The 12th International Symposium on Wireless Personal Multimedia Communications (WPMC 2009)

THROUGHPUT AND CHANNEL CAPACITY OF MULTI-HOP VIRTUAL CELLULAR NETWORK

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ABSTRACT

To reduce the transmit power while increasing a transmission data rate, authors proposed a wireless multi-hop virtual cellular network (VCN). Each multi-hop link needs to be allocated a different channel. This means that for the given total number of channels, as the number of hops increases, the number of channels available for each link reduces. However, the signal-to-interference plus noise power ratio (SINR) of each multi-hop link increases since the communication range of each link is shortened. As a consequence, the achievable throughput or channel capacity may not necessarily reduce as the number of hops increases. In this paper, assuming one-dimensional cell layout, the relationship among transmit power, the channel capacity, and throughput in a multi-hop VCN is discussed.

I. INTRODUCTION

In the next generation mobile communication systems, high speed data services are demanded [1]. However, as the data rate increases, an unacceptably high transmit power is required to satisfy the required transmission quality. Otherwise, the coverage area of a base station shrinks. A multi-hop technique is known as one of the techniques to solve this problem [2]~[4]. We have proposed a multi-hop virtual cellular network (VCN) [5, 6]. As illustrated in Figure 1, many stationary wireless ports (WPs) are distributed in each cell and a central port (CP) acts as a gateway to a core network. In VCN, the signal transmitted from a mobile terminal (MT) is received by a nearby WP and relayed via WPs to the CP by the multi-hop technique. The coverage area can be extended while solving the power problem.

As the number of hops increases, the number of channels available for each link reduces. However, the distance between the transmitter and receiver in each wireless link becomes shorter and thus the received signal-to-interference plus noise power ratio (SINR) increases. Therefore, the achievable throughput or channel capacity may not necessarily reduce as the number of hops increases. We have evaluated the frequency reuse distance of 2-hop VCN using selective repeat (SR) ARQ [7]~[9] and shown that the frequency reuse distance for satisfying the required throughput can be reduced in a 2-hop VCN compared to the conventional 1-hop cellular network (CN). In addition to the throughput, the channel capacity is an important factor to compare different wireless networks.

A mobile propagation channel is characterized by multipath fading, shadowing loss, and distance dependent path loss. The same carrier frequency is reused in places where the SINR is larger than the required level. It is not easy to analytically evaluate the relationship among transmit power, the channel capacity, and throughput under such a complex mobile propagation environment. In this paper, we assume a simple multi-hop VCN model using one-dimensional cell layout and evaluate the relationship among transmit power, throughput, and channel capacity.

The remainder of this paper is organized as follows. Sect. II introduces one-dimensional cell layout. The channel capacity expression is derived in Sect. III and the throughput expression is derived in Sect. IV. Sect. V numerically evaluates the channel capacity and throughput. Some conclusions are offered in Sect. VI.

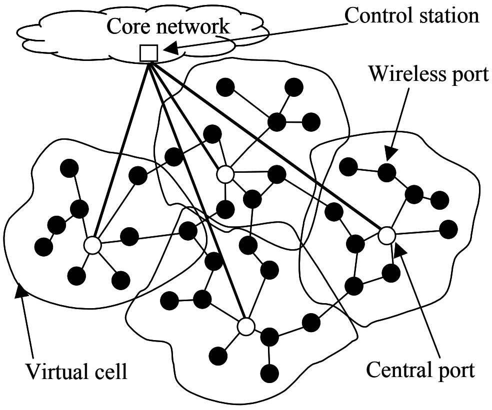


Fig.1 Multi-hop VCN.

II. ONE-DIMENSIONAL CELL LAYOUT

We consider one-dimensional K-hop VCN in which all WPs are arranged along a line as shown in Figure 2, where R denotes the distance between CP and MT and D denotes the distance between nearest co-channel VCs.

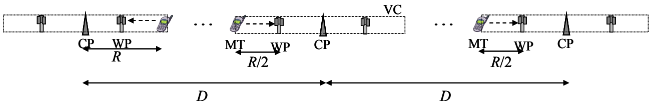


Fig. 2 One-dimensional multi-hop VCN (K=2).

III. CHANNEL CAPACITY

For simplicity, multipath fading and shadowing loss are not considered in this paper. The distance dependent path loss with a pathloss exponent α is considered only. Denoting the transmit power of each WP and an MT, the noise power density, and the available total bandwidth by P_t, N_0, and W, respectively. For a K-hop VCN, the total bandwidth is divided into K blocks, and each frequency block of bandwidth W/K is allocated to each multi-hop link. The received SINR γ_K in each multi-hop link when all MTs are allocated at cell edge and the interference power becomes maximum is given by

$$\gamma_K = \frac{K^{\alpha}}{\frac{1}{K}\left(\frac{P_t r_0^{-\alpha}}{WN_0}\right)^{-1} + \sum_{i=1}^{\infty}\left(\frac{iD}{R}+\frac{1}{K}-2\right)^{-\alpha} + \sum_{i=1}^{\infty}\left(\frac{iD}{R}-\frac{1}{K}\right)^{-\alpha}} . \tag{1}$$

The channel capacity C (bps/Hz) [11] is given by

$$C = \frac{1}{K}\left(\frac{D}{R}\right)^{-1}\log_2(1+\gamma_k) . \tag{2}$$

IV. THROUGHPUT

The error control is an indispensable technique in packet transmission. In this paper, an SR-ARQ with ideal error detection is assumed. In the SR-ARQ, only a packet which is erroneously received by the CP is retransmitted. We assume a total of J packets of M bits/packet are transmitted. The throughput is defined as (MJ bits)/(the mean duration between the initial packet transmission and the successful reception of all packets). In K-hop VCN, since the total bandwidth is divided into K blocks, the packet duration T_K in time becomes K times as long as that of conventional 1-hop, T_1, and is given by

$$T_K = KT_1 . \tag{3}$$

The user throughput s of K-hop VCN is given by

$$s = \frac{MJ}{KT_1}\frac{1}{\sum_{i=0}^{\infty}(J+K-1+i)P(i)} , \tag{4}$$

where $P(i)$ is the probability that the packet transmission duration is $(J+K-1+i)KT_1$. Since the same frequency block is reused in WPs each separated by the reuse distance D, system throughput S is D/R times lower than the user throughput s and given by

$$S = \left(\frac{D}{R}\right)^{-1}\frac{MJ}{KT_1}\frac{1}{\sum_{i=0}^{\infty}(J+K-1+i)P(i)} . \tag{5}$$

To evaluate the throughput, we need $P(i)$.

Assuming that received SINR stays constant during the packet transmission, the average packet error rate p is given by

$$p = 1-[1-p_b]^M , \tag{6}$$

where p_b is the average bit error rate (BER). Assuming quadrature phase shift keying (QPSK) coherent detection and a Gaussian approximation of the interference, p_b is given by [11]

$$p_b = \frac{1}{2}erfc\sqrt{\frac{\gamma_K}{2}} , \tag{7}$$

where $erfc(x) = (2/\sqrt{\pi})\int_x^{\infty} e^{-t^2}dt$ is the complementary error function. $P(i)$ in Eq. (4) can be evaluated by Monte Carlo computation method using the packet error rate obtained by Eqs. (1), (6), and (7).

V. NUMERICAL EVALUATION

The two nearest interfering VCs are considered. Figure 3 plots the channel capacity as a function of a transmit power. Figure 3(a) and (b) show the cases of D/R=5 and D/R=4, respectively. It is seen from Figure 3(a) that if high transmit power is allowed and the frequency reuse distance is long, 1-hop CN provides the largest channel capacity, since the available frequency bandwidth for each wireless link becomes maximum. However, the multi-hop VCN achieves larger channel capacity than the 1-hop CN if low transmit power is only allowed. It is also seen from Figure 3(b) that multi-hop VCN achieves larger capacity than 1-hop if short frequency reuse distance is allowed. The reason for this is because, if the allowable transmit power is low or the frequency reuse distance is short, the distance between the transmitter and receiver is too long in the 1-hop CN to obtain the enough received SINR.

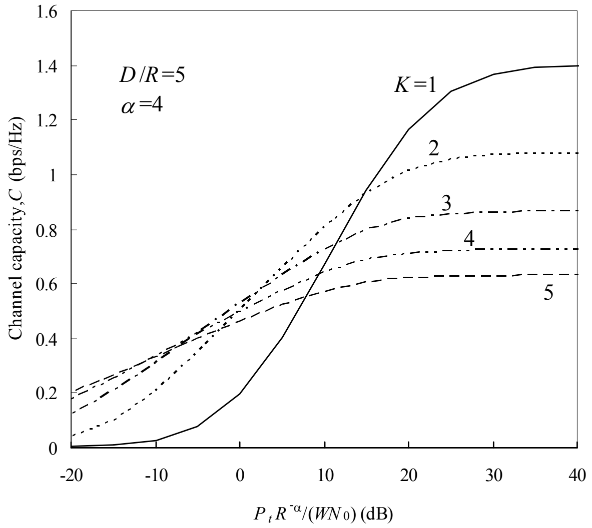
As K increases, the received SINR increases, but the bandwidth of each multi-hop link reduces. Therefore, there exists the optimum value in K that maximizes the channel capacity. The optimum K is discussed below. Eq. (2) can be rewritten as

$$C = \frac{1}{K}\left(\frac{D}{R}\right)^{-1}\log_2\left(1+\left(\frac{P_t R^{-\alpha}}{WN_0}\right)K^{\alpha+1}\right), \tag{8}$$

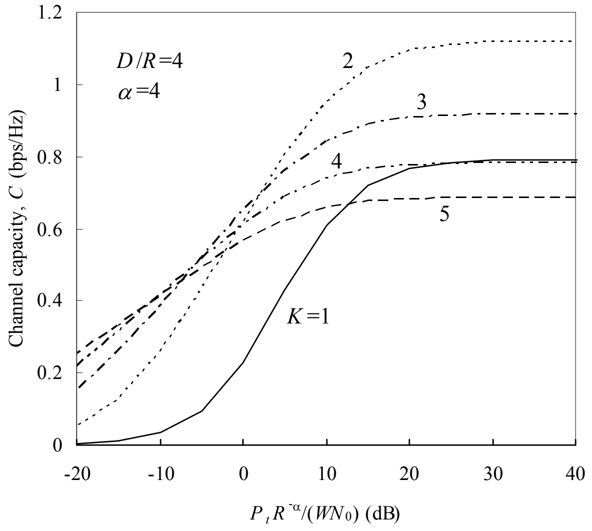
To find the optimum K, we obtain $\partial C/\partial K$ as

$$\frac{\partial C}{\partial K}=\frac{1}{K}\left(\frac{D}{R}\right)^{-1}\left\{\begin{array}{l}-\dfrac{1}{K}\log_2\left(1+\left(\dfrac{P_tR^{-\alpha}}{WN_0}\right)K^{\alpha+1}\right)\\[2ex]+\dfrac{(\alpha+1)\left(\dfrac{P_tR^{-\alpha}}{WN_0}\right)K^{\alpha}}{1+\left(\dfrac{P_tR^{-\alpha}}{WN_0}\right)K^{\alpha+1}}\log_e 2\end{array}\right\}\tag{9}$$

By solving $\partial C/\partial K=0$ and remembering that K is an integer, the optimum K is obtained. When $P_tR^{-\alpha}/WN_0=5\text{dB}$, K=2 is found to be optimum.



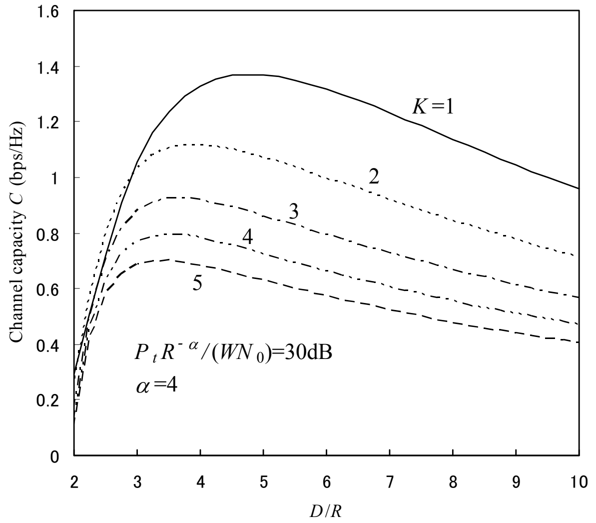
(a)D/R=5



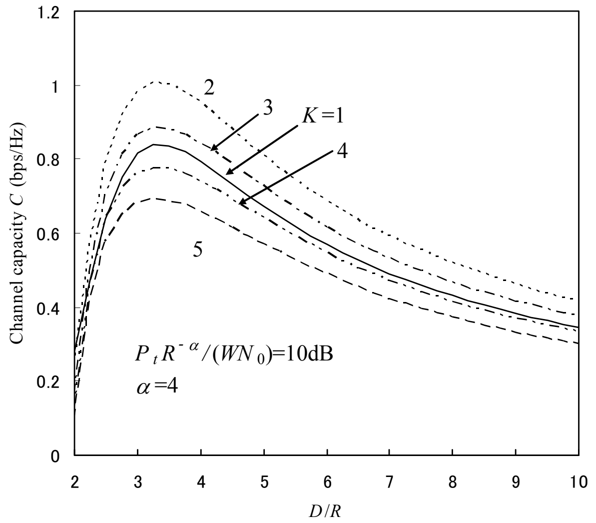
(b) D/R=4

Fig. 3 Channel capacity vs transmit power.

Figure 4 shows the channel capacity as a function of the frequency reuse distance. Figures 4(a) and (b) are the cases of $P_tR^{-\alpha}/WN_0=30\text{dB}$ and 10dB, respectively. It is seen from Figure 4(a) that as K increases, the optimum frequency reuse distance that maximizes the channel capacity decreases. The reason for this is because, as K increases, the distance between the transmitter and receiver becomes shorter and the received SINR increases. It is also seen from Figure 4(b) that the multi-hop VCN achieves larger channel capacity than 1-hop CN for the low transmit power case. The reason for this is because, if the allowable transmit power is low, the distance between the transmitter and receiver is too long in the 1-hop CN to obtain the enough received SINR.



(a)$P_tR^{-\alpha}/(WN_0)$=30dB



(b) $P_tR^{-\alpha}/(WN_0)$=10dB

Fig. 4 Channel capacity vs frequency reuse distance.

From Figure 4, the relationship among the maximum channel capacity, the optimum *K*, and the frequency reuse distance *D*/*R* is found for the given transmit power. Figure 5 plots the maximum channel capacity as a function of the transmit power. For comparison, the 1-hop case is also plotted. In this figure, a combination of the optimum *K* and *D*/*R* to obtain the maximum channel capacity is shown. The channel capacity can be maximized by the 1-hop CN, but very high transmit power is required. As the allowable transmit power reduces, the optimum *K* increases. The reason for this is discussed below. When high transmit power is allowed, the 1-hop can use the frequency bandwidth most widely for each wireless link and can obtain the largest channel capacity. However, if the transmit power should be lowered, 1-hop CN cannot obtain the enough received SINR since the distance between the transmitter and receiver is too long. As *K* increases, the distance between the transmitter and receiver is shortened and the received SNR increases. This increases the channel capacity. When *W*=5MHz and $P_tR^{-\alpha}/WN_0 = 20\text{dB}$, the achievable maximum channel capacity is 1.2bps/Hz when *K*=1. Let's increase the transmit data rate while keeping the transmit power the same. If *W*=200MHz is used, we have $P_tR^{-\alpha}/WN_0 = 4\text{dB}$ and the achievable maximum channel capacity is 0.91bps/Hz when *K*=2. If *K*=1 (1-hop CN) is used, the channel capacity reduces to 0.56bps/Hz.

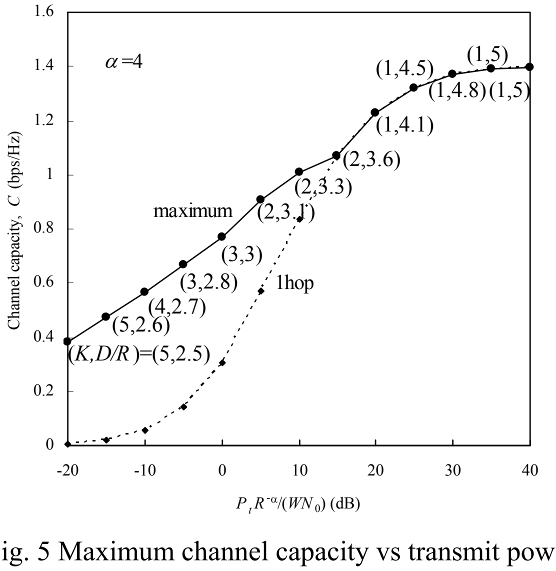
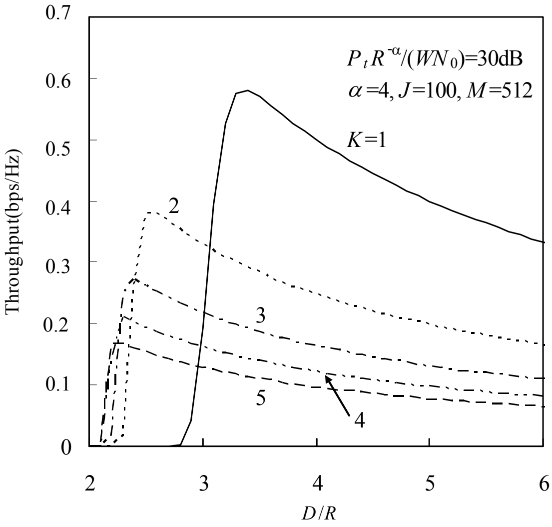
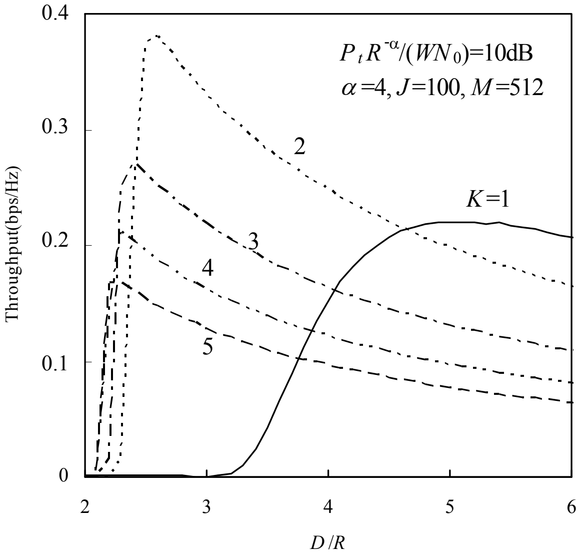


Fig. 5 Maximum channel capacity vs transmit power.

Figure 6 shows throughput as a function of the frequency reuse distance. Figure 6(a) and (b) are the cases of $P_tR^{-\alpha}/WN_0 = 30\text{dB}$ and 10dB, respectively. It is also seen from Figure 6 that the optimum value exists in the frequency reuse distance which maximizes the throughput similar to the channel capacity. It is seen from Figure 6(b) that 1-hop CN cannot achieve maximum throughput if the allowable transmit power is low. This is because the distance between the transmitter and receiver is too long for a 1-hop CN to obtain enough received SINR.



(a)$P_tR^{-\alpha}/(WN_0)$=30dB



(b) $P_tR^{-\alpha}/(WN_0)$=10dB

Fig.6 Throughput vs frequency reuse distance.

The combination of optimum *K* and *D*/*R* for the given transmit power is found from Figure 6. Figure 7 plots the maximum throughput as a function of the transmit power. For comparison, the 1-hop CN case is also plotted. The combination of the optimum *K* and *D*/*R* is shown in this figure. Similar to the case of the channel capacity, *K*=1 (1-hop CN) achieves the maximum throughput if high transmit power is allowed. However, the optimum *K* increases as the allowable transmit power reduces. For example, in the case of *W*=5MHz, the maximum throughput 2.8Mbps (0.56bps/Hz) is obtained when *K*=1 if $P_t R^{-\alpha} \big/ WN_0 = 20\text{dB}$. We want to increase the transmit data rate while keeping the same transmit power. Let's assume W=200MHz. The maximum throughput is 76Mbps (0.38bps/Hz) when K=2 if the transmit power is relatively small, i.e., $P_t R^{-\alpha} \big/ WN_0 = 4\text{dB}$. If K=1 (1-hop CN) is used, the throughput reduces to 0 because the distance between the transmitter and receiver is too long to obtain the enough received SINR.

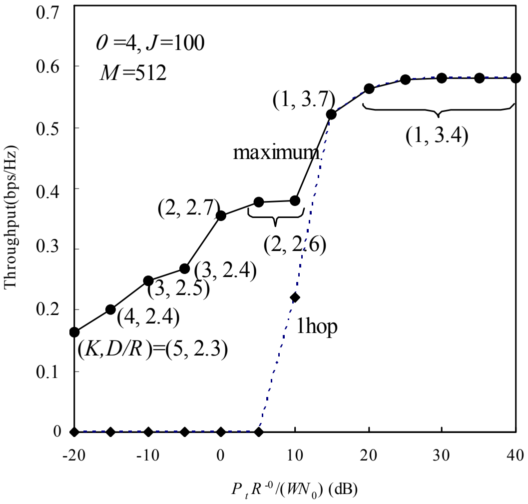


Fig.7 Maximum throughput vs transmit power.

VI. CONCLUSION

In this paper, the relationship among the transmit power, the channel capacity and the throughput was discussed assuming a simple one-dimensional cell layout for the multi-hop VCN. It was shown that if sufficiently high transmit power is allowed, the use of K=1 (1-hop CN) provides the largest channel capacity and throughput, however, if the transmit power is not sufficient, the use of multi-hop relay can maximize the throughput and capacity.

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