Journal of The Institute of Electronics and Information Engineers Vol.52, NO.6, June 2015
http://dx.doi.org/10.5573/ieie.2015.52.6.003
ISSN 2287-5026(Print) / ISSN 2288-159X(Online)

논문 2015-52-6-1

역방향 CDMA 시스템에서 에너지 최적화된 전송기법: 그래프 이론적 접근

(Energy Optimized Transmission Strategy in CDMA Reverse Link: Graph Theoretic Approach)

오 창 윤*

(Changyoon Oh©)

요 약

본 논문에서는 짧은 지연시간을 요구하는 CDMA 시스템 환경에서 전송률 스케줄링과 전력량 할당 문제를 연구한다. 구체적으로, 본 논문은 각각의 단말이 짧은 구간 동안의 평균 전송률을 유지하는 동시에 에너지 효율적인 스케줄링 방안을 제안한다. 다중 코드를 적용한 CDMA 시스템을 고려하며, 각각의 코드는 가상의 사용자로 해석할 수 있다. 논문의 최종 목적은 전송률 과정에서 소모하는 에너지가 최소화되도록 각각의 시간슬럿에 가상의 사용자를 스케줄링하는 방안을 제안하는 것이다. 주목할만한 점은, 본 논문에서 고려하는 전송률 최적화 문제가 최단 경로 알고리즘으로 해결 가능하다는 점이다. 마지막으로, 본 논문이 제안하는 에너지 최적화 스케줄링 방안을 TDMA 형식의 스케줄링 방안과 성능 비교 분석한다.

Abstract

We investigate rate scheduling and power allocation problem for a delay constrained CDMA systems. Specifically, we determine an energy efficient scheduling policy, while each user maintains the short term (n time slots) average throughput. We consider a multirate CDMA system where multirate is achieved by multiple codes. Each code can be interpreted as a virtual user. The aim is to schedule the virtual users into each time slot, such that the sum of transmit energy in n time slots is minimized. We then show that the total energy minimization problem can be solved by a shortest path algorithm. We compare the performance of the optimum scheduling with that of TDMA-type scheduling.

Keywords : Transmit Energy, Shortest Path Algorithm, Scheduling

Ⅰ. 서 론

Energy efficiency in communication network is an attracting issue not only to maintain profitability, but also to reduce the environmental effects. Many researches have investigated to achieve green communications[1~2]. Scheduling plays an important role in enabling efficient transmission for wireless systems with multiple users[3~4]. Scheduling users in a CDMA system have been investigated to support applications with high bandwidth and strict latency requirements[5~6]. Energy efficient power and rate allocation for Direct Sequence (DS)-CDMA systems are investigated in [5], whereas reference[6] investigates the optimal and suboptimal solutions to

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* 정회원, 인하공업전문대학 정보통신과
(Dept. of Information and Communication Engineering, Inha Technical College)
© Corresponding Author (Email: changyoonoh@inhatc.ac.kr)

※ 이 논문은 2015학년도 인하공업전문대학 교내연구비지원에 의하여 연구되었음
Received ; April 13, 2015 Revised ; May 11, 2015
Accepted ; May 22, 2015

the scheduling problem in systems with multiple receive antennas. These protocols achieve the maximum instantaneous system throughput, however, fairness in terms of the throughput of each user is not considered in either of the references. A short term average throughput for each user facilitates fairness. This is the motivation behind our investigation of the efficient scheduling problem with an average throughput requirement. In this paper, we investigate rate scheduling and power allocation problem for a delay constrained CDMA system. Specifically, we determine a power efficient scheduling policy, while each user maintains the short term (n time slots) average throughput. In reference [7], similar problem is investigated. Hybrid TDMA/CDMA approach is considered for energy efficiency transmission. But the proposed solution is heuristic. In this paper, we investigate the energy optimal approach. We consider a multi rate CDMA system facilitated by the aid of multiple codes. The aim is to schedule the virtual users into these n time slots, such that the sum of transmit energy in n time slots is minimized. At the outset, this problem looks similar to the bin packing problem which is NP-complete[8]. Fortunately, the specifics of the problem enable it to admit a simple solution. In this paper, we show that the total transmit energy minimization problem can be solved by a shortest path algorithm.

Ⅱ. System Model and Problem Formulation

A. System Model

We consider the uplink of a CDMA system where K terminals communicate with an access point. It is assumed that the channel gain is quasi-static, so that the channel gain of terminal i during the short term (n time slots) is constant and is equal to g_i. Each terminal may change its transmission rate by the number of codes it uses in each time slot, but maintains the average throughput during the n time slot frame. The multicodes are considered as virtual users. Each code is assumed to be a randomly generated signature sequence following the reference [9]. In this setting, virtual users interfere with each other if they transmit in the same time slot, even if they belong to the same terminal. The signal to interference ratio of kth virtual user of terminal i in the time slot l is defined as

$$SIR_{i_k l} = N \bullet \frac{p_{i_k l} g_i}{\sum_{j=1}^{K} \sum_{m=1}^{K_{jl}} p_{j_m l} g_j - p_{i_k l} g_i + I} \qquad (1)$$

where I represents the sum of noise and the intercell interference power and N is the processing gain. $p_{i_k l}$ denotes the transmit power of kth virtual user of terminal i in the time slot l. K_{jl} denotes the number of virtual users of terminal j in the time slot l. We assume that $g_1 > g_2 > \cdots > g_K$, such that the terminal with lower index has a higher channel gain. In the multicode format, the rate of terminal i in time slot l, R_{il} is defined by the number of multicodes, K_{il}, i.e., $R_{il} = K_{il} \times R_B$. R_B is the rate of a virtual user in one time slot, defined as $\frac{W}{N}$ where W is the spreading bandwidth[9]. Then, the sum of rate of user i during the n time slots is $\sum_{l=1}^{n} R_{il} = \sum_{l=1}^{n} K_{il} R_B$. We assume a common target SIR, i.e., SIR_{target} for all virtual users.

B Problem Formulation

Given the time slot in the frame are of equal duration, minimizing the total energy is equivalent to minimizing the total transmit power of all users in all time slots. We aim to minimize the total transmit power spent by all users in a frame subject to short term throughput constraints. More specifically, the problem is to minimize the sum of transmit power of K users in n time slots, while each user maintains the short term average throughput $\sum_{l=1}^{n}\frac{K_{il}R_B}{n}=\overline{R_i}$. $\overline{R_i}$ denotes the average throughput requirement of user i. We assume that the system has a feasible solution for a given $\overline{R_i}$, that is, the system can accommodate all the users at their SIR target and short term throughput requirements. Formally, the optimization problem is:

$$\min \sum_{l=1}^{n}\sum_{i=1}^{K}\sum_{k=1}^{K_{il}} p_{i_k l} \tag{2}$$

$$\text{s.t. } SIR_{i_k l} \geq SIR_{target} \quad \forall i$$

$$\sum_{l=1}^{n} K_{il} = \frac{n\overline{R_i}}{R_B} \quad \forall i$$

$$p_{i_k l} \geq 0$$

The first constraint maintains the minimum target SIR requirement of each virtual user, while the second constraint imposes the short term average throughput requirement. Because $\sum_{l=1}^{n}K_{il}$ is an integer value, R_i is assumed to be chosen such that $\frac{n\overline{R_i}}{R_B}$ is an integer value. We note that user i may decrease its transmission rate to zero in any given time slot, as long as the average throughput requirement is satisfied. Assuming M_l virtual users in the time slot l, i.e., $M_l=\sum_{i=1}^{K}K_{il}$, the optimum received power for each virtual user is achieved when the SIR constraint in (2) is satisfied with equality, i.e., when the received power of all virtual users in the same time slot are equal. The optimum equal received power for each virtual user in the time slot l is given by

$$q_l^* = \frac{\frac{I\gamma^*}{1+\gamma^*}}{1-M_l\frac{\gamma^*}{1+\gamma^*}} \tag{3}$$

where $\gamma^* = \frac{SIR_{target}}{N}$ is the SIR target normalized by the processing gain. Note that this equal received power solution in the same time slot is well known result in a classical optimal power control theory such as min Power[10]. For the resulting received power value to be feasible, we need $q^* > 0$. Hence, the maximum number of virtual users in a time slot is limited by $\left\lfloor \frac{1+\gamma^*}{\gamma^*} \right\rfloor$. Accordingly, a feasible solution exists when the total number of virtual users in n time slots does not exceed $n\times\left\lfloor \frac{1+\gamma^*}{\gamma^*} \right\rfloor$.Given the relation between the optimum transmit power and the optimum received power for terminal i in time slot 1 $p_{i_1 l}g_i = p_{i_2 l}g_i \cdots = p_{i_{K_{il}} l}g_i = q_l^*$, the optimization problem in (2) is reformulated as:

$$\min \sum_{l=1}^{n} q_l^* \sum_{i=1}^{K}\frac{K_{il}}{g_i} \tag{4}$$

$$\text{s.t. } \sum_{l=1}^{n} K_{il} = \frac{n\overline{R_i}}{R_B}$$

i.e., the optimization problem in (4) is to find K_{il} $\forall i$ and $\forall l$, the number of virtual user for each user i in each time slot l, to minimize the total transmit power in n time slots, while each terminal i has $T_i=\frac{n\overline{R_i}}{R_B}$ virtual users in n time slots. Thus, $T=\sum_{i=1}^{K}T_i$ virtual users are to be scheduled in n time slots such that the total transmit power is minimized. We note that the optimization problem considered here is different from the channel base station assignment problem[8], where multiple base station is considered, which is known as NP-complete.

Ⅲ. Optimum Scheduling

In this section, we provide the solution for optimization problem (5). First, we note that, the structure of the optimum scheduling policy relies on the following Proposition.

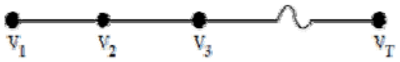

그림 1. 가상사용자 스케즐링 순서로 구성된 스트링
Fig. 1. A string constructed from the virtual users scheduling order.

Proposition 1. The optimum policy schedules the virtual users in such a way that any virtual user with a lower channel gain is assigned to a time slot with a lighter load, i.e., a slot with smaller number of virtual users.

To see why Proposition 1 is valid, suppose the optimum policy schedules users such that one virtual user j with channel gain g_j is assigned to slot 1, and another virtual user i with channel gain g_i $(g_i > g_j)$ is assigned to slot 2. It is assumed that slot 1 has more virtual users than slot 2, i.e., $M_1 > M_2$. Hence, $q_1^* > q_2^*$. If we exchange these two virtual users i and j between two slots, slot 1 and slot 2, all the virtual users except these two need the same transmit power level, because q_1^* and q_2^* remains the same. However, the sum of these two virtual users power level is decreased, i.e., $\frac{q_1^*}{g_i}+\frac{q_2^*}{g_j}<\frac{q_1^*}{q_j}+\frac{q_2^*}{q_i}$.

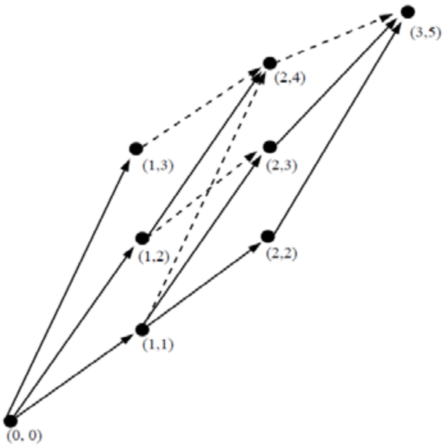

그림 2. 5 개노드를 가진 스트링을 3개로 나눈 네트워크
Fig. 2. Network constructed by 3 partitioning the string having 5 nodes.

Hence, the total transmit power is decreased. Proposition 1 provides a valuable information for determining the power efficient optimum scheduling policy. Define the set of virtual users in time slot l as s_l. We use $|s_l|$ and M_l interchangeably for representing the number of virtual users in time slot l. Note that the sets of virtual users $\{s_1, s_2, \cdots, s_n\}$ should satisfy $|s_l| \neq 0$ and $\sum_{l=1}^{n} |s_l| = T$ for any valid schedule. Note also that, collection of virtual user sets resulting from any scheduling policy can be reordered such that $\{s_1, s_2, \cdots, s_n\}$ where $|s_1| \leq |s_2| \leq \cdots \leq |s_n|$, termed the reordered virtual user sets. This reordering of virtual user sets (time slots) does not change the total power value expended as a result of this policy. That is, the performance of the scheduling policy is a function of how many virtual users are scheduled into each slot only, and not the actual location of these slots in the n-slot frame.

Therefore, we only need to consider scheduling policies with the reordered virtual user sets to find the optimum scheduler. Consider such a group of reordered virtual user sets. The following observation states how the optimum policy schedules the T virtual users to this reordered virtual user sets.

Proposition 2. For any given reordered virtual user sets, the optimum scheduling order of T virtual users is in the order of increasing channel gain, i.e.,

$$\underbrace{g_K, \cdots, g_K}_{T_K}, \underbrace{g_{K-1}, \cdots, g_{K-1}}_{T_{K-1}}, \cdots, \underbrace{g_1, \cdots, g_1}_{T_1} \tag{5}$$

where $T_i = \frac{n\overline{R_i}}{R_B}$. Terminal i is factored into T_i virtual users with an identical channel gain. Note that the scheduling order (5) satisfies Proposition 1.

Hence, (5) is in the form of a candidate for the output of the optimum scheduler. Accordingly, the optimization problem in (4) is to find the best reordered virtual user set group such that the sum of total transmit power is minimized, given the optimum scheduling order in (5).

The optimization problem in (4), by an appropriate transformation, can be formulated as a graph partitioning problem with a solution that has polynomial complexity. Specifically, the optimization problem in (4) can be transformed into a graph partitioning problem following the approach in reference[11], as described next.

We note that (5) in Proposition 2 constitutes a string, which is a graph where all vertices are located along a line, $G=(V,E)$ with vertices $V=\{v_1,v_2,\cdots,v_T\}$ and edges $E=\{(v_1,v_2),\cdots,(v_{T-1},v_T)\}$, as in Figure 1. More specifically, an edge is constructed by connecting two adjacent virtual users. Each virtual user is represented by a vertex along the string. More specifically, each virtual user in (5) is sequentially mapped into the vertex of the string from the left to the right. The weight of a vertex is $w_i=\frac{1}{g_i}$ where g_i is the channel gain of the virtual user corresponding to that vertex.

Given the string $G=(V,E)$ as in Figure 1, let $\{S_1,\cdots,S_n\}$ be the partition of the set of vertices V into n subsets, and each subset S_1 has a set of connected vertices. Note that in a feasible partition, $|S_l|\neq 0$. In this setting, the virtual user sets $\{s_1,\cdots,s_n\}$ is equivalent to $\{S_1,\cdots,S_n\}$. Hence, we use s_1 and S_1 interchangeably. The cost of a virtual user set (subset) s_1 is $q_l^*\sum_{i\in s_l}\frac{1}{g_i}$ and the cost of all virtual user sets is $\sum_{l=1}^{n}q_l^*\sum_{i\in s_l}\frac{1}{g_i}$. Therefore, the optimization problem in (4) is equivalent to finding a feasible n-partition such that given cost is minimized:

$$\arg\min_{\{s_1,\cdots,s_n\}}\sum_{l=1}^{n}q_l^*\sum_{i\in s_l}\frac{1}{g_i} \tag{6}$$

We note that, although the problem of optimally partitioning an arbitrary graph with an arbitrary cost function is NP-hard, partitioning a string optimally with a separable cost function can be solved in polynomial time[8]. Note that the cost function in (6) is separable. In this case, the problem of graph partitioning a string can be reduced to a shortest path problem with complexity $O(nT^2)$.

In the following, the solution of the partitioning problem in (6) by a shortest path algorithm is described. We construct a network from the string that represents the virtual users. The node that lies between the origin-destination pair are given by the set

$$\{(i,j):1\leq i\leq n-1;i\leq j\leq T-n+i\} \tag{7}$$

An edge is placed from node $(i1,j1)$ to $(i2,j2)$ if $i2=i1+1$ and $j2>j1$j2 > j1. Otherwise, there is no edge between $(i1,j1)$ and $(i2,j2)$. There is a one-to-one relationship between the cost function of a feasible partition in a string, and the cost function of a path in the network constructed from the partitioning problem.

For instance, consider $T=5$ and $n=3$. From the string with 5 vertices (virtual users), we first construct the network as Figure 2. At node (i,j), i and j denote the index of the time slot and the index of virtual user, respectively. The cost of a path

between node $(l-1,t)$ and $(l,t+w)$ is the cost of the virtual user set sl, i.e., $q_l^*\sum_{i\in s_l}\frac{1}{g_i}$ where $|s_l|=w$ ..

We note that the optimum policy should satisfy $|s_1|\leq|s_2|\leq\cdots\leq|s_n|$ and the maximum number of virtual users in a time slot, $\left\lfloor\frac{1+\gamma^*}{\gamma^*}\right\rfloor$. Hence, if a path violates any of these two constraints, the cost of that path is set to be infinity. Next, a shortest pathfrom the origin to the destination with cost $\min_{\{s_1,\cdots,s_n\}}\sum_{l=1}^{n}q_l^*\sum_{i\in s_l}\frac{1}{g_i}$ is obtained by using a shortest path algorithm such as Dijkstra's method which has complexity $O(nT^2)$. The resulting optimum partition $\{s_1,\cdots,s_n\}$ provides K_{il} $\forall i$ and $\forall l$.

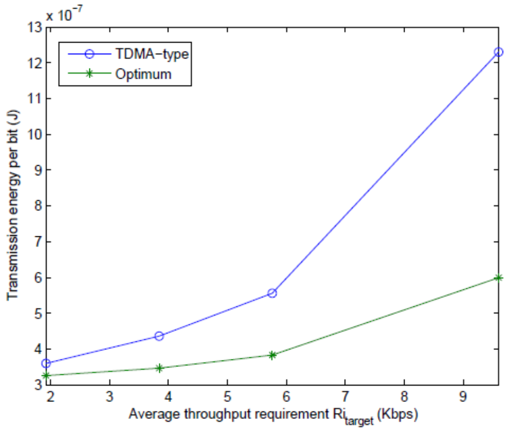

그림 3. 평균적 소모에너지
Fig. 3. Average Energy consumption.

Ⅳ. Numerical Results

We consider the uplink of a CDMA system with a spreading bandwidth $W=1.228MHz$ and the processing gain $N=128$. Other interference other than cochannel interference is $I=10^{-13}$. Target SIR is $SIR_{target}=5$. With $SIR_{target}=5$, maximum number of virtual users in each time slot is limited by 26. $K=5$ users are uniformly distributed within the cell with radius 1km. The frame size is $n=5$ time slots. Channel gain of user i g_i, is modeled $\frac{r_i}{d_i^4}$ as where d_i is distance between the base station and the user i. r_i is the log-normal fading with variance 8dB.

Figure 3 shows the power consumption of two scheduling methods, the optimum scheduling and the TDMA-type scheduling, for average throughput requirement $\overline{R_i}=9.6kbps$, $28.8kbps$, $38.4kbps$ and $48.0kbps$. With $K=5$ users, maximum average throughput is limited by $48.0kbps$. In TDMA-type scheduling, user i transmits with rate $n \times R_i$ and users transmit in a round robin fashion. The result is obtained by averaging 10,000 channel realizations. As the average throughput requirement increases, i.e., the system load gets heavier, the gap between the performance of the optimum scheduler and that of the TDMA-type scheduling increases. This results clearly indicate the benefit of optimum scheduling for a loaded system. Note that if the channel gains of all users are identicall, the optimum scheduler and TDMA result in the same performance. Figures 4 demonstrate the optimum transmission rate allocation for a specific channel realization into $n=10$ time slot frame. The average throughput requirement is $\overline{R_i}=28.8kbps$. It is shown that, for power efficient transmission, the virtual user with lower channel gain is assigned to a less loaded time slot.

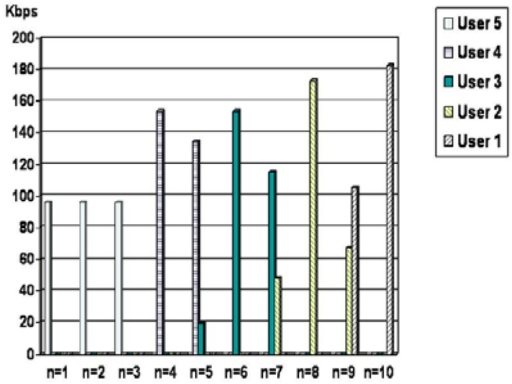

그림 4. 슬럿 구간에서의 전송률 할당
Fig. 4. Rate Allocation in the time slots.

Ⅴ. Conclusions

We have considered power efficient scheduling for delay constrained multicode CDMA services. Short term average throughput requirement is imposed to maintain an average throughput for each user. It is assumed that multiple data rates are provided by means of multiple signatures (codes) each of which is treated as a virtual users. We allow codes assigned to each user to interfere with each other, as well as with codes assigned to other users. For power efficient transmission, these virtual users should be carefully scheduled. The contributions of this paper are twofold. First, graph theoretic approach is applied to the energy efficiency rate scheduling problem. Second, the optimum scheduling algorithm with polynomially solvable complexity is proposed. We have shown that the optimum scheduler can be obtained by solving a shortest path problem. Our numerical results demonstrate that the optimum.

REFERENCES

[1] Z. Hasan et al.,, Green Cellular Networks: A Survey, Some Research Issues and Challenges, IEEE Communications Surveys & Tutorials, vol. 13, no. 4, p534-540, Fourth Quarter 2011.
[2] E. Calvanese Strinati at al., Green Communications: An Emerging, p267-301, May, Journal of Green Engineering, 2011.
[3] S. Cui, R. Madan, A. J. Goldsmith, and S. Lall, Energy-delay tradeoffs for data collection in TDMA-based sensor networks. In IEEE International Conference on communications, ICC'05, May 2005.
[4] Y. Yao and G. B. Giannakis, Energy-efficient scheduling protocols for wireless sensor networks. In IEEE International Conference on Communications, ICC'05, May 2005.
[5] F. Berggren and Seong-Lyun Kim, Energy-efficient control of rate and power in DS-CDMA systems, IEEE Transactions on Wireless Communications, 3(3):725 - 733, May 2004.
[6] Il-Min Kim, R. Yim, and H. Chaskar, Optimum scheduling for smart antenna systems in Rayleigh fading channels, IEEE Transactions on Communications, 53(7):1210 - 1219, July 2005.
[7] Tao Shu and Marwan Krunz. Energy-efficient power/rate control and scheduling in hybrid TDMA/CDMA wireless sensor networks. Computer Networks: The International Journal of Computer and Telecommunications Networking, Vol. 53 Issue 9, 1395-1408. June 2009.
[8] M.R. Garay and D.S. Johnson, A guide to the theory of NP completeness. W.H, Freeman and company, 1991.
[9] S. Ulukus, F. Biglieri, M Win, Optimum modulation and multicode formats in CDMA systems with multiuser receivers, INFOCOM 2001, Vol. 1, 395-402.
[10] P. Viswanath et. al., Optimal Sequences, Power Control, and User Capacity of Synchronous CDMA Systems with linear MMSE Multiuser Receivers, IEEE Transactions on Information Theory Vol. 45, No. 6, September 1999.
[11] C. De Simone, M. Lucertini, S. Pallottino, Fair dissections of spiders, worms, and caterpillers. Networks, 20:323-344, 1990.

저 자 소 개

오 창 윤(정회원)
1999년 연세대학교 전기공학과 학사 졸업
2001년 Pennsylvania State University, Electrical Engineering 석사 졸업
2005년 Pennsylvania State University Electrical Engineering 박사 졸업
2005년～2011년 삼성전자 DMC연구소 책임연구원
2011년～현재 인하공업전문대학 정보통신과 교수
<주관심분야 : Air Interface PHY/MAC 표준화, Resource Management, Frame Structure, Interference Alignment>