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Channel Allocation for a 2-Hop OFDMA Virtual Cellular Network

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Abstract-**A multi-hop virtual cellular network (VCN) was proposed for future broadband mobile communication systems. Orthogonal frequency division multiple access (OFDMA) can be used as the multi-hop wireless access technique. However, since the number of available subcarriers is limited, the same subcarrier must be reused in different multi-hop links and therefore, co-channel interference limits the performance of multi-hop OFDMA VCN. Using OFDMA, the channel is composed of a block of subcarriers. OFDMA VCN requires an adaptive channel allocation to minimize the co-channel interference. The link performance can be improved by allocating a block of subcarriers with a good propagation channel condition. In this paper, we propose a distributed channel allocation scheme based on the maximization of the signal-to-interference plus noise power ratio (SINR) of each multi-hop link. Since the channel allocation is performed at each link, central port does not need to collect the SINR information of all multi-hop links. We numerically evaluate the downlink channel capacity of 2-hop OFDMA VCN and compare it with VCN using 2-hop direct sequence code division multiple access (DS-CDMA).**

Keywords: Multi-hop, Virtual cellular network, Channel allocation, Channel capacity, OFDMA, DS-CDMA

I. INTRODUCTION

In the next generation mobile communication systems, high speed data services are demanded. However, as the data transmission rate becomes higher, the transmit power should be increased to satisfy the required transmission quality. Therefore, unacceptably large transmit power may be required for such high speed data transmission. If the data transmission rate becomes higher without increasing the transmit power, the coverage area of a base station should be decreased. A multi-hop technique is known as one of the techniques to avoid this problem [1, 2]. We have proposed a multi-hop virtual cellular network (VCN) as illustrated in Fig. 1 for the next generation mobile network [3, 4]. In VCN, the signal transmitted from a mobile terminal (MT) is received by a distributed wireless port (WP) and relayed to a central port (CP), which acts as a gateway to core network, using multi-hop technique. The WPs are assumed to be stationary. By using this technique, the coverage area can be expanded while avoiding the large transmit power. In the first stage of the migration from conventional 1-hop CN to multi-hop VCN, the number of hops can be limited to two.

Orthogonal frequency division multiple access (OFDMA) can be used as the multi-hop wireless access technique as in wireless mesh networks [5]. In wireless mesh network, if time division duplex (TDD) is used in relaying node, the throughput degrades due to the increased multi-hop delay. To avoid this problem, we use the frequency division duplex (FDD) relaying, where the WP uses different subcarrier blocks for simultaneous transmission and reception. Therefore, higher transmission efficiency is expected. However, since the number of subcarriers is limited, the same subcarrier block must be reused in different multi-hop links and therefore, co-channel interference limits the performance of multi-hop OFDMA VCN. OFDMA can improve the link performance by allocating a subcarrier block with a good propagation channel condition [6, 7].

In this paper, we propose a distributed channel allocation scheme based on the maximization of the signal-to-interference plus noise power ratio (SINR) of each multi-hop link for the downlink transmission. Since the channel allocation is performed at each link, CP does not need to collect the SINR information of all multi-hop links. The channel is composed of a block of subcarriers. We consider the localized, equidistant, and adaptive channel configurations. We numerically evaluate the downlink channel capacity of 2-hop OFDMA VCN. Next, we compare 2-hop VCN and 1-hop CN to show that 2-hop VCN can achieve larger channel capacity than 1-hop CN. Then, we compare the channel capacity of OFDMA VCN and direct sequence code division multiple access (DS-CDMA) VCN [4, 8, 9] to show that OFDMA provides larger channel capacity than DS-CDMA.

The rest of the paper is organized as follows. In Sect. II, at first we propose the channel allocation schemes for downlink 2-hop OFDMA VCN. Next, for comparison, we present the channel allocation scheme for DS-CDMA VCN. In Sect. III, the channel capacity is evaluated by numerical computation method. In Section IV, we give some conclusions.

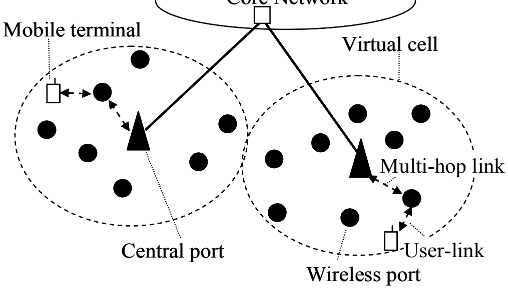
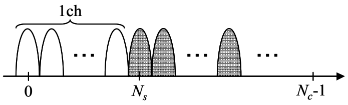


Figure 1. 2-hop virtual cellular network.

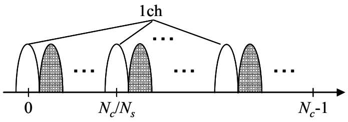
II. 2-HOP VIRTUAL CELLULAR NETWORK

A. Channel Configuration

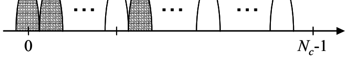
All channels are assumed to be composed of the same number of subcarriers. We consider the three channel configurations: (a) localized, (b) equidistant, and (c) adaptive, as shown in Fig. 2. We assume that N_c subcarriers are available and each channel is composed of N_s subcarriers. For the localized channel configuration, one channel is composed of adjacent N_s subcarriers. For equidistant channel configuration, the channel consists of the subcarriers with equal frequency distance of N_c/N_s. For adaptive channel configuration, the locations of subcarriers constituting a channel are not fixed, but are determined adaptively according to the channel condition.



(a) Localized



(b) Equidistant



(c) Adaptive

Figure 2. Channel configurations.

B. Channel Allocation for Localized and Equidistant Channel Configurations

Below, the distributed channel allocation scheme based on the maximization of geometric mean of SINRs of subcarriers is proposed. Since the following channel allocation scheme is performed at each link of MT-WP link (user-link) and CP-WP link (multi-hop link) as shown in Fig. 1, each MT transmits the received SINR information to its communicating WP. However, CP does not need to collect the SINR information of all links (on the contrary, in the case of centralized channel allocation scheme, the SINR information of all links including the link between WP and MT should be collected to the CP.) The same subcarrier is not used in transmitting and receiving at the same WP as illustrated in Fig. 3(a), because the transmitted signal interferes with the received signal. The same subcarrier also is not allocated to multiple links of the same transmitter in order to avoid the strong interference, as shown in Fig. 3(b). This means that different MTs communicating with the same WP are allocated the different subcarriers. Taking into account of the above conditions, the SINR of each subcarrier is measured by using pilot signal and the channel having the maximum geometric mean of SINR is allocated to each link of user-link and multi-hop link.

The n-th channel is expressed as the channel vector $\mathbf{f}_n=[n(0),\ldots,n(k),\ldots,n(N_s-1)]^T$, where $n(k)$ is the subcarrier index of k-th subcarrier in the n-th channel. For the localized channel configuration, the channel vector $\mathbf{f}_n$ is expressed as

$$\mathbf{f}_n = [nN_s, \cdots, nN_s + k, \cdots, nN_s + N_s - 1]^T . \qquad (1)$$

For the equidistant channel configuration, $\mathbf{f}_n$ is represented by

$$\mathbf{f}_n = \left[n, \cdots, kN_c/N_s + n, \cdots, (N_s - 1)N_c/N_s + n\right]^T . \qquad (2)$$

The channel vector $\mathbf{f}_{\text{assign}}$ to be allocated can be expressed as

$$\mathbf{f}_{\text{assign}} = \arg \max_{n\in\{0,\cdots,N_c/N_s-1\}} \left(\prod_{k=0}^{N_s-1} \gamma(n(k)) \right)^{1/N_s} , \qquad (3)$$

where N_c/N_s is the total number of channels and $\gamma(n(k))$ is the SINR at the k-th subcarrier of the n-th channel.

The propagation channel can be modeled as the product of distance dependent path loss, log-normally distributed shadowing loss and multi-path fading. In this paper, we assume the multi-path fading is the frequency-selective fading channel having L propagation paths with the different time delays. We have used the Gaussian approximation of the interference. The received SINR $\gamma(n(k))$ at j-th MT of the signal transmitted from i-th WP can be expressed as

$$\gamma(n(k)) = \frac{P_t r_{i-j}^{-\alpha} 10^{-\eta_{i-j}/10} \left|H_{i-j}(n(k))\right|^2}{N + \sum_{q,q\neq i} P_t r_{q-j}^{-\alpha} 10^{-\eta_{q-j}/10} \left|H_{q-j}(n(k))\right|^2} , \qquad (4)$$

where P_t is the transmit power, α is the path-loss exponent, $r_{i\text{-}j}$, $\eta_{i\text{-}j}$ and $H_{i\text{-}j}(n(k))$ are respectively the distance, shadowing loss and channel gain of the $n(k)$-th subcarrier between i-th WP and j-th MT. N is the noise power. The second term in the denominator is the co-channel interference from other WPs using the $n(k)$-th subcarrier.

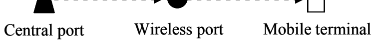
The channel capacity $C(\mathbf{f}_n)$ of n-th channel is given by [10]

$$C(\mathbf{f}_n) = \sum_{k=0}^{N_s-1} \log_2\left(1 + \gamma(n(k))\right). \qquad (5)$$

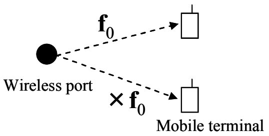
If the SINR $\gamma(n(k))$ is much larger than 1, the channel capacity can be approximated by

$$C(\mathbf{f}_n) \approx N_s \log_2 \left(\prod_{k=0}^{N_s-1} \gamma(n(k)) \right)^{1/N_s} \quad \text{if } \gamma(n(k)) >> 1 . \qquad (6)$$

Therefore allocating the channel having maximum geometric mean of SINRs is equivalent to allocating the channel having maximum channel capacity.



(a) Limitation in transmitting and receiving



(b)Limitation in transmission from same transmitter to multiple receivers

Figure 3. Limitations of subcarrier allocation.

C. Channel Allocation for Adaptive Channel Configuration

Below, the distributed channel allocation scheme based on the maximization of SINR of each subcarrier is proposed. N_s subcarriers are allocated in descending order of SINR. We will show an example of channel allocation as follows. We assume N_c=8 and N_s=2, and the subcarriers allocation to the user-link between WP and MT as illustrated in Fig. 4. When the received SINR at the MT can be obtained like Fig. 4, the subcarrier #2 having the largest SINR and #7 having the second largest SINR are allocated to the link. In the 2-hop communication, the channel allocation is done to the multi-hop link between CP and WP in the same way.

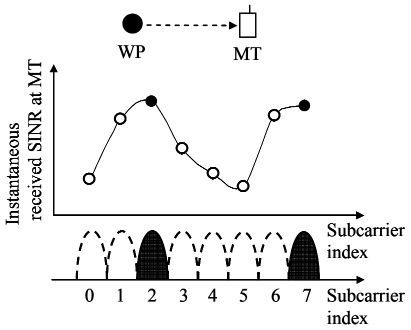


Figure 4. An example of subcarrier allocation for adaptive channel configuration.

D. Routing Algorithm

In this paper, a routing algorithm based on the total propagation loss minimization criterion is used [9]. The total propagation loss is defined as the sum of the propagation losses between CP and WP and between WP and MT. Since the WP is fixed, the propagation loss P_{loss}^{CP-m} between CP and m-th WP is given by

$$P_{loss}^{CP-m}=P_t/P_r^{CP-m}=\left(r_{CP-m}^{-\alpha}10^{-\eta_{CP-m}/10}\sum_{k=0}^{N_c-1}\left|H_{CP-m}(k)\right|^2\right)^{-1},\quad(7)$$

where $P_r{}^{CP\text{-}m}$ is the total received signal power (N_c subcarriers) at the m-th WP of the signal transmitted from CP. The propagation loss P_{loss}^{m-MT} between m-th WP and MT is expressed as

$$P_{loss}^{m-MT}=P_t/P_r^{m-MT}=\left(N_c r_{m-MT}^{-\alpha}10^{-\eta_{m-MT}/10}\right)^{-1},\quad(8)$$

where $P_r{}^{m\text{-}MT}$ is the local average received signal power at the MT of the signal transmitted from m-th WP. The MT selects the WP, indexed as m_{select}, having the minimum total propagation loss.

$$m_{select}=\arg\min_m\left\{P_{loss}^{CP-m}+P_{loss}^{m-MT}\right\}.\quad(9)$$

E. Channel Allocation for DS-CDMA VCN

In DS-CDMA VCN, the available bandwidth is divided into CH frequency channels and SF_{ch} code channels per frequency channel are assumed, as shown in Fig. 5. CH and SF_{ch} should satisfy the following equation to keep the same total number of channels between OFDMA and DS-CDMA.

$$N_c/N_s=SF_{ch}\cdot CH\ .\quad(10)$$

In DS-CDMA, the frequency channel having the maximum SINR is allocated to each link. The frequency channel index c_{assign} to be allocated can be expressed as

$$c_{\text{assign}}=\arg\max_{c\in\{0,\cdots,CH-1\}}\left(\gamma(c)\right),\quad(11)$$

where $\gamma(c)$ is the SINR of c-th frequency channel. When we assume ideal Rake combining, $\gamma(c)$ of the signal transmitted from i-th WP at the j-th MT is given by [8]

$$\gamma(c)=\sum_{l=0}^{L_{ch}-1}\frac{P_t r_{i-j}^{-\alpha}10^{-\eta_{i-j}/10}\left|h_{i-j,c}(l)\right|^2}{\left(\begin{aligned}&N+\frac{U_{i,c}}{SF_{ch}}P_t r_{i-j}^{-\alpha}10^{-\eta_{i-j}/10}\left(\sum_{l'=0}^{L_{ch}-1}\left|h_{i-j,c}(l')\right|^2-\left|h_{i-j,c}(l)\right|^2\right)\\&+\frac{1}{SF_{ch}}\sum_{q,q\neq i}U_{q,c}P_t r_{q-j}^{-\alpha}10^{-\eta_{q-j}/10}\sum_{l'=0}^{L_{ch}-1}\left|h_{q-j,c}(l')\right|^2\end{aligned}\right)},\quad(12)$$

where L_{ch} and SF_{ch} are respectively the number of resolvable paths and spreading factor per frequency channel. If the number of paths and spreading factor when CH is CH=1 are respectively L and SF, L_{ch} is $L_{ch}=L/CH$ and SF_{ch} is $SF_{ch}=SF/CH$. $U_{i,c}$ is the accommodated number of code channels of c-th frequency channel of i-th WP and $h_{i\text{-}j,c}(l)$ is the complex path gain of l-th path. The second term in the denominator is the inter-path interference (IPI) and third term is the co-channel interference from other WPs using c-th frequency channel.

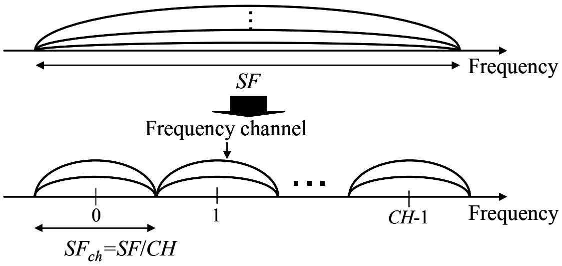


Figure 5. Band division in DS-CDMA VCN.

III. NUMERICAL COMPUTATION

We evaluate, by numerical computation method, the downlink channel capacity when the channel allocation is done to each link as described in Sect. II. The channel capacity per user is the minimum channel capacity of the user-link and multi-hop link. When the channel capacity is denoted by $C_{U\text{-}link}$ and $C_{MH\text{-}link}$ for the user-link and multi-hop link, respectively, the channel capacity per user C_u is given by [11]

$$C_u=\min\{C_{U-link},C_{MH-link}\}\ .\quad(13)$$

If there is no available subcarrier or channel, the channel capacity of the user is zero.

The numerical computation condition is summarized in Table 1. We consider 19 hexagonal VCs, therefore we consider the interference from second tiers VCs. Each VC has M=20 randomly distributed WPs. CP is located in the center of VC. We assume a quasi-static Rayleigh fading channel having L=16-path with uniform power delay profile. The average received SNR at the cell edge is set to SNR=10dB. In the 2-hop transmission, the transmit power of each WP is halved to keep the total transmit power same as in the 1-hop transmission. In OFDMA, we assume the number of subcarriers N_c=64 and the channel consists of N_s=4 subcarriers. In DS-CDMA, we assume that the spreading factor SF is SF=16 and IPI which is the second term of the denominator in Eq. (12) can be perfectly canceled.

TABLE 1
NUMERICAL COMPUTATION CONDITION

Virtual Cell	Number of VCs	19(hexagonal layout)
	Number of WPs per VC	M=1(1-hop),20
	Maximum number of allowable hops	N_h=1,2
Channel model	Path loss exponent	α =3.5
	Shadowing loss standard deviation	σ =6(dB)
	Fading	L=16-path uniform power delay profile
OFDMA	Number of subcarriers	N_c=64
	Number of subcarriers per link	N_s=4
DS-CDMA	Number of frequency channels	CH=2,4,8,16
	Spreading factor when CH=1	SF=16
	Spreading factor per channel	$SF_{ch}=SF/CH$
	Number of resolvable paths per channel	$L_{ch}=L/CH$
Average received SNR at cell edge		SNR=10(dB)

A. Comparison of Channel Configurations in OFDMA

Figure 6 shows the average channel capacity per user of OFDMA normalized by the system bandwidth (hereafter, we call this normalized channel capacity "channel capacity" for simplicity) as a function of the normalized number $U/(N_c/N_s)$ of users per VC, where U is the number of users per VC. The adaptive channel configuration can achieve the highest channel capacity and the localized channel configuration provides larger channel capacity than equidistant channel configuration. The reason for this is discussed below. In the equidistant channel configuration, the SINR of several subcarriers in the allocated channel might be small. Localized channel configuration can allocate the channel composed of the adjacent subcarriers having large SINR. However subcarriers in other channels might have larger SINR than the allocated subcarriers. On the other hand, the adaptive channel configuration can always allocate the subcarriers having the largest SINR among the available subcarriers. Therefore the largest channel capacity can be achieved.

2-hop VCN can improve the channel capacity compared to the 1-hop CN. Figure 7 shows the cumulative distribution function (CDF) of the channel capacity per user, where the adaptive channel configuration is used and $U/(N_c/N_s)$=0.25. Figure 8 shows the 10% outage channel capacity that satisfies CDF=0.1 as a function of the normalized number of users. It is seen from Fig. 7 that the 2-hop VCN can decrease the probability that the channel capacity is small. As a result, larger channel capacity can be achieved in Fig. 8. The reason is described as follows. The average channel capacity is plotted in Fig. 9 as a function of the distance r from CP to MT normalized by the cell radius. The vertical axis is the average channel capacity when the MT is located within the range from r-0.05 to r+0.05 ($0.05 \leqq r \leqq 0.95$). The 2-hop VCN can improve the channel capacity near the cell boundary compared to 1-hop CN. In the 1-hop CN, users near the cell boundary have a very small channel capacity because of the very weak received signal power. On the other hand, the 2-hop VCN can increase the received signal power near the cell boundary by using multi-hop technique. As a result, larger channel capacity can be obtained.

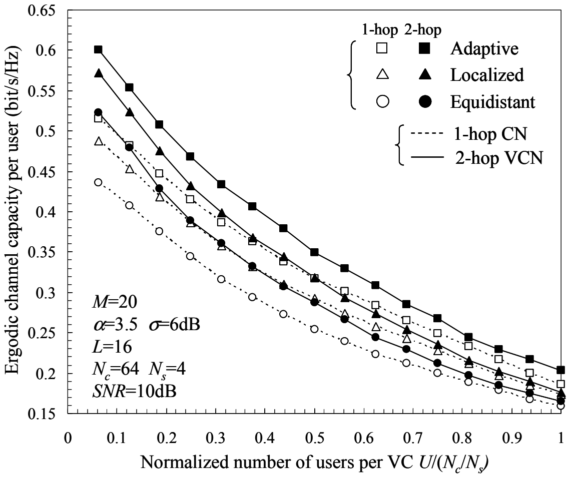


Figure 6. Average channel capacity.

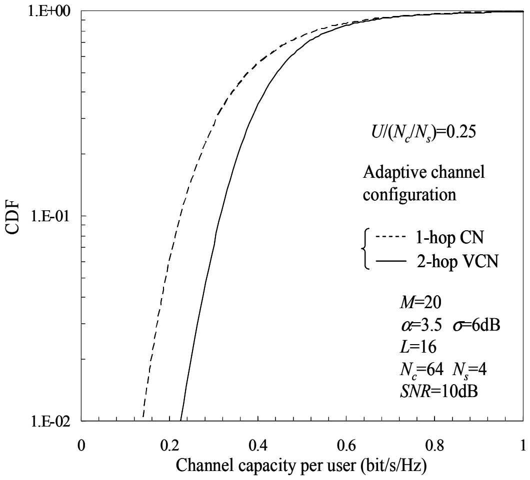


Figure 7. CDF of the channel capacity per user.

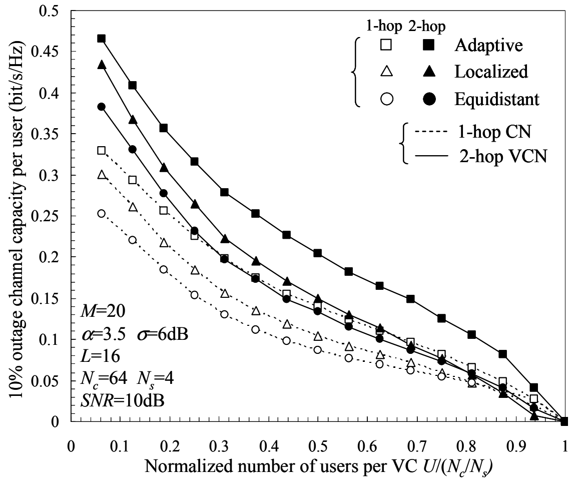


Figure 8. 10% outage channel capacity.

B. Comparison of OFDMA and DS-CDMA

Figure 10 shows the average channel capacity per user of DS-CDMA VCN and OFDMA VCN. Figure 11 shows the 10% outage channel capacity. In OFDMA, the adaptive channel configuration is used. In DS-CDMA, as the number of frequency channels becomes larger, the channel capacity becomes larger. If the number of frequency channels is small, the strong interference which can not be suppressed by processing gain of spreading and de-spreading may be received from the adjacent WP. On the other hand, if the number of frequency channels is large, the probability of allocating the frequency channel avoiding the strong interference increases. OFDMA provides larger channel capacity than DS-CDMA. In OFDMA, the available bandwidth is divided into narrow subcarriers and therefore, OFDMA can allocate the subcarriers with large SINR more flexibly according to the channel condition than DS-CDMA.

IV. CONCLUSIONS

In this paper, we proposed the distributed channel allocation scheme based on the maximization of the SINR of each multi-hop link for downlink 2-hop OFDMA VCN, where CP did not need to collect the SINR information of all multi-hop links. We considered three channel configurations: localized, equidistant and adaptive, and compared the channel capacity. It was shown that the adaptive channel configuration can achieve the highest channel capacity among the localized, equidistant and adaptive channel configurations. We showed that 2-hop VCN can improve the channel capacity compared with 1-hop CN and that the adaptive channel configuration can provide larger channel capacity than DS-CDMA.

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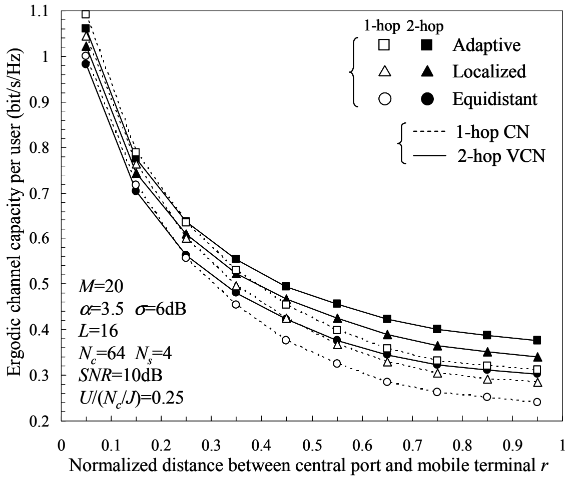

Figure 9. Average channel capacity as a function of the normalized distance from CP to MT.

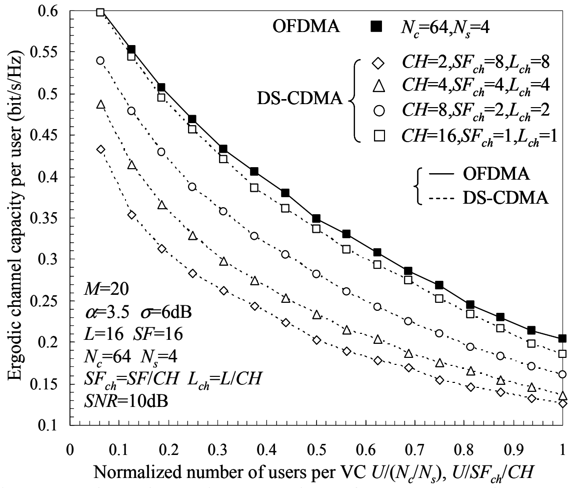

Figure 10. Channel capacity comparison of DS-CDMA and OFDMA.

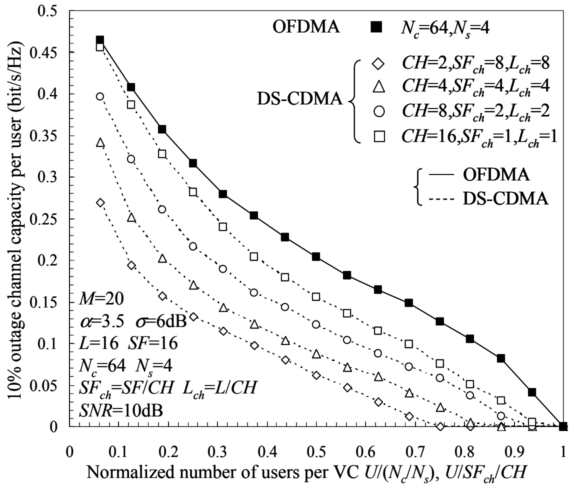

Figure 11. 10% outage channel capacity of DS-CDMA and OFDMA.