Channel Capacity of Parallel Relaying 2-hop OFDMA Virtual Cellular Network

Hitoshi ISHIDA [†], Eisuke KUDOH [‡], *Member*, *IEEE* and Fumiyuki ADACHI [‡], *Fellow*, *IEEE*
Dept. of Electrical and Communications Engineering, Graduate School of Engineering, Tohoku University
6-6-05 Aza-Aoba, Aramaki, Sendai, 980-8579 Japan
[†] ishida@mobile.ecei.tohoku.ac.jp [‡] {kudoh, adachi}@ecei.tohoku.ac.jp

Abstract— **In the next generation mobile communication systems, high speed data services are expected. However, an unacceptably high transmit power is required. Multi-hop technique can solve this problem. In this paper, we propose a parallel relaying scheme using orthogonal frequency division multiple access (OFDMA), in which the multiple parallel logical routes (one subcarrier is allocated to each link of a logical route) are constructed between a mobile terminal and a base station. Collective construction method, which examines all possible logical routes defined by a physical route and subcarriers to each link along the physical route and selects the best logical route having the maximum channel capacity, requires a prohibitively high complexity. Therefore, we propose a successive construction method. We evaluate the channel capacity of the proposed parallel relaying scheme and compare it with cooperative diversity scheme and also with the conventional single hop network.**

Keywords-component; Virtual cellular network, Subcarrier allocation, Route construction, Parallel relaying, Cooperative diversity, Channel capacity, OFDMA

I. INTRODUCTION

In the next generation mobile communication systems, high speed data services are demanded. However, as the data transmission rate becomes higher, 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 [1, 2]. We have proposed a multi-hop virtual cellular network (VCN), as illustrated in Figure 1, for the next generation mobile networks [3, 4]. In VCN, the signal transmitted from a mobile terminal (MT) is received by distributed stationary wireless ports (WPs) and relayed to a central port (CP), which acts as a gateway to the core network. The coverage area can be extended while solving the power problem. In the first stage of the migration from conventional single-hop CN to multi-hop VCN, the number of hops can be limited to two.

Orthogonal frequency division multiple access (OFDMA) can be applied to multi-hop communication [5,6]. For the given multi-hop route, OFDMA subcarrier allocation schemes are considered in [5,6]. In this paper, we propose a parallel relaying scheme using OFDMA, in which the multiple parallel routes (one subcarrier is allocated to each link of logical routes) are constructed between an MT and a CP. In parallel relaying scheme, route construction and subcarrier allocation are done simultaneously to achieve route diversity gain and frequency diversity gain, and thus to efficiently reduce the transmit power and improve the transmission performance.

In order to maximize the channel capacity, it is necessary to search the best set of a route and subcarriers allocated to each link over the route. However, an extensive search is needed. In this paper, we propose a successive construction method. The proposed successive construction method is compared with collective construction method which examines all possible combinations of routes and subcarriers. We evaluate the channel capacity of parallel relaying scheme and compared it with the cooperative diversity scheme [7-9] and conventional single-hop network.

The remainder of this paper is organized as follows. Sect. II proposes a parallel relaying scheme and proposes a collective construction method and a successive construction method. Sect. III derives a mathematical expression for the channel capacity. Sect. IV evaluates the channel capacity. Sect. V gives some conclusions.

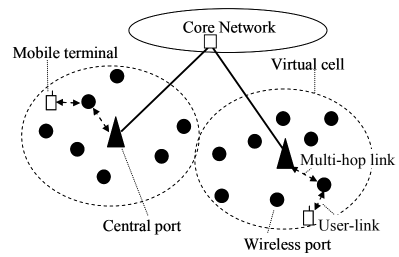

Fig.1 2-hop Virtual Cellular Network (VCN)

II. OFDMA PARALLEL RELAYING SCHEME

In the parallel relaying scheme, different data streams are simultaneously transmitted via multiple logical routes unlike cooperative diversity scheme. In this paper, we consider down link transmission. We assume frequency division duplex (FDD). Fig. 2 shows the parallel relaying concept. Here, N_c is the number of OFDMA subcarriers and M is the number of WPs. Since there are M 2-hop routes ($R1$~RM) and one direct route ($R0$), a total of M+1 physical routes exist. Logical routes are constructed over M+1 physical routes. Each logical route is defined by a set of a physical route and subcarriers allocated to each link over the physical route. One subcarrier is allocated to each link along the logical route.

Transmitting data stream of an MT is divided into N_d data streams. Each data stream is transmitted via one of N_d logical routes. In Figure 2, the number of logical routes is 4 (N_d=4) while the number of physical routes is 3 (M=2). The channel gains of all subcarriers associated with all links are measured, and the different subcarrier is selected for each link over the logical route to avoid interference.

As shown in Figure 2, the data stream $\{d_0\}$ is transmitted via the 0th logical route, which is constructed by using the physical route $R1$ via WP1. Subcarriers #0 and #1 are assigned to the first hop link (CP-WP) and the second hop link (WP-MT), respectively. The data stream $\{d_2\}$ is transmitted via the 2nd logical route. The 2nd logical route is constructed by using the physical route $R2$ via WP2. Subcarriers #4 and #7 are assigned to the first and the second links, respectively. It is necessary for CP to collect channel information of all OFDMA subcarriers on all links and to search the best combination of physical route and subcarriers for each logical route. In this paper, we propose a collective construction method and a successive construction method.

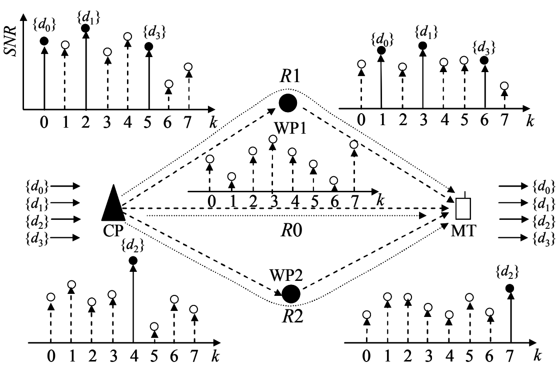

Fig. 2 Parallel relaying concept.

A. Collective construction method

For the collective construction method, the channel capacities of all possible realizations for N_d parallel logical routes are examined. Table 1 shows an example of the constructed logical routes. For example, the data stream $\{d_1\}$ is transmitted via the 1st logical route that uses physical route $R2$ and subcarrier #2 and #4. The number N_F of combinations to be examined is given by

$$N_F = \sum_{i=0}^{N_d} \frac{M^{N_d - i} \cdot N_c!}{(N_c - 2N_d + i)!(N_d - i)!i!} \quad . \tag{1}$$

Figure 3 shows N_F as a function of N_c when $N_d/N_c = 0.5$. It is seen that the collective construction method requires prohibitively high complexity.

Table 1 An example of constructed logical routes

Data stream		$\{d_0\}$		$\{d_1\}$		$\{d_2\}$		$\{d_3\}$	
Logical route		$L0$		$L1$		$L2$		$L3$	
Physical route		$R0$		$R2$		$R1$		$R1$	
Subcarrier									
1st hop link	2nd hop link	#4		#2	#4	#3	#5	#1	#6

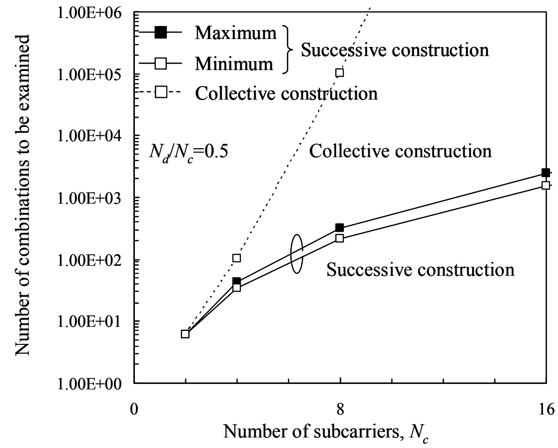

Figure 3 Number of searching for collective construction and successive construction.

B. Successive construction method

Two-step procedure of proposed successive construction method is described below.

(Step 1) The channel capacities for all possible combinations of the physical route and subcarriers are calculated and the optimum combination that maximizes the channel capacity is used for the present logical route.

(Step 2) If the number of constructed logical routes is less than N_d, the used subcarriers are removed from the candidates and then go to step 1 to search for the best combination of the physical route and subcarriers for the next logical route.

The successive construction method constructs the logical routes one by one, while the collective construction method constructs simultaneously all logical routes. The achievable channel capacity using the successive construction method is lower than that using the collective construction method. However, the number of combinations to be examined is much smaller for the successive construction method than for the collective construction method. For the successive construction method, the number of combinations to be examined is maximal when all logical routes use a direct (1-hop) physical route. In this case, only one subcarrier is removed from the candidates to be examined in step 2. Therefore, the maximum number $N_S^{\max}$ of combinations to be examined is given by

$$N_S^{\max} = \sum_{i=0}^{N_d - 1} \left\{ (N_c - i) + \frac{M \cdot (N_c - i)!}{(N_c - i - 2)!} \right\} \quad . \tag{2}$$

The first and second terms in {.} denote the number of combinations to be examined using direct physical route and number M of 2-hop physical routes, respectively.

On the other hand, the number of combinations to be examined is minimal when all logical routes use 2-hop physical route. In this case, two subcarriers are removed from the candidates to be examined in step 2. Therefore, the minimum number $N_S^{\min}$ of combinations to be examined is given by

$$N_S^{\min} = \sum_{i=0}^{N_d-1}\left\{(N_c-2i)+\frac{M\cdot(N_c-2i)!}{(N_c-2i-2)!}\right\} \quad . \tag{3}$$

Figure 3 plots the number of combinations to be examined for the successive construction method. It is seen from this figure that the successive construction method can significantly reduce the number of combinations to be examined compared with the collective construction method as the number N_c of subcarriers increases.

III. Numerical Expression of Channel Capacity

A. Parallel relaying scheme

In the parallel relaying scheme using N_d parallel logical routes, the channel capacity per user is given by [10]

$$C=\frac{1}{N_c}\sum_{d=0}^{N_d-1}\log_2\{1+SNR(L_d)\} \quad , \tag{4}$$

where $SNR(L_d)$ is the effective received signal-to-noise power ratio along the L_d-th logical route and given by

$$SNR(L_d)=\begin{cases} SNR_{CP-MT}(k_{L_d,1}) & if\ direct\ route \\ \min\{SNR_{CP-WP(L_d)}(k_{L_d,1}), SNR_{WP(L_d)-MT}(k_{L_d,2})\} & else \end{cases}, \tag{5}$$

where $\mathrm{WP}(L_d)$ is WP belonging to the L_d-th logical route. $k_{Ld,1}$ and $k_{Ld,2}$ are the subcarrier indices allocated to the first and second links, respectively. $SNR_{\text{CP-}MT}(k)$, $SNR_{\text{CP-WP}(Ld)}(k)$, and $SNR_{\text{WP}(Ld)\text{-MT}}(k)$ are the received SNRs of the k-th subcarrier between CP-MT, CP-WP(L_d), and WP (L_d)-MT, respectively.

The propagation environment is modeled as the product of the distance dependent pathloss, log-normally distributed shadowing loss and the multipath fading. In this paper, we consider an L-path frequency-selective Rayleigh fading channel having a uniform power delay profile. The received SNR at WPj (or MT) from WPi is given by

$$SNR_{i-j}(k)=\frac{P_t}{N_d HN} r_{i-j}^{-\alpha} 10^{-\eta_{i-j}/10}\left|H_{i-j}(k)\right|^2 \quad , \tag{6}$$

where P_t is the total transmit power along all parallel routes, H is the number of hops, N is the noise power per subcarrier, α is the pathloss exponent, and $r_{i\text{-}j}$, $\eta_{i\text{-}j}$, and $H_{i\text{-}j}(k)$ are distance, shadowing loss, and channel gain between WPi and WPj (or MT), respectively.

B. Cooperative diversity scheme

We consider a cooperative diversity scheme using time division duplex (TDD) relaying. In the first time-slot, CP transmits a signal to WPs. In the second time-slot, each WP relays the received signal to MT. MT combines all received signals based on maximum ratio diversity combining. The channel capacity of cooperative diversity scheme is given by [11]

$$C=\frac{1}{2}\min\left\{C_{WP}^{\min}, C_{MT}\right\} \quad , \tag{7}$$

where C_{MT} is the channel capacity of WP-MT link and $C_{WP}^{\min}$ is the minimum channel capacity among all possible CP-WP links. $C_{WP}^{\min}$ is given by

$$C_{WP}^{\min}=\min_{m\in\{1,2,\cdots M\}}(C_m) \quad . \tag{8}$$

Here, C_{MT} and C_m are given by

$$\begin{cases} C_{MT}=\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}\log_2\left(1+\frac{P_t}{N_c N}\sum_{m=1}^{M} r_{WP(m)-MT}^{-\alpha}10^{-\eta_{WP(m)-MT}/10}\left|H_{m-MT}(k)\right|^2\right) \\ C_m=\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}\log_2\left(1+\frac{P_t}{N_c N} r_{CP-WP(m)}^{-\alpha}10^{-\eta_{CP-WP(m)}/10}\left|H_{CP-WP(m)}(k)\right|^2\right) \end{cases}. \tag{9}$$

IV. Computer Simulation

The channel capacity was evaluated by the computer simulation. Figure 4 illustrates the system model. For simplicity in this study, single user environment is assumed. There is the number M of WPs. The distance between each WP and CP is r ($0<r/r_0<1$), where r_0 is the distance between CP and MT. Assuming that WPs are closer each other and their distance is much shorter than r_0, the distance between WP and MT is r_0-r . Each link is assumed to be suffered from independent shadowing loss. We assume an L=8-path channel and the pathloss exponent α=3.5.

As the number N_c of subcarriers increases, the number of combinations to be examined for collective construction method rapidly increases. If N_c is too large, the available subcarriers can be divided into several subcarrier blocks and the logical route construction method is applied to each subcarrier block. Below, we assume N_c=8 and N_d=4. CP transmits data streams using all subcarriers in the cases of conventional single-hop communication and cooperative diversity scheme. Since 2-hop communication is applied, the maximum number of transmitting data streams of parallel relaying scheme and cooperative diversity scheme is half the single-hop communication.

Transmit power of CP that gives the average received signal-to-noise power ratio (SNR) of 0dB at the cell edge is denoted by P_0, i.e.,

$$\frac{P_0 r_0^{-\alpha}}{N_c N} = 1 \ . \qquad (10)$$

The same total transmit power P_t normalized by P_0 is assumed for the parallel relaying scheme, cooperative diversity scheme, and single-hop communication.

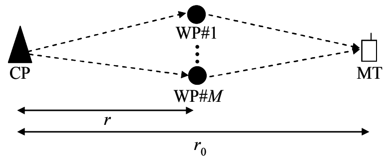

Figure 4 System model.

Figure 5 plots the ergodic channel capacity as a function of the normalized total transmit power P_t/P_0 when the standard deviation of the shadowing loss is σ=0dB, the pathloss exponent is α=3.5, the number of WPs is M=2, and the normalized distance r/r_0=0.5. It is seen that the parallel relaying scheme can achieve the larger channel capacity compared with the single-hop communication when the transmit power is kept small. This is because that the multi-hop communication using parallel relaying scheme can significantly improve the SNR. However, since the parallel relaying scheme requires two subcarriers to transmit one data stream, the maximum number of logical routes is N_d=N_c/2. Therefore, the maximum number of transmitting data streams for a parallel relaying scheme reduces to a half for single-hop communications. If the transmit power is large enough, the single-hop communication can achieve higher channel capacity than the two-hop communication.

It is seen from Figure 5 that the parallel relaying scheme can increase the channel capacity compared with the cooperative diversity scheme. The reason for this is discussed below.

Figure 6 shows the probability density function (pdf) of the channel capacity per user of the first hop link (between CP and WP) and the second hop link (between WP and MT) when P_t/P_0=10dB. For the parallel relaying scheme, successive construction method is used. It is seen that in cooperative diversity scheme, the channel capacity of the first hop link is smaller than the second hop link which uses the maximal ratio combining and therefore the first link limits the channel capacity. On the other hand, in the parallel relaying scheme, the channel capacity is almost the same for the first hop link and the second hop link, since the frequency diversity gain through the subcarrier selection and the route diversity gain through the relay route selection can be achieved for both links. As a result, the parallel relaying scheme can achieve a larger channel capacity than the cooperative diversity scheme.

It is also seen from Figure 5 that the successive construction method can achieve almost the same channel capacity as the collective construction method. The reason for this is discussed below. Figure 7 shows the probability density function of the channel capacity of each logical route for N_d=4. Here, four parallel routes are indexed in the descending order. For the successive construction method, the first constructed logical route (max route) achieves the largest channel capacity because the highest frequency diversity gain can be obtained owing to subcarrier selection. However, the 3rd and 4th constructed logical routes provide lower channel capacity because their frequency diversity gain is lower.

On the other hand, since all logical routes are constructed at one time in the collective construction method, the channel capacity difference among four logical routes is smaller for the collective construction method than for the successive construction method. Therefore, the channel capacities of the 3rd route and the 4th route are smaller for the successive construction method than for the collective construction method. However, the successive construction method can achieve the higher channel capacity than the collective construction method for the maximum and the 2nd routes. Therefore, the sum channel capacity of four logical routes of the successive construction method is almost the same as the collective construction method. On the other hand, the successive construction method can greatly reduce the number of combinations to be examined compared with the collective construction method as shown in Figure 3.

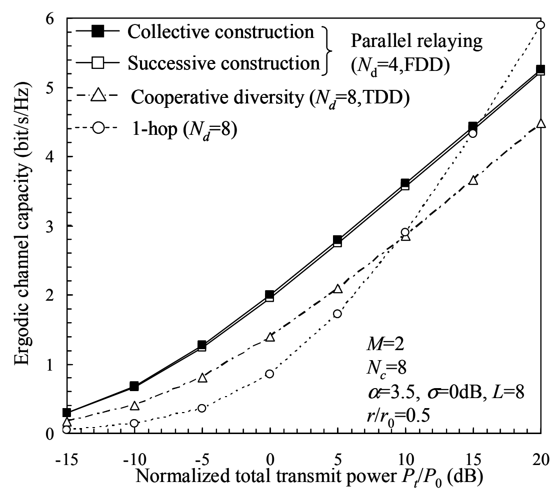

Figure 5 Ergodic channel capacity.

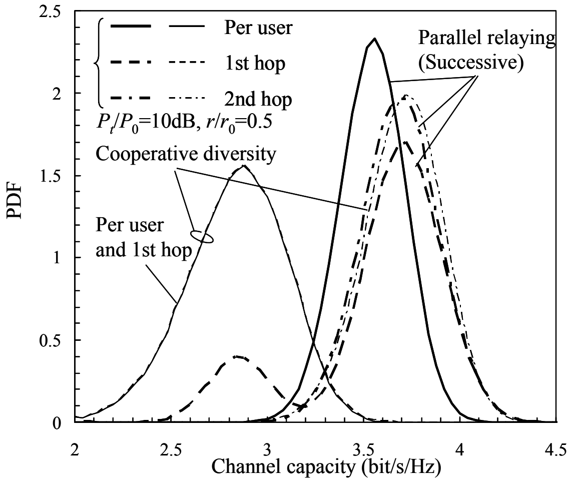

Figure 6 PDF of total channel capacity.

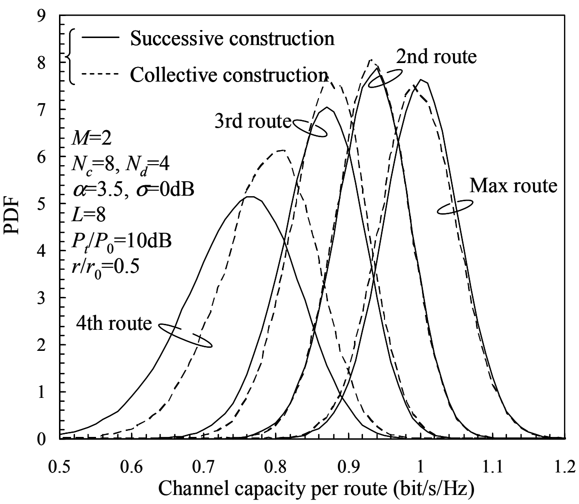

Figure 7 PDF of channel capacity of each logical route.

Figure 8 plots the channel capacity as a function of normalized distance r/r_0 between CP and WP. It is seen from Figure 8 that the channel capacity of the parallel relaying scheme becomes maximal when WP is located at the middle between CP and MT. This is because the first hop and second hop links can obtain the almost same diversity gain as mentioned earlier.

On the other hand, for the cooperative diversity scheme, the channel capacity becomes maximal when WP is located near CP, because the cooperative diversity scheme can improve the channel capacity of second hop link only. It is also seen that the parallel relaying scheme can achieve a larger channel capacity at any location of WP.

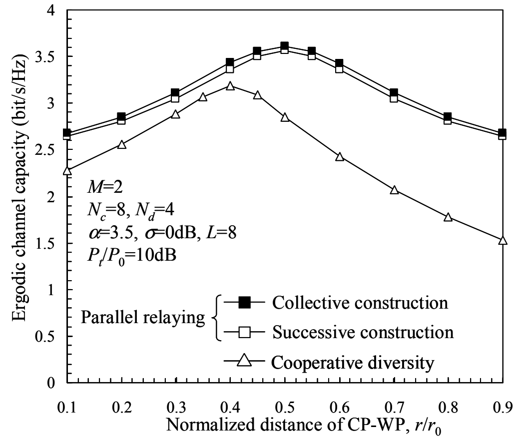

Figure 8 Impact of CP location.

V. CONCLUSION

In this paper, we proposed the OFDMA parallel relaying scheme. In parallel relaying scheme, route construction and subcarrier allocation are done simultaneously to achieve route diversity gain and frequency diversity gain, and thus to efficiently reduce the transmit power while improving the transmission performance. However, an extensive search is needed to search the best logical route defined by a physical route and subcarriers to each link along the physical route. We also proposed the successive construction method that can reduce the number of combinations to be examined.

We evaluated the channel capacity by computer simulation. It was shown that the parallel relaying scheme can achieve the larger channel capacity compared with the cooperative diversity scheme. The parallel relaying scheme can achieve larger channel capacity compared with single-hop communication when the transmit power is kept small.

REFERENCES

[1] R. Pabst, etc., "Relay-based deployment concepts for wireless and mobile broadband radio," IEEE Commun. Mag., vol.42, no.9, pp.80-89, Sept. 2004.

[2] T. Otsu, Y. Aburakawa and Y. Yamao, "Multi-hop wireless link system for new generation mobile radio access networks," IEICE Trans. Commun., vol.E85-B, no.8, pp.1542-1551, Aug. 2002.

[3] E. Kudoh and F. Adachi, "Power and frequency efficient wireless multi-hop virtual cellular concept," IEICE Trans Commun., vol.E88-B, no.4, pp.1613-1621, April 2005.

[4] E. Kudoh and F. Adachi, "Distributed dynamic channel assignment for multi-hop DS-CDMA virtual cellular network," IEICE Trans. Commun., vol.E88-B, no.6, pp.2525-2531, June 2005.

[5] K. Ryoulhee, J.M. Cioffi, "Resource-Allocation for OFDMA Multi-Hop Relaying Downlink Systems," Proc. IEEE GLOBECOM '07, p.3225-3229, 26-30 Nov. 2007.

[6] S. J. Kim, X. Wang, M. Madihian, "Optimal resource allocation in multi-hop OFDMA wireless networks with cooperative relay," IEEE Transactions on Wireless Communications, vol.7, no.5,pp. 1833 – 1838, May 2008.

[7] A. Nosratinia, etc., "Cooperative communication in wireless networks," IEEE Commun. Mag., vol.42, no.10, pp.74-80, Oct. 2004.

[8] J.N. Laneman, D.N.C. Tse, G.W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," IEEE Trans. Info. Theory, vol.50, pp.3062-3080, Dec. 2004.

[9] T. Miyano, T. Murata, H. Araki, "Space time coded cooperative relaying technique for multi-hop communications," Proc. IEEE 60th Veh. Tech. Conf. (VTC) 2004, vol.7, pp.5140-5144, Sept. 2004.

[10] J.G. Proakis, *Digital communications*, 3rd ed., McGraw-Hill, 1995.

[11] R. U. Nabar, H. Bolcskei, F. W. Kneubuhler, "Fading relay channels: performance limits and space-time signal design," IEEE J. Sel. Areas Commun., vol.22, no6, pp.1099-1109, Aug. 2004.