PAPER

Multi-Hop Link Capacity of Multi-Route Multi-Hop MRC Diversity for a Virtual Cellular Network

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SUMMARY In virtual cellular network (VCN), proposed for high-speed mobile communications, the signal transmitted from a mobile terminal is received by some wireless ports distributed in each virtual cell and relayed to the central port that acts as a gateway to the core network. In this paper, we apply the multi-route MHMRC diversity in order to decrease the transmit power and increase the multi-hop link capacity. The transmit power, the interference power and the link capacity are evaluated for DS-CDMA multi-hop VCN by computer simulation. The multi-route MHMRC diversity can be applied to not only DS-CDMA but also other access schemes (i.e. MC-CDMA, OFDM, etc.).
key words: *virtual cellular network, multi-hop multi-route diversity, transmit power control, multi-hop link capacity*

1. Introduction

The mobile communication services are shifting from voice conversation to data transmission through the internet. As the data transmission rate becomes higher, a larger peak transmit power is required. To decrease the peak transmit power, a multi-hop virtual cellular network (VCN) was proposed [1]. In VCN, unlike the so-called wireless ad-hoc network [3]–[6], stationary wireless ports (WPs) relay the signal to other WPs. The routing algorithms that were proposed for wireless multi-hop network or adhoc network [3]–[6] can also be applied to VCN. To increase the frequency efficiency, a routing algorithm that minimizes the total uplink transmit power while limiting the number of hops was introduced [7] to VCN.

Since all the WPs are stationary, the multi-hop route updating interval may not cause any degradation. However, the carrier-frequency of the control channel for route construction is different from the data channels. This means that the fading observed at the control channel may be different from the data channel. Therefore, the multi-hop constructed route may not necessarily minimize the total transmit power for the data transmission. In order to reduce the degradation of the transmit power efficiency, caused by the fading correlation between the control and the data channels, multi-hop maximal ratio combining (MHMRC) diversity is applied [8]. While relaying the data through the constructed multi-hop route, each WP receives not only from its immediately previous WP along the route, but may also receive from multiple previous WPs that have transmitted the same signal to their next WPs. The concurrent received signals transmitted from multiple previous WPs can be combined to reduce the transmit power while achieving the required QoS using MHMRC diversity [8]. For even more exploitation of the transmit power reduction and mitigation of the fading correlation effects, it is effective to use multi-route diversity to combine redundant signals transmitted over independent multi-hop routes.

Multi-route diversity schemes have been attracting much attention [9]–[13]. For the cooperative relaying in Refs. [12], [13] the received signals from the immediately previous ports along all routes are combined. For the multi route diversity in Ref. [11], each port uses the received signal from the immediately previous port along its route only. However, each WP can receive the same signals from all previous WPs along the multiple routes. If all received signals are combined, the larger diversity gain can be expected. Therefore, we propose multi-route MHMRC diversity that combines all received signals from all WPs along the multi-route.

In order to reduce the frequency reuse distance the routing algorithm based on the total transmit power minimization criteria can be applied to VCN. For the multi-route diversity, larger diversity gain can be expected if the independent multiple routes are constructed. To the best of the authors' knowledge, the routing algorithm to construct the independent minimum total transmit power multi-route has not been fully studied yet.

In this paper, in order to reduce the transmit power and the interference power and to increase the multi-hop link capacity, we propose the multi-route MHMRC diversity for VCN. The key features of multi-route MHMRC diversity are as follows: (1) Each WP combines all received signals from all WPs along the multi-route with MRC diversity. (2) Selection of independent routes based on the total transmit power minimization criterion in order to get the larger multi-route MHMRC diversity gain.

This paper is organized as follows. Section 2 presents the multi-route MHMRC diversity principle and the analysis of transmit power, interference power and multi-hop link capacity. In Sect. 3, the power and link capacity efficiencies of multi-route MHMRC diversity are evaluated by computer simulation for DS-CDMA multi-hop VCN. Section 4 gives some conclusions.

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2. Multi-Hop Multi-Route Diversity

The VCN structure is shown in Fig. 1. VCN consists of many virtual cells (VCs); each VC has a central port (CP), which is a gateway to the network, and many distributed WPs. A group of the WPs works as a virtual base station. If all the wireless ports communicate directly with the CP, some WPs may need significantly large transmit powers due to path-loss, shadowing loss and multi-path fading. To avoid this, wireless multi-hop technique is used. For uplink (downlink) data transmissions, many WPs can be used to relay the signal transmitted from a mobile terminal (the CP) to the CP (a mobile terminal). The routing algorithm is an important technical issue to select the relaying intermediate WPs till the CP.

2.1 Principle

In order to realize the multi-route MHMRC diversity transmission, we choose two different multi-hop routes. The minimum transmit power route; which is the 1st route, is selected using the minimum transmit power routing algorithm introduced in [7]. In this routing algorithm, the route construct request message is sent periodically from all WPs to the CP via other WPs, and the route notification message is sent back from the CP to each WP via other WPs. If the relaying WP receives more-than-one route construction request messages, the WP selects the route that has the minimum total required transmit power and multicasts the route construction request message to other WPs. Therefore, the constructed multi-hop route can minimize the total transmit power of WPs along the route. In order to obtain the larger multi-route diversity gain, the 2nd route should be different from the 1st route. The 2nd route will be selected after the selection of the 1st route, using again the introduced routing algorithm with the removal of all the relaying WPs used in the 1st route. Therefore, the 2nd route may not be the 2nd minimum total transmit power route among all possible routes, but it is the minimum total transmit power route among all possible routes after the removal of all the relaying WPs of the 1st route. Using this proposed algorithm, two independent minimum transmit power routes can be constructed. In multi-route transmission, the signal transmitted from a mobile terminal (MT) is relayed through two independent routes until it reaches the CP.

Figure 2 explains the concept of multi-route MHMRC diversity. The port index $\#j(i)$ denotes the i-th relaying WP along the j-th route. An MT transmits its signal, which is received by WPs $\#a(1)$ and $\#b(1)$, but the same signal is received by WPs $\#a(2)$, $\#b(2)$, $\#b(3)$ and the CP. WP $\#a(1)$ relays its received signal to WP $\#a(2)$, and WP $\#b(1)$ relays its received signal to WP $\#b(2)$. If the WP uses the same channel for transmitting and receiving a signal, the transmitted signal interferes with the received signal. To avoid such interference, the different channels should be used. The on-demand channel assignment method [14], using CS-DCA algorithm [15], can be applied. WP$\#a(1)$ and WP$\#b(1)$ transmit the signals simultaneously using allocated channels respectively. In this case, WPs $\#a(2)$ and $\#b(2)$ receive the same signal three times; from the MT and then from the WPs $\#a(1)$ and $\#b(1)$. Therefore, the WPs $\#a(2)$ and $\#b(2)$ can combine the received signals before relaying the combined signal to the CP and WP $\#b(3)$. WP $\#b(3)$ can combine the received signals from the MT and WPs $\#a(1)$, $\#b(1)$, $\#a(2)$ and $\#b(2)$ before relaying the signal to the CP. CP can, thus, receive the same signal six times to combine. During the relaying process, a WP may also receive the signals transmitted from its next WPs. However, those signals from the WPs will be received after having sent the signal and therefore, can not contribute to multi-route MHMRC diversity combining. Since the signal from the immediately previous WP arrives later than the signals from the other previous WPs, the transmission delay time with MHMRC diversity does not increases compared to the case without MHMRC diversity. For diversity combining, the well known MRC [16] can be used.

The multi-route MHMRC diversity can reduce the transmit power of each WP. However, since the multi-route increases the number of WPs for relaying, the multi-route may increase the total transmit power. Therefore the CP compares the transmit powers of the single route and the multi-route MHMRC diversity case, selects the minimum

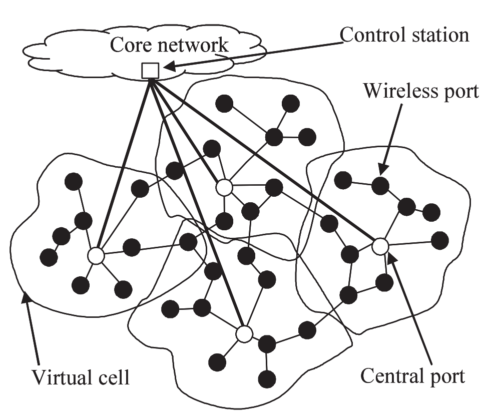


Fig. 1 Virtual cellular network (VCN).

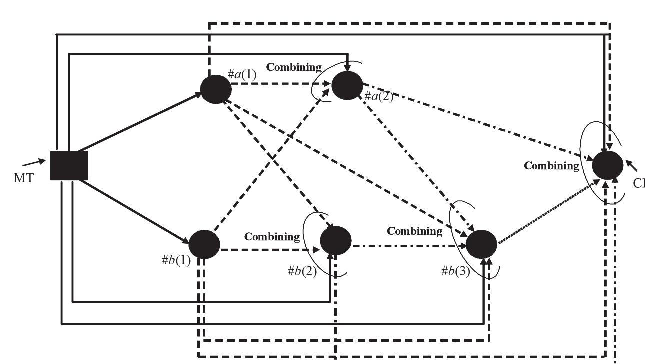


Fig. 2 Multi-route multi-hop diversity relay.

total transmit power case, and sends the route notification message to the relaying WPs and to the MT.

2.2 Transmit Power

We assume ideal transmit power control (TPC) so that the signal-to-noise power ratio (SNR) after rake combining meets required SNR. We assume an L-path fading channel. For a multi-hop relay without diversity, the transmit power $P_t(i)$ from WP #i is given by

$$P_t(i) = P_{req} \cdot \left(d_{i,j}^{-\alpha} 10^{-\frac{\eta_{i,j}}{10}} \sum_{l=0}^{L-1} \left| \xi_{i,j}(l) \right|^2 \right)^{-1}, \quad (1)$$

where P_{req} is the required received signal power, α is the path-loss exponent and $d_{i,j}$, $\eta_{i,j}$ and $\xi_{i,j}$ are respectively the distance, the shadowing loss (in dB) and the l-th path complex path gain between WPs #i and #j. Assuming uniform power delay profile of the multi-path channel, $\{\xi_{i,j}\}$ are independent complex variables with zero-mean and $E\left[\left|\xi_{i,j}\right|^2\right] = 1/L$, where $E[*]$ denotes the ensemble average operation.

To determine the total transmit power along the multi-hop routes, we consider that the a-th (b-th) route is an N-hop (M-hop) connection from MT to CP. Without loss of generality, we assume that $N \leq M$. WP#$a(0)$=WP#$b(0)$ (=WP#0) is the MT and WP#$a(N)$=WP#$b(M)$ is the CP, whereas WP#i = WP#$a(1)$~WP#$a(N-1)$ and WP#$b(1)$~WP#$b(M-1)$ are the intermediate WPs of the a-th route and b-th route.

As an initialization, the transmit power $P_t(0)$ of the WP#0 is the maximum required transmit power between WPs #$a(1)$ and #$b(1)$ determined by TPC and it is given by

$$P_t(0) = \max\left(\frac{P_{req}}{A_{0,a(1)}}, \frac{P_{req}}{A_{0,b(1)}} \right), \quad (2)$$

where

$$A_{i,j} = d_{i,j}^{-\alpha} 10^{-\frac{\eta_{i,j}}{10}} \left(\sum_{l=0}^{L-1} \left| \xi_{i,j}(l) \right|^2 \right). \quad (3)$$

Applying multi-route MHMRC diversity, each WP can combine the received signals from the previously relayed WPs. The received power $P_r(a(n))$ at WP#$a(n)$, $n = 2 \sim (N-1)$, is the sum of all the received powers from all the previous WPs of both routes and is given by

$$P_r(a(n)) = \sum_{i=0}^{n-1} P_t(a(i)) A_{a(i),a(n)} + \sum_{i=1}^{n-1} P_t(b(i)) A_{b(i),a(n)}. \quad (4)$$

Since we assume ideal TPC, $P_r(a(n))$=P_{req}. From this and using Eq. (4), we have

$$P_{req} = P_t(a(n-1)) A_{a(n-1),a(n)} + P_t(b(n-1)) A_{b(n-1),a(n)}$$
$$+ P_t(0) A_{0,a(n)} + \sum_{i=1}^{n-2} \left(P_t(a(i)) A_{a(i),a(n)} + P_t(b(i)) A_{b(i),a(n)} \right). \quad (5)$$

The transmit power of WP #$a(n-1)$ is given by [Appendix]

$$P_t(a(n-1)) = \left(A_{a(n-1),a(n)} A_{b(n-1),b(n)} - A_{b(n-1),a(n)} A_{a(n-1),b(n)} \right)^{-1}$$
$$\times \left\{ \begin{array}{l} P_{req}\left(A_{b(n-1),b(n)} - A_{b(n-1),a(n)}\right) \\ -P_t(0)\left(A_{0,a(n)} A_{b(n-1),b(n)} - A_{0,b(n)} A_{b(n-1),a(n)}\right) \\ -A_{b(n-1),b(n)} \sum_{i=1}^{n-2} (P_t(a(i)) A_{a(i),a(n)} \\ +P_t(b(i)) A_{b(i),a(n)}) \\ +A_{b(n-1),a(n)} \sum_{i=1}^{n-2} (P_t(a(i)) A_{a(i),b(n)} \\ +P_t(b(i)) A_{b(i),b(n)}) \end{array} \right\}. \quad (6)$$

If $P_t(a(n-1))$ is smaller than zero, then the WP#$a(n-1)$ is removed from the route and the transmit power computation restarts from the transmit power $P_t(a(n-2))$.

The total transmit power P_{total} is given by

$$P_{total} = \sum_{i=0}^{N-1} P_t(a(i)) + \sum_{i=1}^{M-1} P_t(b(i)). \quad (7)$$

After computing the MHMRC multi-route total transmit power, the CP compares the transmit powers of the single route and the MHMRC multi-route diversity, selects the minimum total transmit power, and sends the route notification message to the relaying WPs and the MT.

2.3 Interference Model and Multi-Hop Link Capacity

In the multi-user environment, during the data transmission of a user, other active users' relaying links may interfere. A simple interference power model is used to evaluate the link capacity.

Figure 3 illustrates our interference model. Even if DS-CDMA is assumed, when the same channel is used for transmitting and receiving a signal, the transmitted signal interferes with the received signal. Therefore, the different channels should be used. The cluster denotes the area where same frequency channel is not reused. We assume that if a WP uses a certain frequency, then the other WPs in its cluster do not use that frequency. For simplicity we assume that the cluster is a circle with radius R (we call this the cluster size from now on). We assume that the interference power

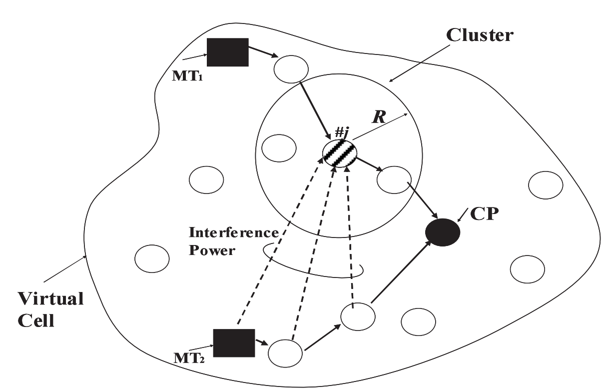


Fig. 3 Interference model.

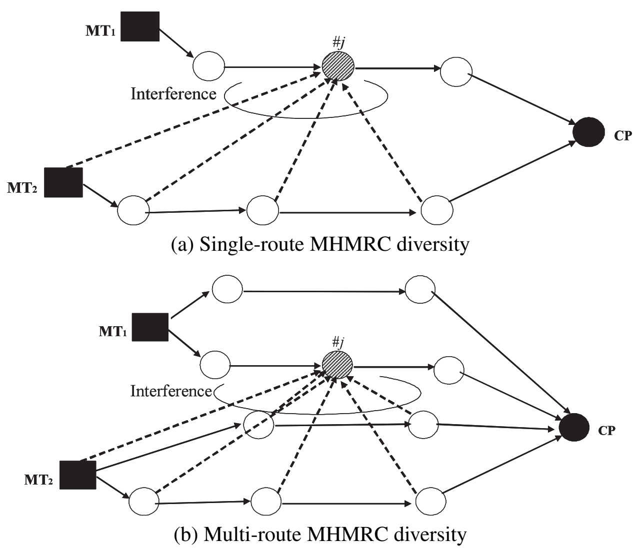


Fig. 4 Interference from active ports.

is the sum of powers received from WPs whose distance is larger than the cluster size R. As the number of channels increases, the probability that the different channel is selected increases, thus decreasing the interference power. Therefore, our assumption is the worst case. Although this model is very simple, it allows us to compare the link capacity of the multi-route MHMRC diversity case and the single route case. To predict a performance closer to the reality, the channel assignment scheme should be considered. However, this is left as an interesting future work.

Figure 4 illustrates the interference in each WP for the single route case (Fig. 4(a)) and multi-route MHMRC diversity case (Fig. 4(b)). The interference power is the sum of all the undesired received powers from the relaying WPs, whose distances from the WP#j are larger than the cluster size R. Using the model explained above, the interference power at the WP#j in the single route case is given by

$$I_j = \sum_{\substack{i \\ i\neq j \\ d_{i,j}>R}} \left(P_t(i) d_{i,j}^{-\alpha} 10^{\frac{\eta_{i,j}}{10}} \sum_{l=0}^{L-1} \left|\xi_{i,j}(l)\right|^2 \right), \tag{8}$$

where WP#i is a relaying WP along the route for other active users, and WP#$(i+1)$ is the next WP along the same route. For the single route with MHMRC, $P_t(i)$ in Eq. (8) is given by Eq. (6) in [8]. For the MHMRC multi-route diversity case, $P_t(i)$ in Eq. (8) is given by Eq. (6).

In this paper, we assume a CDMA system with a spreading factor SF. Assuming a constant bit rate, as SF increases, the spreading bandwidth is wider and hence, the number L of resolvable paths increases. In this paper, we consider L/SF=constant. The received SINR λ_j at a relaying port #j is given by

$$\lambda_j = \frac{P_{req}}{N + \frac{1}{SF} I_j} \approx \frac{1}{SF}\frac{P_{req}}{I_j}, \tag{9}$$

where I_j is the interference power.

The average interference power I_j depends on the average of $X = \sum_{l=0}^{L-1} \left|\xi_{i,j}(l)\right|^2 / \sum_{l=0}^{L-1} \left|\xi_{i,i+1}(l)\right|^2$, which is given by $E[X] = L/(L-1)$ [17]. Therefore, as L (or SF) increases, the average interference power decreases and consequently, the multi-hop link capacity increases.

3. Computer Simulation

MTs and WPs are randomly located in each VC. In order to limit the relay time, the maximum number of hops is limited to N. It is discussed how the total transmit power can be decreased by introducing the multi-route diversity for the given allowable number N of maximum hops. Of course, as N increases, single-route MHMRC diversity can also decrease the transmit power. However, if the multi-route diversity is introduced, the total transmit power can be further decreased compared to the case of single-route MHMRC.

For a single hop case (ie. conventional cellular case), the end-to-end BER $P_b(1)$ is equal to the required BER, $\text{BER}_{\text{single-hop}}$, of single-hop case, i.e.,

$$P_b(1) = \text{BER}_{\text{single-hop}}(1). \tag{10}$$

Whereas, the end-to-end BER $P_b(n)$ of n-hop case is given by

$$\begin{aligned} P_b(n) &= 1 - (1 - \text{BER}_{\text{one-hop}})^n \\ &\approx n \times \text{BER}_{\text{one-hop}} \text{ if } \text{BER}_{\text{one-hop}} \ll 1, \end{aligned} \tag{11}$$

where $\text{BER}_{\text{one-hop}}$ is the BER of one hop. In order to keep the same quality of communication, the required end-to-end BER for both single-hop and multi-hop cases should be equal, i.e., $P_b(1)$=$P_b(n)$; therefore, $\text{BER}_{\text{single-hop}} = n\times\text{BER}_{\text{one-hop}}$ and consequently $\text{BER}_{\text{one-hop}} = \text{BER}_{\text{single-hop}}/n$. For simplicity, we fix the required BER depending on the maximum allowable number of hops N. Therefore, $\text{BER}_{\text{one-hop}}$=$\text{BER}_{\text{single-hop}}/N$. Assuming QPSK data modulation, the required SINR λ_{req} for BER BER_{req} can be determined using [18]

$$\text{BER}_{req} = \frac{1}{2}\text{erfc}\sqrt{\frac{\lambda_{req}}{2}}. \tag{12}$$

As described in Sect. 1, the carrier-frequency of the control channel for route construction is different from the data channels. However the fadings observed at different carrier frequencies are correlated. Therefore, we evaluate the impact of their fading correlation ρ, and the number U of active users in each VC. The normalized average transmit power P_{norm} is defined as the average total transmit power along the route normalized by that of single-hop case, i.e., $P_{\text{norm}} = E[P_{\text{total}}]/E[P_{\text{single-hop}}]$.

Figure 5 plots the normalized transmit power for multi-route MHMRC diversity, and the single-route MHMRC diversity as a function of N. The two extreme cases of the fading correlation ρ (ρ = 0 and 1) are considered for the path-loss exponent α = 3.5, the shadowing standard deviation σ = 7 dB, the number L of propagation paths=2, the required

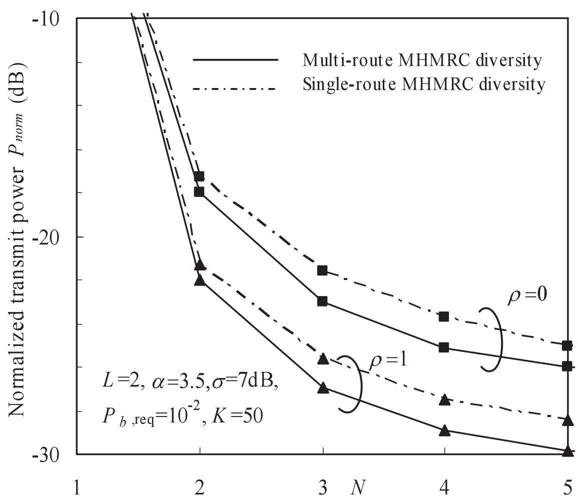


Fig. 5 Normalized transmit power.

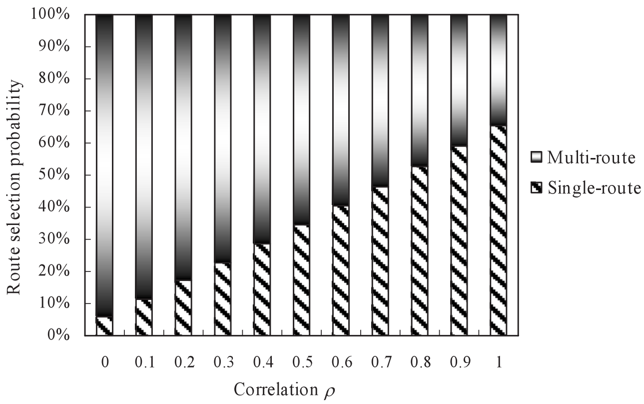
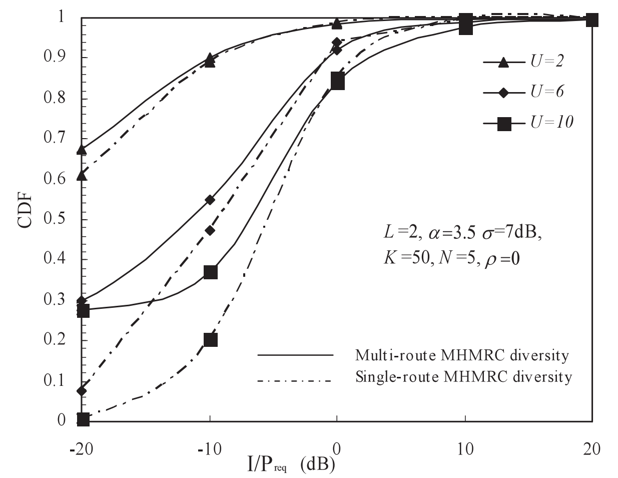
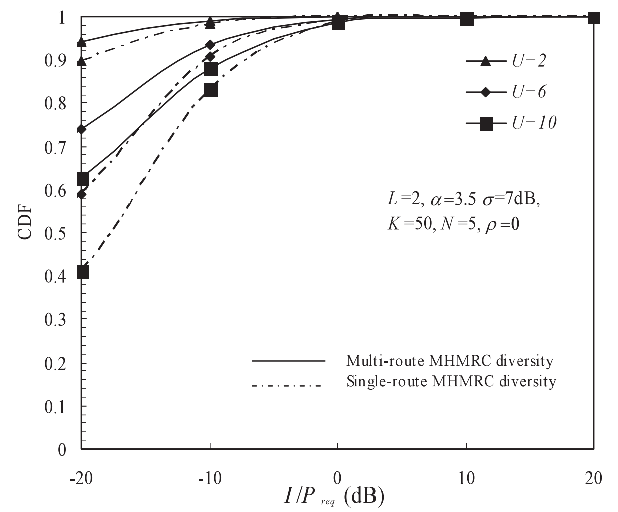


Fig. 6 Route selection probability.



(a) R/D=0.3



(b) R/D=0.5

Fig. 7 Interference power.

end-to-end BER $P_{b,\text{req}} = 10^{-2}$ and the number K of WPs=50 in each VC. It is seen that the multi-route MHMRC diversity gives better performance decreasing more the transmit power compared to single-route MHMRC. This is because the MHMRC multi-route diversity combines more received signals than MHMRC single-route diversity, and also selects the route with smaller total transmit power route between multi-route and single-route cases. It is also seen that as ρ increases, the multi-route diversity gain decreases. This is because the single-route transmit power approaches the minimum transmit power. We evaluate the route selection probability in Fig. 6 with ρ as a parameter for N=5, α=3.5, σ=7 dB, L=2 and K=50. It is seen that as ρ increases, the probability of selection of single-route increases; and this reduces diversity gain.

Figure 7 plots the cumulative distribution function (cdf) of the interference power for multi-route MHMRC diversity case and that for the single-route MHMRC diversity with U as a parameter for N=5, ρ=0, α=3.5, σ=7 dB, L=2 and K=50. R/D = 0.3 and 0.5 (D is the VC radius) are considered. The observed point of the interference power is each WP. It is seen that the multi-route MHMRC diversity decreases the interference power compared to the single-route MHMRC diversity.

The outage occurs if received SINR is smaller than the required SINR. The link capacity is the maximum number of users per virtual cell that satisfies the allowable outage probability. For simplicity, we assume the control channel frequency bandwidth is not taken into account of calculating the link capacity. Figure 8 plots the multi-hop link capacity C normalized by the spreading factor SF as a function of SF for the allowable outage probability P_{allow}=0.1, ρ=0, α=3.5, σ=7 dB, N=5, K=50 and L/SF=1/8. For both single-route and multi-route MHMRC diversity cases, the link capacity increases, as SF increases. The reason for this is explained below. Since L/SF is constant, L increases, as SF increases. Hence, the enhanced path diversity effect contributes to increasing the capacity. It is also seen that the multi-route MHMRC diversity increases the multi-hop link capacity, since it decreases the interference power.

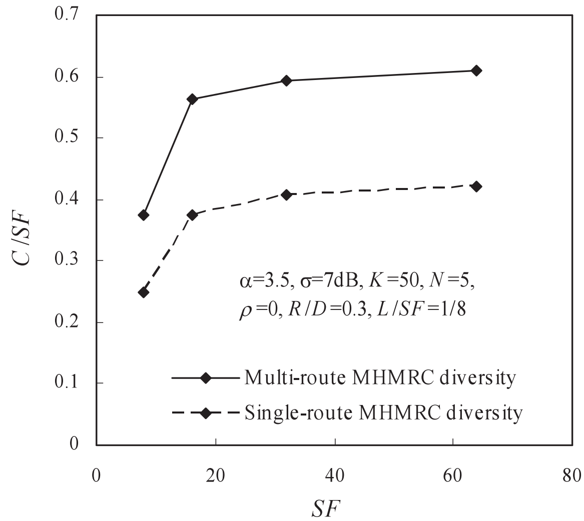


Fig. 8 Effect of *SF* on the multi-hop link capacity.

4. Conclusions

In this paper, multi-route MHMRC diversity was proposed in order to reduce the transmit power and to increase the multi-hop link capacity by reducing the interference power. In multi-route MHMRC diversity, each WP combines redundant signals transmitted over independent multi-hop routes and the CP selects the route with the smallest total transmit power between multi-route and single-route cases. The multi-route MHMRC diversity can be applied to not only DS-CDMA but also other access schemes (i.e. MC-CDMA, OFDM, etc.). In computer simulation, DS-CDMA is assumed as the access scheme.

The transmit power was evaluated by computer simulation. It was shown that the multi-route MHMRC diversity decreases the transmit power more compared to the single-route MHMRC. This is because the MHMRC multi-route diversity combines more received signals than MHMRC single-route diversity. The link capacity was also evaluated by using a simple interference model that if a WP uses a certain frequency, then the other WPs within its cluster do not use that frequency. It was shown that the multi-route MHMRC diversity can increase the link capacity. However, as the number of received signals for diversity combining increases, the diversity scheme becomes complicated. The effect of the number of combining signals to multi route MHMRC diversity is left as an interesting future work.

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Appendix

Similar to Eq. (4), the received power $P_r(b(n))$ at WP#$b(n)$ is given by

$$P_r\,(b\,(n)) = \sum_{i=0}^{n-1} P_t\,(a\,(i))\,A_{a(i),b(n)} + \sum_{i=1}^{n-1} P_t\,(b\,(i))\,A_{b(i),b(n)}. \quad (\mathrm{A}\cdot 1)$$

Since we assume ideal TPC, $P_r(b(n)) = P_{req}$. From this and using Eq. (A· 1), we have

$$P_{req} = P_t\,(a\,(n-1))\,A_{a(n-1),b(n)} + P_t\,(b\,(n-1))\,A_{b(n-1),b(n)} + P_t\,(0)\,A_{0,b(n)} + \sum_{i=1}^{n-2} \left(P_t\,(a\,(i))\,A_{a(i),b(n)} + P_t\,(b\,(i))\,A_{b(i),b(n)}\right). \quad (\mathrm{A}\cdot 2)$$

From Eqs. (5) and (A· 2), $P_t(a(n-1))$ is given by

$$P_t\left(a\left(n-1\right)\right) = \left(A_{a(n-1),a(n)}A_{b(n-1),b(n)} - A_{b(n-1),a(n)}A_{a(n-1),b(n)}\right)^{-1} \times \left\{ \begin{array}{l} P_{req}\left(A_{b(n-1),b(n)} - A_{b(n-1),a(n)}\right) \\ -P_t\left(0\right)\left(A_{0,a(n)}A_{b(n-1),b(n)} - A_{0,b(n)}A_{b(n-1),a(n)}\right) \\ -A_{b(n-1),b(n)}\sum_{i=1}^{n-2}\left(P_t\left(a\left(i\right)\right)A_{a(i),a(n)}\right. \\ \left.+P_t\left(b\left(i\right)\right)A_{b(i),a(n)}\right) \\ +A_{b(n-1),a(n)}\sum_{i=1}^{n-2}\left(P_t\left(a\left(i\right)\right)A_{a(i),b(n)}\right. \\ \left.+P_t\left(b\left(i\right)\right)A_{b(i),b(n)}\right) \end{array} \right\}. \quad (6)$$

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