Transmit Power Efficiency of a Multi-hop Virtual Cellular System

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***Abstract*—Recently, there is a strong demand for higher speed data transmissions in cellular mobile communications systems. However, there will be a serious problem; as data transmission rate becomes higher, the peak transmit power becomes larger. To decrease the peak transmit power while increasing the data transmission rate, the cell size should be made significantly small. We proposed a virtual cellular concept to efficiently realize pico-cell network and showed that the virtual cellular system can significantly reduce the transmit power of a mobile terminal while increasing frequency efficiency. The virtual cell consists of a central port, which is a gateway to the network, and many distributed wireless ports. In the virtual cellular system, data relay between the central port and wireless ports is necessary. In this paper, multi-hop wireless system is applied for data relay. The virtual cell control layer is introduced for the multi-hop transmission. The routing algorithm that minimizes the total uplink transmit power of wireless ports for data relay is presented. The total transmit powers of uplink and downlink for data relay are evaluated by computer simulation to show that the multi-hop system can reduce considerably the total transmit powers, while avoiding unnecessary large time delay, irrespective of the values of path-loss exponent α and the shadowing loss standard deviation σ.**

Keywords: virtual cellular system, multi-hop network, adhoc network, routing, transmit power efficiency

I. INTRODUCTION

Major services provided by cellular mobile communications systems are sifting from voice conversations to data communications. There is a strong demand for higher speed data transmissions. However, there will be a serious problem; as data transmission rate becomes higher, the peak transmit power becomes larger. To decrease the peak transmit power while increasing the data transmission rate, the cell size should be made significantly smaller, resulting in nano- or even pico-cell network [1], [2]. However, if the cell size becomes smaller, control signal traffic for handover and location registration may increase. To avoid this problem, we proposed a virtual cellular concept [3]. Fig. 1 illustrates the virtual cellular system. The virtual cell consists of a central port, which is a gateway to the network, and many distributed wireless ports. Since a group of distributed wireless ports acts as one virtual base station, increase in the control traffic for handover and location registration can be avoided.

A mobile terminal communicates simultaneously with distributed wireless ports. We showed [3] that the virtual cellular system can significantly reduce the transmit power of a mobile terminal and wireless ports for communication between a mobile terminal and wireless ports, and the frequency reuse distance from that of the present cellular system. However, in Ref. [3], the transmit power and frequency efficiencies for data relay among wireless ports in the virtual cell were not discussed.

The virtual cellular system requires the data relay between the central wireless port and distributed wireless ports. For the uplink, the signals transmitted from a mobile terminal and received at wireless ports need to be relayed to the central wireless port, while for the downlink, the signal to the mobile terminal can be multicast from the central wireless port to distributed wireless ports. Therefore, routing among wireless ports is an important technical issue. Routing algorithms proposed for wireless multi-hop network or adhoc network can be applied [4]~[7]. In Ref.[6], a routing algorithm that minimizes the number of hops is presented. Ref.[5] proposes a routing algorithm using the link distance information. In the data relay of virtual cellular system, the frequency reuse is also applied to efficiently utilize the limited frequency bandwidth as in present cellular systems. The frequency reuse distance can be reduced by decreasing the total transmit power of wireless ports for data relay. In Ref.[7], a routing algorithm to minimize the total transmit power of wireless ports for data relay is proposed and the total transmit power is evaluated for the case of the maximum number of hops being limited to 2.

In this paper, multi-hop wireless system is applied for data relay between the central port and wireless ports and the virtual cell control layer is introduced. To avoid large transmission delay, the number of hops should be limited. We present the routing algorithm which minimizes the total uplink transmit power for data relay among wireless ports in the virtual cell while limiting the number of hops. The transmit power may be significantly affected by propagation conditions (i.e. distance dependent path-loss and shadowing loss.) However, Ref.[7] considers only the case of a path-loss exponent of 3.5 and a shadowing loss standard deviation of 8dB. In this paper, the total transmit power for data relay among wireless ports is evaluated by computer simulation for various parameters, i.e., limited number of hops, path-loss exponent and standard deviation of shadowing loss.

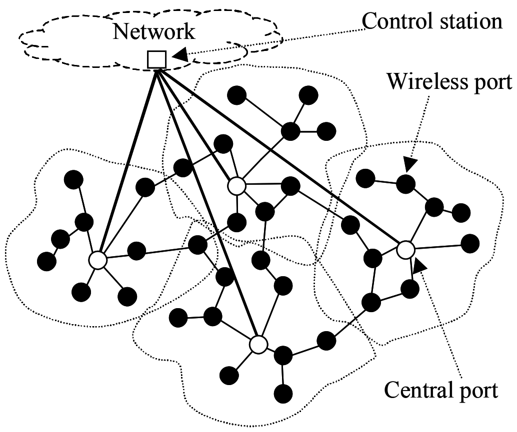

Fig. 1 Virtual cellular system.

II. MULTI-HOP SYSTEM

If all wireless ports communicate with the central port directly, the transmit powers of some wireless ports may become very large due to path-loss, shadowing loss, and multipath fading. To avoid this, multi-hop wireless system is applied. In this paper, the virtual cell control layer that is inserted between the data link layer and the network layer is introduced as illustrated in Fig. 2. The signal transmitted from a mobile terminal is received by all wireless ports. Since each wireless port can act as a site diversity branch, the transmit power of a mobile terminal can be significantly reduced compared to the present cellular systems [3]. The virtual cell control layer manages the construction of multi-hop route between each wireless port and the central port.

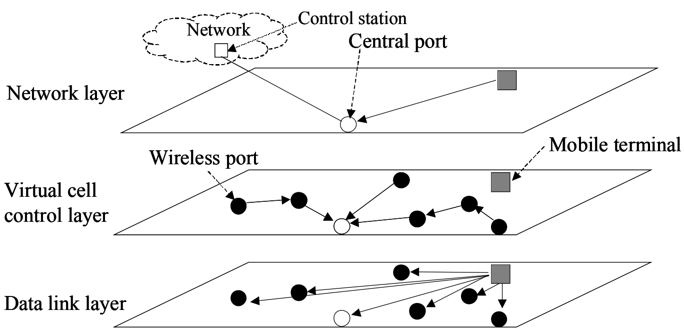

Fig. 2 Layer structure.

A. Uplink (wireless port-to-central port)

Multi-hop route is constructed in order to minimize the total transmit power of wireless ports for data relay. Fig. 3 shows message flow of route construction. Route construct request message is sent periodically from all wireless ports to the central port via other wireless ports, and route notification message is sent back from the central port to each wireless port via other wireless ports. 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) the transmit power, (b) the source wireless port address, (c) the number of hops, (d) the transmitting wireless port address, and (e) the total required transmit power of wireless ports along the route. The header of route notification message includes (a) the destination wireless port address, (b) the transmitting wireless port address, (c) the source wireless port address, and (d) the required transmit power of the destination wireless port. Route construction algorithm is as follows:

Step1: Source wireless port #$k(0)$ (#1 in Fig. 3) sends the route construct request message with transmit power $P_t(k(0))$.

Step2: Upon reception of the route construct request message from the wireless port #$k(n\text{-}1)$, the wireless port #$k(n)$ checks the number n of hops and if n is less than the allowable maximum number of hops, the wireless port #$k(n)$ computes the required transmit power $P_{t,req}(k(n\text{-}1), k(n))$ of the wireless port #$k(n\text{-}1)$ using the following equation:

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

where P_{req} is the required received signal power, $P_t(k(n\text{-}1))$ is the transmit power of the wireless port #$k(n\text{-}1)$, and $P_r(k(n))$ is the received signal power at the wireless port #$k(n)$. Then, the total transmit power P of the wireless ports along the route reaching the wireless port #$k(n)$ is computed from

$$P = \sum_{i=1}^{n} P_{t,req}(k(i-1),k(i)) \quad . \qquad (2)$$

If the wireless port receives more than one route construction request messages, the wireless port relays the route construction request message that has the minimum total required transmit power P. For example, wireless port #3 in Fig. 3 receives the route construction request messages from wireless ports #1 and #2. Since $P_{t,req}(1,2) + P_{t,req}(2,3) < P_{t,req}(1,3)$ is assumed in Fig. 3, the wireless port #3 relays the route construction message received from wireless port #2.

Step3: The central port (wireless port #0 in Fig. 3) chooses the route which minimizes the total required transmit power and multicasts the route notification message that includes the destination wireless port address (#3) and the required transmit power of wireless port #3.

Step4: 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 #1 in Fig. 3).

Step5: The source wireless port (wireless port #1 in Fig. 3) receives the route notification message.

In this paper, we have introduced the route construction algorithm in which the route construct request message is sent from each wireless port to the central port. An alternative algorithm can be used wherein the central port sends the route construct request message to all wireless ports.

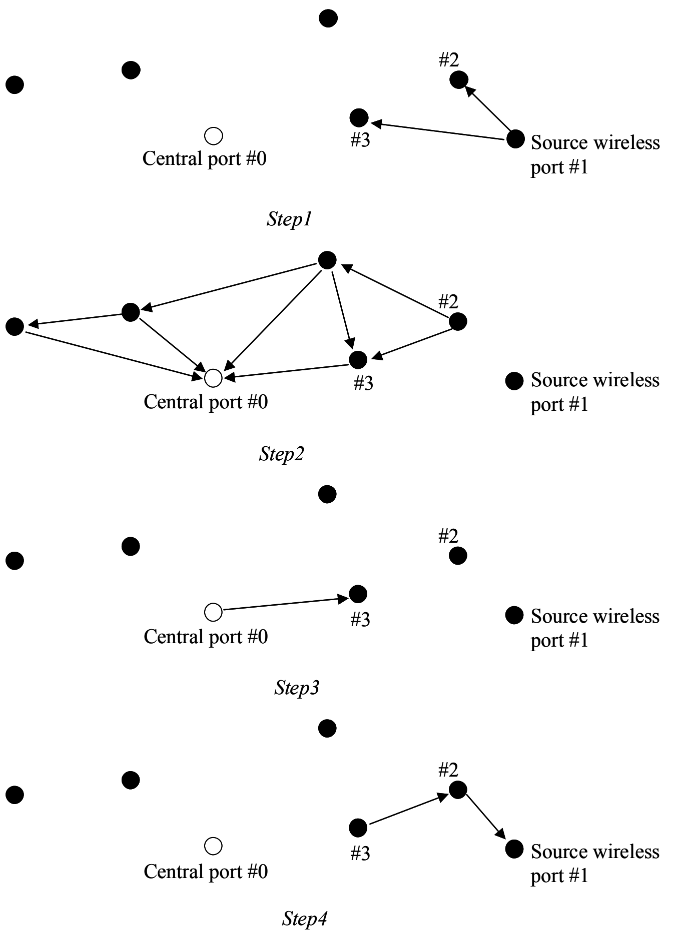

Fig. 3 Example of route construction message flow.

B. Downlink (central port-to-wireless port)

The downlink multi-hop route is the same as the uplink route. The central port can multicast the downlink signal, transmitted from the control station in the network, to all wireless ports. The total required transmit power of the central port and wireless ports for downlink data relay is smaller than that for uplink data relay.

III. COMPUTER SIMULATION

Signal-to-noise power ratio (SNR)-based slow transmit power control is assumed. Wireless ports are randomly located in an entire virtual cell.

A. Multi-hop route

Fig. 4 shows some examples of constructed routes for K=20 and N=5, where K is the number of wireless ports and N is the maximum number of allowable hops, respectively. The propagation path-loss exponent α of 3.5 and the log-normally distributed shadowing loss with standard deviation σ of 7dB are assumed. Fig. 4(a) shows that the central port needs to transmit/receive the uplink/downlink signals via only one wireless port. This suggests that the downlink transmit power of central port can be reduced considerably. Of course, this does not always happen. Sometimes, the central port needs to have multiple connections with surrounding wireless ports.

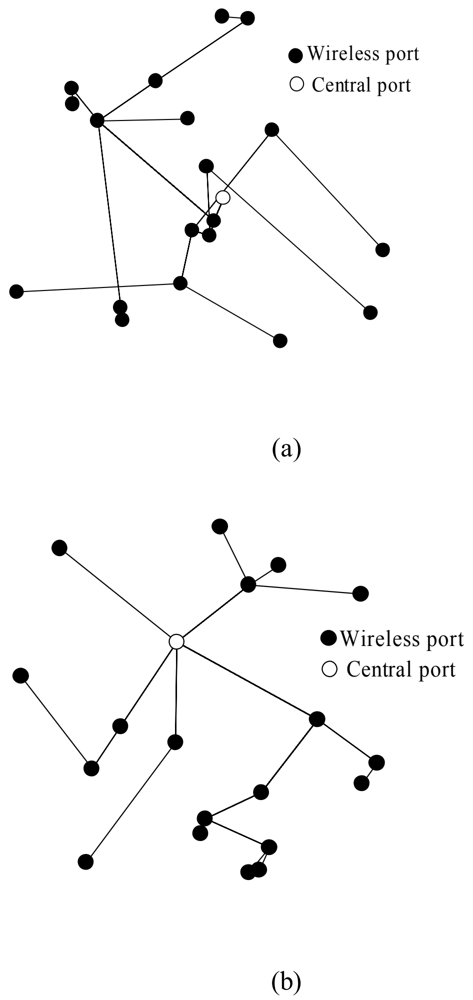

Fig.4 Some examples of constructed routes.

B. Average total transmit power for data relay

The total transmit power of wireless ports in an entire virtual cell is evaluated by computer simulation. The total transmit power is defined as the ensemble average of the sum of transmit power of wireless ports and the central wireless port in an entire virtual cell.

Fig. 5 plots the total transmit power normalized by that of single hop case as a function of the maximum number N of allowable hops with the number K of wireless ports per virtual cell as a parameter for α= 3.5 and σ= 7dB. It is clearly seen that multi-hop transmission can significantly reduce the total transmit power. When N=4 and K=20, the uplink (downlink) total transmit power can be reduced to 0.008 (0.004) of that of the single hop case. The transmit power of uplink is larger than that of downlink. This is because that same signal can be multicast to many wireless ports simultaneously in the downlink. It can also be seen that the normalized total transmit power is almost the same for N>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.

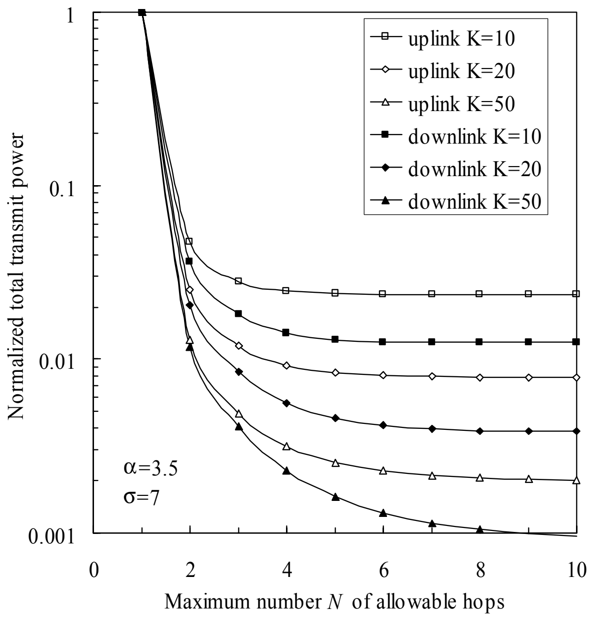

Fig. 5 Normalized total transmit power as a function of the maximum number N of allowable hops with the number K of wireless ports as a parameter.

Fig. 6 plots the total transmit power normalized by that of single hop case as a function of the maximum number N of allowable hops with α as a parameter for K=20 and σ=7dB. It can be seen from the figure that as α becomes larger, the normalized total transmit power reduces. This is because of a significantly shorter link distance between transmitting and receiving wireless ports. Fig. 7 plots the total transmit power normalized by that of single hop case as a function of the maximum number N of allowable hops with the shadowing loss standard deviation σ as a parameter for K=20 and α=3.5. As σ becomes larger, the normalized total transmit power reduces. This is because the route diversity effect increases as the fluctuation of propagation loss between wireless ports becomes larger. Irrespective of the values of α and σ, the total transmit power is almost the same for N>4, 6 and 8 when K=10, 20 and 50, respectively, as seen in Fig. 5.

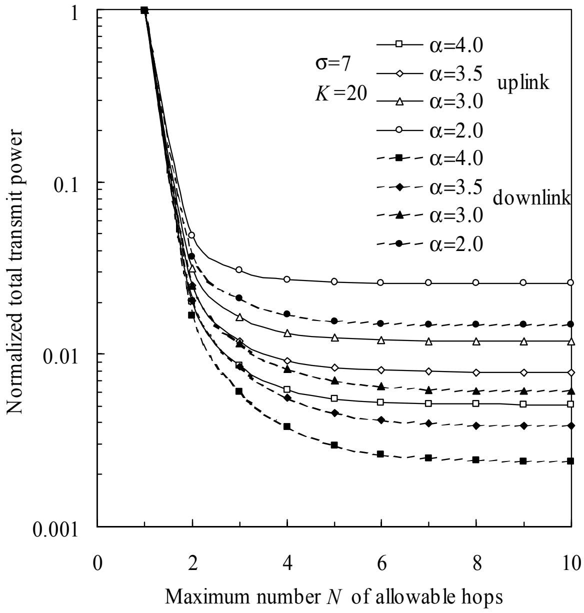

Fig. 6 Normalized total transmit power as a function of the maximum number N of allowable hops with the path-loss exponent α as a parameter.

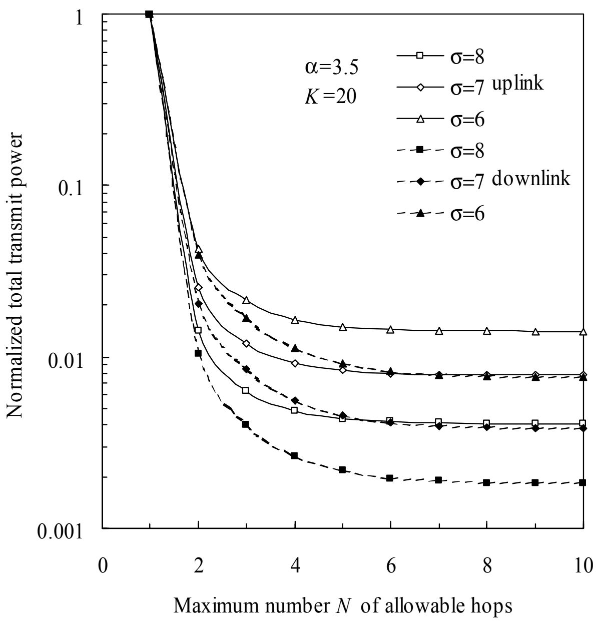

Fig. 7 Normalized total transmit power as a function of the maximum number N of allowable hops with the shadowing loss standard deviation σ as a parameter.

C. *Cdf of transmit power*

Knowing the transmit power distribution of each wireless port as well as the total transmit power is important to design the wireless port [8]. The cumulative distribution function (cdf) of uplink transmit power is evaluated by computer simulation. Fig.8 plots the cdf of wireless port transmit power normalized by the average transmit power for the single hop case (N=1) for K=20, α=3.5 and σ=7dB. It can be seen that multi-hop communication can reduce the transmit power of each wireless port considerably. When $N \geq 5$, the transmit power at the probability of 90% can be made significantly smaller than that of N=1 case. This suggests that in order to avoid unnecessary long time delay, the maximum number of allowable hops can be limited to 5 without increasing the transmit power.

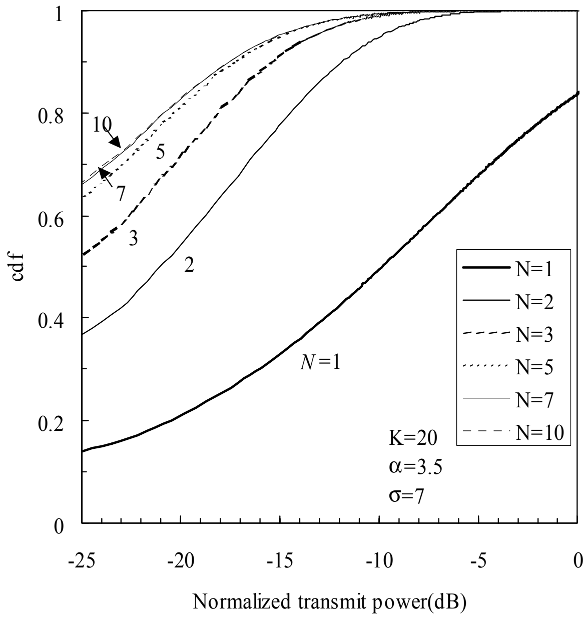

Fig. 8 Cdf of normalized transmit power of wireless port.

IV. Conclusions

In the virtual cellular system, data relay between central port and wireless ports is necessary. In this paper, multi-hop wireless system was applied for data relay and the virtual cell control layer was introduced. The routing algorithm which minimizes the total uplink transmit power was presented. The total transmit power of wireless ports for data relay was evaluated by computer simulation to show that the multi-hop system can reduce considerably the total transmit power while limiting the number of hops. It was found that as the propagation path-loss exponent α or the shadowing loss standard deviation σ becomes larger, the total transmit power normalized by that of single hop case reduces. It was also found that the maximum number of hops can be limited to five irrespective of the values of propagation path-loss exponent α and the shadowing loss standard deviation σ. The evaluation of cumulative distribution function of uplink transmit power of each wireless port showed that in order to avoid unnecessary large time delay, the maximum number of allowable hops can be limited while significantly reducing the transmit power.

In this paper, the frequency efficiency for data relay in the virtual cell was not discussed. A possibility of significant transmit power reductions implies that the same frequencies can be reused for data relay at different wireless ports within the virtual cell as well as in the different virtual cells as suggested in Ref. [3]. The frequency reuse problem for data relay is an interesting future study.

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