell overlapping. Ahmed and Mahmoud [14] demonstrated that cell overlapping reduces the call blocking and dropping probabilities. Katzis et al. [15] showed that fixed channel allocation is an effective way to achieve cell overlapping.

Although cell overlapping can reduce the blocking and dropping probabilities, it also reduces the transmission rate due to the conflicts of network resources. If the original frequency range of a base station is divided into four sub-ranges, the transmission rate is reduced to one-fourth. The transmission rate is more important in information distribution services, e.g. sending promotional information to people in the vicinity of a shop. If a base station can provide high-speed data transfer, it can distribute a large volume of multimedia contents, which are more attractive to most people than text-based contents. Avoiding cell overlapping is one way to increase the transmission rate because it enables the base station to use its entire frequency range.

One technology that prevents cell overlapping has already implemented for wireless LAN access points [16]. The base station senses the transmission power of the base stations in the adjacent cells and adjusts its own power so that it does not disturb their communication. While this technology prevents cell overlapping, it emits excess power to the wasteful space in which there are no nodes. By adjusting its transmission power in accordance with the surrounding node distribution, a base station can reduce the wasteful spatial utilization. We call this scheme “perfect cell partitioning (PCP).”

We have developed a PCP scheme for an information

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distribution service. A base station adjusts the size of its cell so that a node in an adjacent cell is not near the border between the two cells. We also modified this scheme to increase the probability that communication will be successful and to improve radio frequency usage. In this modified PCP (MPCP) scheme, the base station sacrifices the nodes near its border.

Reducing the cell size should increase the probability of communication success. This is because doing so reduces the number of nodes near the border, assuming the node density does not change. Various emerging wireless technologies [5], such as Bluetooth [17] and ZigBee [18], use microcells. PCP should become a key concept achieved using such technologies.

Our PCP scheme is based on a radio frequency interference model. Using an analytic approach, we derived the communication success probability of PCP under the following assumptions.

- The region is divided into cells with a regular hexagon shape.
- Nodes are located at uniformly random positions in the region.
- The direction of communication is one way, from the base station to a node.[1]

Simulation experiments verified the correctness of our analysis and demonstrated the effectiveness of PCP. They also showed that our modified PCP scheme has a higher communication success probability.

The remainder of this paper is organized as follows. In Section II, we introduce the radio frequency interference model. We describe our PCP scheme and give geometrical analysis and simulation results for it in Section III. In Section IV, we explain our modified PCP scheme and present analytic and simulation results that demonstrate its effectiveness. Finally, we conclude in Section V with a brief summary of the main points and a look at future work.

II. RADIO FREQUENCY INTERFERENCE MODEL

We first introduce a model of radio frequency interference in wireless networks. In general, a radio wave is attenuated in inverse proportion to the α-th power of distance [19]–[21]. Suppose that base station bs emits a radio wave with transmission power P. The power of the wave when it reaches node X_i is expressed as

$$P(i) = \frac{P}{||X_i - bs||^{\alpha}}, \tag{1}$$

where $||X_i - bs||$ is the distance between bs and X_i. The perceived radio quality at X_i varies with the distance from bs.

- If $||X_i - bs|| \leq r$, X_i is in a “success zone”, which is an area in which it can receive data from bs correctly.
- If $r < ||X_i - bs|| \leq \Delta r$, X_i is in a “noise zone”, which is an area in which it receives data from bs as noise.
- If $\Delta r < ||X_i - bs||$, X_i is in a “no interference zone”, which is an area in which it does not receive data from bs.

The Δ represents the occupation ratio, which represents the area occupied by the base station. Radius r of a success zone is controlled by adjusting the transmission power.

III. PERFECT CELL PARTITIONING

A. Condition for PCP

In this section, we formulate the condition for PCP. Suppose that a base station is responsible for the connections to all nodes within its maximum transmission range. We denote the nodes as X_i in ascending order of their distance from the base station. If $(1 \leq i \leq n)$, X_i is within the maximum transmission range; if $(n + 1 \leq i)$, X_i is out of range. The base station can thus connect to all nodes within its range if

$$||X_{n+1} - bs|| \geq \Delta ||X_n - bs||. \tag{2}$$

In this case, the base station adjusts the radius of its success zone to $||X_n - bs||$ by changing its transmission power. This equation indicates that the base station can achieve PCP only when all of its nodes are in the success zone and all the nodes of other base stations are in the no interference zone. This prevents its radio waves from disturbing the communication of the other base stations' nodes because none of them are in the noise zone. Each base station controls its transmission power to satisfy this equation. If a base station cannot, it temporarily suspends communication with its nodes[2].

For this mechanism to work, each base station must know the positions of all nodes within its maximum transmission range. It must also know the positions of nodes belonging to neighboring base stations. This information can be obtained by exchanging lists of node positions among neighboring base stations. Although the mechanism for such an exchange remains for future work, we expect that various location sensing techniques are applicable [22], [23]. Yu et al. [23] proposed position estimation methods based on the time-of-arrival of ultra wideband signals. The time difference-of-arrival scheme, which measures the time difference of signals coming from different base stations, is also useful [22].

B. Analysis

In this section, we analyze the communication success probability of PCP. In the traditional analysis of a cellular system, the area is assumed to be a repeated structure of one cell. We improve the precision of the analysis by enlarging the unit of the repeated structure.

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[1] Information distribution services are an example of this type of communication. Here we mainly focus on the transmission rate from the base station to a node rather than the connectivity between them.

[2] In actuality, the nodes do not remain in one location. If a node has trouble communicating with the base station, it will likely move to another location in an attempt to establish communications with the base station.

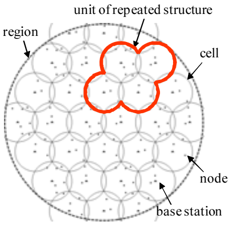

Figure 1. Sample distribution of nodes and base stations for $N_r = 4$

First, suppose that N_r adjacent cells are periodically located in the region. Increasing N_r improves the accuracy of the analysis. Figure 1 displays a sample distribution of nodes and base stations for $N_r = 4$. The large circle drawn with a dashed line represents the region. The smaller circles drawn with solid lines represent cells. The unit of the repeated structure is indicated by the thick line. The triangle in each cell is the base station, and the dots are nodes.

As mentioned in Section I, we assume a cell is shaped as a regular hexagon. Suppose that the length of each edge of the hexagon is R. The radius R_{eq} of the equivalent circle whose area is equal to that of the hexagon is $\sqrt{\frac{3\sqrt{3}}{2\pi}}R$. In the following analysis, we set R_{eq} to 1 without any loss of generality. The node density is n nodes/cell, and the occupation ratio is Δ. We define the communication success probability of PCP, $P_{suc}(n)$, as the probability that all nodes in a cell can communicate with the base station.

We next analytically derive $P_{suc}(n)$ for $N_r = 1$ and 4^3.

1) $N_r = 1$: When $N_r = 1$, all cells in the region has an identical node distribution. We thus focus on seven neighboring cells, as illustrated in Fig. 2. The hexagons represent cells, and the circles drawn with a solid line represent the maximum transmission ranges of the base stations. We define the cell at the center as the main cell and the others as neighboring cells. Here we focus on the main cell. Suppose that r is the distance between the main cell base station and the most distant node in the cell. Since the position of a node is invariant among cells when $N_r = 1$, the distance between a base station and the most distant node equals r in every cell. For successful communication in the main cell, none of the nodes in the adjacent cells can be in the noise zone of the main cell. This means that the most distant node can be no further away than the thick lines in Fig. 2. When $r + \Delta r \leq \sqrt{3}R$, the thick line corresponds to circle with radius r because the success zone of the main cell does not intersect the noise zone of an adjacent cell. When $\sqrt{3}R < r + \Delta r$, the thick line is as shown in Fig. 2. Moreover, the thick line disappears when r exceeds r_0, which is derived from

$$\left(\sqrt{3}R - \frac{\sqrt{3}}{2}r_0\right)^2 + \left(\frac{r_0}{2}\right)^2 = (\Delta r_0)^2. \tag{3}$$

Therefore, we get

$$r_0 = \frac{\sqrt{3}R\sqrt{4\Delta^2 - 1} - 3R}{2(\Delta^2 - 1)}. \tag{4}$$

The sum of the length of the thick lines is defined as

$$S_b(r) = \begin{cases} 2\pi r, & \left(0 \leq r \leq \frac{\sqrt{3}R}{\Delta+1}\right), \\ 12r\left\{\frac{\pi}{6} - \mathrm{acos}\left\{\frac{3R^2-(\Delta^2-1)r^2}{2\sqrt{3}Rr}\right\}\right\}, & \left(\frac{\sqrt{3}R}{\Delta+1} < r \leq r_0\right), \\ 0, & (r_0 < r \leq 1). \end{cases}$$

Thus, the area in which the most distant node can be located is expressed as

$$S_1 = \int_0^1 S_b(r)dr. \tag{5}$$

The communication success probability equals the probability that all n nodes in a cell are located in the success zone. This means that the success probability for a node is

$$P_{suc}(n) = \left(\frac{S_1}{\pi R_{eq}^2}\right)^n. \tag{6}$$

Because $R_{eq} = 1$,

$$P_{suc}(n) = \left(\frac{1}{\pi}\int_0^{r_0} S_b(r)dr\right)^n. \tag{7}$$

2) $N_r = 4$: When $N_r = 4$, there are four types of cells in the region as shown in Fig. 1. Each of them has a unique node distribution. We define one of the four as the main cell and the others as neighboring cells. Again we focus on the main cell. If there are k ($\leq 4n$) nodes in the main cell, the communication success probability of PCP is

$$P_{suc}(n) = {}_4\mathrm{C}_1\left(\frac{1}{4}\right)^{4n} + \frac{1}{n}\sum_{k=1}^{4n-1} E(n,k). \tag{8}$$

The first term on the right represents the success probability when $k = 4n$, and the second one represents the sum of the success probabilities when $1 \leq k \leq 4n - 1$. $E(n,k)$ represents the mean number of nodes that can communicate with bs among those k nodes.

$$E(n,k) = kC_4(n,k)P^k_{success}(n,k), \tag{9}$$

where $C_4(n,k)$ is the probability that k nodes are in the main cell and $P^k_{success}(n,k)$ is the probability that all k nodes in the main cell can communicate with the base station.

Next we derive $C_4(n,k)$. Because the node density is n, the probability that the main cell includes k nodes is defined as

$$C_4(n,k) = {}_{4n}\mathrm{C}_k\left(\frac{1}{4}\right)^k\left(\frac{3}{4}\right)^{4n-k}. \tag{10}$$

We next derive $P^k_{success}(n,k)$. Figure 3 illustrates the main cell, $Cell_1$, and a neighboring cell, $Cell_2$, when the distance between the base station and the most distant node n_1 is r. $Cell_3$ is the $Cell_2$'s neighboring cell that is located on the opposite side of $Cell_1$. When $N_r = 4$, the node positions in $Cell_1$ and in $Cell_3$ are the same. Thus, in $Cell_3$, the distance between the base station

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[3] The results for $N_r = 7$ are not given as they are similar to those for $N_r = 4$.

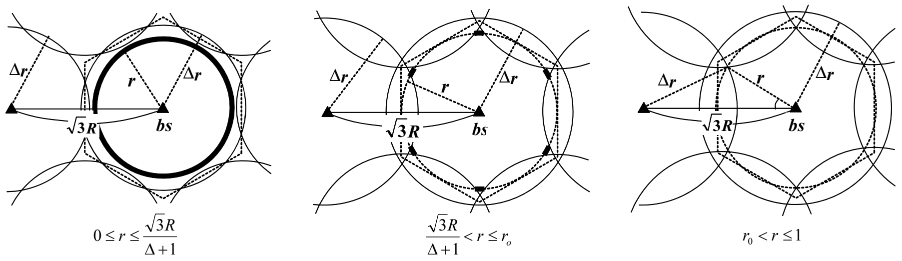


Figure 2. Relationship between r and cell overlapping for $N_r = 1$

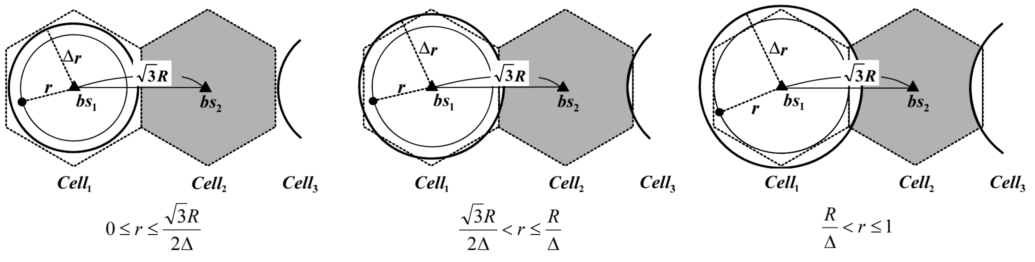


Figure 3. Relationship between r and cell overlapping for $N_r = 4$

and the most distant node is also r. In this case, for successful communication in $Cell_1$, none of the nodes in $Cell_2$ can be located in the noise zone between $Cell_1$ and $Cell_3$. Therefore, they must be located in the grey zone depicted in Fig. 3. If $\Delta r \le \frac{\sqrt{3}R}{2}$, the circle with radius Δr does not overlap $Cell_2$. Hence, the nodes in $Cell_2$ can be located anywhere in $Cell_2$. If $\frac{\sqrt{3}R}{2} < \Delta r$, the grey zone corresponds to that in Fig. 3. The nodes in the other neighboring cells must also be located in the grey zones of their respective cells. As a result, the probability that $4n - k$ nodes in the three neighboring cells are located in a grey zone is

$$p_{adj}(n,k,r) = \left(\frac{3S_4(r)}{3\pi R_{eq}^2}\right)^{4n-k}, \qquad (11)$$

where $S_4(r)$ is the area of the grey zone:

$$S_4(r) = \begin{cases} \pi, & (0 \le r \le \frac{\sqrt{3}R}{2\Delta}), \\ \pi - 4\left\{\frac{\mathrm{acos}\left(\frac{\sqrt{3}R}{2\Delta r}\right)}{2}(\Delta r)^2 - \frac{\sqrt{3}R}{4}\sqrt{(\Delta r)^2 - \left(\frac{\sqrt{3}R}{2}\right)^2}\right\}, & (\frac{\sqrt{3}R}{2\Delta} < r \le \frac{R}{\Delta}) \\ \frac{\pi}{3}\left\{4 - (\Delta r)^2\right\}, & (\frac{R}{\Delta} < r \le 1). \end{cases}$$

The probability that the most distant node from the base station is on the circumference of a cell with radius r is

$$p_{cnt}(n,k,r) = \frac{2r}{R_{eq}^2}\left(\frac{r}{R_{eq}}\right)^{2(k-1)} = 2r^{2k-1}. (12)$$

From Eqs. (11) and (12), we can derive the probability that all k nodes in the main cell can communicate with the base station:

$$P_{success}^k(n,k) = \int_0^1 k\ p_{cnt}(n,k,r)p_{adj}(n,k,r)dr. \quad (13)$$

Substituting Eqs. (9) to (13) into Eq. (8), we obtain $P_{suc}(n)$.

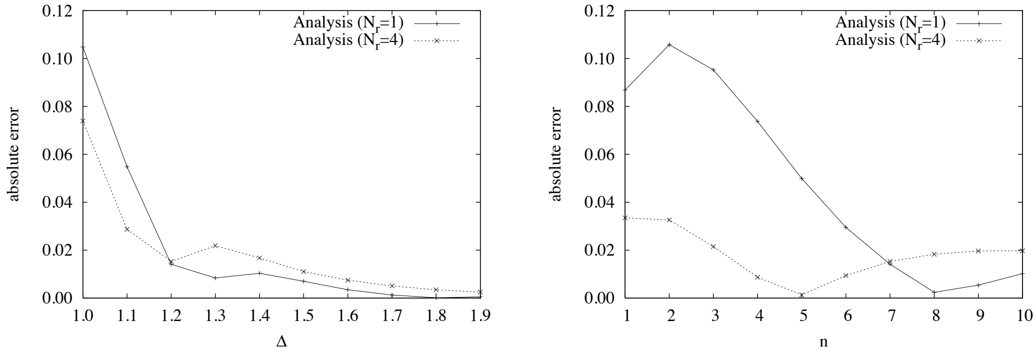
C. Simulation and analytic results

We used simulation to evaluate the accuracy of our analysis and the effectiveness of our scheme. In the simulations, we set the number of base stations in the region to 250 and varied the number of nodes in the region from 250 to 2500. Thus, the average number of nodes in a cell, i.e. node density n, ranged from 1 to 10. The nodes were assumed to be located randomly throughout the region. We defined the success probability as the ratio of the number of nodes that were able to communicate with the base station to the total number of nodes. We ignored nodes near the border of the region because they could not belong to any base station regardless of the transmission power. The results are the average for 1000 runs.

1) Accuracy of analysis: We estimated the accuracy of our analysis by comparing the analytic and simulation results. Figure 4(a) illustrates how the absolute error between the success probability, P_{suc}, in the simulation results and in the analytic results varied with occupation ratio Δ for $n = 7$. When Δ was low, the analysis with $N_r = 4$ was more accurate than that with $N_r = 1$. As Δ increased, the error for both approached zero. Since the occupation ratio of the wireless technologies used in micro-cellular networks is relatively low, analysis using $N_r = 4$ should be useful.

Figure 4(b) illustrates how the absolute error between P_{suc} in the simulation results and in the analytic results varied with node density n for $\Delta = 1.2$. The error for $N_r = 4$ was less than 0.04 regardless of n while that for $N_r = 1$ varied from 0.002 to over 0.10. This indicates that analysis using $N_r = 4$ is more reliable than that using $N_r = 1$.

Consequently, for micro-cellular networks, $N_r = 4$ is useful for analyzing P_{suc} from the viewpoints of the node



(a) $n = 7$ (b) $\Delta = 1.2$

Figure 4. Accuracy of analysis (PCP)

density and the occupation ratio. We use $N_r = 4$ in the following discussions.

2) Effect of node density and occupation ratio: We investigated the feasible area of PCP analytically. We defined radio frequency utilization as the product of the available frequency range and the communication success probability. As mentioned above, PCP can use a frequency range about four times larger than that of the conventional scheme. Thus, in terms of radio frequency utilization, PCP is more effective than the conventional scheme when P_{suc} is larger than 0.25. The non-white area in Fig. 5 illustrates the case when the radio frequency utilization of PCP is larger than 0.25. This figure shows that PCP is more efficient than the conventional scheme when Δ and n are low. However, P_{suc} gradually deteriorates with an increase in n or Δ. In this scenario, we assume that the node positions are uniformly distributed. As n or Δ increases, the possibility that nodes are located in the vicinity among cells also increases. Therefore, the assumption of a uniform node distribution is not suitable for PCP. In actuality, a node tends to move around to obtain a connection to the base station. We simulated this situation and present the results in Section III-C.4.

3) Effect of controlling transmission power: In this section, we describe our investigation of the effect of controlling the transmission power in PCP. First, we define a fixed transmission power to satisfy the condition of PCP. Figure 3 illustrates two adjacent cells, $Cell_1$ and $Cell_2$. Suppose that the transmission range of bs_1 is r_{fix}^{PCP} and that bs_2 can expand its transmission range up to r_2. Since radio waves from bs_2 cannot disturb communications in $Cell_1$,

$$r_2 = \sqrt{3}R - \Delta r_{fix}^{PCP}. \tag{14}$$

Since the transmission range of bs_2 is also r_{fix}^{PCP},

$$r_2 = r_{fix}^{PCP}. \tag{15}$$

Therefore,

$$r_{fix}^{PCP} = \frac{\sqrt{3}R}{\Delta + 1}. \tag{16}$$

Thus, if all nodes in a cell are located in a circle with radius r_{fix}^{PCP} and its center at the base station, they can communicate with the base station. We define a scheme in which every base station sets the radius of its success zone to r_{fix}^{PCP} as $\mathrm{PCP_{fix}}$.

Figure 6 compares the P_{suc} of PCP with that of $\mathrm{PCP_{fix}}$. It shows that PCP was consistently more effective than $\mathrm{PCP_{fix}}$. When Δ was 1.2, for example, the difference between the P_{suc} of PCP and that of $\mathrm{PCP_{fix}}$ was 0.37. The difference decreased when n and/or Δ were increased.

4) Effect of node distribution: As mentioned above, a node will often move around in order to establish a connection with a base station when it cannot communicate. This phenomenon improves the effectiveness of PCP because the number of nodes near the border decreases. Here we estimate P_{suc} for the case in which the nodes are concentrated in the vicinity of the base station. We use a normal distribution, $N(\mu, \sigma^2)$, to obtain this distribution. Consider a cell that is an r-θ plane with its origin at the base station and a radius equal to the maximum transmission range, which is 1. The node coordinates have a normal distribution in the r direction and a random distribution in the θ direction. The average μ of the distance between the base station and a node in each direction is zero. As variance σ increases, the node dispersion increases. Figure 7 shows P_{suc} for four normal distributions $N(0, 0.0025)$, $N(0, 0.005)$, $N(0, 0.0075)$, and $N(0, 0.01)$. Also shown for comparison is that for a uniform distribution. As the average distance between the base station and nodes decreased, P_{suc} increased. Specifically, for $\sigma = 0.0025, 0.005, 0.0075$, and 0.01, the differences from the uniform distribution were 0.56, 0.36, 0.17, and 0.08, on average, respectively. This indicates that the efficiency of our scheme is higher when the nodes are closer to the base station.

IV. MODIFIED PERFECT CELL PARTITIONING

We modified our PCP scheme to improve the communication success probability. This modified scheme is called "modified perfect cell partitioning (MPCP)."

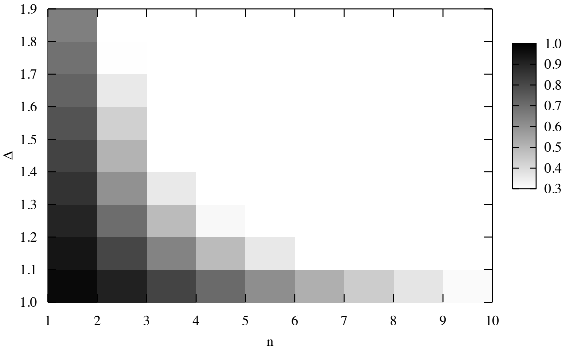


Figure 5. Feasible area of PCP

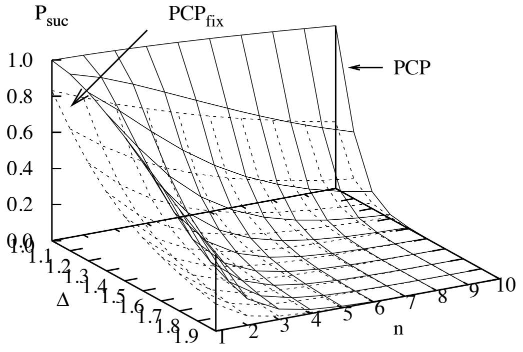


Figure 6. P_{suc} (PCP vs. $\mathrm{PCP_{fix}}$)

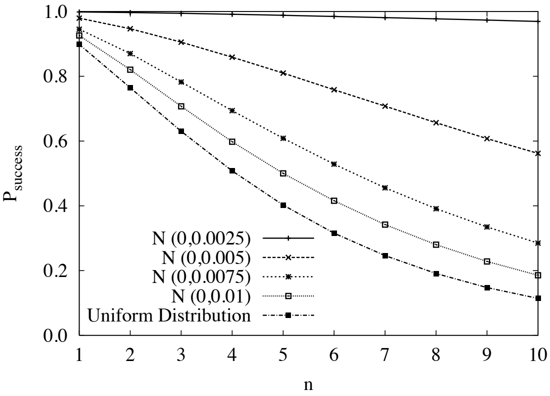


Figure 7. P_{suc} when nodes are concentrated around base station ($\Delta = 1.2$)

A. Condition for MPCP

In this section, we formulate the condition of MPCP for an information distribution service in which a base station is responsible for establishing connections to i nodes within its maximum transmission range. Nodes are denoted as X_i in ascending order of their distance from the base station. If $1 \leq i \leq n$, the node is within range, and if $n+1 \leq i$, it is out of range. The base station first finds the maximum i that satisfies

$$\begin{aligned} &||X_{n+1} - bs|| \geq \Delta ||X_i - bs|| \\ &\quad and\ ||X_{n+1} - bs|| < \Delta ||X_{i+1} - bs||. \end{aligned} \tag{17}$$

It then adjusts the radius of its success zone to $||X_i - bs||$ by changing its transmission power. Note that X_{n+1} denotes the nearest node beyond the maximum range. This equation indicates that the base station can connect to nodes in its success zone only when there are not any nodes belonging to other base stations in its noise zone. It temporarily gives up connecting to nodes that belong to it but in are its noise zone in order to increase radio frequency utilization.

B. Analysis

In this section, we analyze the communication success probability of MPCP. We assume that the region is expressed as a repeated structure of N_r cells, as in Section III-B. Similarly, the terms used in the following explanation have the same meanings as in Section III-B.

1) $N_r = 1$: As explained in Section III-B.1, S_1 is the area in which the nodes in the main cell can be located without disturbing communication in adjacent cells. Thus, the communication success probability of MPCP for $N_r = 1$ equals the ratio of the number of nodes in the area to the total number of nodes in the main cell:

$$P_{suc}(n) = \frac{S_1}{\pi R_{eq}^2}. \tag{18}$$

2) $N_r = 4$: For $N_r = 4$, we define one of four adjacent cells as the main cell and the others as neighboring cells. Here we focus on the main cell. If there are k ($\leq 4n$) nodes in the main cell, the communication success probability of MPCP is defined as

$$P_{suc}(n) = \frac{1}{n} \sum_{k=1}^{4n} \{k\ C_4(n,k)\ P_s(n,k)\}, \tag{19}$$

where $C_4(n,k)$ is the probability that k nodes are in the main cell and $P_s(n,k)$ is the mean probability of communication success in the main cell.

First, we derive $P_s(n,k)$ to obtain $P_{suc}(n)$. We use the relationships shown in Fig. 3, which illustrates the main cell, $Cell_1$, and a neighboring cell, $Cell_2$, when the radius of the success zone in $Cell_1$ is r. For successful communication in $Cell_1$, the nodes in $Cell_2$ must be located in the grey zone in Fig. 3, as described in Section III-B.2. The resulting probability that $4n - k$ nodes in the three neighboring cells are in the grey zone is $p_{adj}(n,k,r)$. This is equal to the probability that a node at distance r from bs_1 succeeds in communication. Since $P_s(n,k)$ is the mean success probability in $Cell_1$,

$$P_s(n,k) = \frac{1}{\pi} \int_0^1 2\pi r p_{adj}(n,r,k) dr. \tag{20}$$

If we substitute Eq. (20) into Eq. (19), we get

$$P_{suc}(n) = \frac{1}{n}\sum_{k=1}^{4n}\left\{k\ C_4(n,k)\ \int_0^1 2r\ \left(\frac{S_4(r)}{\pi}\right)^{4n-k} dr\right\}. \tag{21}$$

C. Simulation and analytic results

We verified the accuracy of our analysis and evaluated the effectiveness of our modified scheme using the simulation environment described in Section III-C.

1) Accuracy of analysis: Figure 8(a) illustrates how the absolute error between P_{suc} in the simulation results and in the analytic results varied with Δ for $n = 7$. The average difference was at most 1.1 % for $N_r = 4$. Figure 8(b) illustrates how the absolute error between P_{suc} in the simulation results and in the analytic results varied with n for $\Delta = 1.2$. The average difference was at most 0.5 % for $N_r = 4$. This clearly indicates that increasing N_r reduces the absolute error between the analytic and simulation results. Moreover, even a relatively small N_r improves the accuracy of the analysis. We thus use $N_r = 4$ in the following.

2) Effect of node density and occupation ratio: We investigated the feasible area of MPCP through analysis. Figure 9 shows P_{suc} for MPCP and PCP against node density n and occupation ratio Δ. It decreased with an increase in n and/or Δ. The decrease for MPCP was less than that for PCP. The higher the n and/or Δ, the larger the difference between P_{suc} for PCP and that for MPCP. For example, P_{suc} for MPCP was 0.67 higher than that for PCP when Δ was 1.2. This is because, with MPCP, a base station sacrifices nodes in the noise zone. In short, the modified scheme has a much higher P_{suc}.

3) Effect of controlling transmission power: To determine the effect of controlling the transmission power, we first defined the fixed transmission power to satisfy the condition of MPCP. Suppose a base station emits radio waves so that the radius of its success zone equals r_{fix}^{MPCP}. Since the radio waves must not disturb communications in adjacent cells,

$$r_{fix}^{MPCP} = \frac{\sqrt{3}R}{2\Delta}. \tag{22}$$

We define a scheme ($\mathrm{MPCP_{fix}}$) in which every base station sets the radius of its success zone to r_{fix}^{MPCP}. The success probability of $\mathrm{MPCP_{fix}}$ is

$$P_{suc} = \frac{\pi(r_{fix}^{MPCP})^2}{\pi R_{eq}^2} = (r_{fix}^{MPCP})^2. \tag{23}$$

Figure 10 shows P_{suc} for MPCP, $\mathrm{MPCP_{fix}}$, and a conventional cellular system. MPCP was always more effective than $\mathrm{MPCP_{fix}}$. When Δ was 1.2, for example, the difference in P_{suc} between MPCP and $\mathrm{MPCP_{fix}}$ was as much as 0.32. In terms of radio frequency utilization, MPCP and $\mathrm{MPCP_{fix}}$ are more effective than the conventional cellular system since their utilization rates were larger than 0.25 for every Δ and n. For Δ between 1 and 1.2, MPCP and $\mathrm{MPCP_{fix}}$ had about 3-4 and 2.5-3.6 times higher utilization than the conventional cellular system while reducing the number of sacrificed nodes. Thus, MPCP and $\mathrm{MPCP_{fix}}$ are more suitable for actual environments[4].

V. CONCLUSION

Our proposed perfect cell partitioning (PCP) scheme is designed for controlling the transmission power of base stations in a cellular communication system to prevent radio frequency interference among adjacent base stations. A base station using this scheme can use its entire frequency range, while one using the conventional scheme can use only a quarter of it. The simulation and analytic results showed that the PCP scheme is more effective than the conventional one when the node density is lower than 6. However, the probability of successful communication is relatively low. Therefore, we modified it to improve the probability. Simulation and analytic results showed that the success probability of the modified scheme is as much as 0.67 higher than that of our original scheme when the occupation ratio is 1.2. They also show that a base station using the modified scheme can use its frequency range more effectively than one using the original or conventional scheme.

We plan to extend our PCP and MPCP schemes to take into account the signal-to-interference ratio [20] as the radio frequency interference model. This model expresses radio frequency interference more accurately but makes the analysis more complicated. Furthermore, we have to tackle problems related to implementing PCP and MPCP in an actual system. For example, a base station needs to know the locations of the nodes in its maximum transmission range. The time-of-arrival of ultra wideband signals and time difference-of-arrival methods should be applicable to this problem.

High-speed downlink packet access (HSDPA) [24] also targets improvement in radio frequency utilization. This 3G mobile telephony communications protocol is composed of several technologies, including hybrid automatic repeat-request, fast packet scheduling, and adaptive modulation and coding. However, it does not consider the avoidance of radio frequency interference among neighboring cells. By combining HSDPA with MPCP, we should be able to further improve radio frequency utilization.

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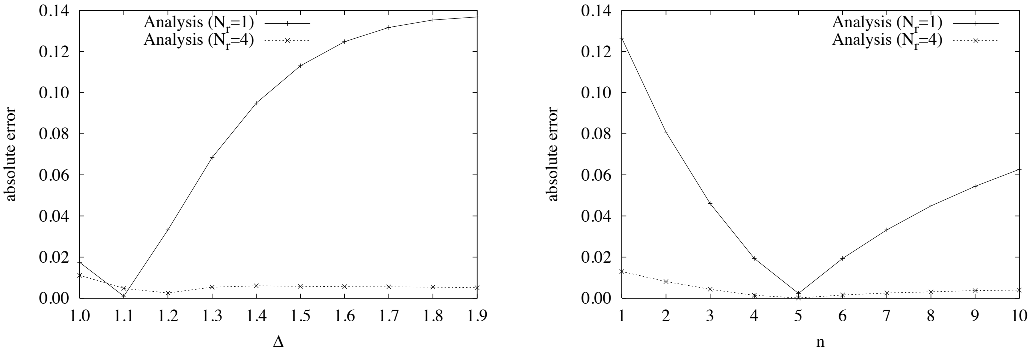
[4] $\mathrm{MPCP_{fix}}$ can be achieved without having to estimate the position of each node if a statistical node distribution is obtained a priori.



(a) $n = 7$ (b) $\Delta = 1.2$

Figure 8. Accuracy of analysis (MPCP)

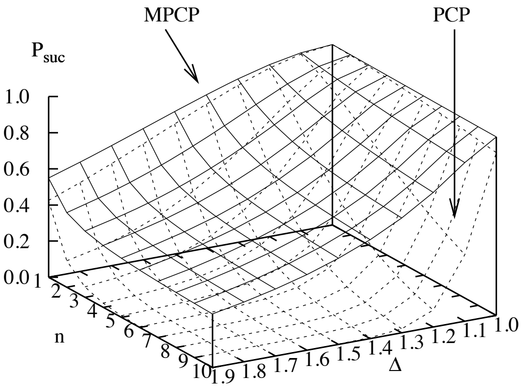


Figure 9. P_{suc} (MPCP vs. PCP)

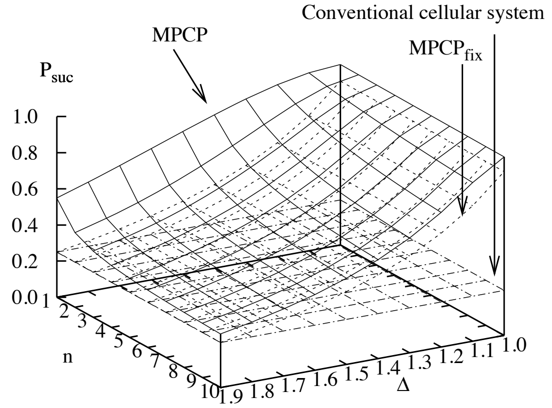


Figure 10. P_{suc} (MPCP vs. $\mathrm{MPCP_{fix}}$ vs. conventional cellular system)

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