PAPER

Blocking Probability of a DS-CDMA Multi-Hop Virtual Cellular Network

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Summary

A wireless multi-hop virtual cellular network (VCN) was recently proposed to avoid the large peak transmit power, resulting from the high transmission rates expected for future mobile communication systems. In VCN, calls hop through several links to reach the central port, which is the gateway to the network. With the use of a routing algorithm based on the total uplink transmit power minimization criterion, the total transmit power of all the multi-hop links between the mobile terminal and the central port can be significantly reduced, in comparison with the present (single-hop) cellular network. In this paper, an "on-demand" channel assignment strategy, using the channel segregation dynamic channel allocation (CS-DCA) algorithm, is proposed for multi-hop DS-CDMA VCN. Computer simulation is conducted to evaluate the blocking probability performance and make a comparison between the VCN and the present cellular network.

Key words:
Virtual cellular network, multi-hop network, channel segregation dynamic channel assignment, blocking probability

1. Introduction

Growing number of wireless users and high data rate multimedia applications with varying QoS requirements for third generation (3G) and beyond wireless systems, are demanding novel wireless communication techniques and network architectures. A multi-hop virtual cellular network (VCN) is one such an architecture, which was proposed [1] to reduce the large peak transmit power, resulting from the high transmission rates expected for mobile communication systems beyond 3G. The multi-hop VCN consists of a central port (CP), which is a gateway to the network, and many distributed wireless ports (WPs), which work as relays used to forward the traffic of the users having poor coverage to the CP. A cluster of distributed WPs acts as one virtual base station (BS).

In 3G mobile communication systems, direct-sequence code division multiple access (DS-CDMA) is adopted as an access technique [2]. DS-CDMA can also be applied to the multi-hop VCN. In DS-CDMA, transmit power control (TPC) is an indispensable technique. However, it may make the transmit power between some WPs and the CP very large. To avoid this, the multi-hop communication [3], [4] was introduced to the VCN [1]. A route construction scheme based on the total transmit power minimization criterion [4], [5], [6] is used to determine the route from each WP to the CP. It was shown in [1] that the transmit power needed for each communication can be significantly decreased in the multi-hop VCN. Decreasing the transmit power may lead to a decreased interference to other users and hence the system capacity may be enlarged.

In the wireless multi-hop VCN, an efficient channel assignment algorithm, to allocate frequency channels to the multi-hop links of each call, is necessary. The problem of dynamic channel assignment (DCA), in the context of cellular networks, has been extensively considered ([7], [8] and other literature). Channel segregation-DCA (CS-DCA) [9], which was proposed for the cellular network, seems to be promising for the multi-hop VCN. In [10], CS-DCA was considered to allocate channels to multi-hop links between the WPs and the CP. In this paper, we consider the channel allocation of the link between the mobile terminal (MT) and the WP as well. If there is no channel available at any link of the multi-hop path, the call is blocked.

In this paper, we propose an on-demand strategy to allocate channels to the multi-hop uplinks between the MT and the CP, using CS-DCA algorithm with some modifications to meet with the wireless constraints in a DS-CDMA VCN (multi-hop downlink study is left for a future work). The rest of this paper is organized as follows. In Sect.2, the multi-hop VCN is briefly described. Then, in Sect.3, we give an analysis and show some computer simulation results concerning the interference in the multi-hop VCN. We present a channel allocation procedure using CS-DCA in Sect.4. In Sect.5, the blocking probability is evaluated by computer simulation. The performance of the multi-hop VCN is compared with that of the present cellular network. Finally, we give some conclusions in Sect.6.

2. Multi-hop VCN Description

The conceptual network structure of the multi-hop VCN is illustrated in Fig.1. Each virtual cell (VC) consists of many distributed WPs and one CP, which is the gateway to the network. All the multi-hop routes from each WP to the CP are decided based on the total transmit power minimization criterion [5], [6].

In the multi-hop uplink, the signal transmitted from the MT is received by its nearest WP. Then, the received signal is relayed to the CP via the constructed route. The major advantage of multi-hopping in the VCN is that it requires lower transmit power than that of (MT-BS) direct link (or single-hop) in the present cellular networks for the same required signal-to-interference plus noise power ratio (SINR). This is because multi-hop routes have short range links to the destination, which leads to low path loss and as a result, lower transmit power is required to achieve the desired signal strength [1]. This can result in reduced co-channel interference, leading to increased system capacity.

In the VCN, a multi-hop call is regarded as a sequence of single hop calls, where the first call arrives on the first link, between an MT and its nearest WP, followed by an arrival on the second link and so on until the last link to the CP. Channels for the multi-hop call can be assigned by repeating the single hop assignment procedure in a sequence over the multi-hop path. Therefore, if there is no channel available at any link of the multi-hop path, the call is blocked.

With using DS-CDMA, the same benefits as in other wireless access schemes such as FDMA and TDMA, including enlargement of area coverage and reduction of transmit power, can be expected. However, if the same frequency band is used for multi-hop transmission, it may be a source of high interference causing the degradation of the system capacity. In order to avoid the interference in the multi-hop links, the available frequency band is divided into several frequency channels and different frequency channels are allocated to the adjacent multi-hop links. In what follows, a channel refers to a frequency channel.

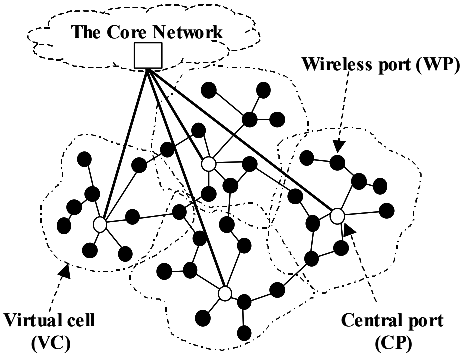


Fig.1 **M**ulti-hop VCN.

3. Interference Power Consideration

In the present DS-CDMA cellular systems, the interference power from other users is the decisive factor in determining the system capacity. If the transmit power is decreased, while keeping the required quality, the interference to other users can be decreased and hence the system capacity can be improved [11]. With using the multi-hop technique in the VCN, we can decrease the transmit power needed for each communication, and hence decrease the interference to other users. However, there are still some other factors determining the system capacity in a multi-hop VCN.

In this section, we will first discuss about the interference power in a multi-hop VCN and make some comparisons with the present cellular network, then, we will discuss some other factors determining the VCN system capacity.

The propagation channel can be modeled as the product of distance dependent path loss, log-normally distributed shadowing loss and multi-path fading [12]. Assuming an *L*-path fading channel with uniform power delay profile, the received power $P^r_{i\_j}$ of the signal transmitted from the WP #*i* and received at the WP #*j* is given by

$$P^r_{i\_j} = P^t_{i\_j} \cdot r_{i\_j}^{-\alpha} \cdot 10^{-\eta_{i\_j}/10} \cdot \sum_{l=0}^{L-1} \left| h_{i\_j}(l) \right|^2 , \qquad (1)$$

where $P^t_{i\_j}$ is the transmit power of the WP #*i,* α is the path loss exponent and r_{i_j} , η_{i_j} and $h_{i\_j}(l)$ are respectively the distance, log normally distributed shadowing loss with the standard deviation σ in dB and the *l*-th (*l*=0~*L*-1) path's complex path gain between the WPs #*i* and #*j*. $\{h_{i\_j}(l);i,j,l\}$ are characterized by time-invariant independent (but location-dependent) complex

Gaussian variables with zero-mean and a variance of $1/L$. Signal-to-noise power ratio (SNR)-based ideal TPC is assumed. The transmit power $P^t_{i\_j}$ is determined as

$$\frac{P^t_{i\_j}}{P_{\text{noise}}} = \Lambda_{\text{target}} \cdot r^{\alpha}_{i\_j} \cdot 10^{\eta_{i\_j}/10} \cdot \left(\sum_{l=0}^{L-1} \left| h_{i\_j}(l) \right|^2 \right)^{-1}, \quad (2)$$

where Λ_{target} is the target SNR and P_{noise} is the noise power.

In the VCN, all the routes from each WP to the CP are constructed based on the total uplink transmit power minimization criterion [5], [6]. Considering the uplink, the signal from an MT in a VC is received by its nearest WP in the same VC, then the signal is relayed via the constructed route from this nearest WP. Fig.2 plots the average transmit power of the MT normalized by that in the present single-hop cellular network, as a function of the number K of WPs per VC, for α=3.5, σ=6dB and L=2. It can be seen that the transmit power of the MT can be reduced significantly compared to the present cellular network. Therefore, obviously the interference from the MT to other users links is decreased compared to the present cellular network. However, as each call has to hop through various links and the channel allocation has to be successful in all the multi-hop links, from the MT to the CP, before the call can be successful, this needs some investigations about the interference from the links between the relaying WPs as well.

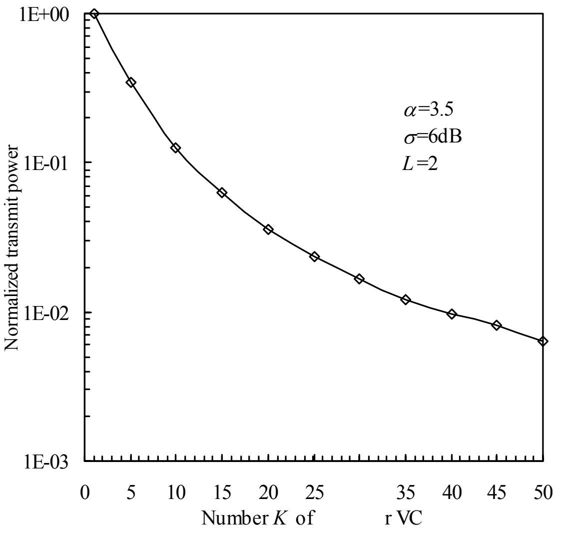


Fig.2 User average normalized transmit power per VC.

As the WPs in the same VC can be close to each other, which might cause high intra-cell interference, so we have made some investigations related to intra-cell interference power between the links connecting two WPs. Fig.3 shows an example of interference caused from a link between two WPs to other similar link. We assume that a channel f_0 is used in the link connecting the WPs #k and #$r(k)$ and that we want to use it also in the link connecting the WPs #i and #$r(i)$. We assume also that $r(i) \neq k$ and $r(k) \neq i$. In this case, the transmitting WP #k may cause interference to the receiving WP #$r(i)$. The interference power can be given as

$$\begin{aligned} I &= P^t_{k\_r(k)} r^{-\alpha}_{k\_r(i)} 10^{-\frac{\eta_{k\_r(i)}}{10}} \sum_{l=0}^{L-1} \left| h_{k\_r(i)} \right|^2 \\ &= \Lambda_{\text{target}} \frac{r^{-\alpha}_{k\_r(i)} 10^{-\frac{\eta_{k-r(i)}}{10}} \sum_{l=0}^{L-1} \left| h_{k\_r(i)} \right|^2}{r^{-\alpha}_{k\_r(k)} 10^{-\frac{\eta_{k\_r(k)}}{10}} \sum_{l=0}^{L-1} \left| h_{k\_r(k)} \right|^2} \quad . (3) \end{aligned}$$

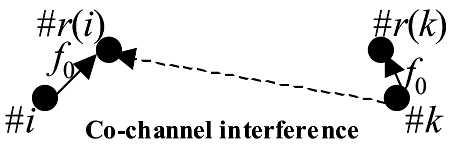


Fig.3 Co-channel interference of a link (WP-WP).

We plot in Fig.4 the cumulative distribution function (cdf) of I normalized by Λ_{target}, for different number N of maximum allowable hops, when K=20, α=3.5, σ=6dB and L=2. We can see that the interference power decreases with the increase of N. This is because the routes from each WP to the CP are constructed based on the total transmit power minimization criterion and increasing N leads to a further decrease in the transmit power of the multi-hop links [1] and hence decreased interference to other links. We can see also that for N>4 the cdf doesn't change much, so we can suggest that the maximum number of allowable hops can be limited to 4 (for similar conditions) in order to avoid unnecessary long time delay.

In Fig.5 we show the impact of the number K of WPs on the cdf of I/Λ_{target}, for N=4, α=3.5, σ=6dB and L=2. Fig.6 plots the average total transmit power of the multi-hop route normalized by the single hop case, as a function of K, for N=4, α=3.5 and σ=6dB and L=2. We can see, from Fig.5, that increasing the number of WPs leads to a further decrease in the interference. This is because, as shown in Fig.6, increasing K decreases more the transmit power of the links and hence decreases the interference to other links.

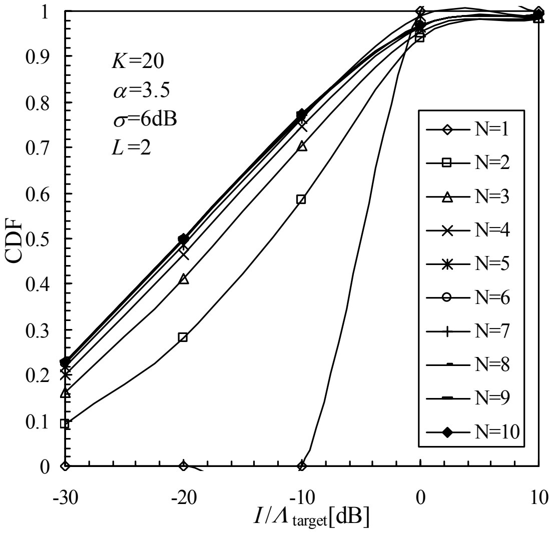


Fig.4 CDF of co-channel interference power of a link (WP-WP) to a similar link.

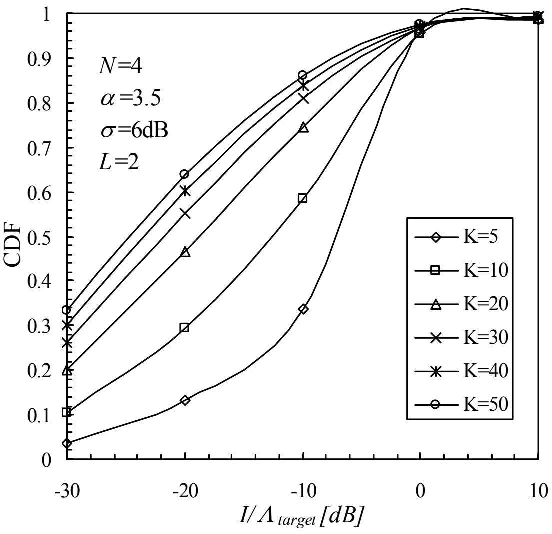


Fig.5 Impact of K on co-channel interference power of a link (WP-WP) to a similar link.

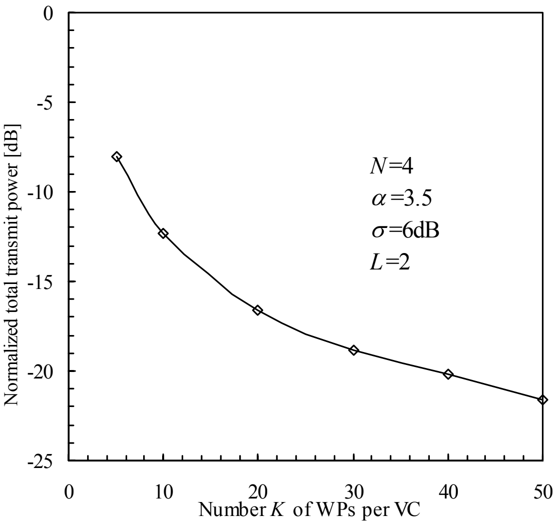


Fig.6 Average normalized total transmit power.

The interference power might be decreased in the multi-hop VCN. However, this factor is not the only one determining the system capacity. As explained before, different channels should be allocated to adjacent links. Therefore, there is a need for several channels to avoid the interference. In the next sections, we will present a channel allocation strategy using the concept of the CS-DCA with some additional conditions to meet the wireless constraints in the multi-hop VCN and also to improve the frequency efficiency. Computer simulation is conducted to evaluate the blocking rate and make comparison with the present cellular network.

4. Application of CS-DCA to Uplink Multi-Hop Communication

We will now address the issue of dynamic channel assignment to the incoming calls in the multi-hop VCN. The problem of dynamic channel assignment has been extensively considered in the context of cellular networks [7], [8]. However, there are significant differences between the two networks. The multi-hop communication imposes additional complexity, as non-conflicting channels must be allocated to the wireless links along the route.

As illustrated in Fig.7, lets consider the data transfer on a link, WP_T - WP_R, using channel f_i. For this link allocation to be successfully made, the following criteria need to be satisfied:

1) WP_T must not receive from any other WP using channel f_i. Otherwise the transmission from WP_T will interfere at WP_T.

2) WP_R must not be involved in any other call transmission in channel f_i. Otherwise the transmission from WP_T will interfere at WP_R.

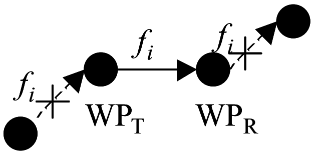


Fig.7 Interference model for an uplink multi-hop transmission.

We consider that the system bandwidth is divided into several frequency channels with different carrier frequencies. One of the available channels is allocated to a link between the MT and its nearest WP or between two adjacent WPs along a multi-hop route. Since DS-CDMA is applied, the same channel can be shared by different multi-hop links. In this case, a link (WP_T-WP_R) can serve multiple calls in the same frequency channel, using different orthogonal spreading codes, if the wireless constraints are satisfied, resulting in an efficient usage of the limited frequency resource.

The construction procedure of the route between each WP and the CP, based on total transmit power minimization criterion [5], [6], is carried out using a control channel having a carrier frequency different from the channels for multi-hop communications. After the whole route between the MT and the CP is decided, the CS-DCA [9], which was proposed for single-hop link calls in the present cellular networks, is applied to assign frequency channels to all the uplinks along the MT-CP path. The single-hop link assignment procedure is repeated in a sequence over the multi-hop path. If there is no channel available at any link of the multi-hop path, the call is blocked.

In CS-DCA, each receiving side WP is equipped with a channel priority table (as in [9]); priority function value and the number of times the channel was checked are listed. Table 1 shows an example of a channel priority table. The channel priority value $P(i)$ is updated each time the channel is checked to show the successful transmission probability on channel i. The WP receiver selects a channel among available ones using its channel priority table. The CS-DCA procedure for one link in the multi-hop communication is as follows.

Step1: For a link (WP_T - WP_R), if a channel f_0 is allocated to the same link in another call, WP_R selects f_0 and measures the SINR. If the measured SINR meets the required quality, the selected channel is allocated and its priority value is increased. Otherwise, the priority value of that channel is decreased and the procedure goes to the next step.

Step2: The WP_R selects the channel with the highest priority among the unchecked channels.

Step3: If the channel is used for transmitting data in another call or is used by the WP_T for reception, the WP_R decreases the priority value of the selected channel and goes back to step2. Otherwise, the procedure goes to the next step.

Step4: The WP_R measures the SINR of the selected channel. If the measured SINR meets the required value, the channel is allocated and its priority value is increased. Otherwise, the priority value of the selected channel is decreased and the procedure goes back to step2.

If the channel allocations for links over the multi-hop route from the MT to the CP are successful, the call is established. Otherwise, the call is blocked.

Table1 An example of channel priority table

Channel index i	Channel priority value $P(i)$	Number of times the channel is accessed $N(i)$
0	0.8	5
1	0.6	8
…	…	…
C-1	0.1	20

5. Computer Simulation

In this section, the blocking probability is evaluated by computer simulation. Comparison between the multi-hop VCN and the present cellular network is given. The impact of different parameters on the blocking probability is also discussed.

5.1 System model

A total of 19 VCs of hexagonal layout (the center VC is the cell of interest) are considered. For a fair comparison, the CP of each VC is set in the middle of the cell. We assume that, the overall network traffic arrival follows a Poisson distribution with a mean arrival rate of λ; the holding time of each call is exponentially distributed with a mean of μ [13]. The offered load G per cell is defined as

$$G=\lambda\mu \quad . (4)$$

The call arrival events are generated before the start of the simulation and are known a priori on the time scale. All these calls go through call admission procedure as it was described in Sect.4.

In CS-DCA, the measurement of the SINR is necessary. The SINR is affected by distance dependent path loss, shadowing loss and multi-path fading. We assume L-path Rayleigh fading with uniform power delay profile. Assuming QPSK data modulation and an ideal SNR-based fast TPC, the required SINR Λ_{target} for a required BER of 10^{-2} (10^{-3}) is given by 7.3dB (9.8dB) [12].

5.2 SINR expression for computer simulation

Using Eqs. (1) and (2) and assuming ideal L-finger coherent Rake combining based on maximum ratio combining (MRC), the SINR after Rake combining at WP #i is given by [10]

$$\lambda = \Lambda_{\text{target}} \sum_{l=0}^{L-1} \lambda_l \quad , (5)$$

where

$$\lambda_l = \frac{\left|h_{i\_j}(l)\right|^2 \Big/ \sum_{l=0}^{L-1}\left|h_{i\_j}(l)\right|^2}{\left(\begin{array}{l} 1+(m+1)\cdot\dfrac{\Lambda_{\text{target}}}{SF}\cdot\left[1-\left|h_{i\_j}(l)\right|^2 \Big/ \sum_{l=0}^{L-1}\left|h_{i\_j}(l)\right|^2\right] \\ +\dfrac{\Lambda_{\text{target}}}{SF}\sum_{\substack{k\\(k,q(k))\neq(i,j)}}\left(\dfrac{r_{k\_j}}{r_{k\_q(k)}}\right)^{-\alpha} 10^{-(\eta_{k\_j}-\eta_{k\_q(k)})/10} \\ \times\dfrac{\sum_{l=0}^{L-1}\left|h_{k\_j}(l)\right|^2}{\sum_{l=0}^{L-1}\left|h_{k\_q(k)}(l)\right|^2} \end{array}\right)} . (6)$$

In Eq.(6), SF is the spreading factor and m is the number of different calls the same link (#i, #j) is being simultaneously used. #$q(k)$ is the index of the receiver WP of the interfering link (#k, #$q(k)$). The second term of the denominator is the own inter-path interference (IPI) and the third term is the interference from other transmitters in other links. Since orthogonal spreading code is assumed, the same path-interference is suppressed. The expression derived above is used for computing the SINR in the computer simulation.

5.3 Simulation results and discussion

First we show in Fig.8 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=4. Other parameters are set as G=4, N=5, SF=16, α=3.5, σ=6dB, and L=2. The CP is located in the middle of the VC. Other 19 WPs, each having omni-directional transmit/receive antenna, are randomly located. We can see that the same channel (e.g., channel#**3**) is reused for many links in the communications resulting in an efficient frequency usage. Also we can see that the same channel (e.g., channel#1 and **2**) is used for the same link (WP-WP) for two different users resulting in efficient frequency usage.

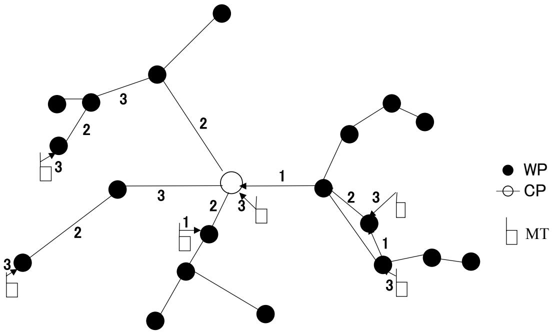
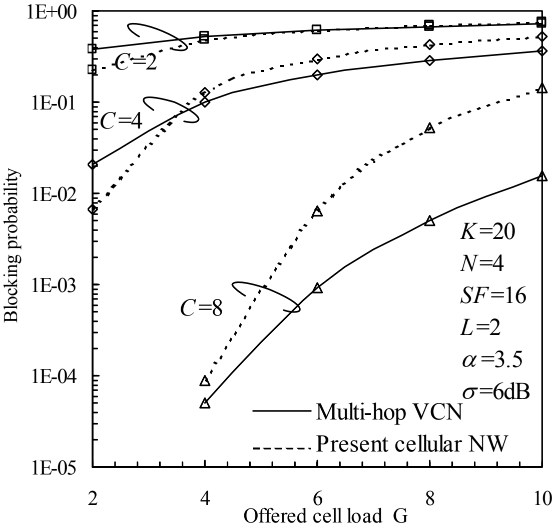


Fig.8 Example of multi-hop calls channel allocation.

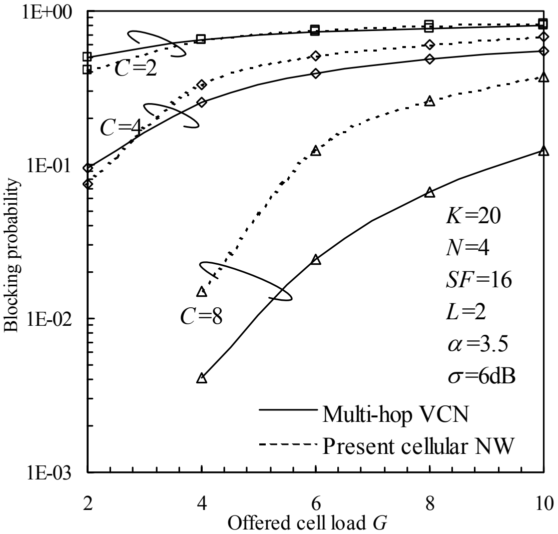
Next, the simulation results for the blocking probability in both the multi-hop VCN and the present DS-CDMA cellular network are presented and discussed. These results are evaluated as a function of the average offered cell load.

(1) Impact of the number of available channels

A comparison of the blocking probabilities of the multi-hop VCN and the present cellular network is shown with C as a parameter in Fig.9 for SF=16, N=4, α=3.5, σ=6dB and L=2. In Fig.9 (a), the required SINR Λ_{target} is assumed to be 7.3dB while in (b) it is 9.8dB. In both cases, we see the same trend of the blocking probabilities of the two networks; it is seen that the performance difference between the two networks depends on C. In high traffic load, the multi-hop VCN performance overcomes the present cellular network. This is because in high traffic load, the large inter-cell interference (from neighboring cells) affects the performance of the present cellular network. However, with using the multi-hop communication, the total transmit power needed for each communication is decreased leading to less interference to neighboring cells. If frequency channels are few like in case of C=2, then the impact of channel exhaustion results in almost equal blocking probability in the multi-hop VCN and the present cellular network. However, as more frequency channels are available, the blocking reduction from multi-hopping is larger as clear from the curves of C=4 and 8. As a consequence, the multi-hop VCN can provide smaller blocking probability while reducing significantly the MT transmit power. The detailed blocking performance in the multi-hop VCN is discussed below.



(a) Δ_{target} =7.3dB.

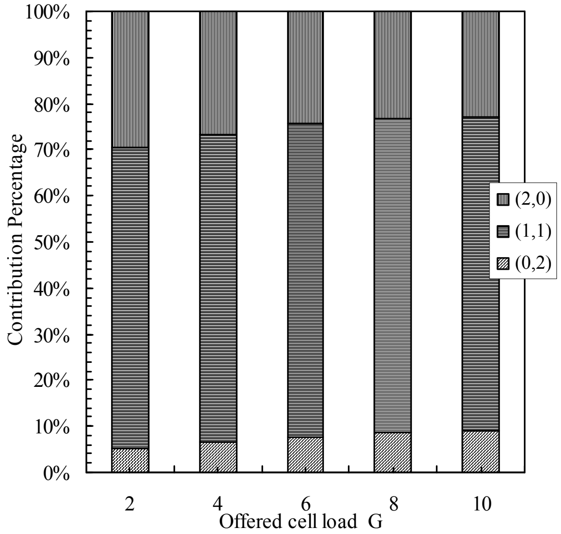


(b) Δ_{target} =9.8dB.

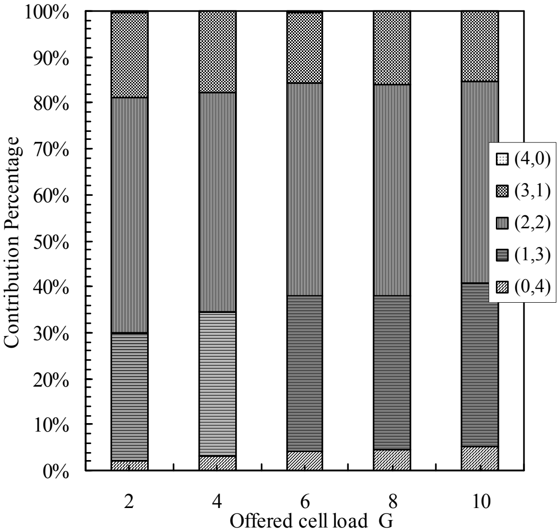
Fig.9 Blocking probabilities of the VCN and the present cellular network (CN) for different number C of available channels.

The blocking in the multi-hop VCN can occur because of two major contributing factors: Poor coverage ($SINR<SINR_{target}$) and unavailability of free channels (because they are used in the adjacent links).

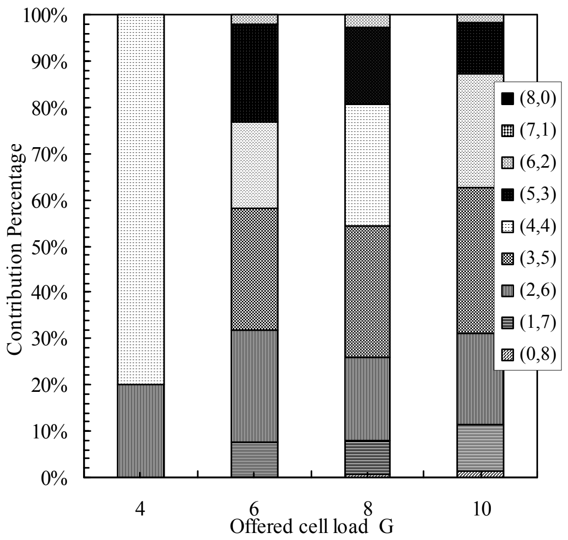
We evaluate in Fig.10 the contribution of these two factors in the multi-hop VCN performances of Fig.9 (a) for C=2,4 and 8 when Δ_{target}=7.3dB, SF=16, N=4, α=3.5, σ=6dB and L=2. Fig.10 gives the contribution percentage of the total blocking calls, where the blocking occurs because n channels are used in the adjacent links and m channels have poor coverage. In Fig.10, n and m explained above are expressed as (n,m) shown on the right of the graphs. It can be seen that the unavailability of many channels, because they are used in the adjacent links, affects the multi-hop VCN performance, which leads to a need to several channels in the multi-hop VCN.



(a) C=2.



(b) C=4.



(c) C=8.

Fig.10 Contribution of different factors in blockings of the multi-hop VCN for different *C*.

(2) Impact of number *K* of WPs per VC.

The impact of number *K* of WPs on the blocking probability is shown in Fig.11 for *C*=8, *N*=4, α=3.5, σ=6dB, *L*=2 and *SF*=16. We can see that as *K* increases, the blocking probability reduces. This is due to further decrease in the transmit power of the multi-hop links and hence less interference on the hops. As *K* increases, the probability to find route with smaller transmit power increases.

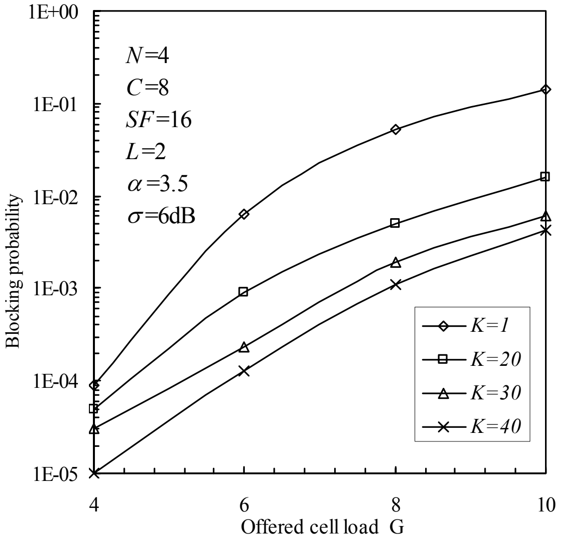


Fig.11 Impact of number *K* of WPs per VC on blocking probability.

(3) Impact of propagation parameters.

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

The impact of α is shown in Fig.12 for *K*=20, *N*=4, *C*=8, σ=6dB, *L*=2 and *SF*=16. We can see that as α increases, the blocking probability decreases. This is due to the decrease in the interference power when α increases.

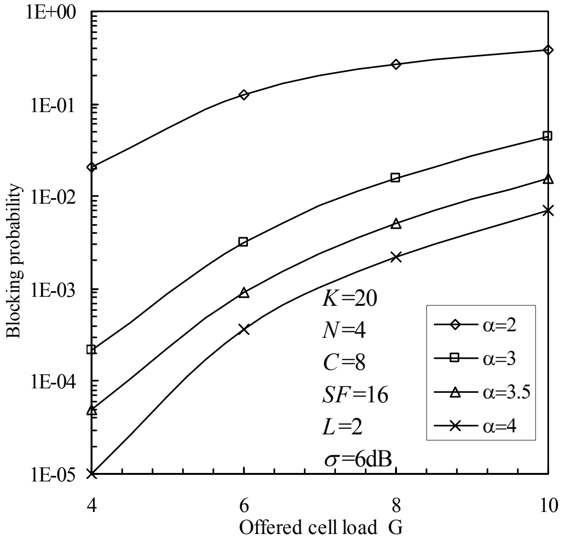


Fig.12 Impact of α on blocking probability.

The impact of σ on the blocking probability is shown in Fig.13 for *K*=20, *N*=4, *C*=8, α=3.5, *L*=2 and *SF*=16. The blocking probability is almost insensitive to σ. Possible reason for this, as already discussed in [10], can be discussed below. Increasing σ means larger variations in the shadowing losses between different links. This can decrease the transmit power of the multi-hop routes from the WPs to the CP, and hence can decrease the interference to other links. Therefore the blocking probability can be decreased. On the other hand, increasing σ may lead to an increase in the interference power and hence increasing the blocking probability. As a consequence, the blocking probability becomes almost insensitive to σ.

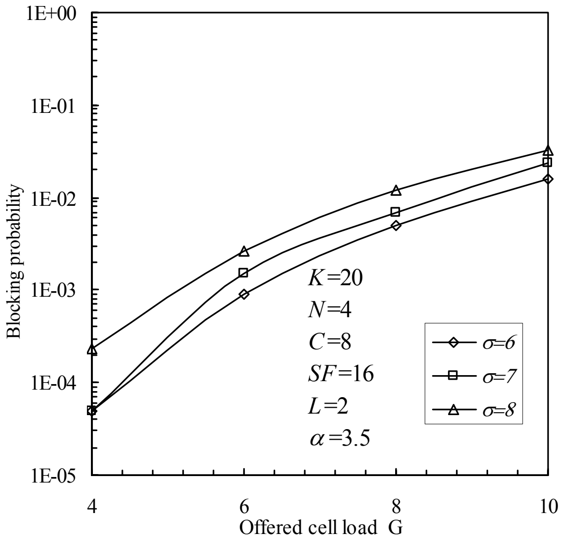


Fig.13 Impact of σ on the blocking probability in the multi-hop VCN.

The impact of the number L of paths on the blocking probability is shown in Fig.14 for $K=20$, $N=4$, $C=8$, $SF=16$, $\alpha=3.5$ and $\sigma=6$dB. We can see that the trend of the blocking probability changes at a certain value of L; this happens when $L=2$. This is because increasing L can increase the path diversity effect obtained by Rake combining and hence the probability of the SINR falling below the required value can decrease. Therefore the blocking probability can decrease. However, as L increases the blocking probability starts to increase due to a high inter-path interference (the first term inside the brackets of the denominator of Eq.(6)).

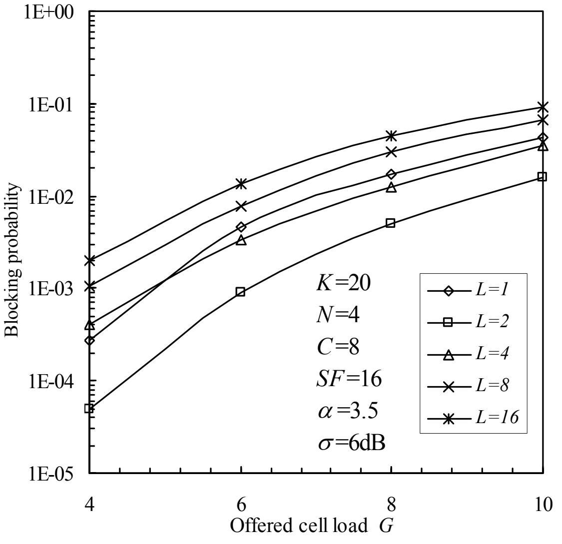


Fig.14 Impact of L on the blocking probability in the multi-hop VCN.

6. Conclusions

In this paper, the blocking probability of DS-CDMA multi-hop virtual cellular network (VCN) was evaluated and the causes behind the call blocking in this network were discussed. An on-demand strategy to assign channels to uplink multi-hop communications in DS-CDMA VCN was proposed. CS-DCA algorithm was used with some additional conditions to meet with the interference constraints of the multi-hop communication. Using computer simulation, comparison between multi-hop VCN and present cellular network blocking probabilities was given.

In high traffic load, due to decreased transmit power in the multi-hop links, the decreased interference leads to less blocking probability compared to present cellular network. The performance difference between the two networks depends on the number of the channels available. Improving the blocking probability performance leads to an increase in the supportable load of the network for the given blocking probability.

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