Power and Frequency Efficient Virtual Cellular Network

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***Abstract*: Recently, major services provided by mobile communications systems are shifting from voice conversations to data communications over the Internet. There is a strong demand for increasing the data transmission rate. However, an important problem arises; larger peak transmit power is required as transmission rate becomes higher. In this paper, a virtual cellular concept is proposed to avoid this power problem and its transmit power and frequency efficiencies are evaluated by computer simulation to compare with that of the present cellular systems.**

Keyword: Virtual cellular system, frequency reuse distance, transmit power efficiency, transmit power control

I. INTRODUCTION

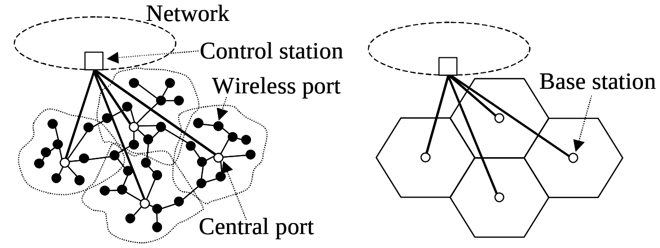
The 3rd generation mobile communication systems, known as IMT-2000 systems, have data transmission capability of up to 2 Mbps. However, since information transferred over the Internet is becoming increasingly rich, even IMT-2000 data transmission rate capability will sooner or later become insufficient. Probably, there will be a demand of peak data transmission rates of around 100Mbps ~1Gbps even in mobile communications systems. This will be the task of the 4th generation (4G) mobile communications systems, which is expected to emerge around 2010. A major objective of 4G systems will be to offer mobile users broadband multimedia services. However, there will be an important problem to overcome; as data transmission rate becomes higher, the peak transmit power becomes larger. Reducing the cell size is an efficient way to avoid larger peak transmit powers while increasing the data transmission rate [1], [2]. However, in realizing nano- or even pico-cell wireless network, the use of present cellular concept may not be optimal. In this paper, a virtual cellular concept is proposed and its transmit power and frequency efficiencies are evaluated by computer simulation to compare with the present cellular systems.

II. VIRTUAL CELLULAR CONCEPT

Figure 1 compares the virtual cellular system and the present cellular system. Many wireless ports are distributed in each virtual cell. One of the wireless ports distributed in each virtual cell acts as a gateway (this is called the central port here) to the network, similar to a base station in the present cellular system. A mobile station communicates with multiple wireless ports simultaneously. The features of the virtual cellular concept are summarized below.

(a) Grouping of distributed wireless ports, to construct each virtual cell, can be different for each user (i.e., the virtual cell can be different for each user) and the virtual cell size for the uplink may not necessarily be the same as for the downlink.
(b) The control signal traffic for handover and location registration to/from the network increases as the cell size becomes smaller. However, in the virtual cellular system, since a group of distributed wireless ports acts as one virtual base station, the control traffic will not increase.
(c) Each wireless port is designed to communicate with the central port via other wireless ports. Installation and removal of wireless ports are made whenever necessary.
(d) Since each wireless port acts as a site diversity branch, the transmit power of a mobile station and the total transmit power of wireless ports in each virtual cell can be made significantly smaller than the present cellular system.
(e) Reducing the transmit power contributes to the reduction in the interference power to other virtual cells, and thus the frequency efficiency improves significantly. Even in the TDMA case, the same frequency may be reused in the same virtual cell.

In the virtual cellular system, traffic routing and wireless access methods among wireless ports are important technical issues. If all wireless ports communicate with the central port directly, some wireless ports may need significantly large transmit powers due to path loss, shadowing loss, and multipath fading. To avoid this situation, adhoc network and multihop network can be applied [4],[5]. Since the objective of this paper is to evaluate the power and frequency efficiencies of the virtual cellular system, ideal communication among wireless ports is assumed.



(a)Virtual cellular system (b)Present cellular system

Figure 1 Comparison of virtual cellular system and present cellular system.

III. NUMERICAL EXPRESSION FOR TRANSMIT POWER AND RECEIVED SINR

TDMA wireless access method is assumed (the same frequency is not reused within a virtual cell). Figure 2 illustrates the virtual cell of interest surrounded by six nearest co-channel virtual cells. The 0-th virtual cell is considered as the virtual cell of interest. Only the first tier (6 nearest co-channel virtual cells) is considered because the interference power from the second tier of co-channel virtual cells is much smaller than the first tier. D is the distance between the co-channel virtual cells and R is the virtual cell radius. The instantaneous propagation loss is modeled as the product of the distance dependent path loss, log-normally distributed shadowing loss and multipath fading power gain. Assuming a short distance between a mobile and its nearest wireless port, frequency non-selective fading is assumed.

Signal-to-noise power ratio (SNR)-based fast transmit power control (TPC) is considered with the target SNR $(S/N)_{target}$ given by [3]

$$\left(\frac{S}{N}\right)_{target} = \chi \cdot \gamma_{req}, \quad (1)$$

where N is the background noise power, χ represents the allowable interference rise factor, defined as the interference plus background noise-to-background noise power ratio and γ_{req} is the required signal-to-interference plus noise power ratio (SINR) for the required bit error rate (BER) P_{breq}. The sum of the background noise and interference is approximated as a Gaussian noise. Assuming coherent quadrature phase shift keying (QPSK) data modulation, the required SINR γ_{req} is obtained using

$$P_{breq} = \frac{1}{2} erfc\left(\sqrt{\frac{\gamma_{req}}{2}}\right). \quad (2)$$

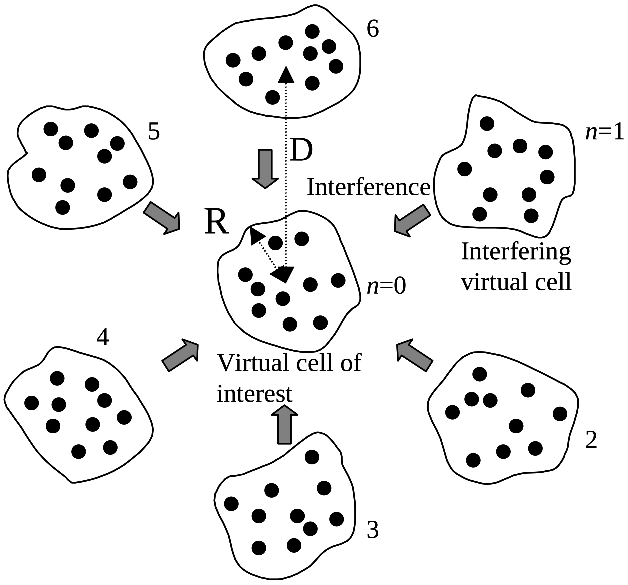


Figure 2 Geometry of co-channel virtual cells.

A. UPLINK

In the uplink, the received signals at wireless ports are transferred to the central port to be diversity combined. Then, the combined signal at the central port is transferred to the control station in the network. Two diversity combining methods are considered: maximal ratio combining (MRC) and selection combining (SC). The transmit power of mobile station is controlled by TPC command that is sent from the central port. It is assumed that there are K wireless ports in each virtual cell, each wireless port being equipped with M receive antennas.

(1) MRC

The SINR γ_0 at the central port in the 0-th virtual cell and the transmit power $P_{t,n}$ of the mobile station in the n-th virtual cell are given by

$$\begin{cases} \gamma_0 = \sum_{k=1}^{K} \frac{\left(\frac{P_{t,0}}{N}\right) 10^{-\frac{\eta_{0,k(0)}}{10}} r_{0,k(0)}^{-\alpha} \sum_{m=1}^{M} \left|\xi_{0,k(0)}(m)\right|^2}{1+\sum_{n=1}^{6} \frac{\left(\frac{S}{N}\right)_{target} 10^{-\frac{\eta_{n,k(0)}}{10}} r_{n,k(0)}^{-\alpha}}{(M-1)\sum_{k=1}^{K} 10^{-\frac{\eta_{n,k(n)}}{10}} r_{n,k(n)}^{-\alpha}}} \\ \left(\frac{P_{t,n}}{N}\right) = \frac{\left(\frac{S}{N}\right)_{target}}{\sum_{k=1}^{K} 10^{-\frac{\eta_{n,k(n)}}{10}} r_{n,k(n)}^{-\alpha} \sum_{m=1}^{M} \left|\xi_{n,k(n)}(m)\right|^2} \end{cases}, \quad (3)$$

where $r_{n,k(n)}$ is the distance from the mobile station in the n-th virtual cell to the k-th wireless port in the n-th virtual cell, α is the path loss exponent, $\eta_{n,k(n)}$ is the shadowing loss (dB) and $\xi_{n,k(n)}(m)$ is the complex fading gain for the propagation channel between the mobile station in the n-th virtual cell and the m-th antenna of the k-th wireless port in the n-th virtual cell.

(2) SC

The wireless port with the largest signal power is selected for data demodulation at the central port. The SINR γ_0 at the central port in the 0-th virtual cell and the transmit power $P_{t,n}$ of the mobile station in the n-th virtual cell are given by

$$\begin{cases} \gamma_0 = \dfrac{\left(\frac{S}{N}\right)_{target}}{1+\displaystyle\sum_{n=1}^{6}\frac{\left(\frac{S}{N}\right)_{target} 10^{-\frac{\eta_{n,k(0)}}{10}} r_{n,k(0)}{}^{-\alpha}}{(M-1)10^{-\frac{\eta_{n,k(n)}}{10}} r_{n,k(n)}{}^{-\alpha}}} \\ \left(\dfrac{P_{t,n}}{N}\right) = \dfrac{\left(\frac{S}{N}\right)_{target}}{10^{-\frac{\eta_{n,k(n)}}{10}} r_{n,k(n)}{}^{-\alpha}\displaystyle\sum_{m=1}^{M}\left|\xi_{n,k(n)}(m)\right|^2} \end{cases}, \qquad (4)$$

where the k-th wireless port is assumed to have the maximum received signal power, i.e.,

$$\begin{aligned} &10^{-\frac{\eta_{n,k(n)}}{10}} r_{n,k(n)}{}^{-\alpha}\sum_{m=1}^{M}\left|\xi_{n,k(n)}(m)\right|^2 \\ &= \max_{j\in\{1,..,K\}}\left[10^{-\frac{\eta_{n,j(n)}}{10}} r_{n,j(n)}{}^{-\alpha}\sum_{m=1}^{M}\left|\xi_{n,j(n)}(m)\right|^2\right]. \end{aligned} \qquad (5)$$

(3) Present cellular system

For comparison, the present cellular system is considered. The SINR γ_0 at the base station in the 0-th cell of interest and the transmit power $P_{t,n}$ of the mobile station in the n-th cell are given by Eq.(4) with $k(n)$ replaced by n.

B. DOWNLINK

Two transmit diversity schemes are considered: multi-transmit diversity (Multi-TD) where the same signal is transmitted from all wireless ports, and site selection transmit diversity (SSTD) where the signal is transmitted from the best wireless port only.

(1) Multi-TD

The signals transmitted from the wireless ports are received and coherently combined based on MRC at the mobile station. The SINR γ_0 at the mobile station in the 0-th virtual cell and the transmit power $P_{t,k(n)}$ of the k-th wireless port in the n-th virtual cell are given by

$$\begin{cases} \gamma_0 = \dfrac{\left(\frac{S}{N}\right)_{target}}{1+\displaystyle\sum_{n=1}^{6}\sum_{k=1}^{K}\frac{\left(\frac{S}{N}\right)_{target} 10^{-\frac{\eta_{k(n),0}}{10}} r_{k(n),0}{}^{-\alpha}}{(M-1)\displaystyle\sum_{k=1}^{K}10^{-\frac{\eta_{k(n),n}}{10}} r_{k(n),n}{}^{-\alpha}}} \\ \left(\dfrac{P_{t,k(n)}}{N}\right) = \dfrac{\left(\frac{S}{N}\right)_{target}}{\displaystyle\sum_{k=1}^{K}10^{-\frac{\eta_{k(n),n}}{10}} r_{k(n),n}{}^{-\alpha}\sum_{m=1}^{M}\left|\xi_{k(n),n}(m)\right|^2} \end{cases}. \qquad (6)$$

(2) SSTD

The SINR γ_0 at the mobile station in the 0-th virtual cell and the transmit power $P_{t,k(n)}$ of the k-th wireless port in the n-th virtual cell are given by

$$\begin{cases} \gamma_0 = \dfrac{\left(\frac{S}{N}\right)_{target}}{1+\displaystyle\sum_{n=1}^{6}\frac{\left(\frac{S}{N}\right)_{target} 10^{-\frac{\eta_{k(n),0}}{10}} r_{k(n),0}{}^{-\alpha}}{(M-1)10^{-\frac{\eta_{k(n),n}}{10}} r_{k(n),n}{}^{-\alpha}}} \\ \left(\dfrac{P_{t,k(n)}}{N}\right) = \dfrac{\left(\frac{S}{N}\right)_{target}}{10^{-\frac{\eta_{k(n),n}}{10}} r_{k(n),n}{}^{-\alpha}\displaystyle\sum_{m=1}^{M}\left|\xi_{k(n),n}(m)\right|^2} \end{cases}, \qquad (7)$$

where the k-th wireless port is assumed to provide the least instantaneous propagation loss.

(3) Present cellular system

For comparison, the present cellular system is considered. The

SINR γ_0 at the mobile station in the 0-th cell of interest and the transmit power $P_{t,n}$ of the base station in the n-th cell are given by by Eq.(7) with $k(n)$ replaced by n.

IV. COMPUTER SIMULATION

For simplicity, hexagonal layout of the virtual cells is assumed. A mobile station is randomly located in each virtual cell. The average transmit power of mobile station (uplink), the total average transmit powers of K wireless ports (downlink), and the frequency reuse distance are evaluated by Monte Carlo simulation. It is assumed that χ=10dB and $P_{breq}=10^{-3}$.

A. TRANSMIT POWER EFFICIENCY

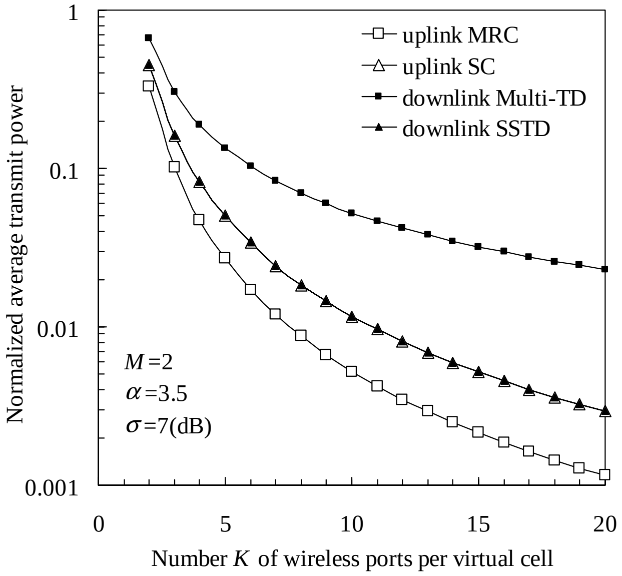


Figure 3 Normalized average transmit power per virtual cell.

Figure 3 shows the average transmit power normalized by the transmit power in a present cellular system as a function of the number K of wireless ports per virtual cell for the pass loss exponent α=3.5, the standard deviation of log-normal shadowing σ=7dB and Rayleigh fading. Two-branch antenna diversity reception (M=2) at both the mobile and wireless port is assumed. It is seen that the average transmit power of the virtual cellular system can be significantly reduced from that of the present cellular system. When K=8 and MRC is used at the central port, the mobile transmit power (uplink) can be reduced to less than 1/100 of that of the present cellular system. The use of SC at the central port instead of MRC increases the mobile transmit power by about 2 times. The total transmit power of wireless ports (downlink) is smaller with SSTD than with Multi-TD. This is because with Multi-TD, all wireless ports transmit the same signal to a mobile, while only the best wireless port transmits with SSTD. However, even with Multi-TD, when K=7, the total transmit power of wireless ports can be reduced by 10 times from that of the present cellular system. This means that the transmit power of each wireless port is less than 1/70 of that of a base station in the present cellular system.

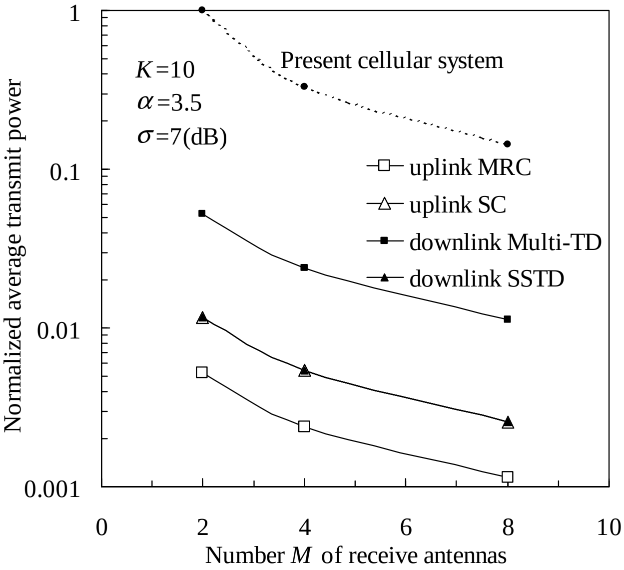


Figure 4 Normalized average transmit power as a function of the number M of antennas.

Figure 4 plots the average transmit power, normalized by the average transmit power of the present cellular system with M=2, as a function of the number M of antennas for K=10. The virtual cellular system can reduce the average transmit power significantly. Similar to the Fig.3, the average transmit power of the mobile station (uplink) is smaller with MRC than the case with SC and the total average transmit power of wireless ports (downlink) is smaller with SSTD than with Multi-TD.

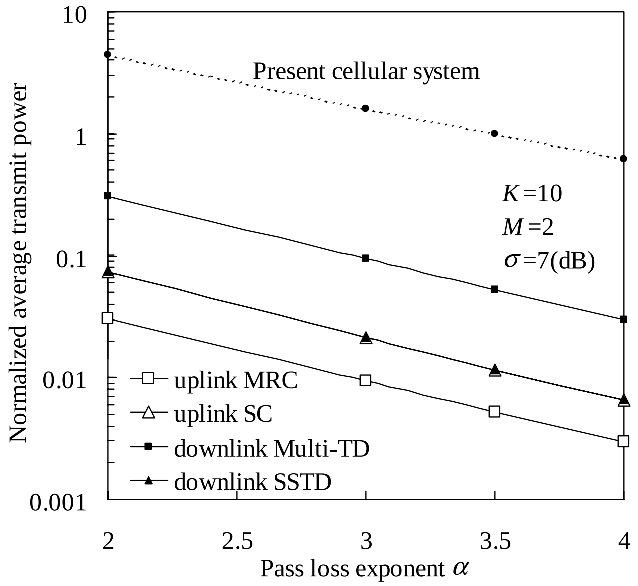


Figure 5 Normalized average transmit power as a function of the path loss exponent α.

Figure 5 shows the average transmit power, normalized by the average transmit power of the present cellular system for α=3.5, as a function of the path loss exponent α. Irrespective of the value of α, the average transmit power of the virtual cellular system can be reduced significantly. As α becomes larger, the average transmit power reduces since the interference power from other virtual cells decreases.

B. FREQUENCY EFFICIENCY

A good indicator of the frequency efficiency in a cellular type communication system is the reuse distance D of the same frequency normalized by the virtual cell radius of R for keeping the outage probability at the allowable value. The outage probability is defined as the probability that the SINR at a central port (uplink) or a mobile station (downlink) becomes less than the required value. When the hexagonal layout of virtual cells is assumed, the allocated channels can be grouped into F groups, where F is called the cluster size and is given by $F = (1/3)(D/R)^2$ [6], each channel group being assigned to different virtual cell.

Figure 6 plots the normalized frequency reuse distance D/R for the allowable outage probability of 10% as a function of the number K of wireless ports per virtual cell for the path loss exponent α=3.5, the standard deviation of log-normal shadowing σ=7dB, and the number of antennas M=2. The normalized reuse distance of the present cellular system is also plotted for comparison. It is found that increasing the value of K can reduce the D/R. It should be pointed out that when $D/R < \sqrt{3}$, the same frequency can be reused within the virtual cell.

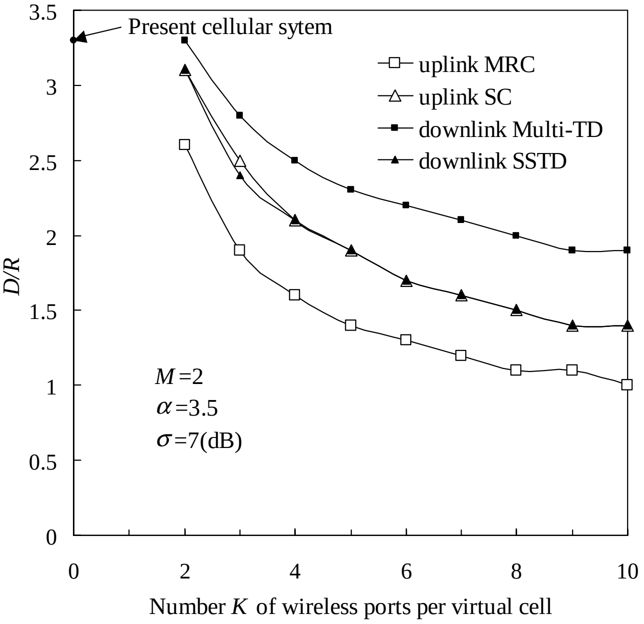


Figure 6 Frequency reuse distance D/R.

V. CONCLUSIONS

The virtual cellular concept was proposed to realize a pico-cell network for broadband wireless communication systems. A virtual cell consists of many distributed wireless ports and a group of distributed wireless ports acts as one base station. The transmit power and frequency efficiencies of the virtual cellular system were evaluated by Monte Carlo simulation to show that the virtual cellular system can considerably reduce the transmit power, irrespective of the value of path loss exponent α and the number M of receive antennas. Reducing the transmit power contributes to reducing the frequency reuse distance. Even in TDMA, the same frequency can be reused within the same virtual cell.

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