

## PAPER

# Power and Frequency Efficient Wireless Multi-Hop Virtual Cellular Concept

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**SUMMARY** 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, we propose a wireless multi-hop virtual cellular concept to avoid this power problem. The virtual cellular network consists of a central port, which is a gateway to the network, and many distributed wireless ports. Transmit power and frequency efficiencies of the virtual cellular network are evaluated by computer simulation to compare with that of the present cellular networks. In the wireless multi-hop virtual cellular network, routing among wireless ports is an important technical issue. We propose a routing algorithm based on the total uplink transmit power minimization criterion and evaluate the total transmit power by computer simulation.

**key words:** *virtual cellular network, frequency reuse distance, transmit power efficiency, multi-hop, routing*

## 1. Introduction

The 3rd generation mobile communication systems, known as IMT-2000 systems, have data transmission capability of up to 2 Mbps [1]. Recently, high-speed downlink packet access (HSDPA) aiming at a maximum peak throughput around 10 Mbps is under development for the enhancement of the IMT-2000 systems [2]. However, since information transferred over the Internet is becoming increasingly rich, even data transmission rate capability of the enhanced IMT-2000 will sooner or later become insufficient. Probably, in the near future, there will be a demand for peak data transmission rates of around 100 Mbps–1 Gbps even in mobile communications systems to offer mobile users broadband multimedia services. This is the task of the so called 4th generation (4G) mobile communications systems, which is expected to emerge around 2010. 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 [3], [4]. However, if the cell size becomes smaller, the control signal traffic for handover and location registration may increase. To avoid this problem, we propose a wireless multi-hop virtual cellular network in this paper. The wireless multi-hop virtual cell consists of a central port, which

is a gateway to the network, and many distributed wireless ports. A mobile terminal communicates simultaneously with surrounding wireless ports. Wireless port has two functions: one is to directly communicate with a mobile terminal and the other is to relay the signal to the central port. When we discuss the communication links between wireless ports and a mobile terminal, those wireless ports that directly communicate with the mobile terminal are called end wireless ports. All wireless ports can be the end wireless ports. Since each end wireless port acts as a site diversity branch, the transmit power of a mobile terminal and the total transmit power of wireless ports in each virtual cell can be made significantly smaller than the present cellular systems. The objective of this paper is to find the theoretically achievable performance limit of the virtual cellular network. Therefore, we assume in this paper each mobile terminal communicates with all end wireless ports in its virtual cell. In the uplink, the signals received by all end wireless ports in its virtual cell are relayed to the central port and diversity combined based on ideal maximal ratio combining (MRC) or selection combining (SC). In the downlink, the signal to be transmitted to a mobile terminal is relayed from the central port to all end wireless ports in its virtual cell.

For the virtual cellular network, relay of signals received at (or transmitted from) the end wireless ports to (or from) the central port is done by means of wireless multi-hop technique. Therefore, routing among distributed wireless ports is an important technical issue. Routing algorithms proposed for wireless multi-hop network or ad hoc network [5]–[8] can be applied. In the virtual cellular network, the frequency reuse is also applied to efficiently utilize the limited frequency bandwidth as in the present cellular systems. The frequency reuse distance can be reduced by decreasing the total transmit power of wireless ports. In [8], a routing method based on the total transmit power minimization criterion is presented and the total transmit power is evaluated for the case when the maximum number of hops is limited to 2. In this paper, we propose a routing algorithm based on the total uplink transmit power minimization criterion.

The remainder of this paper is organized as follows. Section 2 presents the wireless multi-hop virtual cellular concept. Section 3 evaluates, by computer simulation, the transmit power and frequency efficiencies of the user links between the end wireless ports and a mobile terminal. In Sect. 4, the routing algorithm based on total uplink transmit power minimization criterion is described and the transmit

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power efficiency of multi-hop links is evaluated by computer simulation. Section 5 draws some conclusions.

### 2. Virtual Cellular Concept

Figure 1 compares the virtual cellular network and the present cellular network. 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 network. A mobile terminal communicates with surrounding end wireless ports simultaneously. The features of the virtual cellular concept are summarized below.

- (a) 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 network, a group of distributed wireless ports acts as one virtual base station and hence, the control traffic will not increase (however, there exists control signal traffic within each virtual cell for multi-hop route construction and maintenance, but this is not discussed here).
- (b) Each wireless port is designed to communicate with the central port via other wireless ports. We consider stationary wireless ports (this is different from so-called wireless multi-hop network, in which each mobile terminal relays the signal to other terminals [6]); installation and removal of wireless ports are made whenever necessary.
- (c) Since each end wireless port acts as a site diversity branch, the transmit power of a mobile terminal and the total transmit power of end wireless ports can be made significantly smaller than the present cellular system (this is discussed in Sect. 3).
- (d) 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 time division multiple access (TDMA) case, it may be possible to reuse the same frequency in the same virtual cell (this is indicated in Sect. 3).
- (e) Grouping of distributed wireless ports, to construct virtual cell, may not necessarily be fixed but 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.

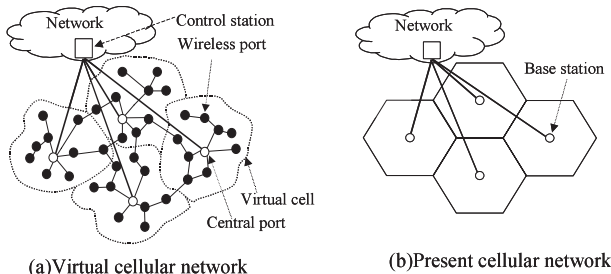


Fig. 1 Virtual cellular network and present cellular network.

### 3. Transmit Power Efficiency For User Link Between a Mobile Terminal and End Wireless Ports

TDMA wireless access method is assumed. In the uplink, different mobile terminal in a virtual cell uses different frequency channel for signal transmission. In the downlink, transmit diversity is applied. Multiple end wireless ports in a virtual cell transmit the same signal to a mobile terminal using the same frequency channel; different frequency channel is used for signal transmission to a different mobile terminal. Figure 2 illustrates the virtual cell of interest and surrounding co-channel virtual cells. The 0-th virtual cell is 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 terminal and its nearest wireless port, frequency non-selective fading is assumed. Below, transmit power efficiency for the user link between a mobile terminal and end wireless ports is evaluated.

Signal-to-noise power ratio (SNR)-based ideal fast transmit power control (TPC) is assumed (so that the evaluation gives the theoretically achievable benchmark). As in [9], we assume the target SNR  $(S/N)_{target}$  given by

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

where  $N$  is the background noise power,  $\chi$  represents the allowable interference rise factor [9], defined as the interference plus background noise-to-background noise power ratio, and  $\gamma_{req}$  is the required signal-to-interference plus noise

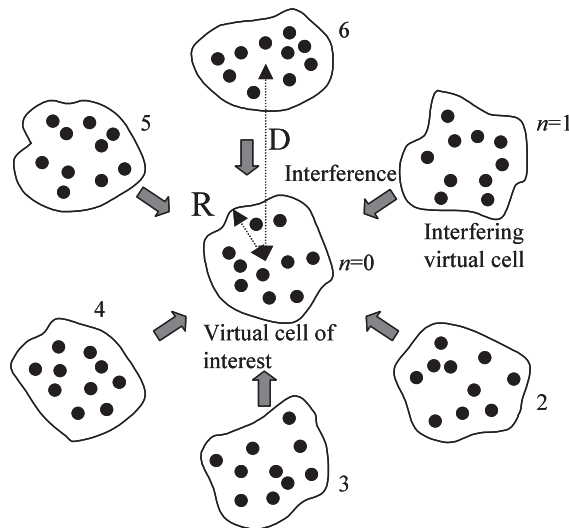


Fig. 2 Geometry of co-channel virtual cells.

power ratio (SINR) for the required bit error rate (BER)  $P_{b,req}$ . The sum of the background noise and interference is approximated as a Gaussian process. Assuming coherent quadrature phase shift keying (QPSK) data modulation, the required SINR  $\gamma_{req}$  is found using [10]

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

### 3.1 Expressions for Transmit Power and Signal-to-Interference Plus Noise Power Ratio

#### 3.1.1 Uplink Case (Mobile Terminal-to-Wireless Port)

In uplink, the signals received at end wireless ports are relayed by means of wireless multi-hop technique to the central port to be site diversity combined. Two diversity combining methods are considered: MRC and SC [10]. The transmit power of each mobile terminal is controlled by TPC command that is sent from the central port. In this paper, it is assumed that a mobile terminal moves slowly and fading rate is slow enough to neglect the transmission delay of the TPC command. Let us assume  $K$  wireless ports (including central port) in each virtual cell, each wireless port being equipped with  $M$  receive antennas.

##### (1) MRC

The received SNR  $(S/N)_{n,k(n)}$  of the signal, which is transmitted from the mobile terminal in the  $n$ -th virtual cell and received at the  $k$ -th wireless port in the  $n$ -th virtual cell, is given by

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

where  $P_{t,n}$  is the transmit power of the mobile terminal in the  $n$ -th virtual cell,  $r_{n,k(n)}$  is the distance from the mobile terminal in the  $n$ -th virtual cell to the  $k$ -th wireless port in the  $n$ -th virtual cell,  $\alpha$  is the path loss exponent,  $\eta_{n,k(n)}$  is the shadowing loss in dB and  $\xi_{n,k(n)}(m)$  is the complex fading gain of the fading channel between the mobile terminal and the  $m$ -th antenna of the  $k$ -th wireless port in the  $n$ -th virtual cell. The signals received at end wireless ports are transferred to the central port to be combined. The SNR  $(S/N)_n$  at the central port in the  $n$ -th virtual cell is given by

$$\left(\frac{S}{N}\right)_n = \sum_{k=0}^{K-1} \left(\frac{S}{N}\right)_{n,k(n)}. \quad (4)$$

Assuming SNR-based ideal fast TPC (i.e.  $(S/N)_n = (S/N)_{target}$ ),  $P_{t,n}$  of the mobile terminal in the  $n$ -th virtual cell is given by

$$\left(\frac{P_{t,n}}{N}\right) = \frac{\left(\frac{S}{N}\right)_{target}}{\sum_{k=0}^{K-1} r_{n,k(n)}^{-\alpha} 10^{-\frac{\eta_{n,k(n)}}{10}} \sum_{m=0}^{M-1} |\xi_{n,k(n)}(m)|^2}. \quad (5)$$

The SINR  $\gamma_0$  at the central port in the 0-th virtual cell is given by

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

where  $\left(\frac{I}{N}\right)_{k(0)}$  is the local average interference-to-noise power ratio at the  $k$ -th wireless port in the 0-th virtual cell (the term ‘‘local average’’ means that the averaging operation is taken over sufficiently long time interval to average out the fading variation, but not to change the shadowing loss variation at all). Using [9]

$$\left(\frac{1}{\sum_{m=0}^{M-1} |\xi_{n,k(n)}(m)|^2}\right) = \frac{1}{M-1}, \quad (7)$$

we obtain

$$\gamma_0 = \sum_{k=0}^{K-1} \frac{\left(\frac{P_{t,0}}{N}\right) r_{0,k(0)}^{-\alpha} 10^{-\frac{\eta_{0,k(0)}}{10}} \sum_{m=0}^{M-1} |\xi_{0,k(0)}(m)|^2}{1 + \sum_{n=1}^6 \frac{\left(\frac{S}{N}\right)_{target} r_{n,k(0)}^{-\alpha} 10^{-\frac{\eta_{n,k(0)}}{10}}}{(M-1) \sum_{k=0}^{K-1} r_{n,k(n)}^{-\alpha} 10^{-\frac{\eta_{n,k(n)}}{10}}}}. \quad (8)$$

##### (2) SC

The end wireless port with the largest received signal power is selected at the central port. The SINR  $\gamma_0$  at the central port in the 0-th virtual cell and the transmit power  $P_{t,n}$  of the mobile terminal in the  $n$ -th virtual cell are given by

$$\left\{ \begin{aligned} \gamma_0 &= \frac{\left(\frac{S}{N}\right)_{target}}{1 + \sum_{n=1}^6 \frac{\left(\frac{S}{N}\right)_{target} r_{n,k(0)}^{-\alpha} 10^{-\frac{\eta_{n,k(0)}}{10}}}{(M-1) \sum_{k=0}^{K-1} r_{n,k(n)}^{-\alpha} 10^{-\frac{\eta_{n,k(n)}}{10}}}}, \\ \left(\frac{P_{t,n}}{N}\right) &= \frac{\left(\frac{S}{N}\right)_{target}}{r_{n,k(n)}^{-\alpha} 10^{-\frac{\eta_{n,k(n)}}{10}} \sum_{m=0}^{M-1} |\xi_{n,k(n)}(m)|^2} \end{aligned} \right. , \quad (9)$$

where the  $k$ -th end wireless port has been assumed to have

the maximum received signal power, i.e.,

$$k(n) = \arg \max_{j \in \{1, \dots, K\}} \left[ r_{n,j(n)}^{-\alpha} 10^{-\frac{\eta_{n,j(n)}}{10}} \sum_{m=0}^{M-1} |\xi_{n,j(n)}(m)|^2 \right]. \quad (10)$$

### (3) Present cellular network

For comparison, the present cellular network using hard handoff (or SC site diversity) is considered. The SINR  $\gamma_0$  at the base station in the 0-th cell of interest and the transmit power  $P_{t,n}$  of the mobile terminal in the  $n$ -th cell are given by Eq. (9) with  $k(n)$  replaced by  $n$ .

#### 3.1.2 Downlink Case (Wireless Port-to-Mobile Terminal)

Two transmit diversity schemes are considered: multi-transmit diversity (MTD), where the same signal is transmitted from all end wireless ports using the same frequency channel, and site selection diversity transmission (SSDT) [11], where the signal is transmitted from the best wireless port only.

##### (1) MTD

The signals transmitted from the end wireless ports are received and coherently combined based on MRC at the mobile terminal. The SINR  $\gamma_0$  at the mobile terminal 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

$$\left\{ \begin{aligned} \gamma_0 &= \frac{\sum_{k=0}^{K-1} \left(\frac{S}{N}\right)_{k(0),0}}{1 + \left(\frac{I}{N}\right)_0} \\ &= \frac{\left(\frac{S}{N}\right)_{target}}{1 + \sum_{n=1}^6 \sum_{k=0}^{K-1} \frac{\left(\frac{S}{N}\right)_{target} r_{k(n),0}^{-\alpha} 10^{-\frac{\eta_{k(n),0}}{10}}}{(M-1) \sum_{k=0}^{K-1} r_{k(n),n}^{-\alpha} 10^{-\frac{\eta_{k(n),n}}{10}}}}, \\ \left(\frac{P_{t,k(n)}}{N}\right) &= \frac{\left(\frac{S}{N}\right)_{target}}{\sum_{k=0}^{K-1} r_{k(n),n}^{-\alpha} 10^{-\frac{\eta_{k(n),n}}{10}} \sum_{m=0}^{M-1} |\xi_{k(n),n}(m)|^2} \end{aligned} \right. \quad (11)$$

where  $(S/N)_{k(n),n}$  is the SNR of the signal, which is transmitted from the  $k$ -th wireless port in the  $n$ -th virtual cell and received at the mobile terminal in the  $n$ -th virtual cell, and  $(I/N)_n$  is the local average interference-to-noise power ratio at the mobile terminal in the  $n$ -th virtual cell.

##### (2) SSDT

The SINR  $\gamma_0$  at the mobile terminal 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

$$\left\{ \begin{aligned} \gamma_0 &= \frac{\left(\frac{S}{N}\right)_{target}}{1 + \sum_{n=1}^6 \frac{\left(\frac{S}{N}\right)_{target} r_{k(n),0}^{-\alpha} 10^{-\frac{\eta_{k(n),0}}{10}}}{(M-1) r_{k(n),n}^{-\alpha} 10^{-\frac{\eta_{k(n),n}}{10}}}}, \\ \left(\frac{P_{t,k(n)}}{N}\right) &= \frac{\left(\frac{S}{N}\right)_{target}}{r_{k(n),n}^{-\alpha} 10^{-\frac{\eta_{k(n),n}}{10}} \sum_{m=0}^{M-1} |\xi_{k(n),n}(m)|^2} \end{aligned} \right. \quad (12)$$

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

$$k(n) = \arg \max_{j \in \{1, \dots, K\}} \left[ r_{j(n),n}^{-\alpha} 10^{-\frac{\eta_{j(n),n}}{10}} \sum_{m=0}^{M-1} |\xi_{j(n),n}(m)|^2 \right]. \quad (13)$$

##### (3) Present cellular network

For comparison, the present cellular network is also considered as in the uplink case. Similar to the uplink case, the SINR  $\gamma_0$  at the mobile terminal 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 Eq. (12) with  $k(n)$  replaced by  $n$ .

### 3.2 Transmit Power and Frequency Efficiencies

For simplicity, hexagonal layout of the virtual cells is assumed. A mobile terminal is randomly located in each virtual cell. The average transmit power of mobile terminal (for uplink), the total average transmit powers of  $K$  wireless ports (for downlink), and the frequency reuse distance are evaluated by Monte Carlo simulation using Eqs. (8), (9), (11) and (12) for the case of  $P_{b,req} = 10^{-3}$ ,  $\chi = 10$  dB and the standard deviation  $\sigma$  of log-normal shadowing of  $\sigma = 7$  dB.

Figure 3 shows the average transmit power normalized by the transmit power in a present cellular network as a function of the number  $K$  of wireless ports per virtual cell for

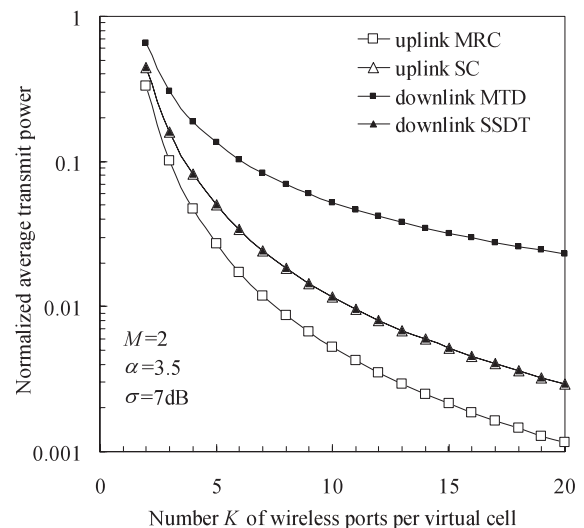


Fig. 3 Normalized average transmit power per virtual cell.

the path loss exponent  $\alpha=3.5$ . Two-branch antenna diversity reception ( $M=2$ ) at both mobile terminal and wireless port is assumed. It is seen that by increasing  $K$ , the average transmit power of the virtual cellular network can be significantly reduced from that of the present cellular network due to the increasing transmit/receive diversity gain. When  $K=8$  and MRC is used at the central port, the mobile transmit power (for uplink) can be reduced to less than 1/100 of that of the present cellular network. 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 (for downlink) is smaller with SSDT than with MTD. This is because with MTD, all wireless ports transmit the same signal to a mobile, while only the best wireless port transmits with SSDT. However, even with MTD, when  $K=7$ , the total transmit power of wireless ports can be reduced by 10 times from that of the present cellular network. 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 network. The same frequency channel is used at all  $K$  wireless ports for signal transmission based on MTD or SSDT. As  $K$  becomes larger, the diversity gain increases and thus, the total transmit power decreases. This reduces the co-channel interference to other virtual cells, thereby increasing the frequency efficiency.

Figure 4 plots the dependency of average transmit power, normalized by that of the present cellular network, on the number  $M$  of antennas when  $K=10$ . As  $M$  increases, the normalized average transmit power decreases due to increasing diversity effect.

Figure 5 shows the average transmit power, normalized by that of the present cellular network, as a function of the path loss exponent  $\alpha$ . As  $\alpha$  becomes larger, the average transmit power reduces since the co-channel interference power from other virtual cells decreases. Irrespective of the value of  $\alpha$ , the average transmit power of the virtual

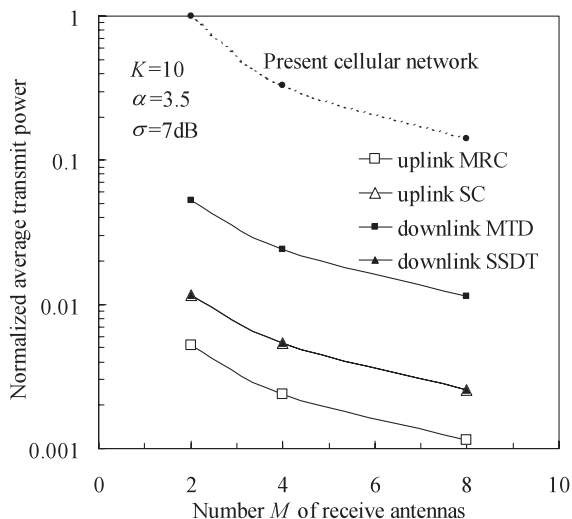


Fig. 4 Normalized average transmit power as a function of number  $M$  of receive antennas.

cellular network can be reduced significantly.

A good indicator of the frequency efficiency in the virtual cellular network (as in the present cellular network) is the reuse distance  $D$  of the same frequency normalized by the virtual cell radius  $R$  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 terminal (downlink) falls below the required value. The available channels are grouped into  $F$  groups, where  $F$  is called the cluster size and is given by  $F = (1/3)(D/R)^2$  [12], each channel group is assigned to a different virtual cell.

Figure 6 plots the normalized frequency reuse distance  $D/R$  for the allowable outage probability of 10% as a function of  $K$ .

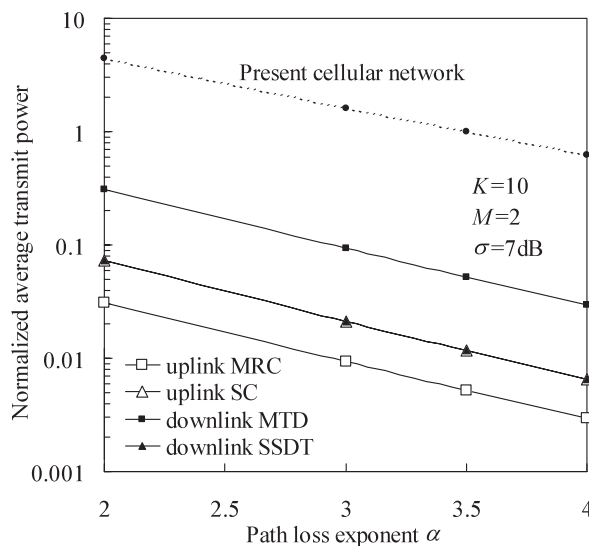


Fig. 5 Normalized average transmit power as a function of path loss exponent  $\alpha$ .

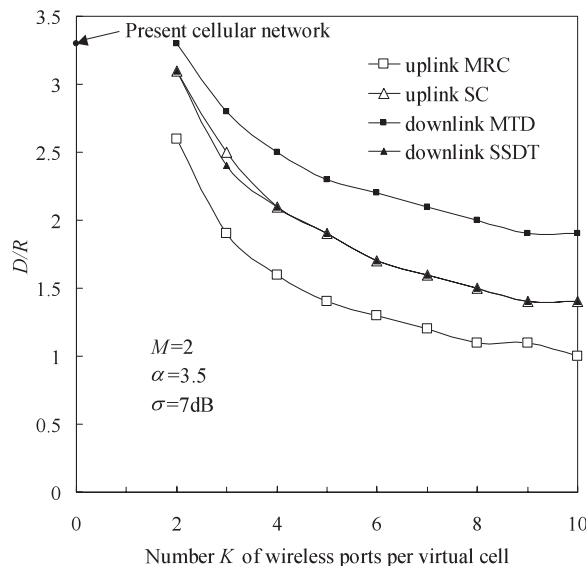


Fig. 6 Frequency reuse distance  $D/R$ .

tion of the number  $K$  of wireless ports per virtual cell for  $\alpha=3.5$ ,  $\sigma=7$  dB, and  $M=2$ . The normalized reuse distance of the present cellular network is also indicated for comparison. Increasing the value of  $K$  can significantly reduce the  $D/R$ . It is worthwhile noting that when  $D/R < \sqrt{3}$ , the same frequency can be reused within the virtual cell.

#### 4. Wireless Multi-Hop among Wireless Ports

The central port acts as a gateway to the network via the control station, similar to a base station in the present cellular network. For the uplink (or downlink) of the virtual cellular network, the signals received at (or transmitted from) end wireless ports need to be relayed to (or from) the central port. If all end wireless ports communicate with the central port directly, the transmit powers of some end wireless ports may become very large due to path-loss, shadowing loss, and multipath fading. To avoid this, wireless multi-hop technique is applied. In this paper, it is assumed that each mobile terminal communicates with end wireless ports in its virtual cell only. Received signals at all end wireless ports in the virtual cell, where the mobile terminal is located, are relayed to the central port to be diversity combined. The virtual cell control layer, which is inserted between the data link layer and the network layer, is introduced as illustrated in Fig. 7. The virtual cell control layer manages the construction and maintenance of multi-hop route between each wireless port and the central port.

##### 4.1 Route Construction Procedure

Multi-hop route is constructed in order to minimize the total transmit power of wireless ports for multi-hop relay. First, uplink case (end wireless port-to-central port) is considered. Figure 8 shows the message flow of route construction. The route construct request message is sent periodically from all wireless ports to the central port via other wireless ports, and the route notification message is sent back from the central port to each wireless port via other wireless ports. To avoid excessive transmission delay, the maximum number of hops is limited. In order to limit the maximum number of hops, the number of hops is included in the route construct request message. The header of route construct request message includes: (a) transmit power, (b) source wireless port

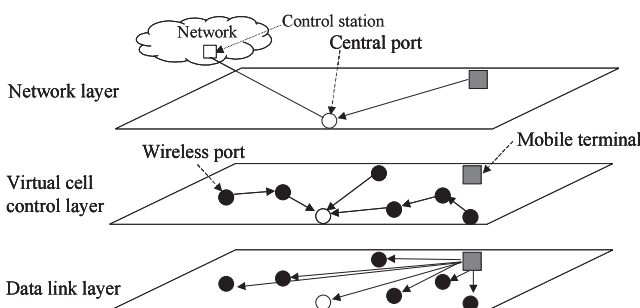


Fig. 7 Layer structure.

address, (c) the number of hops, (d) transmitting wireless port address, and (e) total required transmit power of wireless ports along the route. The header of route notification message includes: (a) destination wireless port address, (b) transmitting wireless port address, (c) the source wireless port address, and (d) required transmit power of the destination wireless port. As the maximum number of hops increases, the route construction control message traffic may increase. However, since we are assuming that all wireless ports are stationary, the multi-hop route updating interval may not necessarily be too short and thus, the increase in the route construction control message traffic is not severe.

Let the wireless port #A be the source wireless port as shown in Fig. 8. There are several candidate routes branching from the source wireless port. The wireless port of the  $i$ -th hop along the candidate route  $k$  is represented as  $W_k(i)$ . The route construction procedure is as follows:

**Step 1:** Source wireless port #A= $W_k(0)$  ( $k=0,1, \dots$ ) (see Fig. 8) sends the route construct request message with transmit power  $P_t(W_k(0))$ .

**Step 2:** Upon reception of the  $k$ -th route construct request message from the wireless port  $W_k(j-1)$ , the wireless port  $W_k(j)$  checks the number  $j$  of hops and if  $j$  is less than the allowable maximum number of hops, the wireless port  $W_k(j)$  computes the required transmit power  $P_{t,req}(W_k(j-1), W_k(j))$  of the wireless port  $W_k(j-1)$  using the following equation:

$$P_{t,req}(W_k(j-1), W_k(j)) = P_{req} + P_t(W_k(j-1)) - P_r(W_k(j)) \text{ in dB,} \quad (14)$$

where  $P_{req}$  is the required received signal power,  $P_t(W_k(j-1))$  is the transmit power of the wireless port  $W_k(j-1)$ , and

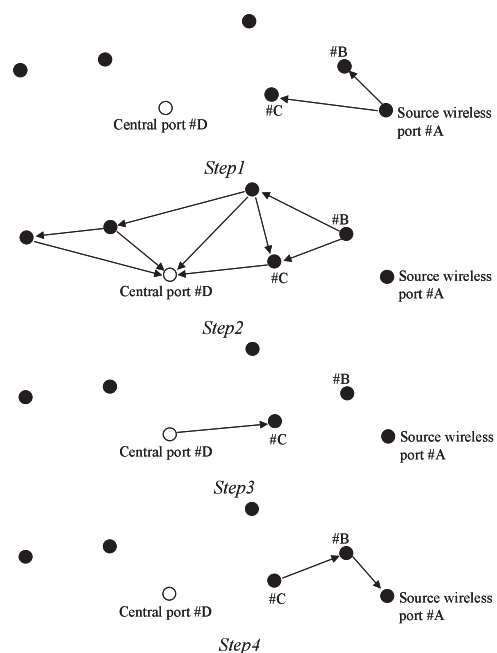


Fig. 8 Example of uplink route construction message flow.

$P_r(W_k(j))$  is the received signal power at the wireless port  $W_k(j)$ . Then, the total transmit power  $P_k$  of the wireless ports along the  $k$ -th route reaching the wireless port  $W_k(j-1)$  is computed using

$$P_k = \sum_{i=1}^j P_{t,req}(W_k(i-1), W_k(i)). \quad (15)$$

If the wireless port receives more-than-one route construction request messages, the wireless port selects the route  $\hat{k}$  that has the minimum total required transmit power:

$$\hat{k} = \arg \min_k \{P_k\} \quad (16)$$

and multicasts the route construction request message to other wireless ports.

For example, wireless port #C ( $=W_0(1)=W_1(2)$ ) receives the route construction request messages from wireless ports #A ( $=W_0(0)$ ) and #B ( $=W_1(1)$ ). Since we assume

$$P_{k=1} = \begin{pmatrix} P_{t,req}(\#A = W_1(0), \#B = W_1(1)) \\ + P_{t,req}(\#B = W_1(1), \#C = W_1(2)) \end{pmatrix} < P_{k=0} = P_{t,req}(\#A = W_0(0), \#C = W_0(1)),$$

the  $k=1$  route is selected and the wireless port #C relays the route construction message received from wireless port #B.

**Step 3:** The central port (wireless port #D) chooses the route which minimizes the total required transmit power and multicasts the route notification message that includes the destination wireless port address ( $\#C=W_1(2)$ ) and the required transmit power of wireless port #C.

**Step 4:** When the wireless port finds its address in the received route notification message, it relays the route notification message to the source wireless port (wireless port #A= $W_1(0)$ ).

**Step 5:** The source wireless port (wireless port #A= $W_1(0)$ ) receives the route notification message.

Figure 9 shows some examples of constructed routes when  $K=20$  and  $J=5$ , where  $J$  is the maximum number of allowable hops for  $\alpha=3.5$  and  $\sigma=7$  dB. Figure 9(a) shows an example in which the multi-hop routes have been constructed, where the central port transmits (receives) the uplink (downlink) signals via only one wireless port. Of course, this does not always happen. Sometimes, the central port needs to have multiple connections with surrounding wireless ports as seen in Fig. 9(b).

### 4.2 Total Multi-Hop Transmit Power

SNR-based TPC is assumed. The total multi-hop transmit power of wireless ports in an entire virtual cell is evaluated by computer simulation. The total multi-hop transmit power is defined as the ensemble average of the sum of transmit powers of all wireless ports and the central wireless port in an entire virtual cell.

Figure 10 plots the total multi-hop transmit power normalized by that of single-hop case as a function of the maximum number  $J$  of allowable hops with the number  $K$  of

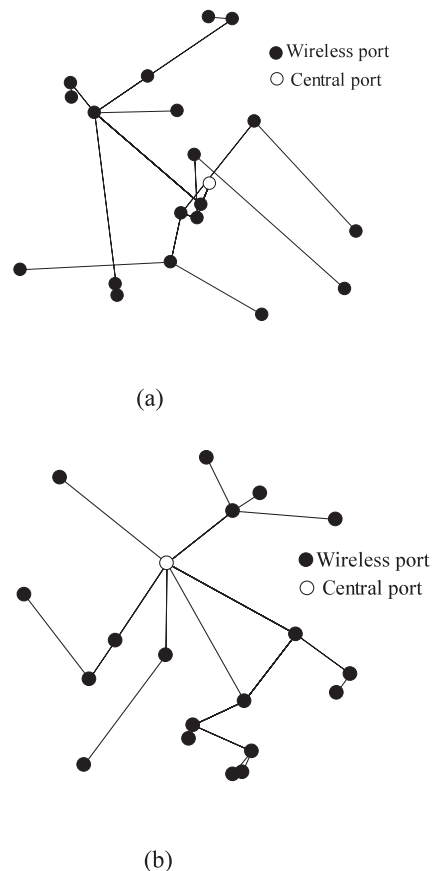


Fig. 9 Examples of constructed routes.

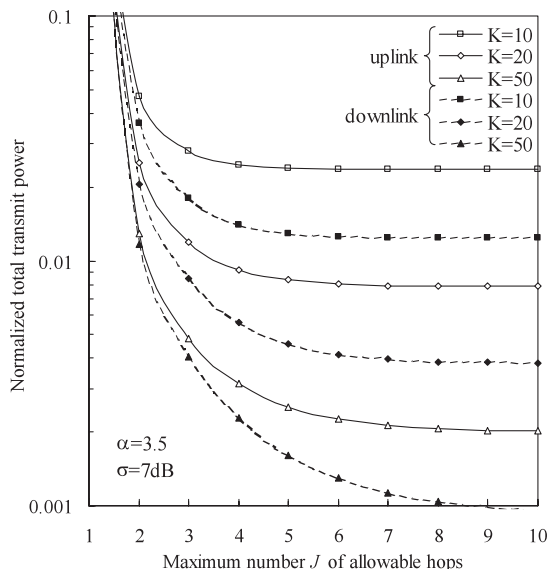
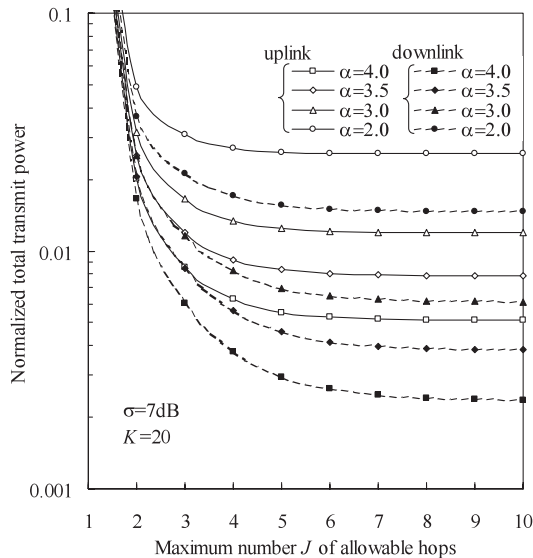


Fig. 10 Normalized total multi-hop transmit power as a function of maximum number  $J$  of allowable hops with number  $K$  of wireless ports as a parameter.

wireless ports per virtual cell as a parameter for  $\alpha=3.5$  and  $\sigma=7$  dB. It is clearly seen that multi-hop communication can significantly reduce the total transmit power for multi-hop

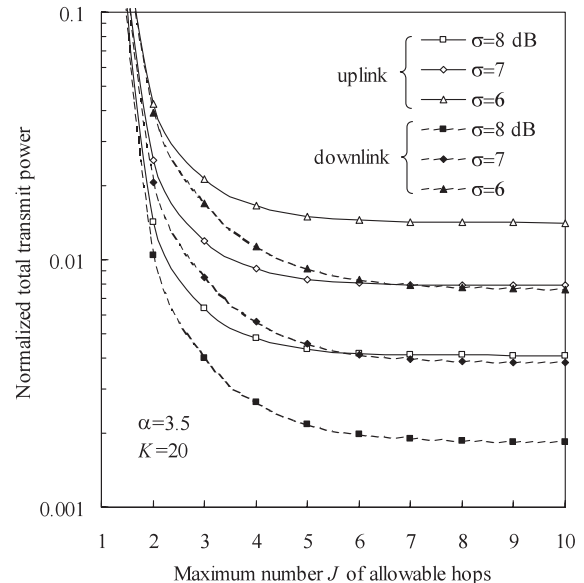


**Fig. 11** Normalized total multi-hop transmit power as a function of the maximum number  $J$  of allowable hops with path-loss exponent  $\alpha$  as a parameter.

relaying. When  $J=4$  and  $K=20$ , the uplink (downlink) total multi-hop transmit power can be reduced to 0.008 (0.004) of that of the single-hop case. The total uplink multi-hop transmit power is larger than that of downlink. This is because the same signal can be multicast to wireless ports simultaneously in the downlink. It can also be seen that the normalized total multi-hop transmit power is almost the same for  $J > 4, 6$  and  $8$  when  $K=10, 20$  and  $50$ , respectively. This suggests that the maximum number of allowable hops can be limited in order to avoid unnecessary long time delay.

Figure 11 plots the total multi-hop transmit power normalized by that of single-hop case as a function of the maximum number  $J$  of allowable hops with  $\alpha$  as a parameter for  $K=20$  and  $\sigma=7$  dB. It can be seen from Fig. 11 that as  $\alpha$  becomes larger, the normalized total multi-hop transmit power reduces. The reason for this is discussed below. Multi-hop communication can reduce a link distance between transmitting and receiving wireless ports. For simplicity, only distance dependent path loss is considered. Suppose that the single-hop link distance between the end wireless port and the central port is  $r$ . If each multi-hop link distance between the wireless ports is  $ar$ , where  $0 < a < 1$ , the transmit power of the wireless port is reduced  $a^\alpha$  times that of the single-hop case. The maximum number of hops is limited to  $J$ . Therefore, the total transmit power is proportional to  $J \times a^\alpha$ . This suggests that the normalized total transmit power reduces exponentially as  $\alpha$  becomes larger.

Figure 12 plots the total multi-hop transmit power normalized by that of single-hop case as a function of the maximum number  $J$  of allowable hops with  $\sigma$  as a parameter for  $K=20$  and  $\alpha=3.5$ . As  $\sigma$  becomes larger, the normalized total transmit power reduces. This is because the route diversity effect increases as the difference in the propagation losses among wireless ports becomes larger. Irrespective of



**Fig. 12** Normalized total multi-hop transmit power as a function of the maximum number  $J$  of allowable hops with shadowing loss standard deviation  $\sigma$  as a parameter.

the values of  $\alpha$  and  $\sigma$ , the total transmit power is almost the same for  $J > 6$ , as seen in Figs. 11 and 12.

## 5. Conclusions

A wireless multi-hop virtual cellular concept was proposed. Each virtual cell consists of many distributed wireless ports and a group of distributed wireless ports acts as one base station in the present cellular network. A mobile terminal communicates with surrounding wireless ports (the end wireless ports) simultaneously. In this paper, the theoretically achievable performance limit of virtual cellular network was evaluated in terms of transmit power and frequency efficiencies of the user links and transmit power efficiency of multi-hop links. It was shown that the transmit power for user links between a mobile terminal and its end wireless ports can be significantly reduced, in comparison with the present cellular network, irrespective of the path loss exponent and the number of receive antennas. Reducing the transmit power contributes to reducing the frequency reuse distance. It may be possible to reuse the same frequency within the same virtual cell even with TDMA. In this paper, it was assumed that all wireless ports in each virtual cell act as the end wireless ports and signals received at all end wireless ports are relayed using the wireless multi-hop technique to the central port to be diversity combined based on ideal MRC or SC. However, this increases the complexity of the virtual cellular network. To reduce the network complexity, the end wireless ports which directly communicate with each mobile terminal can be limited. This is left as an interesting future study.

In this paper, the wireless multi-hop technique was applied to data relaying between the central port and the end wireless port. A routing algorithm based on the total uplink



transmit power minimization criterion was proposed. The total transmit power for wireless multi-hop communication was evaluated by computer simulation to show that the wireless multi-hop can considerably reduce the total multi-hop transmit power, while avoiding unnecessary large time delay, irrespective of the path-loss exponent and the shadowing loss standard deviation.

In the virtual cellular network, an additional frequency band is necessary for multi-hop communication. The available frequency band is divided into two sub-bands: one for the user links (between mobile terminal and wireless ports) and the other for the multi-hop links. Similar to present cellular network, the same frequency channels in the multi-hop band should be reused even within the same virtual cell in order to use the limited frequency band efficiently. For this purpose, a distributed dynamic channel assignment can be applied [13]. Frequency reuse produces the co-channel interference, thereby causing a channel assignment failure when the dynamic channel assignment is applied. The total frequency efficiency taking into account both the user links and multi-hop links and a comparison with the present cellular network are left as important future study.

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