PAPER

Distributed Dynamic Channel Assignment for Multi-Hop DS-CDMA Virtual Cellular Network

Eisuke KUDOH[†a] *and* **Fumiyuki ADACHI**[†b], ***Members***

SUMMARY In this paper, the channel segregation dynamic channel allocation (CS-DCA) scheme is applied to a multi-hop DS-CDMA virtual cellular network (VCN). After all multi-hop routes are constructed over distributed wireless ports in a virtual cell, the CS-DCA is carried out to allocate the channels to multi-hop up and down links. Each wireless port is equipped with a channel priority table. The transmit wireless port of each link initiates the CS-DCA procedure and selects a channel among available ones using its channel priority table to check. In this paper, the channel allocation failure rate is evaluated by computer simulation. It is shown that CS-DCA reduces remarkably the failure rate compared to FCA. The impact of propagation parameters on the failure rate is discussed.

key words: *virtual cellular network, multi-hop network, adhoc network, routing, dynamic channel assignment, channel segregation*

1. Introduction

Recently, mobile communications services are shifting from voice conversations to data communications. There have been strong demands 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 reduce the peak transmit power while increasing the data transmission rates, we proposed a wireless multi-hop virtual cellular network (VCN) [1]. In the wireless multi-hop VCN, an efficient channel allocation algorithm is necessary. The channel allocation scheme is classified as the fixed channel allocation (FCA) and the dynamic channel allocation (DCA) [6]. Using FCA, predetermined fixed channels are allocated to each wireless port. FCA cannot adapt to changing traffic conditions and user distributions. On the other hand, using DCA, all channels are available at each wireless port and one of the available channels is allocated if the channel meets the required quality. DCA can be implemented either in a centralized or a distributed fashion [6]; the latter seems to be promising for the multi-hop VCN.

In this paper, direct sequence code division multiple access (DS-CDMA) technique is considered for multi-hop VCN. We apply the channel segregation DCA (CS-DCA) [7] to multi-hop links among wireless ports. The channel allocations for the multi-hop up and down links need to be simultaneously carried out. After describing the VCN in Sect. 2, Sect. 3 presents a channel allocation procedure using CS-DCA. In Sect. 4, the channel allocation failure rate is evaluated by computer simulation. Section 5 offers some conclusions.

Manuscript received August 11, 2004.
Manuscript revised December 17, 2004.
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DOI: 10.1093/ietcom/e88–b.6.2525

2. Wireless Multi-Hop VCN

The multi-hop VCN consists of a central port, which is a gateway to the network, and many distributed wireless ports (a group of distributed wireless ports acts as one virtual base station), as shown in Fig. 1. Transmit power control (TPC) is an indispensable technique [8] for DS-CDMA. However, when TPC is used, if all wireless ports in a virtual cell communicate directly with the central wireless port, the transmit powers of some wireless ports may become very large due to path loss, shadowing loss, and multipath fading. To avoid this, wireless multi-hop communication [2], [3] has been introduced to the VCN [1]. For the uplink (mobile-to-central port), the signal transmitted from a mobile terminal is received by the end wireless ports (defined as the wireless ports which directly transmit/receive the signal to/from a mobile terminal) and their received signals are relayed to the central wireless port. Since each end wireless port can act as a site diversity branch, the transmit power of a mobile terminal can be significantly reduced in comparison with present cellular systems [1]. On the other hand, for the downlink (central port-to-mobile), the signal to the mobile terminal can be multicast, using wireless multi-hop communication, to the multiple end wireless ports for site diversity transmission. In the multi-hop VCN, there are two types of links: user link between a user terminal and an end wireless port,

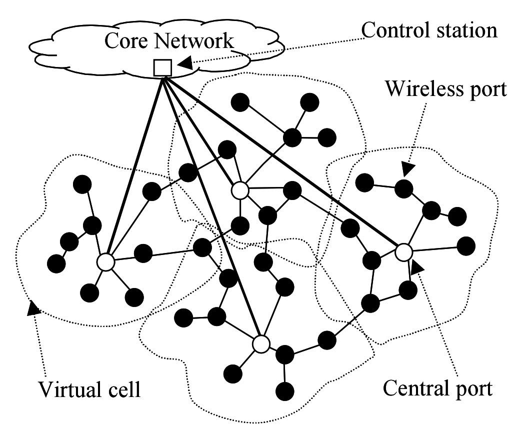


Fig. 1 Wireless multi-hop VCN.

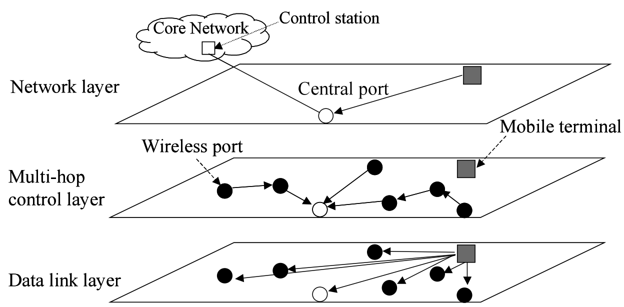


Fig. 2 Layer structure of wireless multi-hop VCN.

and multi-hop link between wireless ports. This paper focuses only on the channel allocation of multi-hop links.

In order to efficiently control the wireless multi-hop communication between the end wireless port and the central wireless port, the multi-hop control layer, that is inserted between the data link layer and the network layer, has been introduced as illustrated in Fig. 2 [4], [5]. The multi-hop control layer manages the multi-hop routing and channel allocation. A route construction scheme based on the total transmit power minimization criterion [4], [5] is used. In the following section, CS-DCA is presented.

3. Application of CS-DCA

The system bandwidth is divided into several frequency channels (hereafter, we use "channel" for simplicity) with different carrier frequencies. One of the available channels is allocated to a link between two adjacent wireless ports along a multi-hop route. Since DS-CDMA is applied, the same channel can be shared by different multi-hop links. The route construction procedure based on total transmit power minimization criterion [4], [5] is carried out using the control channel having a carrier frequency different from the channels for multi-hop communications.

After all routes are constructed, the transmit side on each link initiates the CS-DCA procedure to assign channels to the multi-hop up and down links. For the downlink, several multi-hop routes may branch from a relaying wireless port (for an example, see Fig. 3). In this case, the same channel can be used for all the branching multi-hop downlink routes. Furthermore, the channel assigned to the downlink may be reused for the uplink transmission, resulting in an efficient usage of the limited frequency resource. In the CS-DCA, each wireless port is equipped with a channel priority table as in [7]. Table 1 shows an example of a channel priority table. In table 1 and hence forth, C is the number of available channels. In the channel priority table, priority value and the number of times the channel is tested are listed. The channel priority value is defined as (the number of times the channel has been successfully allocated)/(the number of times the channel has been tested). The channel priority value is updated as follows. When the channel is successfully allocated, the channel priority value P is updated as

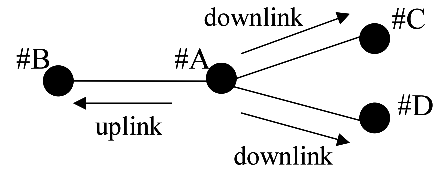


Fig. 3 Uplink and downlink branches.

Table 1 An example of channel priority table.

Channel number	Channel priority value	Number of times the channel is tested
0	0.1	10
1	0.89	100
⋯	⋯	⋯
C-1	0.25	40

$$(NP + 1)/(N + 1) \rightarrow P, \tag{1}$$

where N is the number of times the channel has been tested. When the channel is not successfully allocated, P is updated as

$$NP/(N + 1) \rightarrow P. \tag{2}$$

The probability that the channel is usable (i.e., the SINR of that channel is larger than the required value) is denoted as q. After the channel priority value is updated many times, P approaches a certain value in a steady state, where the following relationship holds

$$q\frac{NP + 1}{N + 1} + (1 - q)\frac{NP}{N + 1} = P. \tag{3}$$

From Eq. (3), we have $q = P$. In other words, the channel priority value P approaches the probability that the channel is usable. Therefore, the channel whose usable probability q is higher is selected more frequently.

The transmit wireless port selects a channel among available ones using its channel priority table. The transmit channel is allocated first for the downlink and then for the uplink. To exchange messages for channel allocation, control channels are necessary [4]. The CS-DCA procedure is as follows.

Step 1 (downlink channel allocation): wireless port of interest (#A in Fig. 3) selects a channel having the highest priority, among available channels that are not in use for receiving and have not been tested for allocation, as the downlink transmit channel. The immediate receiving wireless ports (#C and #D in Fig. 3) are informed via control channel about the selected downlink channel.

Step 2: wireless ports #C and #D measure the SINR of the informed downlink channel and report the measurement results via control channel to wireless port #A. If both SINRs reported from wireless ports #C and #D meet the quality requirement (or the required SINR), the selected channel is allocated as the downlink channel; otherwise, the procedure goes back to Step 1.

Step 3 (uplink channel allocation): wireless port #A first selects the same channel that is allocated for the downlink transmission and informs the uplink immediate receiving wireless port (#B in Fig. 3) of the selected channel via control channel.

Step 4: wireless port #B measures the SINR of the informed channel and reports the measurement result via control channel to wireless port #A. If the measured SINR meets the required value, the informed channel is allocated as the uplink channel and the process goes to Step 6, otherwise it goes to Step 5.

Step 5: wireless port #A selects the new channel having the highest priority, among available channels that are not in use for receiving and have not been tested for allocation, as the uplink transmit channel. An immediate receiving side (wireless port #B) is informed via control channel about the selected uplink transmit channel and the process goes back to Step 4.

Step 6: end of up and down link channel allocation at the wireless port of interest.

The above procedure is repeated one port-by-one port. Channel re-allocation among all wireless ports needs to be done periodically; but this depends on how fast the traffic distribution changes (this is not discussed in this paper).

4. Computer Simulation

4.1 Simulation Condition

For simplicity, a total of 19 virtual cells of hexagonal layout (the center virtual cell is the cell of interest) are considered for simulation. For CS-DCA, the SINR measurement is necessary as described in Sect. 3. The SINR is affected by distance dependent path loss, shadowing loss and fading. In the computer simulation, we assume L-path Rayleigh fading with uniform power delay profile, the SINR expression for which is presented in the next subsection. Coherent quaternary phase shift keying (QPSK) data-modulation and binary PSK (BPSK) spreading is assumed. In this paper, the sum of the background noise and the interference is approximated as a Gaussian variable. Using a Gaussian approximation of the interference, the bit error rate (BER) is given by $(1/2)\,\mathrm{erfc}\sqrt{\gamma/2}$ for QPSK [9], where γ is the SINR. Assuming a required BER of 10^{-3}, the required SINR γ_{req} is given by 9.8 dB.

4.2 SINR Expression for Computer Simulation

In CS-DCA, the measurement of SINR is necessary. Below, we derive the SINR expression for the computer simulation.

The propagation channel can be modeled as the product of distance dependent path loss, log-normally distributed shadowing loss and multi-path fading [10]. Hereafter, i, j and k denote the wireless port indices. Assuming an L-path fading channel with uniform power delay profile, the received power $P^r_{j\_i}$ of the signal transmitted from the wireless port $\#j$ and received at wireless port $\#i$ is given by

$$P^r_{j\_i} = P^t_j \cdot r_{j\_i}^{-\alpha} \cdot 10^{-\eta_{j\_i}/10} \cdot \sum_{l=0}^{L-1} \left|\xi_{j\_i}(l)\right|^2, \tag{4}$$

where P^t_j is the transmit power of wireless port $\#j$, α is the path loss exponent and r_{j_i}, η_{j_i}, and $\xi_{j\_i}(l)$ are respectively the distance, the shadowing loss (in dB) and the l-th path's complex path gain between wireless ports $\#j$ and $\#i$. $\{\xi_{j\_i}(l);\ i,\ j,\ l\}$ are characterized by time-invariant independent and identically distributed (i.i.d.) complex Gaussian variables with zero-mean and a variance of $1/L$. Signal-to-noise power ratio (SNR)-based ideal transmit power control (TPC) is assumed. The transmit power P^t_j is determined as

$$\frac{P^t_j}{N} = \frac{\Lambda_{\mathrm{target}}}{r_{j\_i}^{-\alpha} \cdot 10^{-\eta_{j\_i}/10} \cdot \sum_{l=0}^{L-1} \left|\xi_{j\_i}(l)\right|^2}, \tag{5}$$

where Λ_{target} is the target SNR and N is the noise power. Assuming ideal L-finger coherent Rake combining based on maximum ratio combining (MRC), the SINR γ_i after Rake combining at wireless port $\#i$ is given by

$$\begin{aligned}\gamma_i &= \sum_{l=0}^{L-1} \frac{\left(\frac{P^t_j}{N}\right) \cdot r_{j\_i}^{-\alpha} \cdot 10^{-\eta_{j\_i}/10} \left|\xi_{j\_i}(l)\right|^2}{\left(\begin{array}{l} 1 + \frac{1}{SF}\left(\frac{P^t_j}{N}\right) \cdot r_{j\_i}^{-\alpha} \cdot 10^{-\eta_{j\_i}/10} \cdot \sum_{\substack{l'=0 \\ l'\neq l}}^{L-1} \left|\xi_{j\_i}(l')\right|^2 \\ + \frac{1}{SF}\sum_{k\neq j}\left(\frac{P^t_k}{N}\right) \cdot r_{k\_i}^{-\alpha} \cdot 10^{-\eta_{k\_i}/10} \cdot \sum_{l'=0}^{L-1} \left|\xi_{k\_i}(l')\right|^2 \end{array}\right)} \\ &= \Lambda_{target} \sum_{l=0}^{L-1} \frac{\frac{\left|\xi_{j\_i}(l)\right|^2}{\sum_{l'=0}^{L-1}\left|\xi_{j\_i}(l')\right|^2}}{\left(\begin{array}{l} 1 + \frac{\Lambda_{target}}{SF}\left(1 - \frac{\left|\xi_{j\_i}(l)\right|^2}{\sum_{l'=0}^{L-1}\left|\xi_{j\_i}(l')\right|^2}\right) \\ + \frac{\Lambda_{target}}{SF}\sum_{k\neq j}\left(\frac{r_{k\_i}}{r_{k\_q(k)}}\right)^{-\alpha} 10^{-(\eta_{k\_i}-\eta_{k\_q(k)})/10} \\ \frac{\sum_{l'=0}^{L-1}\left|\xi_{k\_i}(l')\right|^2}{\sum_{l'=0}^{L-1}\left|\xi_{k\_q(k)}(l')\right|^2} \end{array}\right)}, \end{aligned} \tag{6}$$

where SF is the spreading factor and $\#q(k)$ is the index of the wireless port that communicates with the wireless port $\#k$. The second term in the denominator is the own inter-path interference (IPI) and the third term is the interference from other wireless ports. Equation (6) is used for computing the SINR in the computer simulation.

4.3 Simulation Results and Discussions

Figure 4 shows an example of the distribution of channels allocated by the CS-DCA (the number indicates the channel index) when the number C of available channels is C=13. Wireless ports, each having omni directional transmit/receive antenna, are randomly located in each virtual cell. The number K of wireless ports (including the central wireless port) per virtual cell is K=20. Channel #5 is allocated to the downlink at central wireless port #A. The same channel is reused for both uplink and downlink transmissions at different wireless ports (e.g., channel #3 is used for both up and down links at wireless ports #B and #C), resulting in an efficient frequency usage.

To show the advantage of the application of CS-DCA to multi-hop VCN, the channel allocation failure rate of CS-DCA is compared with the case of fixed channel allocation (FCA). In FCA, all C available channels are divided into F groups [10], where F is the cluster size. Each wireless port is allocated C/F channels. We assume that the wireless ports are assumed to be regularly located in each virtual cell to form the hexagonal radio zone pattern. In both CS-DCA and FCA, the channel allocation is considered to have been successfully completed only if channel allocation for all up and down links is successful in the entire virtual cell, otherwise the channel allocation has failed. In the simulation, the log-normally distributed shadowing losses and fading are randomly generated every trial. Accordingly, the multi-hop route changes every trial. After executing a large number of trials, the rate of the channel allocation failure is computed as the failure rate. In the computer simulation, more than 10000 trials were executed. The number K of wireless ports per virtual cell can only take values like K=3, 4, 7 and so on [10].

Only the cases of K=19 and 7 are considered. The failure rate performances of CS-DCA and FCA are compared in Fig. 5 for α=3.5, σ=7 dB, L=2 and SF=64. The maximum allowable number of hops is limited to J. It is seen that CS-

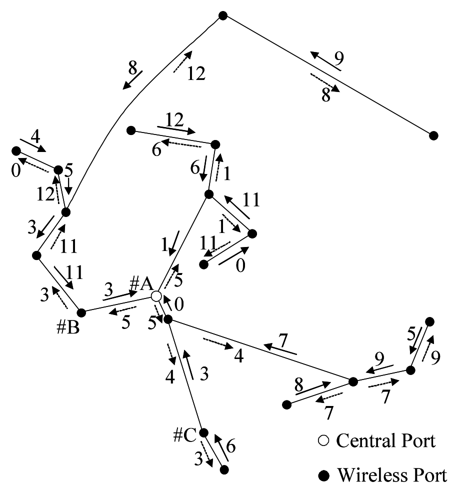
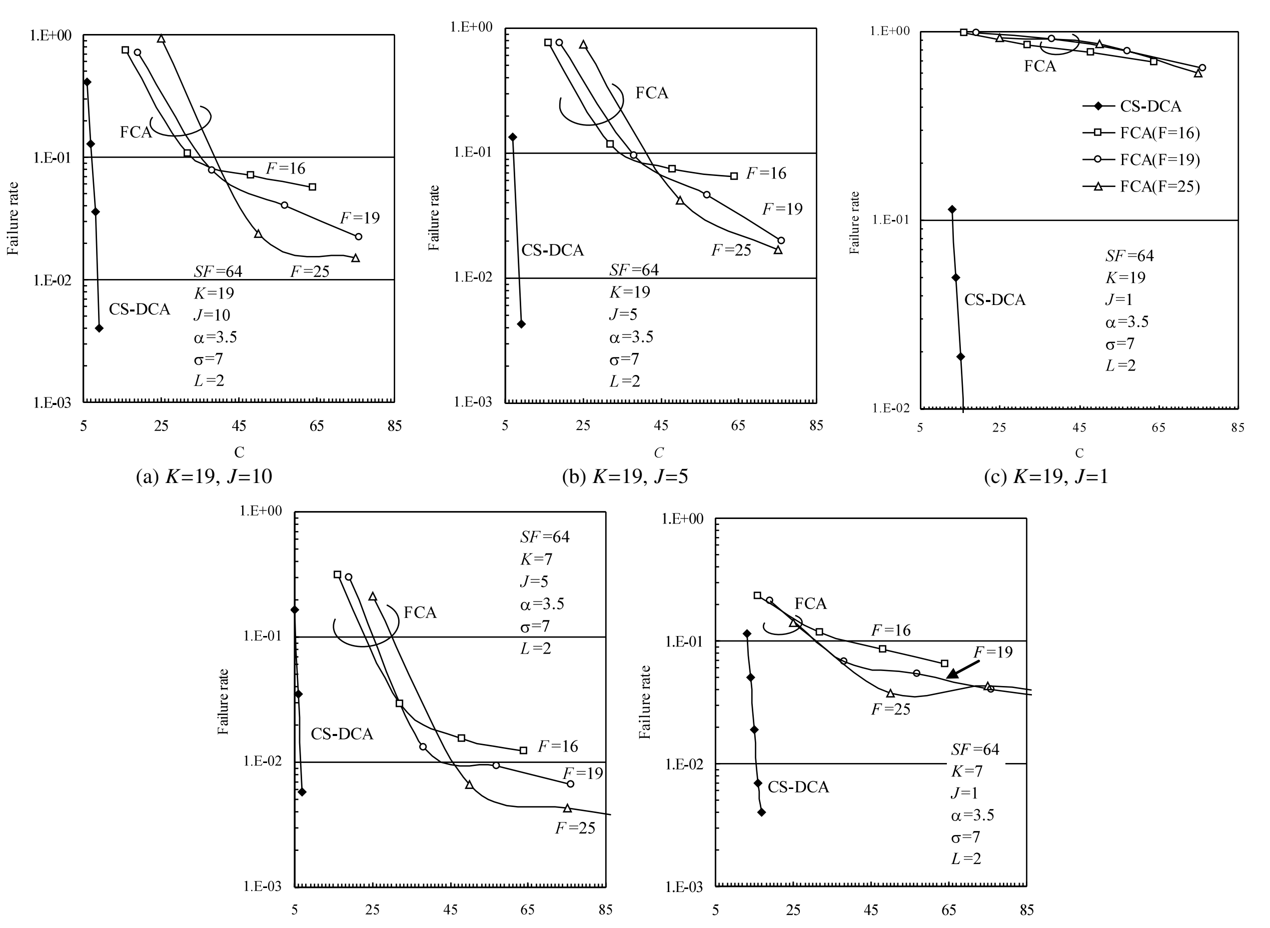


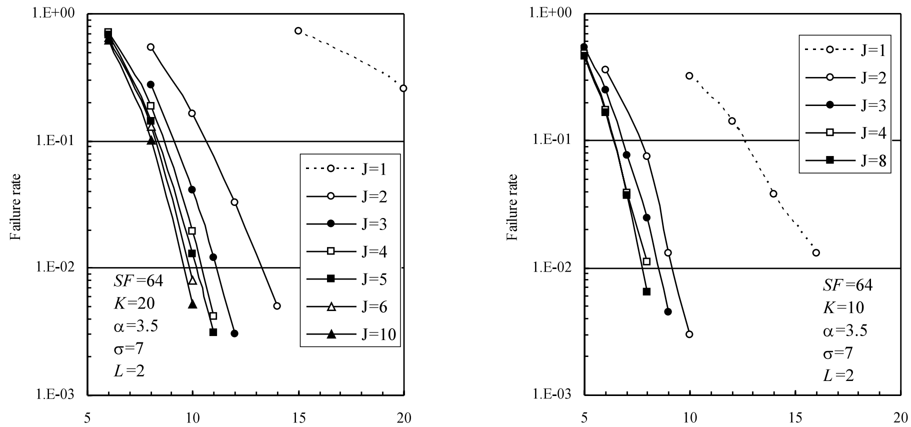
Fig. 4 An example of CS-DCA channel allocation.



(a) K=19, J=10 (b) K=19, J=5 (c) K=19, J=1

(d) K=7, J=5 (e) K=7, J=1

Fig. 5 Comparison of CS-DCA and FCA.



(a) K=20 (b) K=10

Fig. 6 Impact of J on failure rate.

DCA provides significantly smaller failure rate compared to FCA irrespective of the value of K. In FCA, since frequency channels are reused regardless of the amount of interference, some of the frequency channels may suffer from large co-channel interference. One simple solution to reduce co-channel interference is increasing the cluster size F. It can be clearly seen from Fig. 5 that as the cluster size F increases, the failure rate floor reduces. However, when $C < 40$, as F increases, the failure rate increases, because the number of available channels in each wireless port decreases. On the other hand, CS-DCA does not produce failure rate floor, because CS-DCA can allocate the usable channels adaptively in order to avoid the large co-channel interference. It is also seen from Fig. 5 that the FCA failure rate of J=10 is almost the same as that of J=5. This suggests that the maximum number J of allowable hops can be limited in order to avoid unnecessary long time delay.

In the following, CD-DCA failure rate performance is evaluated. In computer simulation, locations of wireless ports are randomly changed in each trial. To avoid large transmission delay, the maximum allowable number of hops is limited to J. The impact of J on the failure rate of CS-DCA is shown for α =3.5, σ=7 dB, L=2 and SF=64 in Fig. 6. In Figs. 6(a) and (b), K=20 and 10 wireless ports are randomly located in each virtual cell, respectively. For comparison, single-hop case (J=1) is also plotted. It is seen that the failure rate reduces as J increases irrespective of K. This is because as J increases, the transmit power of each wireless port can be reduced due to shorter link distance between two adjacent ports, thereby reducing the interference power to other wireless ports. It can also be seen that the failure rate is almost constant for $J > 3$ (K=10) and 4(K=20), respectively. This suggests that the maximum number J of allowable hops can be limited in order to avoid unnecessary long time delay.

As understood from Eq. (6), the SINR of each port is affected by SF and the propagation parameters (α, σ and L). Below we evaluate the impact of α, σ, L and SF on the failure rate. The impact of α on the failure rate is shown

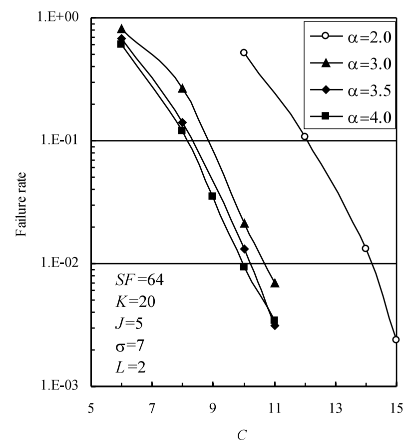


Fig. 7 Impact of α on failure rate.

in Fig. 7 for K=20, σ=7 dB, L=2, J=5 and SF=64. As α increases, the failure rate decreases. This is because the interference power from the interfering ports decreases as α increases.

The impact of σ on the failure rate is shown for α=3.5, L=2, J=5 and SF=64 in Fig. 8. The failure rate is almost insensitive to σ. Possible reason for this is discussed below. Larger σ produces larger variations in the shadowing losses between different wireless ports. In the route construction based on the total transmit power minimization criterion, each possible link between two wireless ports acts as one diversity branch and the multi-hop route (a sequence of links) that provides the least total transmit power is selected. The larger difference in the shadowing losses among different links can increase the route selection diversity effect. This contributes to reducing the total transmit power and consequently to decreasing the interference to other links, resulting in reducing the failure rate. On the other hand, as σ increases, the probability of large interference power may increase. This contributes to increasing the failure rate. As a consequence, the failure rate becomes almost insensitive to σ.

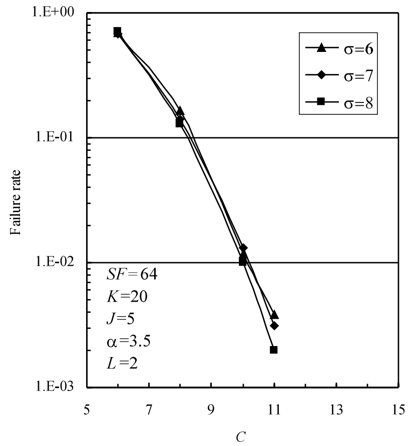


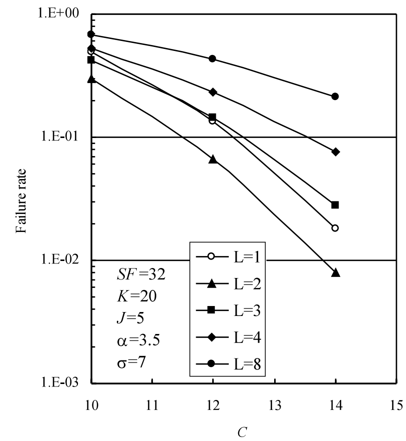
Fig. 8 Impact of σ on failure rate.

The impact of L on the failure rate is shown for α=3.5, σ=7 dB and J=5 in Fig. 9. The failure rate is very sensitive to L. As L increases, the probability of SINR falling below the required SINR decreases due to increasing path diversity gain obtained by Rake combining (see Eq. (2)) and hence the failure rate reduces for the given value of C. However, the failure rate starts to increase due to increasing inter-path interference (IPI) (the second term of the denominator of Eq. (3)). Therefore, the failure rate becomes minimum at a certain value of L. It is seen from Fig. 9 that the failure rate becomes the smallest with L=2, 2, and 3 when SF=32, 64, and 128, respectively. A slight larger L for minimizing the failure rate for larger SF is due to better reduction of IPI. Since L is proportional to the channel bandwidth, the simulation result suggests that there exists an optimum channel bandwidth for the given SF.

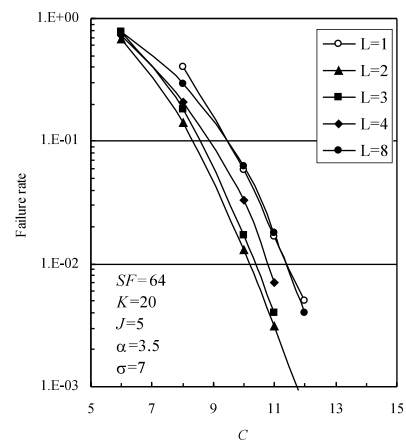
5. Conclusions

Distributed DCA is a promising channel allocation scheme for wireless multi-hop VCN. In this paper, the CS-DCA algorithm was applied to channel allocation for multi-hop DS-CDMA links and the failure rate was evaluated by computer simulation. It was shown that CS-DCA can significantly reduce the failure rate compared to FCA since CS-DCA can assign channels flexibly in order to avoid the large co-channel interference. The impact of the propagation parameters on the failure rate was discussed. The failure rate decreases as the path loss exponent increases. But, it is almost insensitive to the shadowing loss standard deviation, while sensitive to the number L of propagation paths. There exists an optimum value of L that minimizes the failure rate for the given SF. Since L is proportional to the channel bandwidth, the result suggests that there exists an optimum channel bandwidth for the given SF.

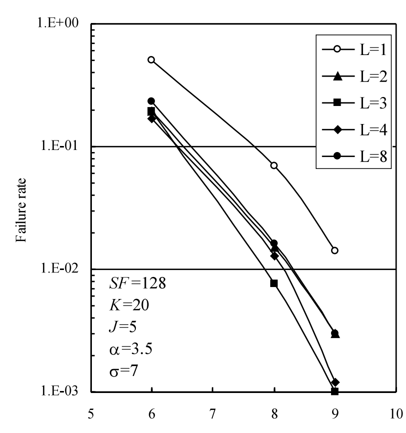
Call blocking probability and throughput are other important quality measures for channel allocation schemes besides the channel allocation failure rate. This paper focused only on the channel allocation of multi-hop links. User link channel allocation, call blocking probability and throughput are left as interesting future studies.



(a) SF=32



(b) SF=64



(c) SF=128

Fig. 9 Impact of L on failure rate.

Acknowledgement

This research was supported in part by the Telecommunications Advancement Foundation.

References

[1] E. Kudoh and F. Adachi, "Power and frequency efficient virtual cel-

lular network," Proc. IEEE VTC 2003 Spring, pp.2485–2489, Cheju, Korea, April 2003.
[2] "Special issue: Mobile adhoc networking-research, trends and applications," Wirel. Commun. Mob. Comput., vol.2, Feb. 2002.
[3] E.M. Royer and C.K. Toh, "A review of current routing protocols for ad hoc mobile wireless networks," IEEE Pers. Commun., vol.6, no.2, pp.46–55, April 2001.
[4] E. Kudoh and F. Adachi, "Transmit power efficiency of a multi-hop virtual cellular system," Proc. IEEE VTC 2003 Fall, Orlando, FL, Oct. 2003.
[5] E. Kudoh and F. Adachi, "Study of a multi-hop communication in a virtual cellular system," Proc. WPMC 2003, vol.3, pp.261–265, Yokosuka, Japan, Oct. 2003.
[6] I. Katzela and M. Naghshineh, "Channel assignment schemes for cellular mobile telecommunication systems: A comprehensive survey," IEEE Pers. Commun., vol.3, no.3, pp.10–31, June 1996.
[7] Y. Furuya and Y. Akaiwa, "Channel segregation, a distributed adaptive channel allocation scheme for mobile communication systems," IEICE Trans. Commun., vol.E74-B, no.6, pp.1531–1537, June 1991.
[8] F. Adachi, M. Sawahashi, and H. Suda, "Promising techniques to enhance radio link performance of wideband wireless access based on DS-CDMA," IEICE Trans. Fundamentals, vol.E81-A, no.11, pp.2242–2249, Nov. 1998.
[9] J.G. Proakis, Digital Communications, 3rd ed., McGraw-Hill, New York, 1995.
[10] W.C. Jakes, Microwave Mobile Communications, John Wiley & Sons, 1974.

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