LETTER *Special Section on Advances in Ad Hoc Mobile Communications and Networking*

Transmit Power Efficiency of Multi-Hop MRC Diversity for a Virtual Cellular Network

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SUMMARY In virtual cellular network (VCN), proposed for high-speed packet mobile communications, the signal transmitted from a mobile terminal is received by wireless ports distributed in each virtual cell and relayed to the central port that acts as a gateway to the core network. In this letter, we apply the multi-hop maximal ratio combining (MHMRC) diversity and propose the route modification algorithm in order to improve transmit power efficiency degradation caused by the carrier frequency difference between the control and the data communication channels for VCN. The transmit power efficiency and the distribution of the number of hops are evaluated by computer simulation for a VCN.

key words: *virtual cellular network, multi-hop MRC diversity, transmit power control, wireless multi-hop*

1. Introduction

The mobile communication systems services are shifting from voice conversation to data transmission through the Internet. However, as the data transmission rate becomes higher, the peak transmit power becomes larger. To decrease the peak transmit power, a multi-hop virtual cellular network (VCN) that can significantly reduce the transmit power was proposed [1]. In VCN, as shown in Fig. 1 [2], each virtual cell (VC) has a central port, which is a gateway to the network, and many wireless ports distributed in VC. The group of the wireless ports works as a virtual base station. If all the wireless ports communicate directly with the central port, some wireless ports 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. Unlike the so-called wireless ad-hoc network [3]–[6], stationary wireless port relays the signal to other wireless ports. For uplink (downlink) data transmissions, many wireless ports can be used to relay the signal transmitted from a mobile terminal (the central port) to the central port (a mobile terminal). The routing algorithm is an important technical issue to select the relaying intermediate ports till the central port. Routing algorithms proposed for wireless multi-hop network or adhoc network [3]–[6] can 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].

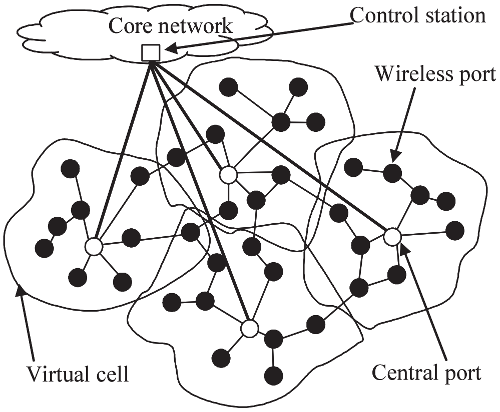

Fig. 1 Virtual cellular network.

While relaying the data through the constructed multi-hop route, each wireless port receives not only from its immediately previous port along the route, but may also receive from multiple previous ports that have transmitted the same signal to their next ports. The concurrent received signals transmitted from multiple previous ports can be combined to reduce the transmit power while achieving the required QoS [8]. In [8], multi-hop maximal ratio combining (MHMRC) is used without transmit power control (TPC) and a single frequency channel is considered. However, in order to accommodate many mobile terminals, multiple frequency channels may be necessary. In this letter, we apply the MHMRC for VCN in multiple frequency channels with TPC. Furthermore, the carrier frequencies used for the control channel for route construction and the data communication channel may be different. Since the fading correlation between the control and the data transmission channels may not be 1, the route which minimizes the total transmit power in the control channel may not minimize the total transmit power in the data transmission channel. In order to improve transmit power efficiency degradation caused by the carrier frequency difference between the control and the data communication channels, we propose the route modification algorithm.

This letter is organized as follows. Section 2 presents the MHMRC diversity concept, and the transmit power analysis for VCN. In Sect. 3, the power efficiency of MHMRC is evaluated by computer simulation for various parameters i.e., path-loss exponent, shadowing, fading correlation, number of propagation paths and number of wireless ports. Section 4 gives some conclusions.

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2. Multi-Hop MRC

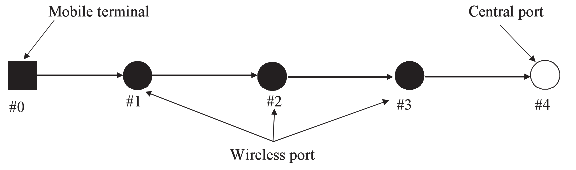
With multi-hop connection along the minimum transmit power route, the transmit power of each wireless port can be significantly reduced; however the introduction of multi-hop diversity may further reduce the transmit power. In multi-hop connection as illustrated in Fig. 2(a), each wireless port relays the signal to its next port. But, the same signal may be received by multiple ports along the route.

Figure 2(b), explains the concept of MHMRC. A mobile terminal transmits its signal, which is received by port #1, but the same signal is received by ports #2, #3 and #4. Port #1 relays its received signal to port #2. Therefore, port #2 receives the same signal twice; first from port #0 and then from port #1. Therefore, port #2 can combine them before relaying the signal to port #3, which can combine the 3 received signals before relaying the signal to port #4. Port #4 can, thus, receive the same signal four times to combine. During the relaying process, a wireless port may also receive the signals transmitted from its next ports. However, those signals from the next ports will be received after having sent the signal and therefore, can not contribute to multi-hop diversity combining. For diversity combining, well known MRC [9] can be used. Using MHMRC relay, the port transmit power can be reduced. Since the same signals transmitted from previous ports have been received before the signal from the immediately previous port is received, the delay time of multi-hop MHMRC is the same as that of the simple multi-hop relay.

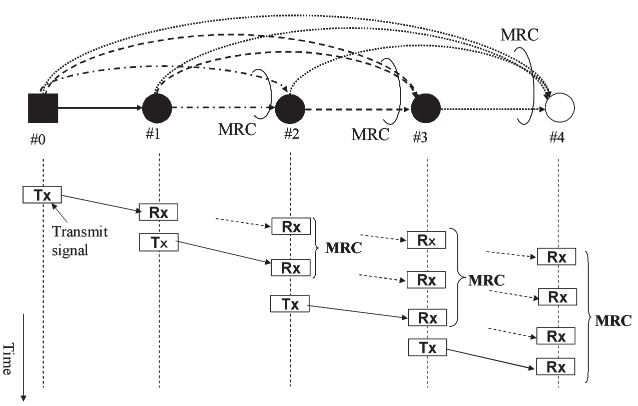
In order to evaluate the transmit power reduction, the numerical expressions of transmit power are derived below. We assume the ideal transmit power control (TPC) based on the signal-to-noise power ratio (SNR) measurement and the ideal rake combining. We assume an L-path Rayleigh fading channel. For a multi-hop relay without diversity, the transmit power $P_t(i)$ from port #i is given by

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

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 wireless ports #i and #j. Assuming the uniform power delay profile of the multi-path channel, $\{\xi_{i,j}\}$ are independent complex Gaussian variables with zero-mean and $E\left[\left|\xi_{i,j}\right|^2\right]=1/L$, where $E[*]$ denotes the ensemble average operation.



(a) Multi-hop relay.



(b) MHMRC relay.

Fig. 2 Multi-hop diversity relay.

To determine the total transmit power along the MHMRC route, we consider an n-hop connection from the mobile terminal to the central port; port #i=0 is the mobile terminal and port #$i=n$ is the central port, whereas port #$i=1\sim n-1$ the intermediate port. The received power $P_r(1)$ of from the mobile terminal #i=0 is given by

$$P_r(1)=P_t(0)d_{0,1}^{-\alpha}10^{-\frac{\eta_{0,1}}{10}}\sum_{l=0}^{L-1}\left|\xi_{0,1}(l)\right|^2.\qquad(2)$$

Therefore, the mobile terminal transmit power $P_t(0)$ is expressed as

$$P_t(0)=\frac{P_{req}}{d_{0,1}^{-\alpha}10^{-\frac{\eta_{0,1}}{10}}\displaystyle\sum_{l=0}^{L-1}\left|\xi_{0,1}(l)\right|^2}.\qquad(3)$$

For ports #$i=2\sim n-1$, the received power $P_r(i)$ at port #i is the sum of all the received powers from all the previous ports and is given by

$$\begin{aligned}P_r(i)&=\sum_{j=0}^{i-1}P_t(j)\,d_{j,i}^{-\alpha}10^{-\frac{\eta_{j,i}}{10}}\sum_{l=0}^{L-1}\left|\xi_{j,i}(l)\right|^2\\&=\sum_{j=0}^{i-2}P_t(j)\,d_{j,i}^{-\alpha}10^{-\frac{\eta_{j,i}}{10}}\sum_{l=0}^{L-1}\left|\xi_{j,i}(l)\right|^2\\&\quad+P_t(i-1)\,d_{i-1,i}^{-\alpha}10^{-\frac{\eta_{i-1,i}}{10}}\sum_{l=0}^{L-1}\left|\xi_{i-1,i}(l)\right|^2.\end{aligned}\qquad(4)$$

The total transmit power P_{total} is given by the sum of the transmit powers along the route:

$$P_{total}=\sum_{i=0}^{n-1}P_t(i).\qquad(5)$$

Since $P_r(i)=P_{req}$ with TPC, the transmit power $P_t(i-1)$ of the port #$(i-1)$ is given by

$$P_t(i-1)=\frac{P_{req}-\displaystyle\sum_{j'=0}^{i-2}P_t(j')\,d_{j',i}^{-\alpha}10^{-\frac{\eta_{j',i}}{10}}\sum_{l=0}^{L-1}\left|\xi_{j',i}(l)\right|^2}{d_{i-1,i}^{-\alpha}10^{-\frac{\eta_{i-1,i}}{10}}\displaystyle\sum_{l=0}^{L-1}\left|\xi_{i-1,i}(l)\right|^2}.\qquad(6)$$

If the received power $P_r(i)$ at the port $\#i$ from the other previous ports, $\#0 \sim \#(i-1)$, is larger than the required received power P_{req}, i.e., $P_r(i) \geq P_{req}$, the port $\#(i{-}1)$ can be removed from the constructed route, i.e., $P_t(i{-}1)=0$; the transmit power $P_t(i-2)$ of the port $\#(i-2)$ becomes

$$P_t(i-2) = \frac{P_{req} - \sum_{j'=0}^{i-3} P_t(j')\, d_{j',i}^{-\alpha} 10^{-\frac{\eta_{j',i}}{10}} \sum_{l=0}^{L-1} \left|\xi_{j',i}(l)\right|^2}{d_{i-2,i}^{-\alpha} 10^{-\frac{\eta_{i-2,i}}{10}} \sum_{l=0}^{L-1} \left|\xi_{i-2,i}(l)\right|^2}. \tag{7}$$

Using this route modification algorithm, the number of hops decreases and consequently, the delay time also decreases.

3. Computer Simulation

Mobile terminals and wireless ports are randomly located in each VC. The average total transmit power along the route from a mobile terminal to the central port is evaluated by computer simulation. In order to limit the relay time, the maximum number of hops is limited to N. We evaluate the impact of the radio propagation parameters (path-loss exponent α, the shadowing standard deviation σ, the number L of propagation paths and also the fading correlation ρ between the control channel and data communication channel). The number K of wireless ports in each VC is also an important design parameter.

The normalized average power P_{norm} with the MHMRC diversity is defined as the average total transmit power along the route normalized by that of single-hop case, i.e., $P_{norm} = E[P_{total}]/E[P_{single-hop}]$, where P_{total} is given by Eq. (5) and $P_{single-hop}$ is given by Eq. (1) with i=0 (mobile terminal) and $j = n$ (central port). Therefore, P_{norm} is given by

$$\begin{aligned} P_{norm} &= \frac{E[P_{total}]}{E[P_{single-hop}]} \\ &= \frac{E\left[\sum_{i=0}^{n-1}\left(\dfrac{1 - \sum_{j=0}^{i-1} \dfrac{P_t(j)}{P_{req}} d_{j,i+1}^{-\alpha} 10^{-\frac{\eta_{j,i+1}}{10}} \sum_{l=0}^{L-1} \left|\xi_{j,i+1}(l)\right|^2}{d_{i,i+1}^{-\alpha} 10^{-\frac{\eta_{i,i+1}}{10}} \sum_{l=0}^{L-1} \left|\xi_{i,i+1}(l)\right|^2}\right)\right]}{E\left[\dfrac{1}{d_{0,n}^{-\alpha} 10^{-\frac{\eta_{0,n}}{10}} \sum_{l=0}^{L-1} \left|\xi_{0,n}(l)\right|^2}\right]}. \end{aligned} \tag{8}$$

The transmit power $P_t(j)$ is given by Eq. (3) for port $\#j$=0, and is given by Eq. (6) for ports $\#j = 1 \sim n{-}1$ with replacing $i-1$ by j. $P_t(j)$ is obtained recursively from Eq. (6). Since $P_t(0) \propto P_{req}$, it can be easily understood that $P_t(j)/P_{req}$ is not a function of P_{req}. As a consequence, P_{norm} does not depend on P_{req}.

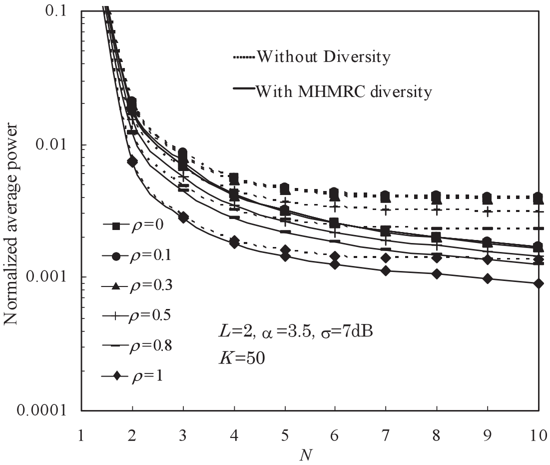


Fig. 3 Impact of ρ on the transmit power.

Figure 3 plots the normalized average power as a function of N with ρ as a parameter for α=3.5, σ=7 dB, L=2 and K=50. It is clearly seen that the MHMRC decreases the total transmit power for all ρ values. The power reduction by MHMRC is larger when ρ becomes smaller. For $\rho \geq 0.5$, the MHMRC diversity gain gets smaller, and becomes very small when ρ=1. This is because, when ρ=1, the route construction channel and the data communication channel experience the same fading, and hence the data communication route is also the minimum transmit power route. The fading correlation property between the control channel and the data communication channel may be given by [10]

$$\begin{aligned} \rho = \frac{1}{L} & \frac{\sin\left(\dfrac{2\sqrt{3}\pi L}{\sqrt{L^2-1}} \Delta f \tau_{rms}\right)}{\sin\left(\dfrac{2\sqrt{3}\pi}{\sqrt{L^2-1}} \Delta f \tau_{rms}\right)} \\ & \cdot \exp\left(j2\sqrt{3}\pi \sqrt{\frac{L-1}{L+1}} \Delta f \tau_{rms}\right), \end{aligned} \tag{9}$$

where Δf is the carrier frequency separation between the two channels and τ_{rms} is the rms delay spread of the fading channel. When L=2 and $\Delta f \cdot \tau_{rms}$=0.165, the frequency separation is Δf = 165 kHz for ρ=0.5.

To evaluate the MHMRC power reduction, we computed the MHMRC diversity gain as a function of N. The diversity gain is defined as the ratio of the average total transmit powers with and without MHMRC diversity. Figure 4 plots the MHMRC diversity gain (in dB) as a function of N with ρ as a parameter for K=50, α=3.5, σ=7 dB, and L=2. It is seen from this figure that as ρ decreases, the diversity gain increases; it is about 3.7 dB when ρ=0 and N=10.

Figure 5 plots the MHMRC diversity gain as a function of N with α as a parameter for K=50, σ=7 dB, L=2 and ρ=0. It is seen that as α decreases, the diversity gain increases. A reason for this is discussed below. Comparing Eq. (1) and Eq. (6), we can see that the MHMRC diversity gain depends on the second term of the numerator of Eq. (6),

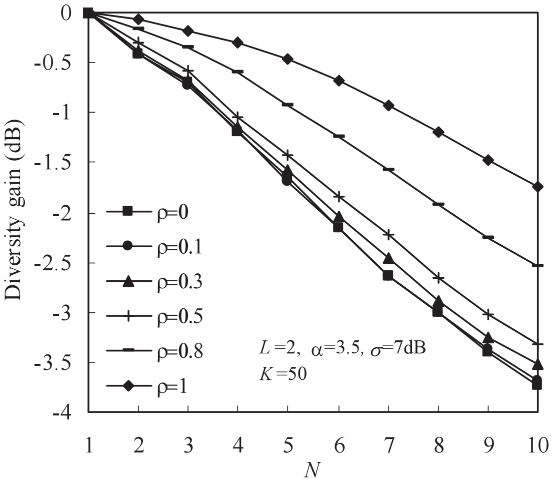


Fig. 4 Impact of ρ on the diversity gain.

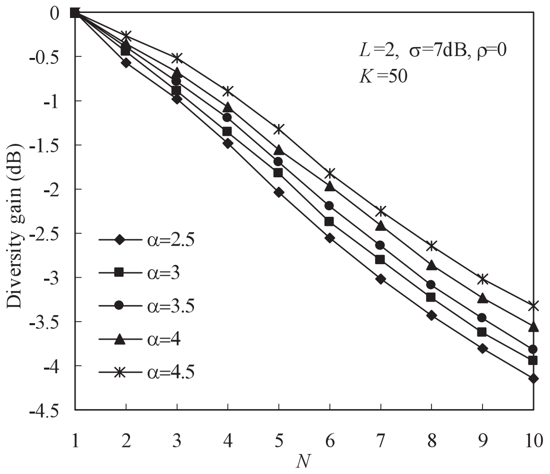


Fig. 5 Impact of α on the diversity gain.

i.e., $\sum_{j'=0}^{i-2} P_t(j')\, d_{j',i}^{-\alpha} 10^{-\frac{\eta_{j',i}}{10}} \sum_{l=0}^{L-1} \left|\xi_{j',i}(l)\right|^2$, which increases as α decreases, and hence the transmit power reduces. Consequently, the diversity gain increases as α decreases.

Figure 6 plots the MHMRC diversity gain as a function of N with σ as a parameter for K=50, α=3.5, L=2 and ρ=0. As σ increases, the diversity gain decreases. This can be explained below. As σ increases the route selection diversity effect increases [7]. Therefore, the port transmit power even without MHMRC reduces and hence, the second term of the numerator of Eq. (6) decreases. As a consequence, the diversity gain decreases as σ increases.

Figure 7 plots the MHMRC diversity gain as a function of N with L as a parameter for α=3.5, σ=7 dB, K=50 and ρ=0. As L decreases the MHMRC gain increases, and L=1 gives the best performance. The reason for this is given below. As L decreases, the variations of $\sum_{l=0}^{L-1} \left|\xi_{j',i}(l)\right|^2$ in the second term of the numerator of Eq. (6) increases; therefore, the diversity gain increases as L decreases.

Figure 8 plots the MHMRC diversity gain as a function of N with K as a parameter for α=3.5, σ=7 dB, L=2 and ρ=0. As K increases the MHMRC gain decreases. This is because as K increases, the possibility of choosing smaller transmit powers route increases; therefore, the port transmit

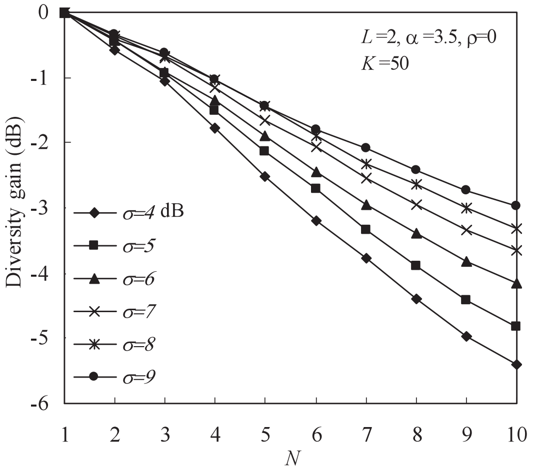


Fig. 6 Impact of σ on the diversity gain.

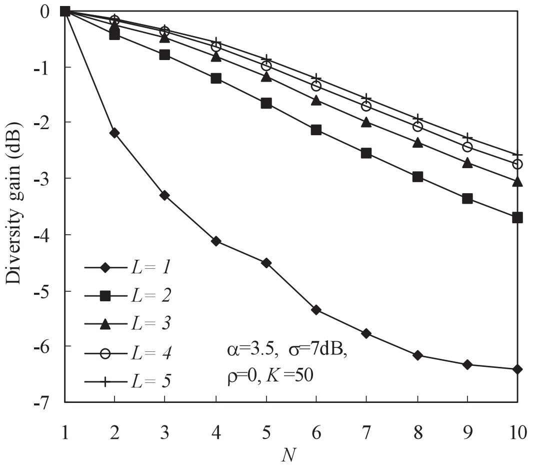


Fig. 7 Impact of L on the diversity gain.

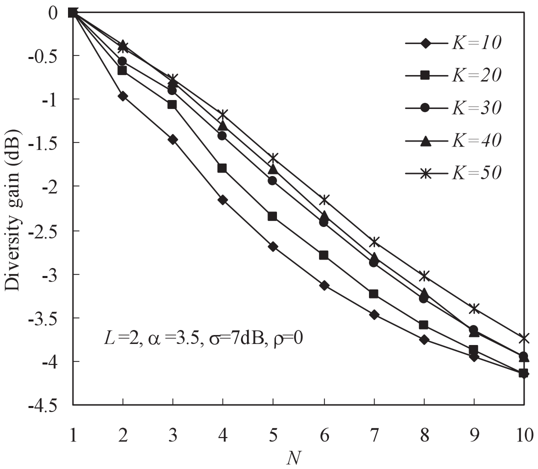


Fig. 8 Impact of K on the diversity gain.

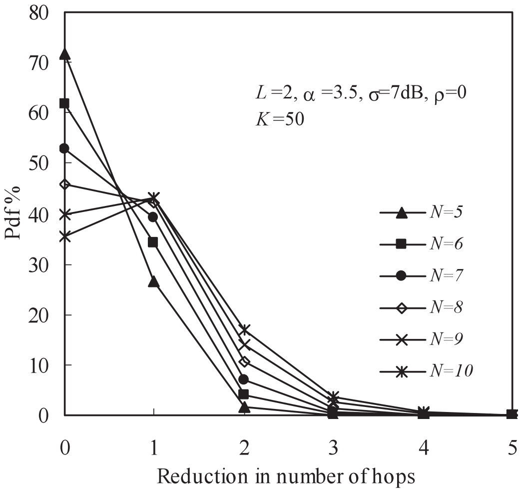


Fig. 9 Distribution of the reduction in the number of hops by MHMRC.

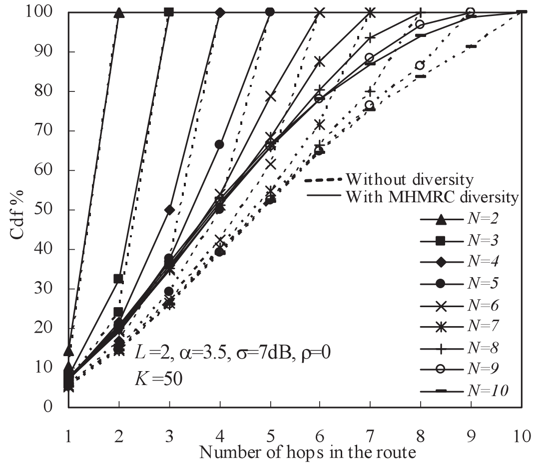


Fig. 10 Cdf of the number of hops in the route with N as a parameter for with and without MHMRC cases.

power without MHMRC diversity can be reduced; hence, the second term of the numerator of Eq. (6) decreases also, thereby the decreases diversity gain as K increases.

Using the proposed route modification algorithm with MHMRC diversity, the number of hops reduces and this reduces the data relay time between the mobile terminal and the central port. To evaluate the relay time reduction, we compute the distribution of the difference between the number of hops without MHMRC diversity and that with MHMRC diversity. Figure 9 plots the distribution of the reduction in the number of hops by MHMRC diversity with N as a parameter for L=2, α=3.5, σ=7 dB, ρ=0 and K=50. It can be seen that as the maximum allowable number N of hops increases, more hops can be reduced. This is because as N increases, the number of diversity branches (or the number of the same signals received from previous ports along the route) increases; thereby larger diversity gain is obtained, and thus, more number of hops can be removed by using the route modification algorithm.

Figure 10 plots the cumulative distributions of the number of hops with and without MHMRC cases with N as a parameter for L=2, α=3.5, σ=7 dB, ρ=0 and K=50. When N=5, the number of hops at the probability of 90% is almost the same for both with and without MHMRC; however, when N=10, it is 8 hops using MHMRC, while 9 hops without diversity.

4. Conclusions

In this letter, MHMRC diversity was introduced to reduce the route total transmit power in the multi-hop VCN and a route modification algorithm was presented. The power reduction effect of MHMRC diversity was evaluated by computer simulation. The MHMRC diversity gain in the route total transmit power depends on the propagation conditions as the path loss exponent α, shadowing loss standard deviation σ, the number of paths L and fading correlation ρ, as well as on the number K of wireless ports in each virtual cell. It was found that as α and L decrease, the diversity gain increases and that as σ and K increase, the MHMRC diversity gain decreases. MHMRC diversity can reduce the number of hops in the route (and reduce the multi-hop delay time). It was shown that the number of hops can be reduced by one hop for N=10 at the probability of 90%.

In this letter, we have considered a single-user case only. For the SNR-based TPC, the target SNR, P_{req}/P_{noise}, is given by $P_{req}/P_{noise} = \chi \cdot \gamma_{req}$ [11], where P_{noise} is the 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 satisfying the required communication quality. To allow multiple users in the VCN while maintaining the required quality, χ should be increased. This means that P_{req} must be increased in a multi-user environment. If many users are uniformly distributed over an entire VCN area, the interference power received by each wireless port may be identical due to the law of large numbers. Therefore, P_{req} is the same for all wireless ports. Since the normalized average power does not depend on P_{req} (see Sect. 3), the multi-hop diversity gain is the same as the single-user case. However, in the real multi-user environment, the interference power received by each wireless port may be different. Therefore, χ may be different for a different wireless port. Performance analysis of multi-hop diversity taking this fact into account is not easy. This is left as an interesting future work.

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References

[1] E. Kudoh and F. Adachi, "Study of Multi-hop communication in a virtual cellular system," Proc. WPMC'2003, pp.261–265, Yokosuka, Oct. 2003.

[2] E. Kudoh and F. Adachi, “Power and frequency efficient virtual cellular network,” Proc. IEEE VTC’2003 Spring, Cheju, Korea, April 2003.

[3] E.M. Royer and C.K. Toh, “A review of current routing protocols for adhoc mobile wireless networks,” IEEE Pers. Commun., vol.6, no.2, pp.46–55, April 1999.

[4] T. Mukai, H. Murata, and S. Yoshida, “Study on channel selection algorithm and number of established routes of multihop autonomous distributed radio network,” IEICE Trans. Commun. (Japanese Edition), vol.J85-B, no.12, pp.2080–2086, Dec. 2002.

[5] C.E. Perkins, E.M. Belding-Royer, and S. Das, “Ad hoc on demand distance vector (AODV) routing,” IETF RFC 3561, July 2003.

[6] A. Fujiwara, S. Takeda, H. Yoshino, T. Otsu, and Y. Yamao, “Capacity improvement with a multihop access scheme in broadband CDMA cellular system,” IEICE Trans. Commun. (Japanese Edition), vol.J85-B, no.12, pp.2073–2079, Dec. 2002.

[7] E. Kudoh and F. Adachi, “Transmit power efficiency of a multihop virtual cellular system,” Proc. IEEE VTC’2003 Fall, Orlando, Florida, USA, Oct. 2003.

[8] S. Hares, H. Yanikomeroglu, and B. Hashem, “A relaying algorithm for multihop TDMA TDD networks using diversity,” Proc. IEEE VTC’2003 Fall, Orlando, Florida, USA, Oct. 2003.

[9] W.C Jakes, Jr., ed., Microwave mobile communication, Wiley, New York, 1974.

[10] A. Katoh, E. Kudoh, and F. Adachi, “A study on optimum weights for delay transmit diversity for DS-CDMA in a frequency non selective fading channel,” IEICE Trans. Commun., vol.E87-B, no.4, pp.838–848, April 2004.

[11] K. Sawa, E. Kudoh, and F. Adachi, “Impact of shadowing correlation on spectrum efficiency of a power controlled cellular system,” IEICE Trans. Commun., vol.E87-B, no.7, pp.1964–1969, July 2004.